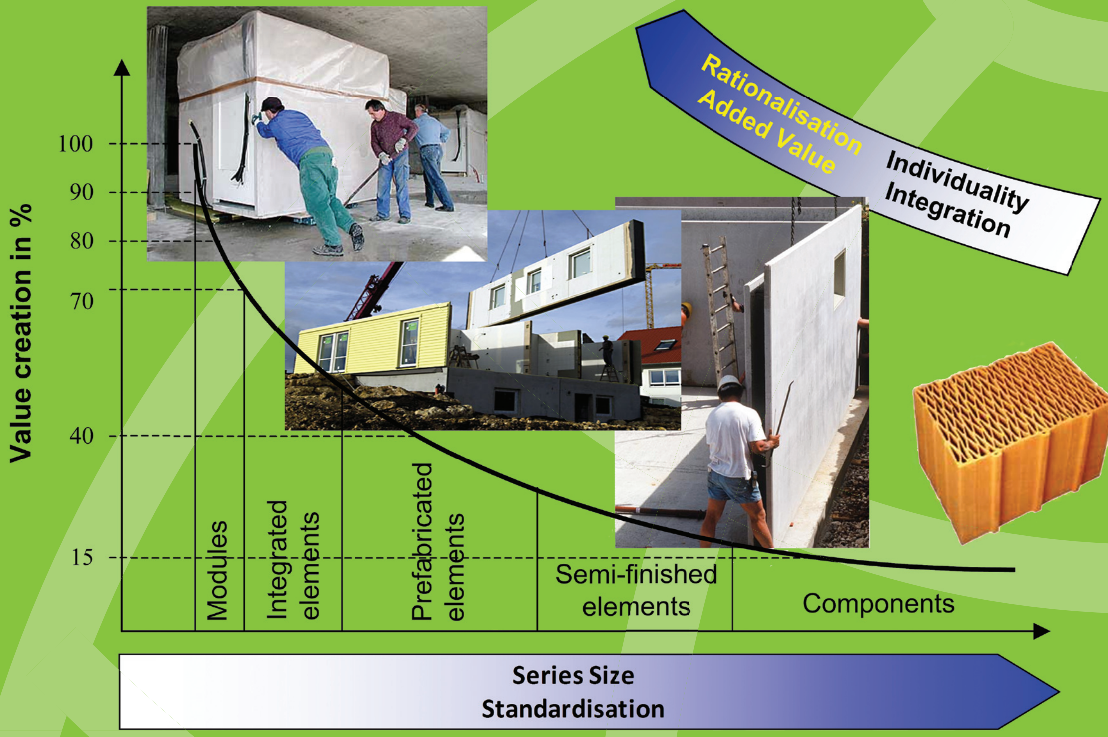


New Perspective in Industrialisation in Construction - A State-of-the-Art Report

CIB Publication 329

ISBN 978-3-906800-17-2

CIB Task Group 57 “Industrialisation in Construction”

New Perspective in Industrialisation in Construction

A State-of-the-Art Report

Edited by
Gerhard Girmscheid
Frits Scheublin

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Institut für Bauplanung und Baubetrieb
Prof. Dr.-Ing. G. Girmscheid
ETH Zürich

Girmscheid, G., Scheublin, F. (Eds.):
New Perspective in Industrialisation in Construction - A State-of-the-Art Report
IBB – Institut für Bauplanung und Baubetrieb.
Zurich: Eigenverlag des IBB an der ETH Zürich, 2010
ISBN 978-3-906800-17-2

ISBN 978-3-906800-17-2

PREFACE

This book is a compilation of the best papers written by the members of CIB Task Group 57 on Industrialisation in Construction.

The Task Group 57 was founded at the Triennial Conference of CIB in Montreal 2004. The Board of CIB came to the conclusion that there was a growing need for market driven research with a strong focus on industrialisation. The editors of this book, Prof. Gerhard Girmscheid from the Swiss Federal Institute of Technology Zurich (ETH Zurich) and Prof. Frits Scheublin from Eindhoven University of Technology (TUE) were appointed as the founding coordinators of the Task Group. Approximately 30 members attended the Task Group meetings and communicated between meetings about their research projects. This publication is a compilation of the best papers presented and discussed during the annual meetings of the Task Group. Where needed papers were re-edited to better meet the requirements of a formal CIB-publication.

ACKNOWLEDGEMENT

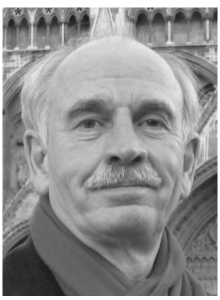
This publication would not have been possible without the contributions by the members of Task Group 57. Almost all of them hold very demanding positions at leading universities or national research institutes worldwide. The editors are grateful to the members for their enthusiasm and dedication.

We are also grateful to the staff of CIB. Without their practical assistance and mental support this work would never have reached the final stage.

A special thank-you is addressed to Thomas Rinas, PhD student at ETH Zurich for his enthusiasm and tremendous support whilst realising this publication. It was him who did the main task of technical editoring, collecting texts and chasing authors when deadlines came too close. This publication could not have been brought to fruition without his enormous efforts in editing and layouting it.

Finally we wish to mention Prof. Alistair Gibb of Loughborough University who assisted the editors as a peer reviewer and who gave much helpful advice for authors and coordinators.

Gerhard Girmscheid
Editor



Frits Scheublin
Editor

Thomas Rinas
Technical Editor

STRUCTURE OF THE BOOK

The aim of the editors is to give the reader an overview of the State of the Art in respect of Industrialisation in Construction. This book is divided in 4 sections

- Context
- Strategies
- Methods and Tools
- Products

We start with a general introduction into the subject. Here the context in which industrialisation must finds its way is described. This introduction into the context is followed by two chapters specifying the strategies and the methods and tools available for industrialised construction. In the last chapter some successful examples of industrialisation are shown.

The editors,

Prof. Gerhard Girmscheid

Prof. Frits Scheublin

INTRODUCTION

Historic perspective

Looking back at how industrialisation started brings us to the 19th century. Early in that century mechanical power came available and gradually replaced manpower and horsepower. In those days production technologies underwent a major transfer. Small hand held tools were replaced by heavy machines. This caused a need to move the production of most goods from the manufacturer's dwellings to factories. In factories big, dirty and noisy machines could be installed and the massive output could be stored and handled better. This move from small scale production to mass production caused by the availability of mechanical power is generally known as the Industrial Revolution. For construction this early stage of industrialisation had hardly any affect on the traditional processes. Products had never been home-made. The work place had always been out in the open and it stayed as it was. Some mechanical tools were adapted such as drills, lifting devices and motorised means of transport, but mechanised production was not an option.

A second industrial revolution was driven by the invention of the computer. Not only mans' power, but also the functions of mans' brains, ears and eyes could be performed by equipment. Calculating, planning, sensing, steering and decision making became step by step computerised tasks. And again the construction industry was a late adaptor, if there was any adaption at all. At the end of the 20th century almost all handling in factories was done by computer driven devices. But in construction brick layers, carpenters and plumbers continued to position materials by hand guided by visual information only.

As a consequence construction became one of the most labour intensive industries. Housing became a luxury good, hardly affordable for average income people. While the quality of most industrial goods became better and better, the quality of construction work suffered from lack of craftsman and poor labour conditions. Now 10% of all jobs are in construction and this percentage is still growing steadily. If the industry cannot benefit more from industrialisation then construction will soon be too expensive for anyone.

The CIB Task Group 57 on Industrialisation in Construction is aware of the difficulties and constraints we meet when trying to industrialise construction work, but we also are convinced that industrialisation is inevitable and not impossible.

Definitions for Industrialisation

Industrialisation is not easy to define. Dictionaries give a variety of descriptions. But little consensus is found. Several aspects are usually linked with industrialisation such as:

- Use of mechanical power and tools
- Use of computerised steering systems and tools
- Production in a continuous process

- Continues improvement of efficiency
- Standardisation of products
- Prefabrication
- Rationalisation
- Modularisation
- Mass production

This list could probably be completed with many more characteristics of industrialisation. An all inclusive definition was not found. Most authors in this publication present their personal view on this.

The Task Group agreed in its first meeting on a short definition being: “Industrialisation in Construction is a rationalisation of the work processes in the industry to reach cost efficiency, higher productivity and quality.”

Alistair Gibb wrote a more elaborate definition: “Industrialisation in construction is a change of thinking and practice to improve the production of construction to produce a high quality, customised built environment, through an integrated process, optimising standardisation, organisation, cost and value, mechanisation and automation.”

Roger-Bruno Richard from the University of Montreal focussed part of his research on the definition case. We include three papers from his hand. In chapter 1 he presents his vision on the 5 stages of industrial production, in chapter 2 followed by 4 strategies for industrialised building. Finally in chapter 4 his classification system for industrialised building is explained.

Drivers, conditions and consequences

When defining Industrialisation we must understand that there are three types of characteristics or aspects. First the drivers (why we industrialise), second the conditions (essential and therefore part of the definition) and third the consequences (resulting from the chosen process, other than the drivers).

Drivers to industrialise are:

- Need for safety
- Need for better quality control
- Need for better occupational health
- Need for better environmental care.
- Need for cheaper production
- Lack of skilled labour

Conditions are:

- Mechanised tools
- Automated tools
- Intelligent tools

Consequences are:

- Mass production
- Mass customisation
- Prefabrication
- Standardisation
- Modularisation

CONTENTS

CONTRIBUTORS LIST

AUSTIN, S.A.
BSc PhD CEng MICE, Professor of Structural Engineering, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 222608, s.a.austin@lboro.ac.uk ... 149

BECHTHOLD, MARTIN
DDes., Professor of Architectural Technology, Co-Director of Master in Design Studies Program, Director of Fabrication Labs, Harvard Graduate School of Design, 48 Quincy Street, Cambridge MA 02138, Phone +1 617 495 6012, Fax +1 617 495 2943, mbechthold@gsd.harvard.edu ... 53

BOCK, THOMAS
Prof. Dr.-Ing./ Univ. Tokio, Chair for Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.bock@bri.arch.tu-muenchen.de ... 161, 207, 263, 281

BRÄM, MATTHIAS
Dipl. Architect ETH-Z, Managing director BWA bausysteme GmbH, CH-1006 Lausanne, Phone +41 (0)21 312 81 06, Professor at HEPIA, haute école du paysage, d'ingénierie et d'architecture de Genève, CH-1202 Genève, matthias.braem@sunrise.ch ... 317

BUSWELL, R.A.
BEng, PhD, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 223783, r.a.buswell@lboro.ac.uk ... 149

COX, MARK
Ir., Eindhoven University of Technolgy, Department of Achitecture, Building and Planning, Vertigo Building, floor 7, room 7.28, PO Box 513, 5600MB EINDHOVEN, The Netherlands, Phone +31-(0) 40-2474050, Fax +31 40 2475887, m.g.d.m.cox@bwk.tue.nl ... 381

EGMOND-DE WILDE DE LIGNY, EMILIA VAN
Dr. Ir. PhD, M.Sc., Senior Lecturer and Researcher, Innovation, Technology and Knowledge Transfer for Sustainable Construction, Faculty of Architecture, Building and Planning, Eindhoven University of Technology, POBox 513, Vrt 7.24, 5600MB Eindhoven, The Netherlands, Phone +31 40 2472439, Fax +31 40 2457234, e.v.egmond@tue.nl ... 37, 67

GIBB, A.G.F.
PhD BSc CEng MICE MCIOB, Professor of Construction Engineering Management, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 223097, a.g.gibb@lboro.ac.uk ... 149

GIRMSCHEID, GERHARD
Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch ... 3, 29, 103, 131, 139, 233, 417

GIURDANELLA, VALERIA
Dr.-Arch. Ph.D. in Technology and Design for Environmental Quality, Building Environment Sciences and Technology Department, Faculty of Architecture & Society, Politecnico di Milano, IT-20133 Milano, Phone/Fax +39.02 23995105, valeria.giurdanella@polimi.it ... 333

HAAS, TIM DE
Ir., Chair of Product Development, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Phone +31 40 2474050, Fax +31 40 2475887, t.c.a.d.haas@tue.nl ... 381

HAREN, LEO VAN
Ir., Chair of Product Development, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Phone +31 40 2474050, Fax +31 40 2475887, lcmvanharen@hotmail.com ... 381

LANDIN, ANNE
Prof. Dr.-Ing., Head of the Division of Construction Management, Lund University, Faculty of Engineering, PO Box 118, 221 00 Lund, Phone +46 46 2227417, Anne.Landin@Construction.LTH.se ... 197

LAWSON, R. MARK
Prof Dr MICE, MIStuctE, MASCE, SCI Professor of Construction Systems, University of Surrey, GU2 7XH, UK, Phone +44 1483 686617, Fax +44 1483 682135, m.lawson@surrey.ac.uk ... 371

LIMBURG, S.M.
Ir., Delft University of Technology, P.O. Box 5043, 2600 GA Delft, The Netherlands, S.M.Limburg@tudelft.nl ... 123

LINNER, THOMAS
Dipl.-Ing., Scientific Assistant, Building Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.linner@bri.ar.tum.de ... 161, 207, 263, 281

LUNZE, DAVID
Dipl.-Ing., Chair of Construction Process and Enterprise Management, Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3370, Fax +41 44 633 1088, lunze@ibb.baug.ethz.ch 139
MONJO-CARRIÓ, JUAN
Prof. Dr.-Arch., Full Professor, Escuela Técnica Superior de Arquitectura, Universidad Politécnica de Madrid, Av. Juan de Herrera 4, 28040 Madrid, Phone +34 91 336 6570, Fax +34 91 336 6560, juan.monjo@upm.es 191
OGDEN, RAY
Prof Dr, SCI Professor of Architecture, Oxford Brookes University, OX3 OPB, UK, rgogden@brookes.ac.uk 371
OOSTRA, MIEKE
Dr. Ir., Netherlands Organisation for Applied Scientific Research (TNO), Built Environment and Geosciences, PO Box 49, NL-2600 AA Delft, Phone +31-15 2673110, Fax +31-15 2763024, mieke.oostra@tno.nl 91
OTEIZA, IGNACIO
Dr.-Arch., Científico Titular, Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC), c/ Serrano Galvache 4, 28033 Madrid, Phone +34 91 302 0440, ioteiza@ietcc.csic.es 191
PAOLETTI, INGRID
MSc Arch., Phd, Assistant Professor in Technology for Architecture, Coodinator of Innovative Technologies and Construction Industry Cluster, BEST - Building Environement Science Technology Dept., Politecnico di Milano, Via Bonardi, 9 - 20133 Milano, Phone +39.02.23995117, Fax +39.02.23995151, ingrid.paoletti@polimi.it 357
QUEIPO DE LLANO, JUAN
Arch., Titulado Superior, Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC), c/ Serrano Galvache 4, 28033 Madrid, Phone +34 91 302 0440, jqueipo@ietcc.csic.es 191
RICHARD, ROGER-BRUNO
Prof., M.Arch. (Berkeley), Architect (OAQ), Head of the graduate Design & Systems for Construction (DSC) profile, School of Architecture, Université de Montréal, P.O. Box 6128 Centre- ville, Montreal (Quebec) H3C 3J7 CANADA, Phone +1 514 343 7968, Fax +1 514 343 2455, roger.richard@umontreal.ca 15, 79, 303
RUTTEN, P.G.S.
Prof. Ir., Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands, P.G.S.Rutten@bwk.tue.nl 123
RYŃSKA, ELŻBIETA D.
Prof. PhD. MSc. Arch. working at the Faculty of Architecture Warsaw University of Technology from 1987. Stipends in USA and Japan. Main interests - sustainable architecture and urban planning, economy of design, dagny.rynska@arch.pw.edu.pl 399
SCHEUBLIN, FRITS
Prof. Ir., Eindhoven University of Technology, Eindhoven, The Netherlands, Faculty of Arcitecture, Building and Planning, chair of Construction Technology, Director of Engineering Bam Construction Group, Swedish Concrete Award 2005, Phone +31 653.33.84.53, Frits.Scheublin@live.nl or F.J.M.Scheublin@tue.nl 183
THILLART, CASPAR VAN DEN
Dr. Ir., Universities of Delft, Eindhoven & Twente and Esprit huis, Javakade 504 1019 SC Amsterdam www. Esprithuis.nl, Phone +31-204191241, c.thillart@xs4all.nl 91
THORPE, A.
CEng CITP BSc MSc PhD FICE FBCS FCIOB FRICS MIMgt, Professor of Construction IT, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 223771, a.thorpe@lboro.ac.uk 149
VASTERT, ERIC
Dr. Ir., Assistant Professor, Chair Construction Engineering, Department of Architecture, Building and Planning, University of Technology Eindhoven, the Netherlands, Phone +31 40 2473281, e.w.vastert@tue.nl 389
ZANELLI, ALESSANDRA
Dr.-Arch. Ph.D., Assistant Professor in Technology of Architecture, TensiNet Associate Member and Regional Representative, Building Environment Sciences and Technology Department, Faculty of Architecture & Society, Politecnico di Milano, IT-20133 Milano, Phone/Fax +39.02 23995135, alessandra.zanelli@polimi.it 333

CHAPTER I:
CONTEXT OF INDUSTRIALISATION

Industrialisation not only creates new opportunities, it also forces the construction industry to adapt new practices. The most applied industrial practice is Prefabrication. Gerhard Girmscheid analysed the available prefabrication systems. He explains the definitions, opportunities and threats of on-site and off-site production, followed by an analysis of open and closed prefab systems.

Industrialisation enables the construction industry to manage material and energy flows better. Optimised material management stands at the beginning of environmental careful construction. It is a condition for sustainable construction. Emilia van Egmond, University of Technology Eindhoven, managed a comparative research project on sustainable construction practices in Chile and in The Netherlands. She found opportunities and threats to industrialised sustainable construction. In a separate contribution she discusses the innovative attitude and paradigm shift required for a successful industrialisation process.

The most powerful driver behind the second industrial revolution was - and still is - the emergence of computer technology. Martin Bechthold - Harvard USA - looks into the state of the art in computer aided design (CAD) and computer numerically controlled construction (CNC). Roger-Bruno Richard, University of Montreal, goes one step further. He argues that 3-dimensional reproduction technology will facilitate the next big step forward in industrialisation.

A) Context of Industrialisation – Introduction

GERHARD GIRMSCHEID[1]

1 Introduction – Status Quo

Today's technology enables construction companies to focus more on industrialised processes and production methods. For the planning as well as the operation on site are computer supported tools, equipment etc. available. But still most sides are operating on craftsmanship.

If construction companies are to survive successfully over the long term they have to identify and exploit any potential for increasing efficiency by means of a continuous improvement process (CIP) within both the company and the construction process and, not least, to create innovations. The options offered by industrial construction for small and medium-sized construction companies to develop the potential include the following:

- Market orientation
  - Focus on specific segments of the market
  - Supraregional specialisation in certain fields of activity
  - Provision of sustainable products and services
- Resource orientation
  - Detailed planning of work preparation
  - Optimised processes and optimised organisation
  - Use of prefabricated components
  - Standardisation of construction methods and of the materials used,

Adopting these measures allows construction companies to:

- Focus on those fields of activity that offer the most value added
- Increase the share of value adding works and reduce the non-productive support and ancillary works
- Improve product quality and service

---

1 Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch

- Reduce internal costs as a result of CIP
- Improve cost transparency and cost predictability
- Possibly venture into new market sectors and/or develop new customer segments

The cost structure of the overall work performed is analyzed in order to identify possible streamlining options in relevant cost areas. Table A.1 illustrates the typical spread of construction costs and investment costs when erecting a building in Switzerland. The two main cost groups can be clearly identified as materials and labour/equipment. Both of these groups can be influenced by construction companies.

Table A.1: Construction and investment costs by cost group (Girmscheid, 2005)

Cost groups	**Total construction costs**			**Portion of investment costs**
	Share of labour/equipment	Share of material	Portion of construction costs	
	%	%	%	%
Site				25 %
Planning/Construction management			~ 10 %	5 %
Design	70 %	30 %	14 %	
Structure	50 %	50 %	36 %	
Technical facilities	40 %	60 %	30 %	
Interior work	60 %	40 %	20 %	
Construction costs	~ 50 %	~ 50 %	100 %	53 %
Outdoor facilities				7 %
Financing				5 %
Marketing				5 %
Total				100 %

This table shows that wages and equipment account for about 50 % of the construction costs. Building construction is still particularly labour intensive. A more detailed breakdown of how worktime is spent on a construction site is shown in Fig. A.1 (Boenert and Blömeke, 2003).

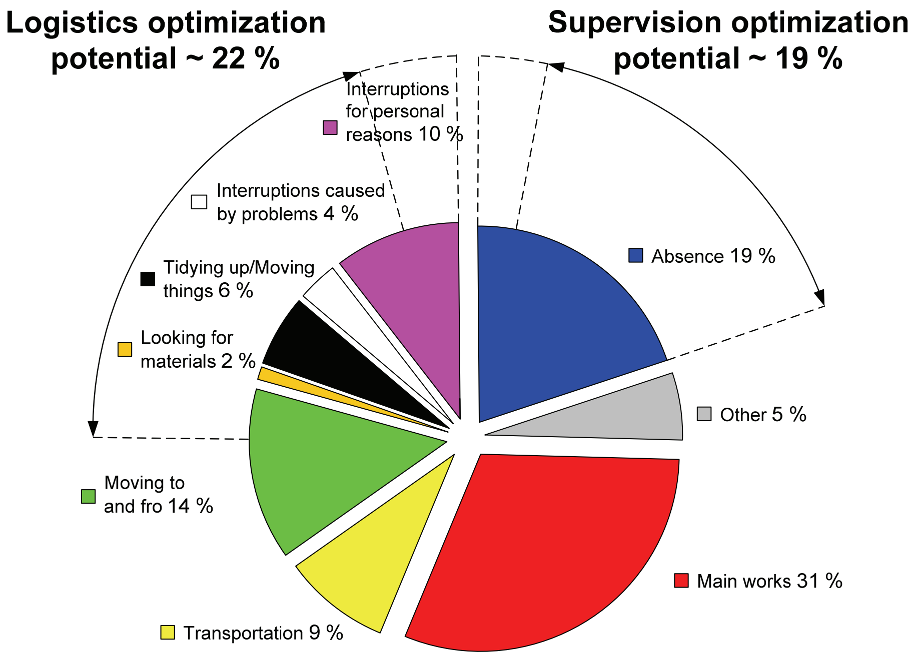


Fig. A.1: Cost reduction potentials: Use of worktime for interior building works (Boenert and Blömeke, 2003)

Fig. A.1 clearly reveals streamlining potential for better work preparation, logistics and continuous improvements which would have a major impact on the cost structure of a company. For example, the cost savings that could be achieved by optimizing construction site logistics are more than 20% of the total labour costs.

Analyzing the individual cost groups in isolation would, however, only allow a sub-optimal restructuring within the construction company since it would not be possible to recognise and overcome disadvantages that are inherent in the labour-intensive on-site construction work. As such, it is not just a question of aligning optimisation plans to partial aspects, but rather of reviewing strategic approaches and orientations (Fig. A.2). Industrialisation in construction - the rationalisation, standardisation and streamlining of work processes to achieve improved cost efficiency, productivity and quality - therefore offers various approaches. Possible solutions are not just restricted to operational areas, but encompass both operational and strategic aspects.

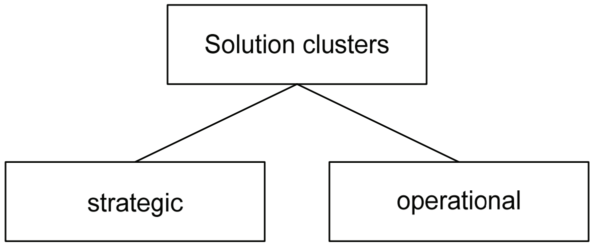


Fig. A.2: Solutions clusters for exploiting efficiency potential

2 Generics of Industrialisation

Previous attempts to industrialise construction primarily focused on the following objectives of replacing manual labour with machinery and robots or automation processes and to “automate” recurring processes. To be successful, however, any approach aimed at creating industrial structures in the construction industry must extend far beyond these processes, and must lead to process reengineering, or even the establishment of system provision.

Industrialisation of production can be reached by:

- Process oriented work preparation and production cycles
- Optimised (mechanical/automated) machinery and plant for both on-site and off-site production

Business and cooperation models are required for implementation in the construction industry. The industrialisation of construction (Fig. A.3) is a generic process with

- Standardisation
- Systematisation
- Flexibilisation
- Rationalisation

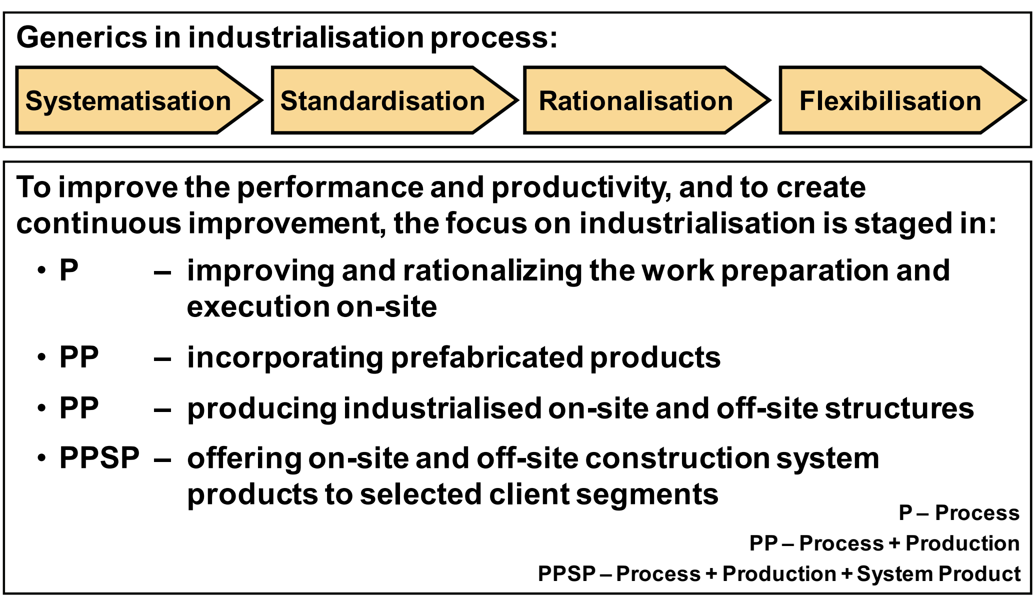


Fig. A.3: Generics of industrialisation process

In the case of production orientation, collaboration and cooperation are required with key designers and trade contractors with core competencies for the product in either case of investment oriented or life cycle oriented construction products. The focus on Industrialisation should be staged to improve performance and productivity, and to create continuous improvement for small, medium and large enterprises (Fig. A.4). Focus is therefore staged in

- Improving and rationalizing the work preparation and execution on-site
- Incorporating prefabricated products
- Producing industrialised on-site and off-site structures
- Offering on-site and off-site construction products to selected client segments.

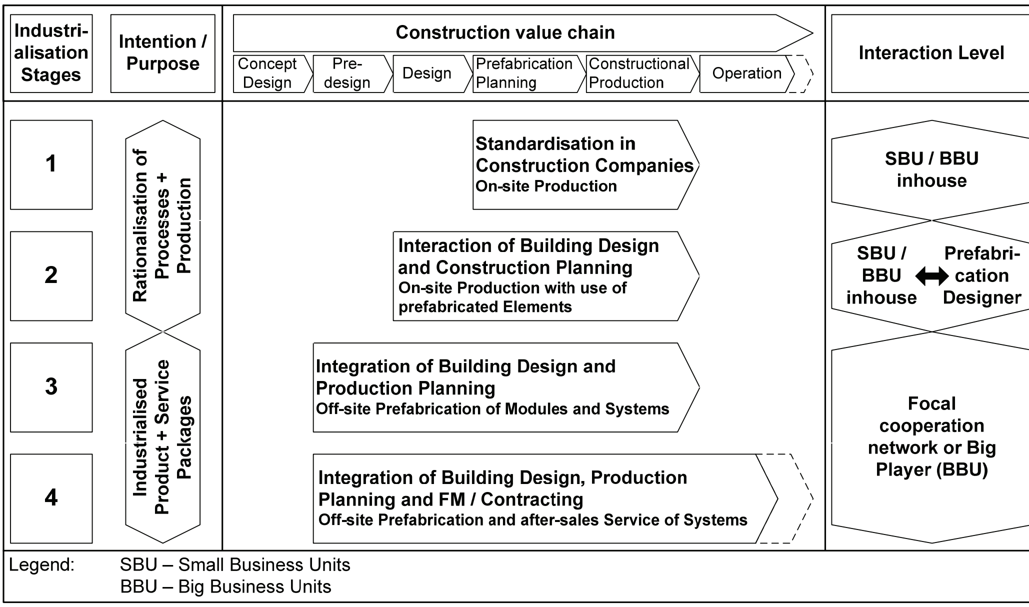


Fig. A.4: Generic organisational developing stages of Industrialisation

3 Classification of Prefabricated Components

The term prefabricated component is used to describe components that are prefabricated to a certain degree. Prefabricated components are either prefabricated on the construction site or in a prefabrication plant and then transported to and assembled at their site of installation.

Using system theory, these can be categorised as follows:

- Semi-prefabricated structural elements
- Prefabricated structural elements
- Prefabricated integrated elements
- Prefabricated structural room modules
- Prefabricated finished room modules
- Building systems

The meaning of these individual terms is as follows:

Semi-prefabricated structural elements (hybrid constructions), act as structural elements and lost formwork or composite elements.

Prefabricated structural elements are manufactured in a plant and transported to their site of installation where the relevant connections are made on the construction site (e.g. flights of stairs, supports, wall panels) and interior works performed where necessary (e.g. surface design).

Prefabricated integrated elements are functional elements consisting e.g. of a structural reinforced wall with integrated insulation, building services and finishes that are manufactured in a plant and transported to their site of installation on the construction site where the connections only need to be performed (e.g. facade elements).

Prefabricated structural room modules are equivalent to prefabricated structural elements but include single rooms (e.g. garages).

Prefabricated finished room modules are spatially distinct, functional units that can consist of numerous elements/components (e.g. bathroom or sanitary units). Unlike structural room modules, the interior works on prefabricated room modules can be performed during prefabrication.

Building systems have a high degree of user specific variety. They normally build on a module system with a platform orientated element system. The client can design the building quite individually with a high variety of exterior and interior elements which are based on different platform systems (like walls, windows, kitchen etc.). Building systems as prefabricated systems can consist of prefabricated room modules or prefabricated elements (e.g. industrial hall built using a support-beam system).

This distinction produces the systematisation of the elements in terms of content and spatial integration as illustrated in Fig. A.5.

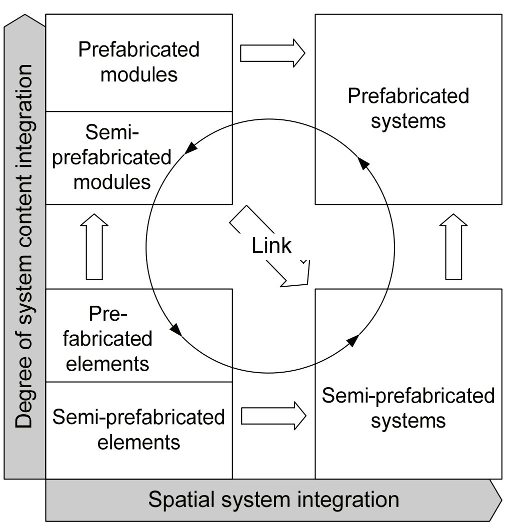


Fig. A.5: Systematisation of prefabricated components according to their degree of integration and connectivity

Further differentiation can be achieved according to Fig. A.6 by characterizing the degree of content integration and spatial connectivity.

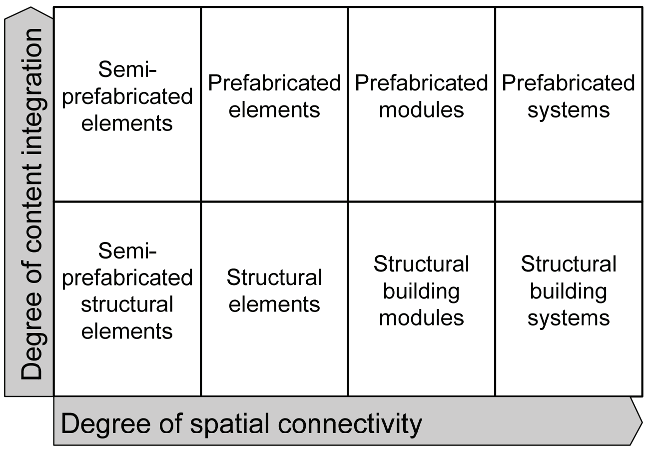


Fig. A.6: Conceptual differentiation of the prefabricated components with regard to the content integration of constructional and interior elements and the degree of spatial integration

The term **content integration** applies to the integration of various properties assigned to originally separate construction elements into one component or module. The increasing degree of content integration can be illustrated using an exterior wall element as an example:

- Concrete wall – sole purpose is load transfer
- Concrete wall with insulation – for load transfer and thermal insulation
- Concrete wall with insulation, installation cables for technical equipment and plaster/painting - for load transfer, thermal insulation and other functions relating to the overall interior works (e.g. preparation of electrical socket/PC network/telephone connections)

As content integration grows, the need to plan and coordinate the desired properties of the element, module or system also increases. Usually, more trades also need to be involved in the process as content integration grows. The fact that possibilities for shifting to prefabrication increase as content integration grows is an advantage.

By contrast, **spatial integration** describes the complexity of a component, module or system with regard to its spatial dimensions, composition using sub-systems and the associated interfaces. Growing spatial integration can be illustrated using the following example:

- Individual struts and girders (1 dimension) with predefined connection on the ends (girder as an element)
- Roof truss consisting of individual struts and girders (2 dimensions) with predefined interfaces to the spatial bracing in the cross direction of the roof truss (roof truss as a module)
- Roof supporting system consisting of prefabricated 2-dimensional roof trusses and prefabricated bracing (3rd dimension). In this case the system consists of different modules and elements (roof as a system).

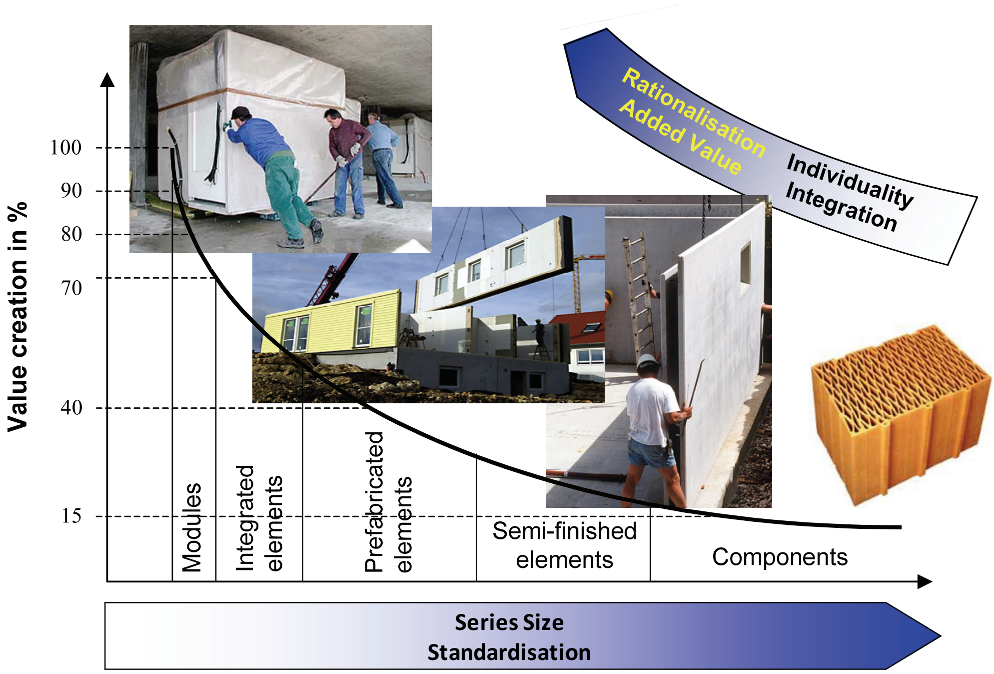


Fig. A.7: Impact of content and spatial integration in CAD-NC-controlled fabrication

The content and spatial integration of construction elements/modules in prefabrication has two main aspects (Fig. A.7):

- Increasing the individuality, content and spatiality of modules results in a reduction of the series size
- Increasing content and spatiality adds more monetary value due to rationalisation effects in the factory.

These positive effects of value creation can only be utilised effectively by applying robotised and automated CAD-NC process chains and NC-controlled manufacturing equipment. The following standardisation of systems will be used for production classification purposes.

A modular system is an organisational principle that allows various combinations to be designed from a collection of standardised construction elements or platform systems (building set). These standardised elements or platform systems are combined to create the planned result using computer aided design. Various combinations can be created by using

- different elements from the modular system each time,
- different numbers of the same elements,
- the same number of the same elements with a different spatial organisation.

Depending on the number and type of different available elements within the modular system, a distinction is made between closed and open systems (Fig. A.8).

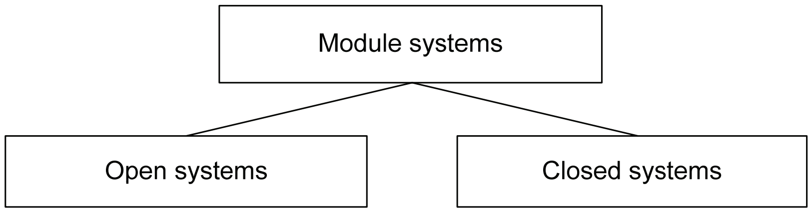


Fig. A.8: Breakdown into open and closed systems

A closed system is a system where its sub-elements are developed as an integrated set of elements and produced for use solely within this set. It's not possible to include non-system elements in a closed system. The various sub-systems within the closed system do not have to be produced by one manufacturer, but can come from different sources.

The open system is comprised of interchangeable sub-systems from various independent manufacturers. Open systems are characterised by defined interfaces that are accessible for other sub-systems. As such, an open system generally offers a wider range of alternatives and variety, as well as a certain degree of independence. It can be adapted to changing requirements by adapting or substituting sub-systems. An illustration of an open system is shown in Fig. A.9.

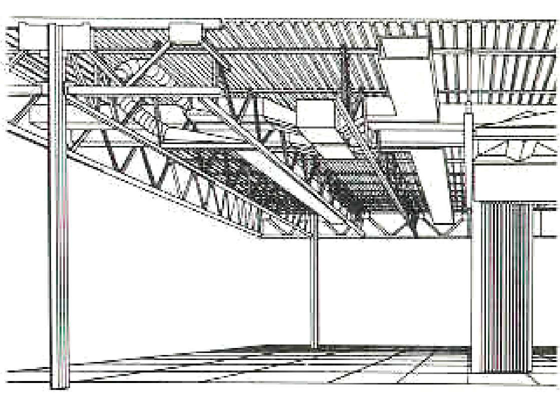


Fig. A.9: Diagram of an open system (Weller, 1985)

Platform systems refer to a basic framework where significant aspects, such as module dimensions, connection details, materials or component thicknesses, are standardised yet still enable the individual design of the separate components. For example, surrounding wall panels can be manufactured to individual requirements as platform systems. The lengths and widths and components can be individually determined for each element although industrial mass production is used to manufacture them.

As the degree of functional and organisational complexity increases, so does the degree of integration of the various trades. As such, the aforementioned definitions are not restricted to concrete construction.

4 In Plant Prefabrication – Advantages and Disadvantages

The **advantages** of precasting concrete components in a prefabrication factory can be split into the 3 major partial areas of quality improvement, reduction of manufacturing costs and reduction of construction time (cf. Kotulla and Urlau-Clever, 1992, Steinle, 1998):

- Quality improvement
  - Fabrication regardless of weather conditions
  - Higher output from using industrial methods
  - Better adherence to the component's dimensions
  - High level of product quality by using better formwork or specialised machinery during production
  - Improved concrete curing or more uniform surface treatment by using standardised methods and environmental conditions
  - Options to vary the surface design (structure, colour)
  - Ensuring efficient quality management using standardised and process-oriented quality control
- Reduction of manufacturing costs
  - Reduction of non-value adding worktime by using repetitive, automated and logistics-supported manufacturing processes at the plant
  - Reduction of manufacturing costs by increasing prefabrication efficiency, e.g. by the more efficient, multiple and standardised use of formwork for concrete components
  - Reduction of the follow-on costs on the building site: including lower scaffolding costs and lower expenditure on tolerance compensation measures or labour-intensive follow-up work
  - Material savings - no losses caused by the weather / organisational issues
  - Concrete components can be prestressed in a stressbed - repetitive use reduces costs
  - Indirect price benefits: fixed prices to ensure adherence to calculated costs
  - Lower follow-on costs for follow-up works and tolerance compensation measures
  - Lower financing costs and earlier utilisation income from shortened construction time
- Reduction of construction time
  - Virtually totally independent of the weather (production and assembly possible in winter)
  - Simultaneous production in the plant, e.g. of wall and ceiling elements while the foundation on site is also being built at the same time
  - No extensive construction site equipment
  - Building structure is dry and immediately capable of bearing

- Shortened planning time and preparatory work by being able to resort to typified or modularised platform elements
- Intermediate storage and supply on demand options

The **disadvantages** of plant prefabrication include the following:

- A lack of standardisation among companies makes it harder to cooperate with other companies
- Higher transport costs for large components, resp. limitations with regard to the delivery radius
- A high-performance mobile crane is needed for assembly (space requirements / stability / costs)
- The prefabricated components must be suitably dimensioned for transportation
- High ratio of fixed costs due to the high level of automation in production incurs higher costs for individual fabrication using certain manufacturing methods
- Higher planning costs for individual solutions
- Other static systems may require different dimensions (continuous beam made from in-situ concrete and prefabricated single-span girder)
- Tolerance problems when combining differing methods of construction (in-situ concrete and prefabricated parts) or construction materials (steel-glass façade and in-situ concrete supporting structure)

Some disadvantages can be avoided by implementing an appropriate market and bidding strategy and by coordinating schedule and construction planning and the tolerances.

5 Conclusions

Nowadays construction production processes still offer a huge potential for increasing efficiency and effectivity. Industrialisation in construction - as one driver to realise these potentials - can be achieved by process oriented workflows (effectivity) and automation on-site or off-site (efficiency). Standardisation, systematisation, flexibilisation and rationalisation are drivers for the automation off-site in a plant with its advantages of quality improvement, reduction of manufacturing costs and reduction of construction time. The given classification of prefabricated components systemises the outcome (products) of off-site prefabrication in the context of industrialisation.

6 References

Boenert, L.; Blömeke, M. (2003) Logistikkonzepte im Schlüsselfertigbau zur Erhöhung der Kostenführerschaft. In: Bauingenieur, Heft 06

Girmscheid, G. (2005) Industrialisation in Building Construction – Production technology or management concept? In Proceedings: 11th Joint CIB Int'l Symposium "Combining Forces", Helsinki

Kotulla, B.; Urlau-Clever, B.-P. (1992) Industrielles Bauen, Bd. 1 Grundlagen. Expert-Verlag, Ehningen

Steinle, A. (1998) Bauen mit Betonfertigteilen im Hochbau. Ernst & Sohn, Berlin

Weller, K. (1985) Industrielles Bauen 1, Grundlagen und Entwicklung des industriellen, energie- und rohstoffsparenden Bauens. Kohlhammer, Stuttgart

B) Five Degrees of Industrialised Building Production

ROGER-BRUNO RICHARD[1]

1 Introduction

Even if a large number of components and sub-assemblies (windows, roof trusses, kitchen cabinets, etc.) are actually produced with industrialised methods in many countries, construction is still a site-intensive handicraft activity. If a car were produced the way a building is delivered, very few people would be able to own one; similarly, if a computer were produced the way a building is delivered, it would cost a fortune. But those products and a lot of others are affordable due to the implementation of industrialised strategies and technologies.

Industrialisation is a generic organisation based on quantity and offering an individualised finished product (Richard 2007). Quantity means that a large market can amortise the investment in strategies and technologies that are capable, in return, of simplifying the production of complex goods.

That is the very nature of industrialisation: the production of a large quantity of units divides the investment into small (eventually infinitesimal) fractions, thereby reducing the fixed production costs of a single unit down to marginal amounts and making the product affordable for a large public. When "mass-customisation" strategies are applied, that product can meet the specifics of each individual.

Furthermore, an important part of that investment can be "shared" with others by delegating some work to sub-contractors, as these sub-contractors will in turn arrange for their investment in specialised tooling to be amortised by the various other contractors that will call upon them.

2 The Degrees: Tradition vs. Innovation

Five degrees of industrialisation can be identified, mainly by extrapolating from what is going on in the others industries: Prefabrication, Mechanisation, Automation, Robotics and Reproduction.

The first four degrees are still more or less under the influence of the traditional methods of building. Prefabrication aims rather at the location of the production whereas the next three (Mechanisation, Automation and Robotics) aim at substituting labour with machinery.

---

[1] Prof., M.Arch. (Berkeley), Architect (OAQ), Head of the graduate Design & Systems for Construction (DSC) profile, School of Architecture, Université de Montréal, P.O. Box 6128 Centre- ville, Montreal (Quebec) H3C 3J7 CANADA, Phone +1 514 343 7968, Fax +1 514 343 2455, roger.richard@umontreal.ca

The fifth degree, Reproduction, implies Research & Development of innovative processes capable of short-circuiting the long linear sequences based on labour, thus capable of truly simplifying production.

2.1 Prefabrication

The word Prefabrication starts with “pre”, which means “before” and/or “elsewhere”. In the building industry, Prefabrication generally implies building at the factory components, sub-assemblies or full modules which are quite similar to what is produced on a traditional construction site, very often using the same processes and the same materials.

In North-America, as illustrated on Fig. B.1, most modular housing manufacturers are building wood-framed panels and 3D modules very close to traditional construction. But, as they have to meet the severe constraints of road transportation, they are usually stapled and glued, whereas site construction is generally performed using hammered nails.

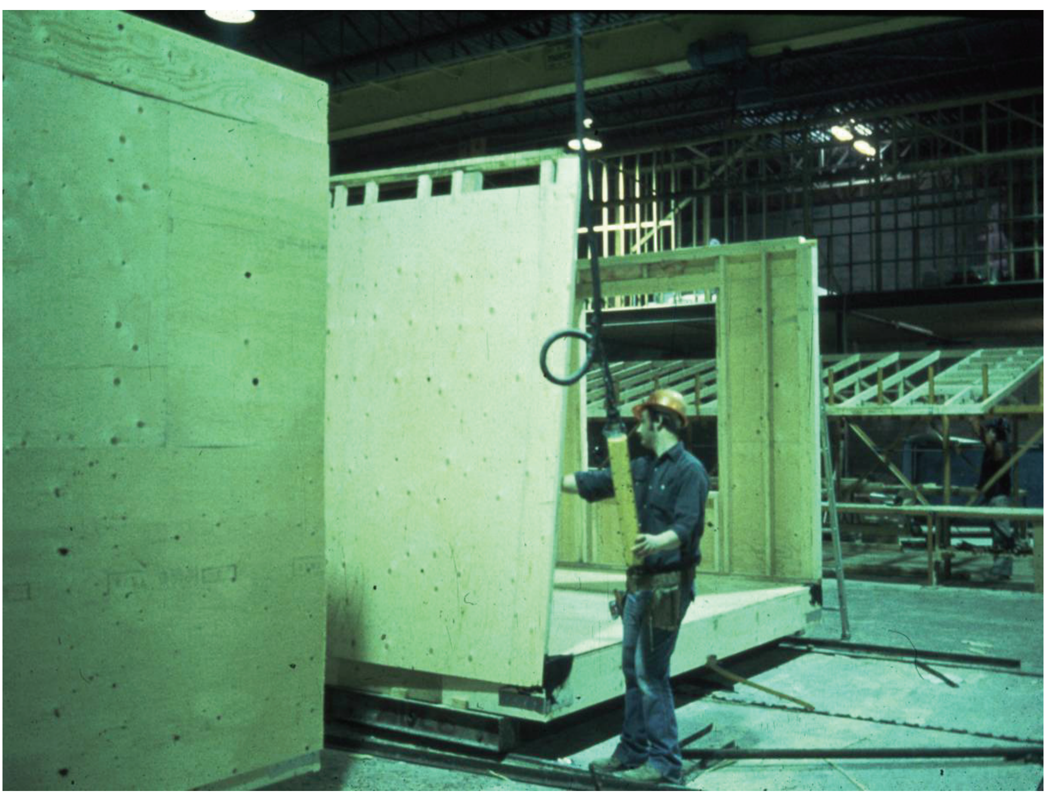


Fig. B.1: Prefabrication of a 3D wood-framed factory-made module

Still, for the following reasons, Prefabrication does bring the construction costs down by as much as 15% when the plant is producing at full capacity (i.e. when sufficient “quantity” is obtained).

- Climatic protection: the work is done under the protection of a roof, which means it can go on during the most hostile weather conditions and, as a bonus, the materials are not damaged by water, snow or solar radiation.
- Rationalisation of the tasks along a production line: the main assembly line is fed by sub-assemblies which are themselves directly connected to the supply of components or raw materials.
- Specialised tooling and assembly jigs: the tasks are subdivided and made simple through pre-adjusted tools and jigs.
- Salary scale: the average salary scale is normally lower than at the site since trade certification is not really required for most phases of the production sequence. However, computer skills are necessary for Computer Numerical Control (CNC) operations.
- Better quality control: a consequence of the above mentioned reasons and because inspectors are usually assigned for that purpose, as recommended by most certification agencies (Ex. PCI, the Precast and Pre-stressed Concrete Institute in North America).
- Bulk purchasing of raw material: an economy due to the single delivery point.

2.2 Mechanisation

Mechanisation comes in whenever machinery is employed to ease the work of labour (power tools, material handling equipment, etc…). Usually, large scale Prefabrication will be accompanied by some Mechanisation. For instance, the modular housing manufacturers will use pneumatic hammers and gantry cranes.

2.3 Automation

With Automation, the tooling is completely taking over the tasks performed by labour. A moving production line will reproduce the traditional operations using only machinery and operating in a more straightforward way. To produce the traditional wood or steel stud wall panel, for instance, the line will feed the studs to a spacing jig, then to a sheathing setter, then to a multiple points stapling machine like the one shown on Fig. B.2, then to a 180° rotor, then to an insulation layer, then to another sheathing setter, then to another multiple points stapling machine and so on.

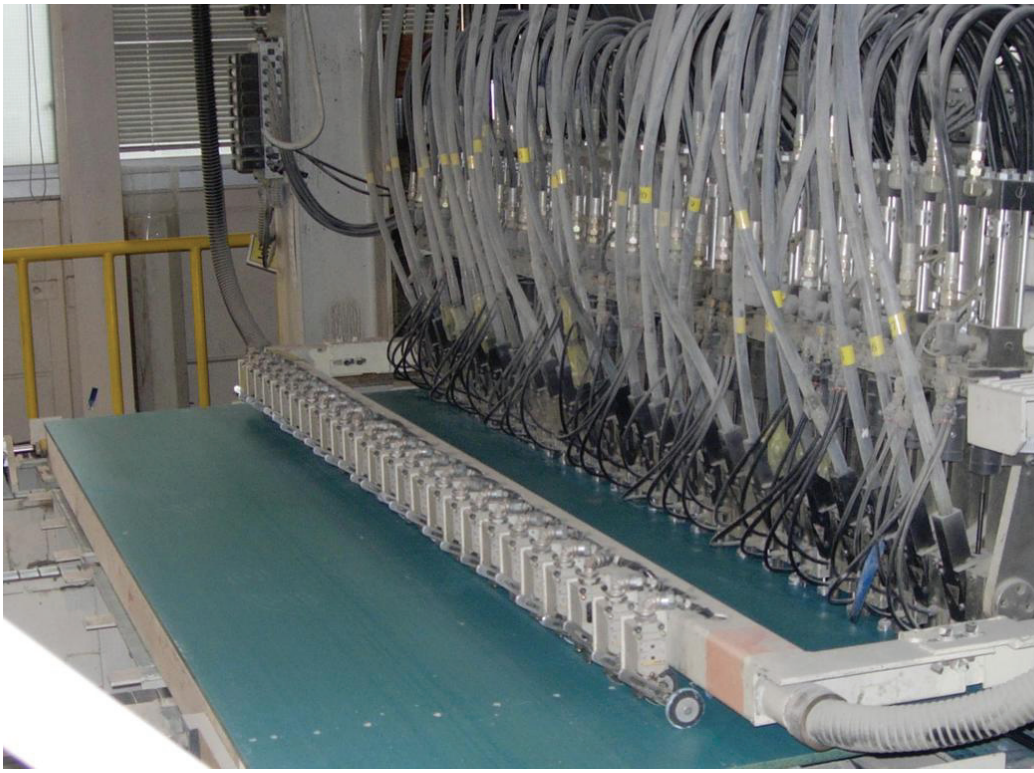


Fig. B.2: Automated multi point stapling machine

A "supervisor" is still around, although the industrial engineer and the programmer are the critical participants involved. Some manufacturers are reporting an economy up to 27% compared with traditional construction methods, as long as the plant is operating at full capacity.

2.4 Robotics

With Robotics, the same tooling has the multi-axis flexibility to perform diversified tasks by itself. Robotics is universally acclaimed as very efficient in terms of precision and speed, but highly demanding in terms of capital investment.

The robot is obviously too sophisticated for just nailing studs or laying bricks. The robot is mainly related to Computer-Aided Manufacturing (CAM): generating complex forms different from one unit to another, opening the way to individualisation within "Mass-Customisation".

A good example of Robotics is the application of the "Contour Crafting" process to the production of buildings (Khoshnevis 2003): using a quick-setting concrete, the robot forms the various geometrical features of a whole house layer by layer while incorporating the relevant components, services and equipment at the same time.

2.5 Reproduction

The word "Reproduction" is borrowed from Printing technology, not from Biology. It refers to the fact that once the plate or the carrier is mounted on the printing press, documents are multiplied easily at an astonishing speed.

Reproduction can be defined as the introduction of an innovative technology capable of simplifying the "multiplication" of complex goods. Its purpose is to short-cut the repetitive linear operations which are the trademarks of the handicraft approach, like nailing wood studs, laying bricks, etc.

Instead of investing straight into machinery, Reproduction is first calling upon Research & Development for "ideas" to generate a simplified process. Reproduction is not necessarily fully available as a downright option: it often accompanies some of the other degrees Industrialisation.

Diverse types of Reproduction approaches have been applied in the industrialisation of building so far:

- Developing a **single multi performance material** which can replace the assembly of several complementary ones. The "Precast Autoclave Lightweight Concrete" (PALC), developed by Misawa Homes in Japan, is doing exactly that (Richard and Noguchi 2007). A "PALC" monolithic aerated concrete panel performs as thermal and acoustical insulation, air and vapour barrier, bracing as well as both exterior and interior finishes. The Misawa PALC covered module shown on Fig. B.3 is sometimes called "Misawa Ceramics" due to the appearance of the material after the Autoclave phase. As illustrated on Fig. B.4, the casting of that panel and the application of its coating are replacing the numerous operations required to assemble the various materials composing a wood-framed wall: the studs, the insulation blankets, the air and vapour barrier membranes, the exterior sheathing and cladding as well as the interior finish.

Fig. B.3: Installation of a PALC covered Misawa 3D module

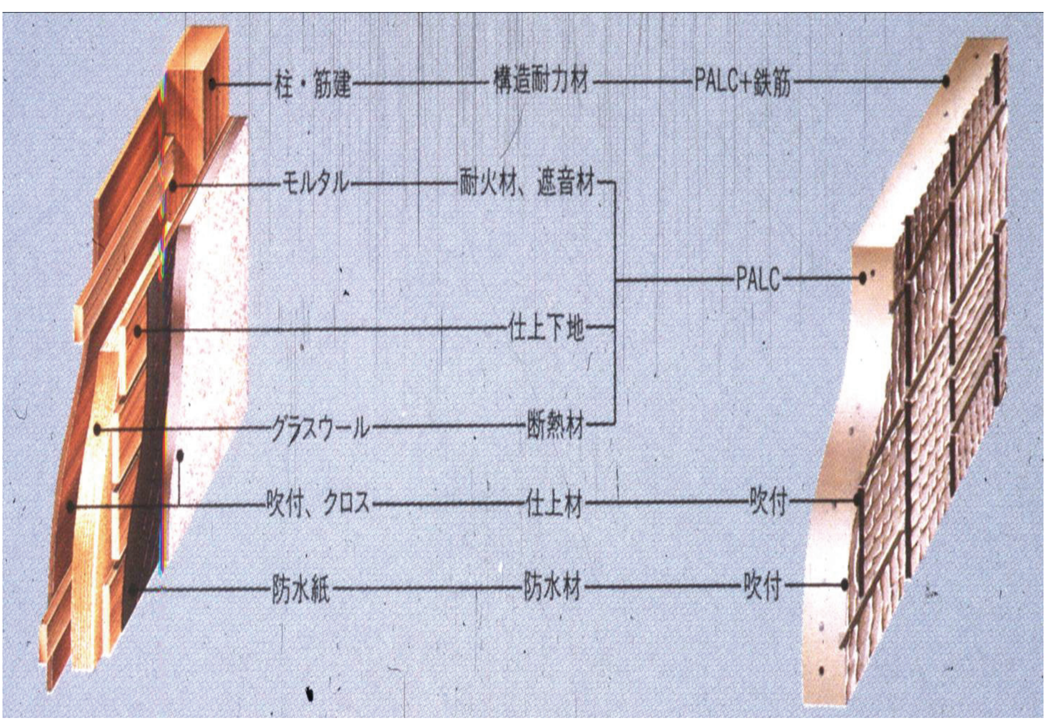


Fig. B.4: Conventional stud wall compared with a Misawa Home PALC Wall

- Concentrating in a **single element** what is usually requiring a collection of parts and fixations. The best example is the Printed Plumbing Core, explained in the next paragraph.
- Adopting a process capable of **generating a complex product in a single operation**. The Hollow Core Prestressed Concrete Slab extruded along a line of pre-stressed cables, is replacing in one operation the multiple activities required to cast a slab at the site (constructing and dismantling the formwork, installing the reinforcing, pouring the concrete and hand-finishing the exposed surface). The main advantage of that slab is the reduction of dead load, clearly demonstrated on Fig. B.5.

Fig. B.5: Hollow Core Prestressed Concrete Slabs

- Defining **geometries that will facilitate the jointing**. An obvious solution is to locate the jointing outside the geometrical meeting point, as it is the case with the "Integrated Joint" type of Building Systems. For instance, the cruciform Componoform component shown on Fig. B.6 does exactly that.
- Distributing the work into **modular sub-assemblies** done at the same time by different specialised sub-contractors, following a distribution pattern like the one shown on Fig. B.7. "*Production has gained in efficiency with the increase in modular assembly by outside suppliers…The average overall savings in the manufacturing cost of a car in 1999 were 14.9% when compared to manufacturing in 1996*." (Kieran and Timberlake 2004).

Fig. B.6: Installation of Componoform integrated joint precast concrete components

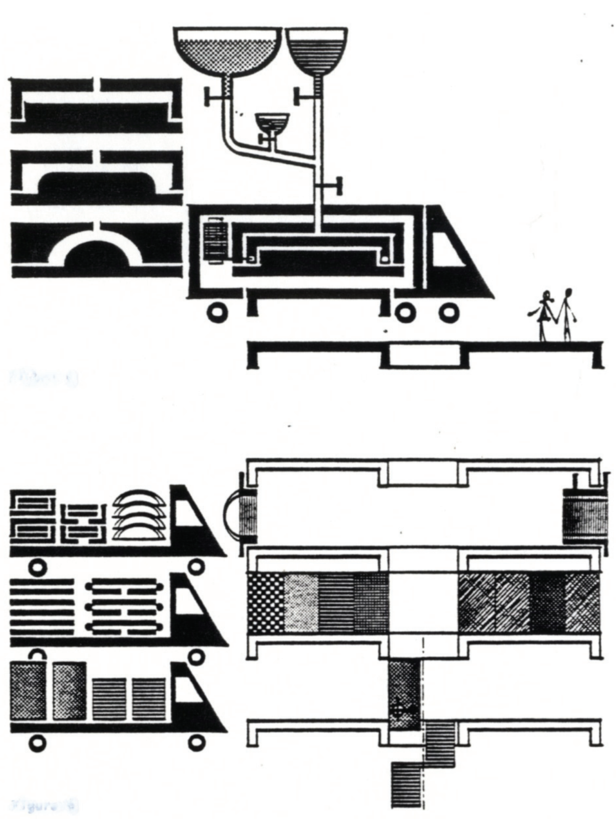


Fig. B.7: Prefabricated sub-systems supplied by different manufacturers

3 The "Printing" Analogical Model

The analogical chain of models initiated by the Printing process is quite prolific and quite appropriate to illustrate the full meaning of Reproduction (Richard 2005):

- **Printing** did replace in two movements the long sequential activities of the copyist rewriting books one after another;
- The **Printed Circuit** produces in two operations all the connections between the components of an electronic device that were previously manually done one by one;
- The **Integrated Circuit** replaces the plugging of components with a few additional semi-conductor layers that take over the role of the components;
- The **Printed Plumbing Core** is providing in two operations all the distribution and drainage conduits required for a dwelling unit.

3.1 Printing

Instead of hiring a staff of copyists to rewrite "n" copies of the Bible, Gutenberg carved a large amount of wood types representing each letter of the alphabet. He invested a lot of time in doing that, more time than to rewrite five or even ten copies of the Bible. But when the types were available, Gutenberg assembled them to produce a full page, inked them and then made contact with "n" sheets of papers to produce "n" copies of the page. Reassembling the types to produce the other pages, he was thereafter able to reproduce "n" copies of the Bible a lot faster than the copyists.

Gutenberg had therefore quantitatively justified a process capable of simplifying the production of a complex product. The process is quite different: two operations (inking and pressing) instead of a repetitive linear sequence of rewriting operations. The product is also a book, but a different one: a closer look shows types rather than cursive writing. Different process, different product. Many years after, the rotary press went even further by replacing the on-off operations with a continuous production, using a "knife" to separate the pages thereafter.

3.2 The Printed Circuit

If the electronics industry had substituted machines for the crews welding components to wires in the wired circuit, they would have moved to Mechanisation, Automation or even Robotics. But, as schematised on Fig. B.8, a "new Gutenberg" had the idea of replacing the time consuming hand-made weldings by two simple and rapid operations: silk-screening a negative of the circuit paths on a plate and generating a positive conductor network by electro-deposition on the void areas.

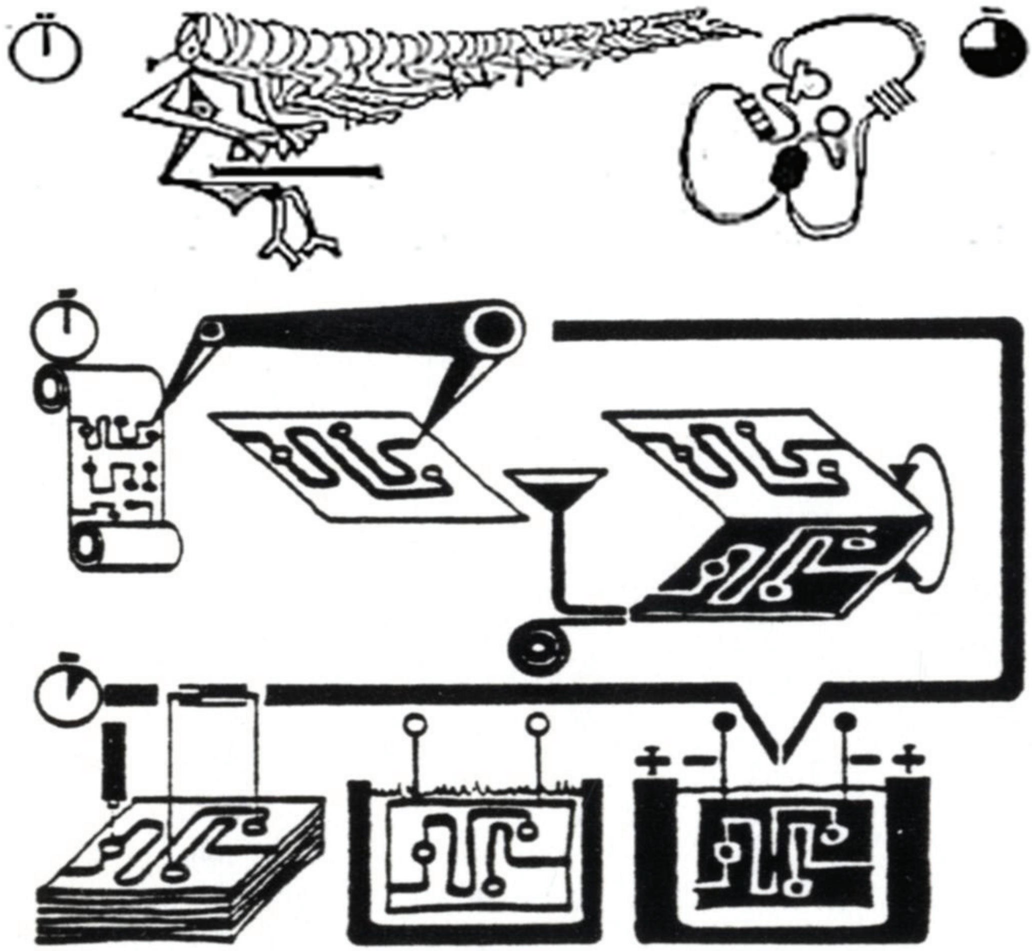


Fig. B.8: The Wired Circuit replaced by the Printed Circuit

The “Printed Circuit” shows a completely different configuration than the wired circuit, whether man-made or automated, but it meets the performance criteria much better (less space, high precision and more robustness). And the product can be modified just by changing the drawing to be silk-screened.

The “performance criteria” are the keys to selecting the appropriate process: determining what the product should do rather than should be. By recognising what the electronic circuit should do (connecting the components) and not what it used to be (wires going from one component to the other), those criteria opened the door to the idea of distributing all the connections on a single 2D surface rather than in space. Thereafter, the idea of printing them using a conductive metal gave birth to the Printed Circuit.

3.3 The Integrated Circuit

The Integrated Circuit went one grand step further: printing specific additional semi-conductive patterns on the circuit to take over the role of the components. This simplified process explains the low cost of electronic devices available on the market today.

3.4 The Printed Plumbing Core

As plumbing is also a network connecting components, the analogy between the printed circuit and residential plumbing becomes relevant.

In the traditional handicraft approach, the pipes are cut to pieces, attached to couplings / gaskets and connected on the site between themselves and to the fixtures; one after another. Years ago, some manufacturers did offer a "Prefabricated Plumbing Core". But as the work was quite similar, done at the factory instead of at the site, no real cost reduction was achieved.

In the initial Descon proposal for the Operation Breakthrough housing competition, a lightweight plumbing module was proposed (HUD 1973): the piping was traditional but its gauge was reduced as the whole unit was inserted in a block of polyurethane dense enough to pick up the pressure and, at the same time, to insulate the hot conduits from the cold ones. That concept was not implemented.

Heinz Wager (Wager 1962) as well as Biondo & Rognoni (Biondo & Rognoni 1976) proposed an innovative “Printed Plumbing Core”, directly related to Reproduction. The plumbing is redrawn in order to arrive at a 2D network avoiding any overlapping. All the paths are embossed (vacuum formed plastic or deep-drawn aluminium) as half-circles on two symmetrical sheets and then an adhesive is applied with a roller, obviously covering only the flat parts. When the two sheets are bonded face-to-face, the flat parts become unified and the twin half circles become open conduits. Fig. B.9 shows both in elevation and section what such a Printed Plumbing Core looks like.

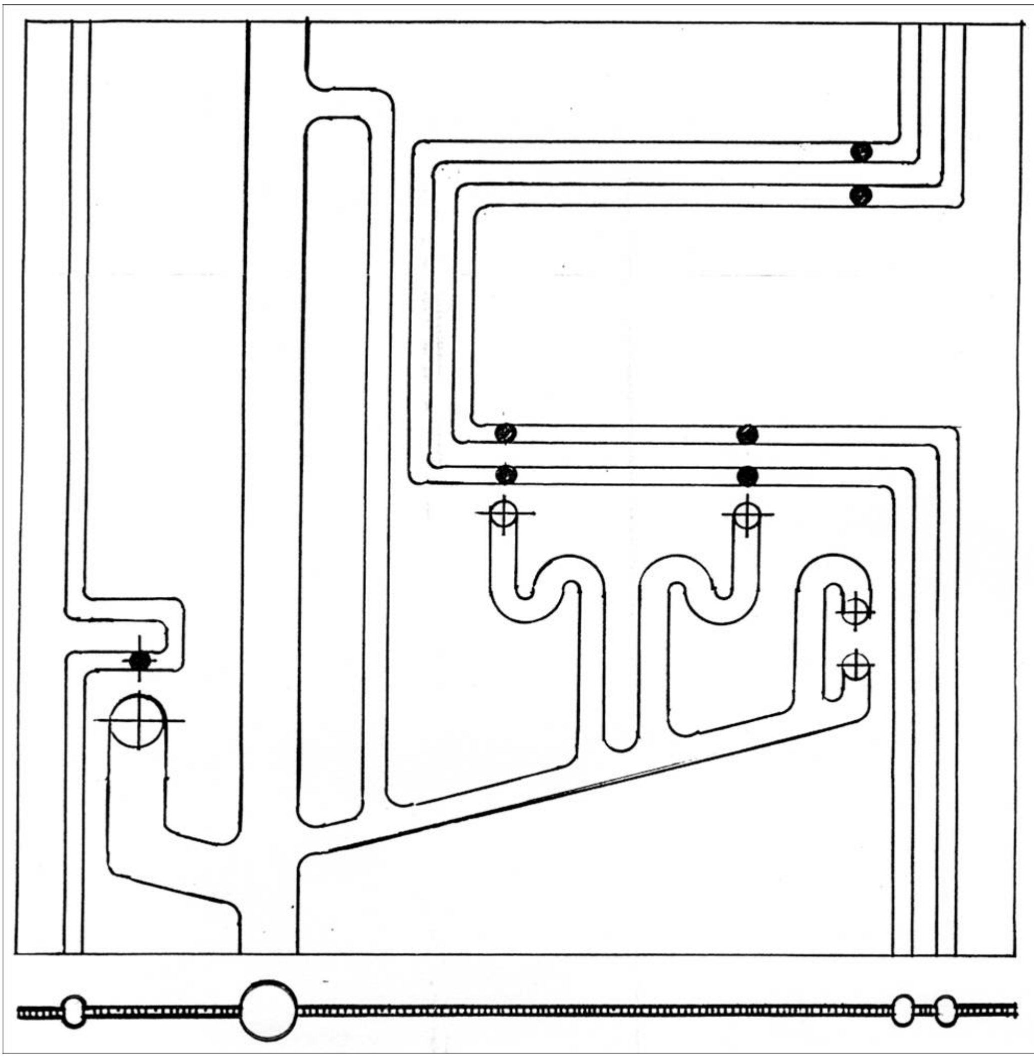


Fig. B.9: The Printed Plumbing Core: Elevation and Section

4 Conclusions

When a new process is involved, the topology of the product is necessarily subject to change. For instance, the Integrated Circuit has completely transformed the electronic industry. Logically, the new image of a product should celebrate the new process. That is logic in the design world, although it takes some time: the first automobiles did look like stage coaches before getting more streamlined and adopting specific shapes. The injected plastic chair is completely different from the famous Thonet chair since it has to be structured according to the nature of the material and of the process; but it supports the same weight, it can provide a lumbar curve and it is ± 5 to 8 times less expensive!

Celebrating the interaction between the process and the product may be a challenge in architecture, especially with residential buildings where the attachment to traditional forms is strong. For instance, most modular housing manufacturers tend to hide the very presence of modules, mainly due to the unjustified bad reputation attached to prefabrication or to the negative reactions that modern architecture produces in some people. The marketing operations may then have to assume an educational mission.

The real message of the fifth degree of Industrialisation, Reproduction, is to give priority to ideas rather than to machinery. These ideas will pop out when the following three conditions are present together:

- a clear vision of the performance expected from the product;
- the ability to imagine a functional topology;
- the knowledge of the processes presently or prospectively available.

Reproduction will then lead to solutions capable of delivering affordable quality architecture to the vast majority of people. The architecture will most likely project a different image, but different can mean better.

5 References

BIONDO, G. & ROGNONI (December 1976) E. Prefab 7/1 blocchi cucina, *Domus*, no. 565, p. 14.

EHRENKRANTZ, Ezra D. (1989) *Architectural Systems*, McGraw Hill, New York,

HUD - U.S. Department of Housing and Urban Development (1973) *Design and Development of Housing Systems for Operation Breakthrough*, Washington, pp. 66-75.

KHOSHNEVIS, B. (2003) Towards Total Automation of On-Site Construction – An Integrated Approach based on Contour Crafting. *Proceedings of ISARC 2003*, Eindhoven, pp. 61-66.

KIERAN, S. and TIMBERLAKE, J. (2004) *Refabricating Architecture: How Manufacturing Methodologies Are Poised to Transform Building Construction*. McGraw Hill, New York, p.107.

RICHARD, R.-B. (2007) A Generic Classification of Industrialised Building Systems, Chapter 3 (pp. 33-48) of the manual *Open Building Manufacturing: Core Concepts and Industrial Requirements*, published by ManuBuild and VTT-Technical Research Center of Finland.

RICHARD, R.-B. and NOGUCHI, M. (2007) *Japan Solar Photovoltaic Manufactured Housing Mission 2006*, CANMET Energy Technology Centre, Varennes (Quebec), 38 p.

RICHARD, R.-B. (2005) Reproduction Before Automation and Robotics, *Automation in Construction Journal*, Elsevier, Amsterdam, Issue 663, pp. 442 – 451.

WÄGER, H. (1962) Design II, ULM 8/9 Journal of the *Hochschule für Gestaltung*, no. 8/9, pp. 33-35.

http://www.contourcrafting.org/

http://books.google.ca/books?id=PkxQKygXe2cC&dq=Refabricating+Architecture:+How+Manufacturing+Methodologies+Are+Poised+to+Transform+Building+Construction&printsec=frontcover&source=bl&ots=d_G2pQswC7&sig=Lv3QMKwkOmpBM41ycJ2erR9xEgI&hl=fr&ei=rbeRSq3tLMOSlAf25_CjDA&sa=X&oi=book_result&ct=result&resnum=1#v=onepage&q=&f=false

http://www.manubuild.org/downloads/OpenBuildingManufacturing_Book1-2007.pdf

http://cetc-varennes.nrcan.gc.ca/fichier.php/codectec/En/2006-166/2006-166e.pdf

http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V20-4DV1RC2-1&_user=10&_rdoc=1&_fmt=&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=988374896&_rerunOrigin=google&_acct=C000050221&_version=1&_urlVersion=0&_userid=10&md5=cc9c9bb30db45b1587a01f2aa7068da6

C) Potentials of Computer Aided Construction

GERHARD GIRMSCHEID[1]

1 Introduction

Measures and methods of Industrialisation in construction enable construction companies to reduce costs, improve the transparency of their processes, benefit from learning curves, and expand existing or venture into new areas of business. Specific measures need to be drafted and tailored to the relevant strategy of a company and its areas of business, and implemented within the company. The courses of action offered by Industrialisation in construction are not restricted solely to a strategy of cost leadership; if applied correctly they also do not result in limitations on the individuality of our buildings.

The following definitions have emerged to address the implementation of industrial construction measures in companies.

CIM (Computer Integrated Manufacturing) is the overall term for computer-integrated production.

In construction, CIM can be divided into:

- **CAD:** Computer Aided Design of construction components and elements.
- **CAM** (Computer Aided Manufacturing): direct control of production units and associated logistics systems

Production by **NC** or **CNC machines** is also part of CAM. NC (Numerical Control) is a precursor of CNC (Computerised Numerical Control). CNC is the term used for the computerised control of a production machine's tools.

PPS - Production Planning and Scheduling - encompasses the entire process relating to production, starting with order receipt right up to completion and order monitoring. It therefore also encompasses the operational, schedule, volume and spatial planning, management and control of the individual processes.

[1] Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch

When Industrialisation and assembly line production were introduced to the automobile industry, the maxim was still:

"Any customer can have a car painted any color that he wants so long as it is black."

Henry Ford (1863-1947)

Nowadays, platform systems offering a wide range of compatible modules and partial systems are being developed by the automobile industry. These enable a relatively high degree of design varieties and production-related adaptability. Nowadays, customers can choose from a large number of models and can select interior design, engine performance, tires, etc. to suit their individual preferences. This is made possible by the modular platform design and the computer-controlled logistics of the assembly process. The IT link between Cartesian Computer Aided Design (CAD) data and technical Computer Aided Manufacturing (CAM) commands, the design of platforms in conjunction with complex production process management supported by Production Planning and Scheduling (PPS) and the capturing of operating data by Factory Data Recording (FDR) provide an ideal basis for converting Henry Ford's mass production into mass customisation production (Bechthold 2006, Pine 1993, Piller 1998, 2003) while still retaining the benefits of mass production, such as

- lower costs compared with individual or handmade production,
- constant quality level, and
- continuous improvement of products and processes.

Just like the consumer goods industry, the construction industry also has to

- break its manufacturing processes down into modular, repetitive processes by using a platform strategy for its products (e.g. housing, office buildings) and subproducts (e.g. windows, walls, slabs)
- industrialise its upstream processes, and
- apply the knowledge gained during production to other projects.

Customers' requirements and expectations are individual, both in the consumer goods industry and in the construction industry. When deciding what to purchase in the consumer goods industry, customers choose their "individual product" from a wide range of alternatives, whereas in the construction industry architects frequently still sell a completely unique product to the property developer. There is justification for critically challenging the extent to which customers feel that this individual design is always necessary, for example, given the large share of prefabricated single-family and two-family houses. Wooden structures are particularly well represented in this area, where industrialised fabrication methods are used and knowledge gained from the learning curve. Customers can compile their dream house from a wide range of alternatives based on a platform strategy and modular construction. The potential offered by industrial methods of fabrication is still largely unutilised in the area of solid buildings.

2 Potentials in the Construction Industry

2.1 A Need to Rethink

Customer demand in general is shifting away from uniform mass products toward individually customizable mass products. Today's technology allows the construction industry to shift production toward Industrialisation. This development will also impact the planning of construction processes and the methods used in the construction industry in future.

Generally speaking, the construction industry is caught between two conflicting types of contractor,

- those that perform the works mechanically or by hand-craft on-site, generally Small and Medium-sized Enterprises (SMEs), and
- those that industrialise the works or use industrialised methods in work preparation and construction and controlling, generally Medium and Big-sized Enterprises (MBEs).

SMEs generally account for the largest share of construction industry output in the overall economy. They do not exploit the simple potential for streamlining by systematizing and standardizing their processes since work preparation standards are usually non-existent. Nor do they systematically exploit the possibilities offered by prefabrication or the benefits in terms of system concepts and real net output ratio offered by the utilisation of production machinery and aids.

By contrast, medium and big corporations largely adopt streamlining approaches in terms of systematisation and standardisation and yet there is a lack of tendency toward the Industrialisation offered by computer-controlled customizable production technology with regard to the overall building. Progress still needs to be made in integrating the planning and execution processes. Here, too, there is a need for a paradigm shift.

The uniform architecture of the 1960s and 70s, which is nowadays frequently linked to industrial construction, is not the goal of modern industrial construction. On the contrary, Industrialisation in the construction industry needs to result in closer customer orientation in conjunction with a streamlining of the construction processes while at the same time ensuring the individual design of the products and structures.

As Industrialisation in the construction industry progresses, the following developments can be expected:

- Interlinking of processes, integrative, interactive design, production and execution planning, heightened focus on goal-oriented communication, holistic project management
- Rationalisation within the SMEs through systematisation and standardisation of work preparation, equipment, ancillary aids
- Increase in the degree of prefabrication
- The remaining construction site works will become further mechanised and automated
- Development of buildings tailored to individual clients based on a platform offering a wide range of alternatives

2.2 Potential – Process Interaction

The common practice in many countries today of not involving construction companies until the actual execution phase is a huge obstacle to the further development of construction methods and processes, since by then it is no longer possible to incorporate the expertise of the company performing the works nor its company-specific requirements in terms of low-cost production, for example by utilizing special on-site or off-site construction methods, or potential platform systems offering a wide range of design alternatives, or existing resources, such as manpower, inventories, experience and business contacts. On-site and off-site production experience or knowledge of platform systems with varying ranges of design alternatives can then only be backtracked into the planning to a minor degree.

Since property developers and owners obviously want to award the works at market prices, they correctly promote competition among the construction companies. But they should set life-cycle orientated aspects as the determining goals in these competitions. A price-performance competition requires a functional tender based on the building permit planning, which comprises plans and a specification that defines the quality standards, including a room program and floor plans. Alternative delivery models should be explicitly permitted. Within the functional limitations dictated by the tender, construction companies can then offer innovative solutions comprising a high degree of modular, platform-oriented prefabrication. Compared with individual works specifications, evaluating the bids involves more effort but in return property developers gain access to potential means of improvement and cost reductions that they would otherwise not have. Execution planning in industries such as shipbuilding and plant engineering, where prototypes are also produced, is performed by or on behalf of the producer. As such, producers can exert influence on the quality-defined yet cost-optimised planning and bring in their own expertise. In terms of the construction industry, such a project delivery model would result in the experience, knowledge and skills of construction companies being incorporated into the execution planning, thus producing cost benefits for property developers and owners. This could afford access to the following efficiency potentials, for example:

- Corporate solutions could be developed that provide warranties for leak-proof, thermal protection, noise protection and load-bearing requirements,
- The decision could be made whether to prefabricate individual or all load-bearing components or to manufacture them on the construction site ,
- Insignificant changes to the architect's plans could be coordinated to enable the multiple and standardised use of formwork and/or prefabricated components or the use of large-scale brickwork,
- Alternative building materials could be used.

As such, a company could highlight its industrialised construction strengths to the benefit of the property developer and owner.

The ability of construction companies to exert influence on the execution planning from an early stage is crucial for the willingness of construction companies to invest in new machinery and information technology and in the associated training of its workforce. By exerting influence on the execution planning, the apparently unique character of buildings as propagated by architects is not necessarily in contradiction to the standardisation of construction methods and processes. As such, corporate solutions can also be developed as comparative competitive advantages.

Continued closer coordination and communication among clients, planners, entrepreneurs and manufacturers of prefabricated components, for example, is needed if the entire potential that is so far not being exploited is to be put to use in the interests of the client. For example, the following interface issues need to be clarified:

- Marketing and customer support
- Holistic approach and planning
- Uniform project management
- Definition and agreement of uniform standards

2.3 Potential – Standardisation and Rationalisation within SMEs

The implementation of industrial construction, i.e. the standardisation and rationalisation of products and processes, means that a company has to implement both strategic and operational measures. Since both areas are closely linked, focusing on only one of the two solution clusters is a sub-optimal alternative that disregards the overall rationalisation potential.

2.4 Potential – Prefabrication

Prefabrication – Intermediate products

Some subcontractors and partial trades in the construction industry, such as

- window manufacturers
- facade manufacturers

already make full use of platform systems supported by Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and Production Planning and Scheduling (PPS). These methods are also already being used to manufacture prefabricated concrete system components in prefabrication plants.

Other components, such as reinforcing cages, concrete components as concealed formwork or shaft elements, can also be prefabricated under industrial conditions to simplify the construction process.

Prefabrication – Prefabricated components

The processing of any bid must include an analysis of whether the use of prefabricated/semi-prefabricated components is commercially more viable than conventional execution methods. To ensure that planning amendments do not become a necessity, architects or planners should be made aware of the possibility of using prefabricated components and take account of this alternative before the tender is launched. The biggest financial benefits can be generated by architects, planners and construction companies working together from an early stage in order to exploit the potential offered by prefabrication and thus take advantage of being able to run construction processes in parallel.

Prefabrication – fully prefabricated individual houses

In the case of timber constructions, buildings based on a platform system with a wide range of design varieties are nowadays largely prefabricated by linking CAD and CAM and optimizing PPS. Unlike solid buildings, the idea of platform products is already widespread in timber construction.

The prefabrication industry in Japan has already made enormous progress (Bock 2000). At **TOYOTA HOME** (2006) customers can compile their dream house from more than 350,000 individual components on a platform base with the corresponding production-related ability to adapt to the design variance offered. The building is compiled on a computer and can then be virtually toured in advance (Fig. C.1). Once the purchasing contract has been signed, the building is completed within 4 days: one day for order processing, two days for prefabrication in the plant, and one day for delivery. The building is delivered in several room modules that are already equipped with the appropriate technical fixtures; it takes just 4 - 6 hours to erect the building. Depending on the type of building, clients are given a warranty period of between 10 and 20 years on the building. The marked client orientation and the linking of marketing and industrial fabrication have resulted in the manufacturer now occupying a significant share of the residential housing market in Japan. The degree of construction prefabrication can also be expected to increase in Europe in line with this development.

Fig. C.1: One of the models offered by Toyota Home (2006)

3 Conclusions

The goals of industrial construction shifted from the uniform architecture of the 1960s and 70s to a customer's expectation for individual products. The potentials of industrialisation in the construction industry sourced in the provision of almost individual products on platform basis. Computer Aided Construction interlinks processes and information of design-phase, production-phase, execution-phase and utilisation-phase and makes individual solution, prefabrication of integrated solutions on platform basis achievable.

4 References

Bechthold, M.: (Mass-) Customization in Architecture – Hype or Innovation? In Proceedings: International Conference On Adaptable Building Structures, Eindhoven, The Netherlands, 2006

Bock, Thomas: Technologiefusion als Innovationstriebkraft in der japanischen Bauwirtschaft. In: Japan Analysen Prognosen Nr. 167 vom Mai 2000, Japan-Zentrum der Ludwig-Maximilians-Universität, München

Piller, F.T.: Kundenindividuelle Massenproduktion: Die Wettbewerbsstrategie der Zukunft. Carl Hanser Verlag, Wien, München, 1998

Piller, F.T.: Mass Customization und Kundenintegration: Neue Wege zum innovativen Produkt. Symposion Publishing GmbH, Düsseldorf, 2003

Pine II, B.J.: Mass Customization, The New Frontier in Business Competition. Harvard Business School Press, Boston, Massachusetts, 1993

Toyota home: http://www.toyotahome.co.jp/home/since_raison/top.html (03.05.2006)

D) Industrialisation for Sustainable Construction?

EMILIA VAN EGMOND-DE WILDE DE LIGNY[1]

1 Introduction

Sustainable construction (SuCo) advocates the creation and operation of a healthy built environment based on resource efficiency and ecological principles (Kibert, 2003). The principles proposed for SuCo include: reduce, reuse, and recycle resources; protect nature in all activities; eliminate toxic substances from construction; apply life cycle economics in decision making; and create a quality built environment (Kibert, 2003). The credo that has been launched since the new millennium is: "doing more with less" (McDonough and Braungart 2002). Of paramount importance in SuCo is the optimum application of these principles during all stages of the life cycle of buildings. Industrialised construction – i.e. off-site standardised manufacturing of building parts and even of whole buildings- has shown to contribute to the achievement of at least a large part of these objectives. The residential building industry in North American and European countries for example has undergone industrialisation processes, alike those in manufacturing sectors. This has shown to benefit on-site construction with 16% lower labour and materials cost; 26% less material utilisation and 37% less building time (Schuler 2004). Enhancing factors like an increasing competitive pressure, more demanding and knowledgeable customers, increasing lack of skilled labour were due to changing enterprise strategies focused at innovation and industrialisation. These strategies were rooted in conceptual approaches such as supply management, design for manufacture, just-in-time (JIT) and assembly production to reduce cost and time, whilst increasing productivity and quality. Lately sustainability requirements have more or less complemented those for quality. The industrialisation strategies in building construction in majority involved the substitution of traditional building materials into factory built components such as roof and floor trusses, wall panels, cladding, prefab structural timber and steel structures and concrete wall systems. This so-called componentisation (Schuler 2003) implied that the construction industry has out-sourced parts of the construction process to the materials manufacturers, who produce components, which are delivered just in time for assembly on-site. Component manufacturing has seen a tremendous growth of 100% in ten years time (1992-2002) in the USA (Schuler 2002). Next to this there is a trend of offering customer oriented complete manufactured houses, like for example the Ikea houses in Sweden, focused at profitability and satisfying customer demands for affordability, comfort and flexibility.

---

[1] Dr. Ir. PhD, M.Sc., Senior Lecturer and Researcher, Innovation, Technology and Knowledge Transfer for Sustainable Construction, Faculty of Architecture, Building and Planning, Eindhoven University of Technology, POBox 513, Vrt 7.24, 5600MB Eindhoven, The Netherlands, Phone +31 40 2472439, Fax +31 40 2457234, e.v.egmond@tue.nl

The question is whether the stakeholders in the construction industry are indeed all aware and willing to share innovative ideas to achieve SuCo and put them into practice for example by application of industrialised standardised construction technologies? After all the construction industry is characterised by reluctance amongst the stakeholders to apply innovative products and processes that are not familiar to them. In the US for example still 69% of the residential building construction takes place on traditional basis (Schuler 2003a). Another question is whether there are in one way or the other incentives – such as government policies and regulations- that further stimulate sustainable building practices?

In the following first the findings will be presented of an explorative study on the environmental responses which have been developed by the stake holders of the CI in Chile. These will be compared thereafter with those in the Netherlands and the USA. Finally lessons learnt and possible solutions for SuCo for example through industrialised construction will be discussed.

2 Methodological Background

Traditional construction processes are blamed to be un-sustainable in terms of resource depletion and waste generation due to the application of un-sustainable products and construction processes. Thus SuCo requires investment in innovations, i.e. new knowledge creation for sustainable products and building processes, their diffusion, adoption and implementation in projects. These are all long-term, high risk ventures (Manseau & Seadan, 2001). Moreover eco-innovations are normally not self-enforcing. The research described in this paper leans back on (1) production management theories and (2) innovation theories. SuCo Performance is seen as the ultimate outcome of how construction projects are managed, which and why certain products and production processes are selected and applied.

Packendorff (1995) put forward that construction should be seen as a temporary organisation process i.e. "a deliberate social interaction occurring between people working together to accomplish a certain, inter-subjectively determined task". Koskela and Howell (2002) considered construction performance within the production management theories of "transformation", "flow" and "value" generation. By integrating Packendorff's (1995) and Koskela and Howell's (2002) models to investigate how the sustainability of construction performance can be achieved, one can see a framework with three mutually related determining factors on construction processes, i.e., (1) expectation/ motivation/ incentives of the individual stakeholders to carry out the construction process in a certain manner by application of certain building products, (2) Action as central element in the construction process and (3) Learning/ knowledge to select and apply certain building products and processes.

In a similar line of thinking the innovation theories pose that the major factors that have an impact on construction performance are to be found in the Innovation System of the Construction Industry: the Stakeholders Network and the prevailing Technological Regime (TR). The stakeholders' network includes the project executing stakeholders as well as the governmental agencies and the knowledge institutions. The TR includes the stakeholders' (1) practices and actions, (2) knowledge and experience and (3) expectations, motivations and incentives (Egmond 2005). Cleff & Rennings (2000) added an extra dimension and put forward that, since factors of technology push and market pull alone do not seem to be strong enough, eco-innovations need specific regulatory support. Hence the role of supporting and regulating public and private organisations in funding and encouraging sustainable innovations is considered critical. Thus the National Government is hold responsible for the development of clear sustainability policies and legal, fiscal or financial measures resulting in actions that change the behaviour in the market either in a voluntary or in a compulsory way in order to minimise the negative impacts on the environment (Bourdeau, 1999). Also Educational and R&D institutes are supposed to support in knowledge for innovative eco-solutions, whilst banking organisations may offer financial support. The following theoretical framework was derived from the above described theories.

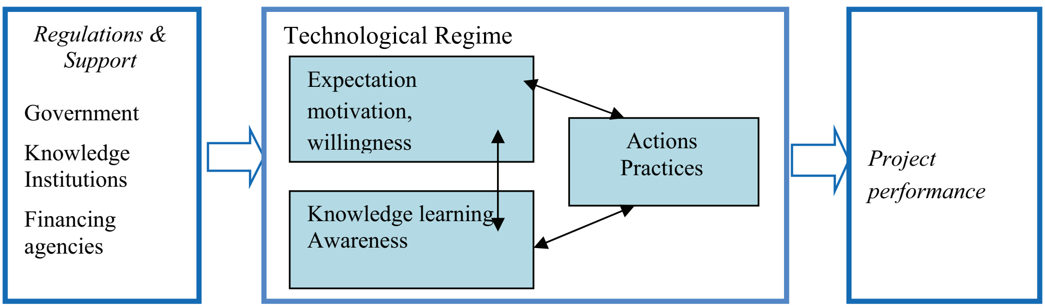


Fig. D.1: Theoretical framework

As shown in Fig. D.1, the regulatory and supporting framework has an impact on the sustainability of project execution by the stakeholders in the innovation system of the CI which on its turn depend on (1) the practices with the applied technologies and building systems; (2) the knowledge and awareness amongst the stakeholders with regard to their valuation of environmental aspects which in turn influences their behaviour and their capacity to act environmental friendly (3) their motives, willingness and commitment to sustainability i.e. 'the extent to which people are willing to give sacrifices for public interest'. The actions taken by the stakeholders also depend on their financial capacity vs. the costs of the sustainable solutions.

Based on these views a study was carried out to investigate the environmental response of the major stakeholders -including the supporting and regulating organisations- of the innovation system of the CI in Chile. Questionnaires were distributed to collect the data amongst the designers and contractors in the Santiago Metropolitan Region, where 75% of the total number of contractors in Chile is considered to be active (Serpell, Solminihac & Figari, 2002). The regulatory and supporting framework was investigated by using literature, documents and interviews with experts. For the comparison with the environmental response of the CI in the Netherlands and US, literature and expert opinions were used as source of data.

3 Sustainable Construction in Chile

3.1 Sustainability in Chilean Construction Practice

The sustainability of the building practices of Chilean designers was investigated by means of looking at their application of energy saving measures and energy, waste and material considerations in design, their awareness, knowledge, motivation and willingness to build in a sustainable manner.

Energy saving measures were applied by designers by insulating (parts of) the envelope of the building. In 90% of the projects roof insulation is applied; wall insulation in 65%, insulated glass in 40% and floor insulation in 30% of the projects. Designers mentioned to have taken into account energy considerations in the design by means of looking at (a) the orientation and natural ventilation of the building by 75 % of the respondents; (b) solar protection by 65% of the respondents; (c) passive solar design by about 50% of the respondents.

Minimisation of losses in primary materials and sustainable material use has been enhanced by an increased competition in the CI at the end of the 1990s, due to a drop in building production (the Asian crisis). This stimulated the designers to take measures for cost reduction. This is mainly accomplished by using (a) standardised building materials in 85% of the projects; (b) prefab elements in about 30% of the projects; (c) recycled materials in 10% and renewable materials in 5% of the projects; (d) design for flexibility and dismantling in about 20% of the projects. The decrease in building production has resulted in an absolute decrease in waste production and the decrease in waste generation factor has resulted in a larger decrease in waste generation. About 50% of the designers did not commit themselves completely to SuCo voluntarily in the last years (2000-2004). This means that only 23% have incorporated environmental issues in the mission statement of the firm, none of them have a specific employee for SuCo, 9% of the design firms have environmental policy document; only. 27% of the designers call for a waste treatment plan from the contractor.

The majority of measures that were taken by 75% of the *contractors* are to reduce material waste and dust by 70% of them. Measures to reduce noise were taken by 55% of them; to reduce water use by 45%; to reduce toxic chemicals by 35%. Measures to save energy were taken by 45% of the firms. The contractors indicated to have implemented innovative clean technologies during the years 2000-2004: by 11% of the contractors for energy saving; by 78% to reduce dust and by 64% to reduce noise. The major motive to reduce waste and material utilisation during the years 2000-2004 was to prevent over-ordering. In 87% of the construction companies, no more materials than needed are purchased. Besides they applied prefab elements in about 30% of the projects, whilst the re-use of building materials has taken place in 40% of the projects. In only 30% of the projects the contractors separated the different wastes they produced. 22% of the contractors did not commit themselves to any form of SuCo; 31% of them have an employee for SuCo; 25% of the contractors have an environmental policy document. 8% in majority middle-sized companies has signed the Clean Production Agreement (APL). They have implemented more and more often measures and technologies on the building site to control or reduce waste, dust, and noise than those that did not sign the APL. The conclusion is that 60% of the contractors in the Santiago Metropolitan Region perform below average in terms of SuCo. Designers attach more importance to SuCo than contractors do (see Fig. D.2). There appears a strong positive relationship between (1) the degree of knowledge, awareness and importance dedicated to the environment by the firms and (2) the environmental sustainability of their building practices, which became noticeable in the application of energy saving technologies and the use of standardised, industrially produced building materials and elements.

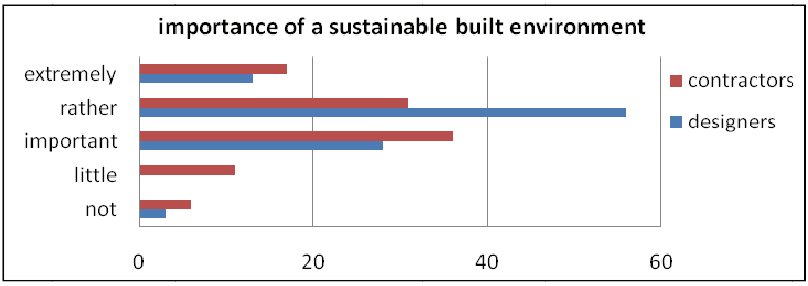


Fig. D.2: Opinion on the importance of a sustainable built environment

To the opinion of designers environmental awareness stimulates sustainable building practices more than other factors, such as cost reductions and norms and regulations. Least important for the designers is the impact of SuCo practices on their position in the market. Fig. D.3 shows how designers prioritise the design criteria. The availability of building materials does not play an important role in the design process and last comes the client's preference. Being innovative has no priority. Also contractors have the opinion that environmental awareness stimulates sustainable building practices more than other factors. In contrast to the designers the contractors stated that their image on the market is a rather important factor as well as norms and regulations and cost reduction to stimulate SuCo practices. Nevertheless nearly 20% of the contractors have no knowledge of waste legislation whatsoever; 12% of them do not know anything about Environmental Impact Assessment.

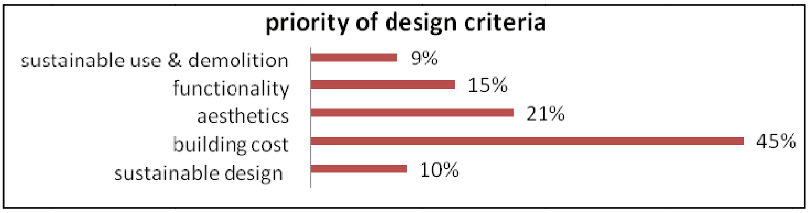


Fig. D.3: Priority of design criteria

3.2 Support for Sustainable Construction in Chile

In 1990, the National Commission of the Environment (CONAMA) was created in Chile with the purpose to institutionalise environmental issues in the country. Four years later (1994), the Chilean Environmental Act was approved, which includes three major policy instruments (Camus & Hajek, 1998):

(1) Direct regulations encompass the following obligations for building construction (a) to carry out Action, Prevention, and Decontamination plans, especially focussed at waste management. Four dump spots especially for construction & demolition (C&D) waste are allocated to support these plans; (b)

to stick to norms and regulations, such as those for energy saving in housing and reduction of emissions. There are no specific norms for C&D waste.

(2) Indirect regulations include charges for waste dumping, and subsidies & technical assistance for the improvement of the environmental practices. There are no government interventions or tax policies on energy.

(3) Self-regulation policy instruments include the facilitation of dialogue between the public and private sector to voluntary change the behaviour in the CI towards SuCo, such as through the creation of the national council of clean production (CPL December 2000). CPL promotes and supports the realisation of initiatives for clean(er) production – i.e. reduction of emissions (solid, liquid and air), solid waste and noise- in Chile, by means of its Clean Production Agreement (APL; www.produccionlimpia.cl). Solid construction and demolition (C&D) waste is one of the focal points in the APL for the CI. This has resulted in the establishment of a waste recycling firm, which collects and disposes waste and separates waste (57% is earth) on their dumpsite and recovers materials for reuse conform current regulations. 0.4% metals, 0.6% paper & carton, and 0.03% plastics is reused. Besides government authorities provide information for example by means of demonstration projects. Self regulation is also supported by private organisations such as the Chilean Chamber of the Construction Industry (CCC) which provides information for example by means of manuals for construction companies on how to minimise the negative effects (dust, noise, and solid waste) of construction.

The environmental awareness appeared to be limited amongst the relevant regulating and supporting authorities for the CI. Interest for and knowledge on sustainability in building practices is lacking at the governmental level although the ministry of public works (MOP) has made some commitments by establishing an Environmental Administration office and participating in demonstrations projects.

Advice on environmental norms and rules was given to 80% of the designers and to 85% of the contractors; whilst advice on energy saving in buildings was given to 68% of the designers. Information on prevention of contamination and clean production was given to 46% of the contractors and on end-of-pipe technologies to 32% of them. In contrast to the designers, who are less interested, 39% of the contractors received training on SuCo. Universities and technology centres are the most used (68%) source of information for designers, next follow consultants and government agencies (15%). The Chilean Construction Chamber is the most often used source of information (67%) for contractors; whilst universities and technology centres are seldom consulted. There is a relatively low financial support for designers and contractors for SuCo investments. This can partly be explained by the unfamiliarity amongst designers (20%) and contractors (33%) with these possibilities.

3.3 Major Barriers for Sustainable Construction in Chile

A number of barriers that hamper the improvement of SuCo are mentioned in interviews held amongst the regulating and supporting organisations. Most important barriers mentioned by them are the (1) level of knowledge and lack of awareness and attitude amongst the stakeholders in the CI; (2) financial and market constraints; (3) a lack of attention to SuCo in the educational system of Chile. A major aspect is mentioned to be the short-term thinking of the CI versus the long-term stretch of sustainability. Less significant constraints are of a technology or policy nature, although a lack of interest at policy level is also mentioned.

The major barriers for SuCo practices mentioned by the CI stakeholders are (1) Lack of government support; (2) Bureaucracy; (3) Lack of integral design; (4) Price structure that does not reflect environmental costs and the focus at investments costs (short-term vs. long-term) (5) Perception of high costs and the economic aspects that have a priority in enterprise management. Knowledge constraints according to the contractors are caused by a lack of interest and culture within the organisation, whilst following the designers the knowledge constraint is a barrier caused by a lack of schooling programmes. Other barriers they mentioned are a lack of economic resources in general; lack of information on norms; the inappropriateness of environmental norms for Chile; the inconsistency between different governmental agents; lack of availability of appropriate technologies. Small firms see more barriers. Companies that did not sign APL find the lack of government support and the lack of integral design bigger constraints than companies that did sign the APL. The more sustainable contractors operate the higher the financial barrier they mention of the price structure.

The solutions for these barriers as indicated by the designers and contractors are of financial nature and include a discount on taxes for companies that invest in sustainability practices; more direct regulations; 28% of the designers mention subsidies, whilst only 8% of the contractors care for subsidies as stimulating instrument to achieve SuCo. In contrast according to the government officials solutions are to be found in (1) education - Universities should play an important role in this by offering integrated sustainability education-; (2) increase of prefabrication and industrialisation; (3) demonstration projects and monitoring data on environmental impacts.

4 Sustainable Construction in Netherlands

4.1 Sustainability in Dutch Construction Practices

Since the beginning of the 1990's a relatively small network of green organisations composed of green consultants, green architects, green real estate developers, and green contractors operate in the field of sustainable construction. In the course of time methodologies for lifecycle analysis were developed -most at universities and at research institutes - stimulated by the government to support SuCo practices. The lifecycle analyses were carried out in demonstration projects financed by the government. The knowledge and experience developed in demonstration projects is used to further develop and improve the design tools (Anink and Mak, 1993; Haas, 1992; Stofberg, 1996). The awareness amongst construction stakeholders regarding the importance of achieving a more sustainable built environment has been given a new boost during the last years in the Netherlands. Increasing construction resource costs and a growing lack of on-site skilled labour -enhanced by a greying society, stimulated innovation in construction towards industrialisation and improved sustainability. Measures to reduce energy, materials and waste are the most popular whilst water saving measures are seldom implemented in practice.

The so-called Trias Energetica strategy (1) prevention of unnecessary use; (2) the use of renewables; (3) the deliberate use of clean and high performance non-renewables- is employed to decrease energy utilisation. All newly built houses are presently fully insulated in the Netherlands. Building regulations are the major factor for construction professionals to implement energy measures, although energy saving is often mentioned as a priority by the major clients in their environmental policies to emphasise a green image. To increase the energy efficiency window insulation, high performance boilers for central heating and solar boilers are applied (MNC, www.rivm.nl).

The strategies employed to improve the sustainable use of building materials include (1) dematerialisation; (2) substitution; (3) increase of the lifespan of the building and building parts; (4) enhance the reuse and recycling of building parts and materials. The majority of measures to improve the sustainable use of building materials involve the substitution of the traditionally used building materials in more than 50% of the built houses by for example the use of eco-materials and products like FSC timber, water based acrylic binders, recycled PVC rainwater pipes, water saving toilets, water saving showers. Paints with limited solvents, concrete aggregates to substitute gravel, and high performance glazing are less often applied in building construction, whilst separate water tubes for hot water and second hand building materials are applied to an even much lesser extent. (Klunder 2002)

Based on the awareness of the important role which industrialised building can play in driving up quality and value while cutting resource utilisation and construction costs Industrial. Flexible and Demountable systems (IFD) were developed, based on the following requirements: (1) a completely dry building method: no pouring of concrete, mortar joints, screeds, stuccowork, sealant or PUR spray; (2) a perfect modular dimensioning: a great deal of attention has to be given to the engineering details, prototype testing, and assembly instructions (3) the adjustability/ adaptability of all parts in differing degrees: bearing structure (limited),installation (practically unlimited), outer shell (limited and modular),interior finishing (practically unlimited and modular); (4) a maximum flexibility with respect to vertical and horizontal piping, providing various possible locations for toilets, kitchens and bathrooms (System catalogue IFDToday 1999). IFD also requires a process innovation: early co-operation between the stakeholders and a multidisciplinary approach during design and production, with changes in the traditional roles of the stakeholders. Specific skills are required for the organisation and facilitation of and participation in the design, production and construction process. IFD building can be seen as a three-pronged strategy to innovate the building process: (1) flexibility for the client, (2) industrial production for the manufacturer to cut materials, costs and time and increase quality, and (3) demountability for society to decrease waste. (Van den Brand et all, 1999) The industrial production of components offers increasing opportunities for IFD construction. Demountable building enables a separate replacement of components with various life spans, thereby extending the life of the building as a whole. (Steering Committee Experiments in Social Housing IFD/SEV www.sev.nl)

Large investments in innovation have taken place to meet the goals for IFD by collaborations between the so-called knowledge institutions, industry and housing corporations. Much research was particularly focused at developing innovative load-bearing structures, building envelopes and interior building components. A result of research on the load bearing structure was a main structure that is composed of a steel support construction of hot-rolled standard profiles with concrete panel floors usually made of hollow elements Piping can be integrated in the supports and the floor panels and partitions can be placed anywhere which provides various layout possibilities (Hendriks 1999). A rather successful development was the replacement of on-site solid masonry for the industrially produced hollow ceramic tile cladding system for external façades, maintaining the “ceramic architectural look“, while reducing mass and increasing flexibility and dismantling/re-use option. It is a sandwich construction (cavity wall) with a concrete inner wall (80mm), a core of 120mm insulation and a concrete outer wall with a finishing of split burnt bricks. Glazed window frames are integrated in the prefab masonry facade elements. Wall sockets are integrated in the inner cavity wall.

A pilot study of construction resource costs in the EU in 2006 showed that the Netherlands, Belgium and the Scandinavian countries perform rather well in terms of sustainable resource utilisation. The common factors that made this possible included: Substantial off-site profit; Highly mechanised site distribution; Just-in-time delivery of material and components; Low load of material waste; Well-paid onsite workforce; Skilled and well-trained workforce; High level of R&D; Flexible relationship between design/architecture and contractors; Early influence of contractors in the design process; Use of liability insurance (Hamelin 2007). The Swedish construction industry for example uses industrialised techniques to cut costs for residential construction. So-called catalogue housing units are prefabricated with different modules allowing the design of fully personalised buildings, fully finished, including wallpaper, radiators, bath and kitchen units. The building site is protected from the weather and the house can be assembled by a team of four people (Goodall 2007). Belgium has several factories producing pre-fabricated units with a well trained workforce, limited subcontracting and lean management. A contractor provides detailed technical designs whilst alternative solutions and extensive R&D are made possible through partnerships with universities. The pre-fabricated units lead to at least 30% savings in steel and concrete (Goodall 2007).

A major focus in technological innovation and industrialisation for SuCo has been on residential construction. In office building construction only marginal improvements have been established, and this mainly depends on the client’s ambitions to expose a green image. An important development in this sector has been the reduction of the constructed volume by means of an innovative organisational concept: the flex-working concept with which up-to 50 % space reduction has been achieved. In this working concept most of the employees especially those who are only part of the time present in the office have to seek for a desk which they can occupy anywhere in the office building.

With regards to *Waste Management* the Netherlands is internationally known, because of the relatively high percentage of recycling and reuse of construction & demolition (C&D) waste. Today, 95% of total C&D stony material waste is reused in concrete, replacing sand and gravel. In addition, a significant amount of timber is reused. The reuse of waste has strongly increased, stimulated by an increase in dump tariffs.

4.2 Support for Sustainable Construction in the Netherlands

In 1990, SuCo became a policy issue in the Netherlands via the National Environmental Policy Plan Plus of the Ministry of Housing, Spatial Planning and the Environment (VROM). The national and municipal government authorities mostly stimulated the developments of eco-innovations by means of a reasonable coherent mix of policy instruments.

By means of *direct regulations* the Dutch government tried to stimulate energy savings. Only after 1995, a first breakthrough in the CI took place, when the Energy Performance Norm (EPN) came into force being part of the Building Code. The EPN implies that applicants of building permits have to show that their building specifications meet the energy performance requirements before a municipality will issue a permit. How this energy efficiency target is achieved is left over to the actors in the CI, which makes this policy instrument highly appreciated by the CI (www.epn.novem.nl).

Indirect policy instruments -largely used in the Dutch SuCo policies- encompass both negative (based on the polluter pays principle) and positive instruments, such as subsidies and tax relief. For (1) consumers there are energy subsidy schemes and for (2) eco-innovators and project developers there are Innovation Subsidies managed by different Ministries.

The *self-regulation instrument*s include the Energy Performance Advise (EPA) to stimulate energy saving in existing buildings; DuBo packages (DuBo = Dutch for SuCo): the establishment of a DuBo information centre and the development of sustainability assessment methods. *DuBo packages* were developed to provide information and support to increase awareness and knowledge about SuCo. DuBo packages include almost hundred guidelines for SuCo Terms of Reference, Design, Construction, and Use and several prescriptions related to waste & material management. The packages have no legal enforcement power and were mainly applied in combination with DuBo-contracts in which agreements were made between municipalities and private companies to adhere to the DuBo packages. The packages have been useful in being rather practical, but too detailed in prescribing how to implement SuCo. Freedom in design and construction was gone, provoking resistance among the building industry. The *DuBo*- information *centre* for SuCo, is created in collaboration with market parties and research institutes. Several regional DuBo consultants support the DuBo-centre. In the course of time also several methods were developed for sustainability assessment of the built environment, such as Greencalc. This is a software programme for mapping environmental costs throughout the building life cycle by calculating the prevention or recovery costs of activities that cause environmental damage. Mapping of environmental costs can stimulate environmental awareness. Other tools such GPR are rating tools comparable to the US Leed and UK Breeam sustainability rating tools that support communication and decision making in design for SuCo, without prescribing them. The most important examples of self-regulations were the demonstration projects, in which SuCo is put in practice. By means of demonstration projects and experiments designers were pointed at the opportunities of Industrial, Flexible, and Demountable (IFD) building methods.

4.3 Barriers to Sustainable Construction in the Netherlands

The impact of the Dutch DuBo policy can be noticed in improvements in SuCo practices thanks to the coherence of the policy mix (van den Brand 2004). Broad support for the SuCo policy could have been achieved by its development in close collaboration with the target group. (Bueren & Priemus, 2002). However the actual results in terms of reduction of environmental pressure by the CI were less significant. Bueren (2001) indicates that SuCo measures are not adopted on a large scale. The lasting effects do stay away at present, only a small part of the market uses SuCo as a mean to distinguish itself. Klunder (2002) mentions that the actual impact of applying energy saving measures so far contributed less than 5% to decrease the environmental pressure, whilst there even is 6-9% increase of environmental pressure due to the continuous use of non-renewables although they are used deliberately. Also the sustainable material utilisation measures to decrease the environmental pressure, is rather limited: 0% by dematerialisation and 5% by reusing and recycling of building parts and materials. However 13% decrease of environmental pressure is established by particular material selection, and industrialised construction and 20% by an increase of the lifespan of the building and building parts (Klunder 2002). This underpins the valuable contribution which industrialised construction can have to improve sustainability in the construction industry.

The learning effects of demonstration projects are too small, since often these projects are not evaluated. If so, the results are not widely communicated (van Hal 2000). Sunikka and Boon (2002) put forward that sustainability measures are usually considered in the early phases of new construction projects whilst sustainable maintenance and demolition is often still neglected. The real threat to sustainable building, however, is the lack of market demand. A market research in 2001 concluded that there was still not much interest in sustainable building in the Netherlands (Sunikka and Boon 2002). For example only 44% of the housing corporations that were interviewed mentioned to be interested in having a green image, whereas 41 % said they rarely profile themselves as being sustainable. They indicated that only 33% of their tenants have interest in sustainable building, 49% tenants are only interested to a certain extent and 9% are not interested at all. Moreover the willingness to invest in SuCo is rather limited: only 16% of the tenants are willing to pay extra for environmental measures. Costs, capacity and knowledge amongst construction clients, such as housing associations, and acceptance of building users and tenants, are important barriers to sustainable construction. It has changed in the meantime, although the actual implementation of sustainability measures in the construction industry in the Netherlands still has not very much taken off.

Government support was an absolute condition to create loyalty to SuCo in the Netherlands. Subsidies are considered as an important stimulation measure. Besides after years of promotion and stimulation of environmental building practices, the Dutch government has decided to change its policy line into a more commercial approach. From 2004, the market was expected to pick up the phenomenon of sustainable building (van Hal, 2002). The high score of lack of government support indicates that the industry does not want to pay for environmental building practices itself but considers SuCo a collective responsibility of the government.

5 Conclusions

In SuCo environmental aspects and building life cycle thinking are expected to be integrated alongside the traditional factors such as functionality, aesthetics, technical & physical durability, producability and costs that are taken into consideration in the development of design, building elements and components as well as in the execution of construction projects. The CI is challenged to change their practices in order to achieve SuCo targets. Although the driving factor was cost reduction, measures including the minimisation of losses in primary materials and material use in Chile have underpinned that industrialised construction, which takes into account the environmental aspects contributes to the achievement of this objective. By focussing in design and project execution at standardised materials, recycled and renewable materials, flexibility and dismantling of these and the use of exact sizes of prefab panels, the waste generation factor decreased significantly. However SuCo is understood to be more than only insulation and waste reduction in traditional building construction. Although policies in many countries have focussed on those aspects as was shown in the

Chilean case, where the major focus is on energy saving in buildings and waste reduction (particularly emissions and noise) during the construction process. There still are barriers to overcome for true SuCo in the CI. Moreover SuCo should imply -following the new concept that has taken nature as model- that buildings are designed from the outset so that even after their functional lives, they will provide nourishment for something new (McDonough and Braungart 2002). Hence SuCo requires the implementation of innovative solutions in the CI and project execution that goes beyond the traditional and generally accepted way of building. Designers, building material producers and contractors thus need to bring about design concepts, building elements and components as well as adaptations in the building processes by integrating the ecological aspects in order to achieve the optimum application of the sustainability principles during all stages of the life cycle of buildings.

Innovative sustainable solutions for design, building materials en processes require investment in time and research costs, whilst such efforts are risky and their results cannot always be predicted to turn out positively. This boosts the perception of high investment costs of SuCo. Besides life cycle thinking implies additional costs that occur on top of the initial investments. Although the Chilean case learns that there is apparently no dispute in the CI about their responsibility to meet the SuCo targets, there is reluctance amongst the various stakeholders in the construction projects to be individually responsible in risky endeavours. A weakness of the construction industry to innovate for improved sustainability is the division of roles and responsibilities in the construction industry. Design and selection of building systems and materials is in the majority of the projects in the hands of the designers and consultants rather than the contractor, which results in aesthetically sound but often expensive buildings, waste, longer construction times and inferior guarantees. Another difficulty is that it is almost impossible to specify a sustainable building. There are new practices, such as componentisation and manufactured building. Yet sustainable innovation should take into account the fragmented nature of the industry with lots of small SMEs as well as long and complex supply chains. Although SMEs form the largest proportion of the construction industry yet are not well represented among the bodies that develop sustainability standards, new practices and best practices. Sustainability standards and norms are essentially to support the construction practice but there is a lack of knowledge in the construction industry. Moreover, the industry is largely project-oriented, so learning and knowledge tends not to be passed on outside the small firm and its co-contractors (Desmijter 2007). This calls for building teams in which the construction project parties collaboratively share the risks. Also from the Dutch experience can be learned that government support is necessary to stimulate SuCo and that for the achievement of the adoption of SuCo measures on a large scale, it is essential to accompany environmental gains with gains in building-economics terms and in health improvements. Hence policy should incorporate incentives for the industry to partly carry the risks.

A rather successful example of such collaborative undertakings to bring about innovative solutions for SuCo is the program called Building America (BA), which is a private/public partnership sponsored by the U.S. Department of Energy that conducts research to find energy-efficient solutions for new and existing housing that can be implemented on an industrialised production basis (www.eere.energy.gov/buildings/). The long-term goal of the BA program is to develop cost-effective systems for homes that can produce as much energy as they use - a zero energy home. BA unites segments of the CI that traditionally work independently of one another in consortia by using a systems engineering approach. It forms teams of architects, engineers, builders, equipment manufacturers, material suppliers, community planners, mortgage lenders, and contractor trades. The research participants in the BA projects agree to: Provide all construction materials and labour for research projects; Evaluate their design, business, and construction practices; Identify cost savings; Re-invest cost savings in improved energy performance and product quality; Extend their efforts from discussion of possibilities to development of solutions; Use a design, test, redesign, and retest process to resolve technical barriers. The systems engineering approach recognises that characteristics of one component of the building can greatly affect others. It enables the teams throughout an integral process of design and construction to incorporate SuCo strategies from the very start of the building process. Research participants in BA projects evaluate the interaction between the building site, envelope, mechanical systems, material and energy-use factors. Cost tradeoffs often allow the teams to incorporate these strategies at no extra cost. Initial cost-effective strategies are analyzed and selected during the pre-design phase, after that they evaluate their design, business, and construction practices to identify cost savings. Examples of SuCo innovations are such as new techniques for tightening the building envelope that enable builders to install smaller, less expensive heating and cooling systems These cost savings can be reinvested for example in high-performance windows that even further reduce energy use and costs, whilst improving the sustainability and product quality. An example of an innovative solution for industrialised production of houses that meet the SuCo targets is the BA house in Cambridge, (Mass. USA), which is constructed of factory-made modules stacked one on top of the other, which reduces construction time and costs. Treating the modular construction process as a system, energy and environmental efficiency, health features, and high quality can be built in at the factory - resulting in lower costs to the home buyer. By supporting industry-driven systems engineering research the program provides the feedback required to develop critical "next generation" building systems.

The research by Building America teams provides valuable information for residential building projects of the future which is published on the web site, which boosts the diffusion of the innovative solutions and increase the awareness about the need for SuCo in the CI market. This is important given the finding in this study that environmental awareness has a positive relation with SuCo practices. The government can set requirements for energy and material savings as well as minimisation of waste generation. Additionally the CI can make itself economically stronger and small companies have the opportunity to distinguish themselves on the market. Rethinking and discussing the BA strategies is considered worthwhile to achieve SuCo targets.

6 References

Anink, D. and J. Mak, Eds. (1993) *Handleiding Duurzame Woningbouw. Milieubewuste materiaalkeuze bij nieuwbouw en renovatie* (Rotterdam) SEV, Stuurgroep Experimenten Volkshuisvesting ISBN 90-5239-095-9.

Bourdeau, L (ed) 1999, *Agenda 21 for Sustainable Construction*, CIB report, Publication 237, CIB, Rotterdam

Brand, G. Van den, Rutten, P., Dekker, K. 1999, *IFD Bouwen, Principes en Uitwerkingen.*TNO (Netherlands Organization for Applied Scientific Research) report1999-BKR-R021, TNO Bouw (Building and Construction Research)Delft.

Bueren, E.M. van (2001) Sustainable Building Policies: Exploring the Implementation Gap. in. Maiellaro (ed.) *Towards Sustainable Building*, Kluwer Academic Publishers, Dordrecht

Bueren, E.M. van, H. Priemus (2002) Institutional Barriers to Sustainable Construction. in *Environment and Planning B: Planning and Design*, volume 29(1) January, pages 75 – 86 Pion Ltd., London,

Cleff T. and Rennings K., (2000) Determinants of environmental product and process innovation—evidence from the Mannheim Innovation Panel and a follow-up telephone survey. In: J. Hemmelskamp, F. Leone and K. Rennings, Editors, *Innovation-oriented Environmental Regulation: Theoretical Approaches and Empirical Analysis*, Physica Verlag, Heidelberg (2000), pp. 331–347.

Desmyter J. (2007) *Barriers to eco-innovation in the Construction World*– Belgian Building Research Institute (BBRI), Belgium (2007)

Egmond- de wilde de ligny, e.l.c. van (2005) Succesful Industrialisation, innovation and prefabrication in construction, in Proceedings *COMBINING FORCES - Advancing Facilities Management and Construction through Innovation* June 13-16, 2005 Helsinki

Goodall John (2007) *Belgian experience in using Industrialised Building Techniques* – European Construction Industry Federation (FIEC), UK paper presented during the European Forum on Eco-Innovation | Markets for Sustainable Construction Brussels, 11 June 2007

Haas (1992) NIBE *Milieuclassificatie bouwmaterialen* (Bussum)

Hal, A van. (2002) Amerikaanse toestanden : *commerciële kansen voor duurzame woningbouw.* Boxtel:Æneas, 2002. ISBN 9075365551

Hamelin, J.P. (2007) *Visionof the industry towards 2030 and beyond European* Construction Technology Platform (ECTP), France paper presented during the European Forum on Eco-Innovation | Markets for Sustainable Construction Brussels, 11 June 2007

Hendriks, N, (1999), *Industrieel, Flexibel en Demontabel Bouwen IFD:Ontwerpen op veranderbaarheid*, Eindhoven University ofTechnology.

IFD Today, 2000,Leaflet.

Kibert Charles J. (2003). FORWARD: Sustainable Construction at the Start of the 21st Century. Special Issue article in: *The Future of Sustainable Construction. International Electronic Journal of Construction* (IeJC) .

Klunder, G. (2002) Hoe milieuvriendelijk is duurzaam bouwen? De milieubelasting van woningen gekwantificeerd. Delft UniversityPress The Netherlands

Koskela, L. and Howell, G. (2002b) *The Theory of Project Management: Explanation to Novel Methods*. Proceedings of IGLC-10, Aug., Gramado, Brazil

Kuijsters, A., Egmond, E. van , Brand, G.J. v.d. E; Serpell, A., (2004) *Environmental response of the Chilean building sector; efforts and constraints towards environmental building practices in the Santiago Metropolitan Region*, Thesis, Eindhoven University of Technology, Eindhoven

Manseau A. and Seaden G. (2001) http://www.sciencedirect.com/science?_ob=ArticleURL&_udi=B6V9H-4FNNC5T-1&_user=499892&_rdoc=1&_fmt=&_orig=search&_sort=d&_docanchor=&view=c&_searchStrId=1005620262&_rerunOrigin=google&_acct=C000024518&_version=1&_urlVersion=0&_userid=499892&md5=1a00502405f6d7e872e6e336a1e54d7e - bbib24 *Innovation in construction: An international review of public polices*, Spon Press, London and NY (2001).

McDonough, W and Braungart, M., (2002), *Cradle toCradle: remaking the way we make things*, North Point Press, New York

Packendorff, J. (1995) Inquiring into the Temporary Organisation: New Directions for Project Management Research, *Scandinavian Journal of Management*, 11(4), 319-333.

Schuler, Al (2002) Industrialization in Housing — Implications for Building Material Suppliers in *Structural building components Magazine* Economic Environment March 2002 Truss Publications, Inc. Madison, USA

Schuler, Al (2003) The Factory Built Components Industry Is Almost as Large as the Softwood Lumber Industry *Structural building components Magazine* April 2003

Serpell A., De Solminihac H., Figari C. (2002) *Quality in construction: the situation of the Chilean construction industry. Total Quality Management, 13, 5, 579-587.*

Stofberg, F. (1996) *Bouwstenen voor een duurzame stedebouw 75 aanbevelingen voor een milieubewust ontwerp*; Published in 1996, Vereniging van Nederlandse Gemeenten (Den Haag)

Sunikka, M. & Boon, C. (2002) *Housing associations and sustainable management, Environmental efforts in the social housing sector in the Netherlands*, Delft (Delft University Press).

Web sites:

www.productionlimpia.cl, www.epn.novem.nl, www.rivm.nl, www.sev.nl (SEV , Stuurgroep Experimenten Volkshuisvesting (SEV) IFD)

Interviews:

Brand, G.J. van den (2004) Sustainable Construction expert, Eindhoven University of Technology, Eindhoven

Hal, A. van (2004) Sustainable Construction expert, Delft University of Technology

E) A Continuous Challenge in Custom Construction

MARTIN BECHTHOLD[1]

1 Introduction

The industrialised production of building products and components has brought previously unprecedented quality and affordability to architectural construction, albeit at the cost of uniformity and standardisation. In today's age of customised experiences, services and products there is increasing need for variation in architectural components. Clients seek an individualised architectural expression that reflects their programmatic needs, performance expectations, and values. State of the art computer-aided design and manufacturing methods can now allow for unprecedented efficiencies in producing customised architectural components, albeit only if used strategically.

2 A Legacy of Product Variation in Architecture

In the pre-industrial age of building construction craft-based construction processes facilitated variations in the way buildings of all scales were designed and eventually put together. Little advantage was gained through repeated use of identical elements, and often the technology to replicate dimensions accurately was entirely missing (Fig. E.1). In the craft-based construction of windows, for example, craftspeople would certainly produce jigs and templates to speed up the production of identical windows, but the cost of these simple tools was insignificant, and the saws and drills used in these fabrication processes were general purpose tools that could quickly be set up to accommodate varying window sizes or types of profiles.

[1] DDes., Professor of Architectural Technology, Co-Director of Master in Design Studies Program, Director of Fabrication Labs, Harvard Graduate School of Design, 48 Quincy Street, Cambridge MA 02138, Phone +1 617 495 6012, Fax +1 617 495 2943, mbechthold@gsd.harvard.edu

Fig. E.1: Slight variations of façade shingles in vernacular buildings are rather difficult to replicate with today's industrialised production methods.

Mechanised production techniques were first introduced by U.S. gun producers in the early 19th century. This new concept involved the standardisation and interchangeable of parts – finally made possible by increasingly accurate machine tools that allowed operators to replicate parts precisely based on paper drawings. The implications of this approach proved to be far-reaching, and echo until the present day. Mechanised and standardised production methods soon pervaded all areas of manufacturing, and were eventually used in the production of architectural components, products, as well as in the manufacturing of entire buildings (Fig. E.2). Early corrugated sheet metal products are a prime example of these types of construction products that were inexpensive, consistent in their quality and produced in large quantities under industrial conditions. The roll-forming devices employed in forming flat metal sheets were costly and necessitated large production volumes. Changes to size and geometry involved significant time and investment – something that manufacturers had no interest in unless market research indicated a solid demand for an alternative product.

Fig. E.2: Modular housing construction quickly developed with the rise of industrialised production, and continuous to thrive today. Possibilities for design variations tend to be very limited even in contemporary production settings.

Increasing competition between producers, the drive towards a competitive edge in product innovation, and diversifying needs soon lead to a constant increase in product variety – a trend that continues at an accelerated speed today. Process management software, sophisticated computer-aided design, engineering and manufacturing (CAD/CAE/CAM) solutions combined with more flexible manufacturing systems contributed significantly to the economic viability of smaller production series. Architectural construction, however, relies only in part on industrially produced components, and much customisation still happens on site or in small fabrication shops. The following section looks at the mechanisms of customisation in architectural construction, with a focus on the role of CAD/CAM processes. It is assumed that the reader has a basic familiarity with design development environments such as CATIA, SolidWorks, or Unigraphics – the primary design environments used in CAD/CAM processes.

3 Customisation in Architectural Construction – a Persistent Need

Today architectural design produces highly varied and individualised buildings. Clients and design teams wish to differentiate themselves more than ever through highly individualised architectural concepts and construction. This is true for all sorts of buildings ranging from single-family homes, to housing and commercial buildings and public projects.

The need for individual design solutions in architecture originates in site conditions that are local and unique, in building codes, construction traditions, program and performance needs, design values and other factors. The need for sustainability has also triggered a wave of custom solutions which often involve complex, adjustable construction elements that are highly customised. Local conditions of climate, building and energy codes, program and user behaviour have led an architectural responses that includes highly integrated environmental control systems coupled with a carefully designed and constructed building fabric.

In the pre-industrial age local traditions and conditions had grown over centuries into a consistent and often highly regional type of architecture and construction, thus limiting variation to a much smaller range than is common today. Most construction essentially consisted of shaping and placing basic materials and elements directly on site (e.g. brick or stone construction, timber framing). This construction approach remains valid and common today, and its nature has not been fundamentally altered through the use of CAD techniques, but the range of available construction materials has been greatly expanded. Today's construction materials are produced and distributed globally, and they are designed to respond to increasingly specialised performance specifications that include aesthetic, structural, thermal, acoustical and other aspects. This product diversity supports increasingly customised design and construction approaches, without however fundamentally altering the underlying processes. The problem of choosing the right product for the task at hand, however, is becoming increasingly challenging. Product configuration environments are becoming more widespread in response, their characteristics are outlined below. Another change has been the use of building information models (BIM) that are extremely useful in deriving quantities that facilitate cost estimates and control.

4 Prefabrication and CAD/CAM

The opportunities of pre-fabrication techniques are closely allied to CAD/CAM techniques. This is true for structural elements such as steel framing members or heavy timber elements as well as for non-structural components such as façade or interior elements (Fig. E.3). Pre-fabrication techniques enable the implementation of numerically-controlled (CNC) fabrication techniques that are difficult or impossible to realise on site. These technologies, paired with cad/cam techniques, have allowed for unprecedented modes of customisation, including the often-quoted approach of mass-customisation discussed later.

Much attention and coverage has been dedicated in recent years to the use of CAD/CAM for highly intricate and complex designs. How have these types of designs profited from CAD/CAM environments and computer-numerically controlled (CNC) fabrication processes? Quite often the complexities lie primarily in the geometry of the envelope. At times these projects can only be realised by resorting to unconventional methods and participants that may even be drawn in from outside the industry.[2] There is no doubt that this type of work has greatly benefited from CAD/CAM techniques, since these have made it easier for designers to communicate their design intent and prepare the design for fabrication. The ability of CAD/CAM environments such as CATIA, Unigraphics, or SolidWorks to completely and without ambiguity describe the geometry of complex components has been a main aspect of highly complex projects. The direct use of the designer's digital model for fabrication, however, remains usually limited to rather small projects where risks and liabilities are more easily managed in personal relations between the design team and the fabricator. Issues of data exchange between designer's digital environment and fabricator's specialised CAD/CAM environments also continue to be obstacles.

2 Boat build Goetz Custom Boats, for example, fabricated the envelope for the suspended technical library of the Yazaki Corporation.

Fig. E.3: This gate in Dublin, Ireland, involves only a simple length variation of the individual aluminium elements. When open the bottom edge translates up vertically, and the gate forms into a complexly curved form.

Many fabricators rely heavily on CNC machines for fabrication. In highly customised work a main fabrication challenge is often the high cost of part set-ups on machines. Fabrication strategies that employ only a limited range of manufacturing technologies tend to be advantageous from a cost standpoint, and CAD/CAM environments allow designers to incorporate fabrication limitations that may result from use of a limited range of manufacturing processes. An example is the production of curved structural steel sections (I sections). For modest curvatures standard sections can be bent on CNC bending machines. Tighter curvatures are usually produced by CNC bending the flanges from flat stock, CNC cutting the web and then welding the three parts together into the curved section. Undoubtedly the latter approach is usually more costly than a simple bending process, but curvatures of bending are restricted.

4.1 Project-based automation approaches

While fascinating and valuable it is true that unique, custom solutions for highly intricate projects often generate solutions that cannot be easily transferred to other projects. The possibility of transferring approaches is often more likely for project-based systems. These are more systematic approaches to design variation that often employ a parametric design development environment, and extend the digital variation of components into an equally parametric variation in fabrication. An example is the grid shell roof for the British Museum Courtyard (London, architect Foster and Partner, structural engineer Buro Happold, fabricator Wagner Biro, Fig. E.4), or a number of projects based on varying steel space frames. The challenge is here that a relatively large number of elements (often several thousand) describe a complex geometry that leads to varying member lengths and many different node configurations. Structural optimisation may also dictate varying cross-sections of members in response to stresses and deflections.

Fig. E.4: Parametrically varied members of the grid shell covering the British Museum courtyard. The members were welded on an automated welding robot to CNC cut node plates (right)

This type of work necessitates the integration between the CAD design environments and CNC fabrication processes. Indeed, the higher production volume means that efforts in streamlining the production process, and automating certain manufacturing steps, are economically more feasible. The number of manufacturing processes and set-ups used, however, has to remain limited. Clearly, project-based systems are hardly conceivable without the ability to enable large data sets to migrate between the various participants in the design to production process. Project-specific file translator applications are often encountered and custom-coded, to translate data between the design team and fabricators. Manually re-entering geometry data on thousands of individual elements is prohibitive for time and cost reasons. Project-specific systems undoubtedly remain an area where innovative approaches have been able to thrive, funded by relatively large projects that posed complex challenges.

4.2 Proprietary automation solutions

Partially automated solutions for varied fabrication of components do not have to be project-specific. Instead, they can also be specific to a product or technology that a fabricator has specialised in. An example of this type is Mero's integrated spaceframe design to production system, designed using the company's proprietary design environment that allows for structural design, detailing and the connection to CNC fabrication processes. The proprietary spaceframe system consists of spherical steel nodes with CNC cut threaded holes that connect to CNC custom cut steel sections. Construction logistics employ management systems that track bar-coded elements throughout transport and erection.

Another implementation of a proprietary automation solution is the design and fabrication of tensile membranes (Fig. E.5). Here many fabricators offer full design-build services that include design development, possibly engineering, and fabrication. The data for the CNC cutting of the membrane panels or foils (e.g. cutting patterns) is eventually derived from the same design environment that supports the generation of the membrane form and the engineering analysis. Alternatively these design services can be provided by an independent engineering office that then provides the data for the CNC cutting of membrane panels directly to the fabricator. Proprietary automation solutions are usually quite specialised in their scope, but integrate well vertically and provide all services necessary for the product in question. CAD/CAM techniques and CNC fabrication are integral part of these approaches.

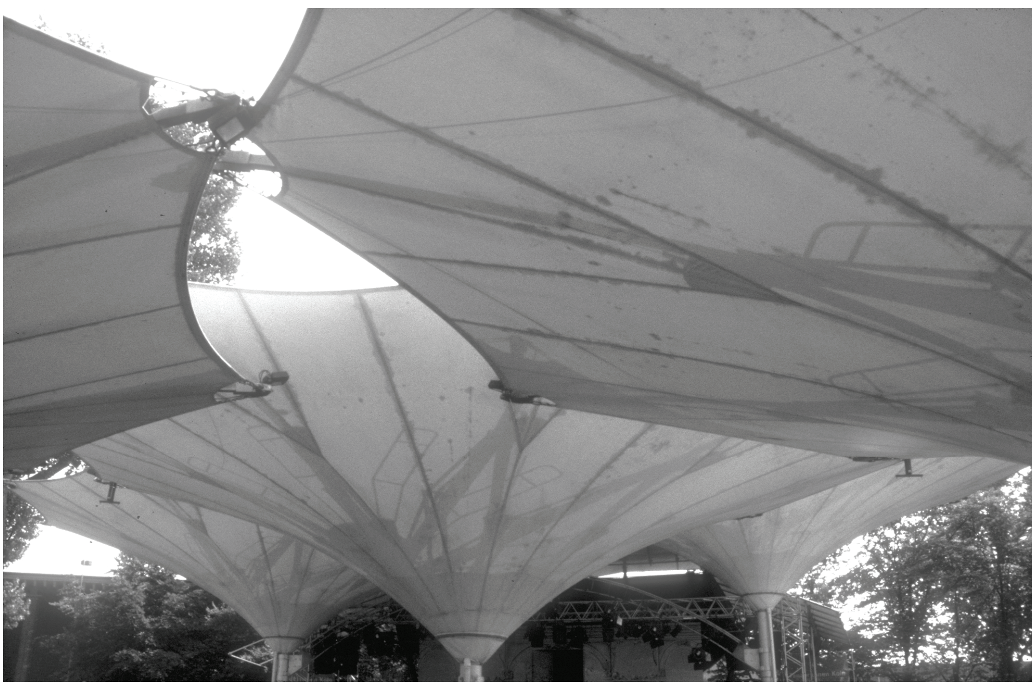


Fig. E.5: Tensile membranes are a good example of custom fabrication, supported by well-developed and integrated design and fabrication automation systems.

4.3 System-specific design-to manufacturing approaches - building systems

For decades fabricators have sought to streamline the construction drawing and shop drawing process by introducing specialised digital design systems for timber, steel, or concrete design and detailing. The beginnings of these building systems trace back to the 1970s -they thus precede the introduction of CAD in the architectural design process. Beginning in the 1990s these detailing packages were increasingly able to output machine instructions for computer-numerically controlled (CNC) fabrication processes. These standalone design and detailing systems derive all data views from a parametric 3D model in the effort to reduce errors and enhance productivity. The design environments usually contain libraries of standard elements (e.g. standard timber sections, standard steel connectors and bolts) and incorporate applicable detailing rules (e.g. minimum bolt spacing). Output from these parametric models includes bills of quantities as well as traditional shop drawings. The geometry of individual elements, for example the roof joists, can be processes such that elements can be CNC cut on machining centers.

Despite interesting steps to automate the detailing and shop drawing process building system applications remain largely disconnected from the design team's CAD model – they are typical islands of design to construction automation. Even integrating structural analysis capabilities with detailing and construction packages has been challenging, since the structural data view is based on member centerlines and the construction view of the same model is based on top of member elevations.

4.4 Digital product configurators

The vastly increased product variety, increasingly affordable database and web-technology, and the desire by producers to make it easy for designers to specify their products have been the main drivers behind the development of product configurators. Configurator software is available for a wide range of products that range from suspended ceilings, light fixtures, windows or furniture. Applications range from simple search interfaces for a database to complex interfaces with built-in expert checks for system compliance. Online and stand-alone applications are both used. Common in this model is that the data generated in the configurator is not directly used to place the order and trigger production mechanisms. Instead, the order needs to be placed in a separate step, a discontinuity that inherently leads to inefficiencies.

A prime example for the configurator model is the process of selecting and specifying windows. The author conducted several case studies on major US manufacturers, among them Andersen Corporation and Marvin Windows and Doors. Product configuration for windows is complex since a large number of different models are available. Dimensional variation (window size) is an obvious need, as are colour and finishes, glass types, hardware, screens and dividers. Geared towards building professionals, brand-specific window configurators can be downloaded for use on personal computers. Designing a custom window starts by choosing a standard window or assembling one from modular parts and then adding custom features to it. Users may be able to specify custom dimensions (Marvin) since production facilities are prepared to cater to these types of custom orders. Once complete the information can be saved, plotted, or exported as text files or dxf drawing files. Placing an order and obtaining a quote is handled exclusively through dealers with access to the order submittal software. Orders are generally submitted electronically to manufacturing facilities. The production is at least partially organised using CNC machining centers, and custom windows are shipped 2- 5 weeks after the order is placed.

Efforts are currently under way to streamline the information flow and integrate the configuration with submitting an actual order. Marvin is working on integrating the dealer based ordering system with the design configurator, while Andersen recently introduced an online product configurator that will also deliver instant quotes and photographic views. Similar configurator approaches are present in other areas as well. When choosing kitchen cabinets and appliances, for example, the configurator visualises the future kitchen that ultimately consists of standard modular units. Producers of manufactured houses have long attempted to allow potential clients to configure their dwellings online.

4.5 Mass-customisation

The increasing trend towards custom solutions and highly individualised buildings mirrors tendencies in almost all other aspects of life. Today's products, services and experiences have become highly customised. Individuals and corporations recognise that their needs are poorly served with standard solutions. Internet sites that call up specific interfaces depending on user profiles, products like from shoes, apparel, bicycles or books are made to order and on demand. The often-quoted business model of mass-customisation has indeed been a successful niche approach.

Mass-customisation has become a widely used term for many different modes of customisation, including the building systems and configurator approaches presented earlier. Mass-customisation in the domain of consumer products relies on high production volumes on flexible manufacturing systems. Modular products are configured using digital configurator systems that also allow for orders to be placed directly. These highly integrated and efficient design-to-order processes eliminate the costly collection of large numbers of individual orders. Only orders that conform to the modular design system are possible within the configurator. The cost-effective procurement of large numbers of individual orders is an important condition for successful mass-customisation. Production settings are usually highly efficient and waste is eliminated wherever possible. Just-in time delivery and lean production principles are core aspects of these production settings.

Architectural adaptations of this business model usually deviate at least in production volume. A good example for a successful mass-customiser in architecture is E-Skylight.com, producer of modular skylights, and described in detail in SCHODEK (2005). Customers can configure their units online while a 3D CAD model is generated in real time on the company's server. Detail drawings, quotes, and data for CNC production are all generated from the 3D model. In the case of e-Skylight the same technology is also used for the production of one-off, high-end skylights and curtain walls, as for example for architect Moshe Safdie's Peabody Essex Museum in Salem, MA, or the MIT Ray and Maria Stata Center.

5 A Framework of Parametrically Varied Design and Fabrication Methods

The challenge of customisation persists in particular for smaller projects where project-based systems or building systems are not feasible because of the limited numbers of components. What lessons can be learned for custom fabrication from the customisation strategies outlined above? What are feasible strategies for customisation when the variety of available standard products is exhausted?

The importance of early collaboration with fabricators can hardly be overemphasised, but designers need to be knowledgeable about basic manufacturing processes in order to be able to evaluate alternatives. Case studies by the author in SCHODEK (2005) show that design teams often pair up repeatedly with the same fabricators and contractors. The trust that builds up throughout previous projects, paired with the designers understanding of the abilities and limitations of their fabrication partners, is often the most promising avenue towards successful customisation. The risk, however, is that designs tend to become standardised because the fabrications limits or collaborating companies are too readily accepted. The following sections outline some of the key aspects when designing for custom construction.

5.1 Geometric Complexity and Rationalised Forms

Much customised construction centers on form, and designs with complex and intricate shapes are among the most challenging construction tasks when budgets and time are limited. Rationalizing forms can contribute significantly to cost and time savings. For surface elements this usually means that forms should be developable, since those shapes can more readily be produced from flat stock. The amount of curvature present should be carefully coordinated with the materials the surface is meant to be made from. Wood-based materials such as plywood, for example, have limited bending radii, and tight radii can only be accommodated with thin sheets that may be insufficient structurally. Mild radii of single curvature can often be produced directly on site by bending sheets over rigid linear or curvilinear elements. In that case no additional forming devices are required. Polygonal surfaces are usually even more cost effective, but may compromise the design if forms were initially conceived as smooth and continuous.

Introducing a double curvature normally leads to additional fabrication or construction steps that inevitably add cost. Designing these complex systems is also usually more time-consuming. The molding, casting, or forming processes needed for shape flat surface elements into complex forms always require tooling that cannot usually be reused or be incorporated into the finished product. Concrete formwork is also usually made from flat sheets that need to be post-processed in the much the same way. The tooling costs can be reduced only if they are distributed among multiple identical parts. Alternative strategies are illustrated below.

An example for surface rationalisation based on curvature analysis was the design development of the pre-fabricated façade panels at the M.I.T. Stata Center. The façade sub-contractor, Zahner Architectural Metals, was set up to produce the panels using sheet metal and metal studs, but required developable surfaces. The design team at Gehry & Partners changed the double curved form into a developable surface in order to make construction feasible.

All design development environments allow for surface curvature analysis – a powerful and direct way to understand the degree of curvature of a surface. Only developable surfaces have a Gaussian curvature that is zero. It should be noted that all developable surfaces are ruled, but that not all ruled surfaces are developable. Certain types, including hyperboloids and hyperbolic paraboloids are ruled but not developable.

5.2 High-value Processes and Reduced Waste

The efficiency of fabrication approaches itself is of crucial importance. The value created in each step should be maximised and wasteful steps should be avoided. This includes a reduction in tooling costs. The CNC milling of foam molds, for example, has been used in several projects to create forms and molds for the fabrication of concrete or fibreglass sandwich components. Projects include concrete walls for Gehry's 'Neuer Zollhof' project in Düsseldorf, Germany, a Chillida concrete sculpture for a museum in Hombroich, Germany, or architect Moshe Safdie's fibreglass-foam sandwich roof for the Rabin Center in Jerusalem. These types of molds are rather costly and relatively wasteful to produce, since the mold is discarded after its use. This may be acceptable in high-end construction projects, but would normally be too costly for more moderate budgets.

An interesting strategy for reducing mold costs is the reuse of foam molds in thermoforming thermoplastic sheets. Here a slight re-shaping of the foam on a CNC milling machines customises the mold, thus reduces waste and associated tooling costs alike. A manufacturing process developed by the author uses the foam mold as the structural core of a sandwich panel with polymer composite or wood facing, thereby reducing the waste produced and increasing the value generated in the milling of the foam (Fig. E.6). The process allows for complexly shaped sandwich surfaces that are load-bearing for use in shell roofs and similar elements.

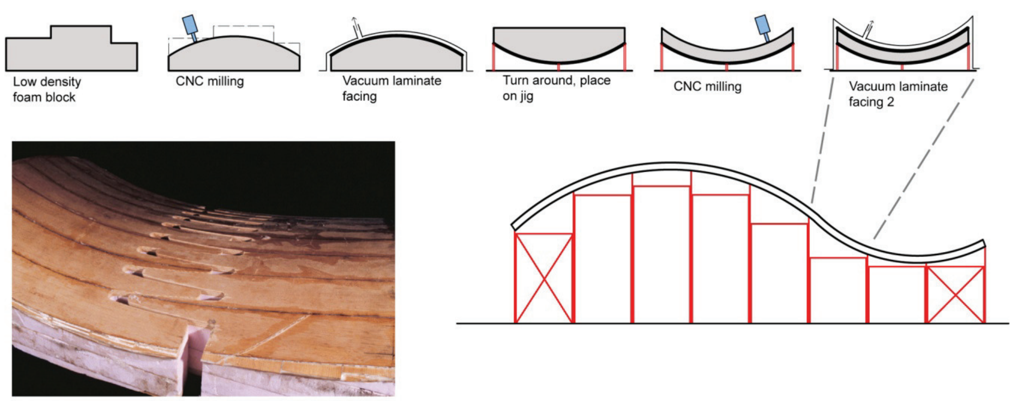


Fig. E.6: Wood-foam shells can be made by shaping a foam mold that eventually becomes the structural core of the sandwich. After the facings are laminated on the first side the panel is flipped over, CNC shaped on the second side to then receive the second facing.

5.3 Choice of Fabrication Processes and Trades

It is normally an advantage to design components such that only a limited number of fabrication and construction processes are needed. Increasing the number of processes also involves multiple fabrication set-ups, tooling costs, transfer of parts and other complexities. An example is the fabrication of curved structural steel members mentioned earlier. Reducing the number of parties involved also usually improves the efficiencies of transferring digital design data, since the number of design environments used is also smaller.

5.4 Pre-fabrication versus On-site Construction

Making complex components and parts is normally better achieved under well-controlled shop conditions that allow for the use of CNC technologies. But an element or component may be fabricated successfully by using a mixed approach. The recent construction of two doubly-curved concrete shells, for example, employed pre-fabricated formwork elements in combination with site-built formwork. In one case, the construction of the Fukuoka Park (architect Toyo Ito), pre-fabricated formwork was only used for the most sharply curved areas, whereas other surfaces were formed with site-built formwork. In the other case, the construction of a series of roof shells for a department store in Lübeck, Germany (architect Ingenhoven Architekten), the contractor and formwork fabricator devised a system that allowed for a parametrically varied series of doubly-curved concrete shells to be built economically. A limited number of pre-fabricated formwork elements were re-used throughout the construction, even though the size and geometry of the shell elements varied. For the smallest shell the pre-fabricated formwork elements were positioned close together, and for all other larger shells the formwork elements were spaced apart at a distance. The interstitial spaces were filled in with conventional plywood formwork on site. Overall curvatures were controlled by the accurate pre-fabricated elements (Fig. E.7).

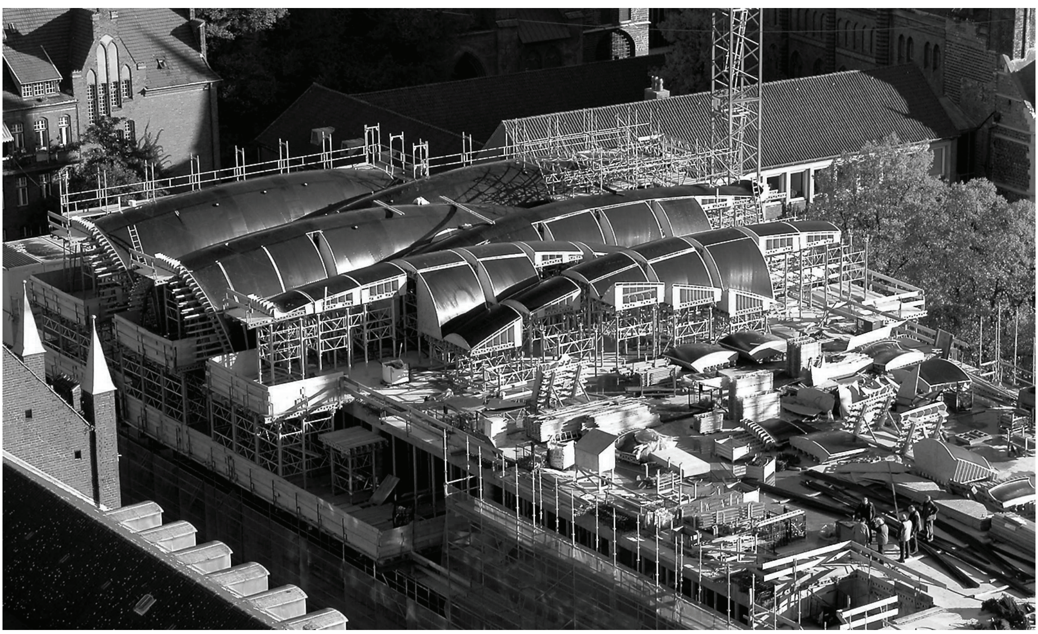


Fig. E.7: Concrete formwork for a shell in Lübeck, Germany. Pre-fabricated formwork elements were used in conjunction with an on-site infill to compensate for varying shell sizes. (Image courtesy: Peri GmbH).

5.5 Design for Assembly

Design development environments play a crucial role in pre-fabrication, especially since CNC technologies require accurate, ‘watertight’ digital models. Larger overall components usually need to be subdivided into segments that can be transported and assembled easily. Assembly and erection processes can be conveniently tested using these design environments by actually modeling components with their constituent parts. Tolerances can also be incorporated into digital models.

The ability to actually model assemblies of systems instead of merely representing overall components is a key factor when designing complex systems for easy assembly and erection. Prototyping and testing fit and assembly procedures with physical mock-ups, however, also remains important, albeit less so if design developments are used in the design process. When using those design development environments conflicting dimensions, for example, can be detected using collision detection function.

6 Conclusions

Architectural construction has a long history of individualisation. Despite an increasing range of architectural products the need for custom fabrication and construction persists, driven by the growing trend towards intricacy and complexity in architectural design. Design development environments that are parametric and dimensionally-driven facilitate the design process, but the ease of variation and modification must be matched by an appropriately devised fabrication process. Variability of construction can be achieved when designing components such that the number of fabrication steps involved is kept small, design complexity is rationalised, efficiency in fabrication is maximised, and the design is developed for pre-fabrication and efficient assembly processes.

7 References

BECHTHOLD, M. (2006) Mass-Customization - Hype or Innovation? Adaptables2006, TU/e, International Conference On Adaptable Building Structures Eindhoven

PERI GmbH, Schalung Gerüst Engineering, Formwork Scaffolding Engineering, Rudolf-Diesel-Strasse, 89264 Weissenhorn, Germany, Phone +49 7309.950-7230, Fax +49 7309.951-7230, www.peri.de

SCHODEK ET. AL. (2005) Digital Design and Manufacturing, Hoboken, John Wiley & Sons.

F) Conditions for Industrialisation and Innovation in Construction

EMILIA VAN EGMOND-DE WILDE DE LIGNY[1]

1 Introduction

The importance of the construction industry to the national economies is no subject for debate. Its contribution to GDP, fixed capital formation, government revenue and employment is significant. In terms of production output the construction industry proves to be one of the largest industries. On the other hand construction industry is often blamed for being inefficient, labour intensive, with a low level of innovation, technology diffusion and a low level of technological advancement of on-site construction. More than often the example of the manufacturing industry is taken to point at opportunities of industrialisation to improve the performance in construction, by application of innovation and prefabrication. It is stating the obvious to mention that the construction industry differs in many respects from the manufacturing industries also in the case of industrialisation and innovation in construction. In the following first contemporary theoretic views regarding the factors impeding or stimulating industrialisation in manufacturing will be reviewed. After that we will discuss the application of these views in the construction industry.

2 Industrialisation and Innovation

Industrialisation is a rather complex concept. The process of industrialisation in West-European countries involved extensive changes of production systems which resulted in a shift from home-based manual production to large-scale factory production. Industrialisation and socio-economic changes are closely intertwined with technological innovation, particularly the development of large-scale energy production and developments in the field of new materials such as metallurgy, plastics, and polymers (Dicken, 2000). "Industry" is hereby equated with the manufacturing sector which comprises establishments primarily engaged in the mechanical, physical or chemical transformation of materials, substances or components into new products. The production systems in manufacturing changed through mechanisation, systematisation, standardisation, automisation and flexibilisation of the production processes in a sequence of era. In response to the customer's demand for more variability of the production output the production processes became more flexible with a movement towards reaching a higher quality of output and the production of finished products of different kinds.

[1] Dr. Ir. PhD, M.Sc., Senior Lecturer and Researcher, Innovation, Technology and Knowledge Transfer for Sustainable Construction, Faculty of Architecture, Building and Planning, Eindhoven University of Technology, POBox 513, Vrt 7.24, 5600MB Eindhoven, The Netherlands, Phone +31 40 2472439, Fax +31 40 2457234, e.v.egmond@tue.nl

The conclusion is that in manufacturing sectors industrialisation could have taken place thanks to *innovation.* Innovation is not only the *invention* -i.e. the development of new technologies (products and production processes) and knowledge-, but also the *diffusion* (acceptation, adoption) and *application* of these in manufacturing sectors that enhanced the changing production characteristics over time (Rogers, 1995).

A key question that should be raised now is: What were the major factors that enhanced the invention and diffusion of new technologies and knowledge which made manufacturing sectors industrialise?

3 Theories on Industrialisation and Innovation

1st The answers to the question above have been a subject for research by many scholars already since a long time. The role of innovation in improvement of production performance and competitiveness has developed considerably over the past decade in economic literature. In neoclassical economic theories the basic assumption is that a motivated *profit-maximizing, cost minimizing and output maximizing* entrepreneur has to make choices among various production technologies in a perfect competition environment (Schumpeter, 1934). The neoclassical theories however could not offer a clear insight on the content and process of innovative activity or on the existence of persistent differences in the volume, scope and quality of innovations across firms, sectors or countries (Rosenberg, 1976). In these views the ultimate incentives are economic in nature; but economic incentives to reduce cost always exist in business operations and precisely because such incentives are so diffuse and general, they do not explain much in terms of the particular sequence and timing of innovative activity. Incentives thus constitute only a necessary condition for innovation. The traditional theories in the field of economics have traditionally had difficulties in addressing issues surrounding technological change. This is also due to the special nature of technology. Technology and knowledge are seen as a system of interrelated know-how, skills and knowledge (know-why, when, where and by whom) regarding production processes and products. Technology and knowledge that is general and widespread to the industry and is partially un-codified is seen as public good. Firm-specific technology and knowledge that is often patented, protected, or secret is seen as private good is not freely available (Stiglitz, 1999).

In recent years, both extensions of the neoclassical theory (e.g., new growth theory), as well as alternative approaches to this dominant paradigm have emerged, including the broad field of evolutionary economics. The core concept in these theories is the innovation within technological paradigms. The theoretical approach often draws on Thomas Kuhn's seminal thesis (1962) in which the word *paradigm* is introduced (Kuhn, 1962). This relates to. social constructs -a pattern- made of knowledge, rules, conventions, consensual expectations, assumptions, or thinking which characterise professional practice. A *paradigm shift* is a significant, profound and irreversible change from one fundamental view to another, a different model of behaviour or perception. It can be either evolutionary (i.e., a slow pace of change) or revolutionary-dramatic, short-term, and immediate high impact. Innovations -technological and knowledge developments- can thus bring about a paradigm shift.

However innovation processes do not take place in isolation (Dosi, 1982). Nelson & Winter's (1982) stated that sectoral asymmetries in industrial dynamics and innovativeness can be interpreted on the grounds of technological regimes (Nelson & Winter, 1982). A technological regime defines the particular knowledge environment where innovation (problem-solving activities by firms) take place (Winter, 1984). In this sense technological regimes (a set of rules that guide the design and further the development of a particular technology) sets the boundaries and form a constraint to what can be achieved in innovative activities associated with a given set of production activities, and the directions (natural trajectories) along which solutions are likely to be found (Marsili & Verspagen, 2002). Malerba & Orsenigo (1996), Breschi *et al.* (2000) define technological regimes as a particular combination of four factors -technological opportunity, appropriability of innovations, cumulativeness of technological advances, and properties of the knowledge base- as being common to specific activities of innovation and production and shared by the population of firms undertaking those activities (Malerba & Orsenigo, 1996); (Breschi, Malerba & Orsenigo, 2000). *Technological opportunities* indicate the likelihood of innovating for any given amount of money invested in search. High opportunities are to be found in an economic environment that is not functionally constrained by scarcity. This situation provides powerful incentives to the undertaking of innovative activities, thus potential innovators may come up with frequent and important technological innovations. There also is a policy and regulatory environment that might form either an opportunity or a constraint to innovation. *Appropriability of innovations* indicates the possibilities of protecting innovations from imitation and of reaping profits from innovative activities. High appropriability reflects the potential to successfully protect innovation from imitation by means of patents, secrecy, lead times, costs and time required for duplication, learning curve effects, superior sales efforts, and differential technical efficiency due to scale economies. *Cumulativeness of technical advances* reflects the existence of a technology and knowledge base that forms the building blocks for future innovations. Based on existing technologies and knowledge a stream of subsequent innovations can be generated that are incremental changes of the original one, or it may create new knowledge that is used for other innovations in related areas.

Economic environments characterised by continuities in innovative activities and increasing returns are considered to have high levels of cumulativeness. The last is also related to the cognitive nature of the learning process (e.g., learning by doing). The *property of the knowledge base* relates to the *nature* of the technology and knowledge that is available to support innovative activities. Technology and knowledge can be classified in various ways: generic versus specific; public vs. private; degree of complexity, tacitness etc. Previous literature mainly focuses on specificity, i.e. specialised and targeted to specific applications (Breschi, Malerba & Orsenigo, 2000). The level of specificity reflects that knowledge can be universal and widely applicable, or more specific to particular ways of doing things. The knowledge base is to be found in a network of more or less interrelated enterprises institutions and organisations that all together form the industrial *innovation system*. The opportunities to innovate depend on the extent to which an industry can draw from the knowledge base, the technological advances of its suppliers and customers, and major scientific advances in universities and R&D institutes.

Conclusion Industrialisation in manufacturing thus could have taken place thanks to a sequence of innovations. Innovativeness of industries highly depends on technological regimes and the characteristics of the innovation system. Fig. F.1 shows this relation.

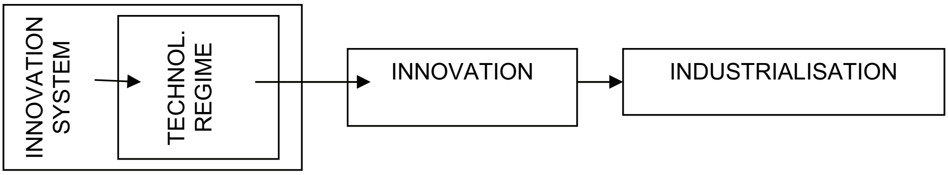


Fig. F.1: Factors influencing Industrialisation and Innovation

4 Industrialisation and Innovation in Construction

In line with the definition for manufacturing one could state that construction is the transformation of materials, substances or components into buildings and infrastructural works. A building construction process can be seen as a complex multi stage production system. Each of the stages involves a production process in which intimately related interactions take place between various parties:

- Product development stage; planning, design, engineering, specification;
- Process development and production stage, which includes determination of the construction system, construction planning, work breakdown, work packaging, the schedule and layout of the construction site, organisation structure, cost estimation, tendering, preparation, transformation and assembly of materials, components for physical realisation of a building. cost and quality control;
- Production process stage of the building materials, elements and components (van Egmond, 1999).

The construction industry is commonly characterised as one that is labour intensive, with a low level of innovation, of technology diffusion, of technological advancement of on-site construction and thus a low level of industrialisation compared to manufacturing. In traditional building construction processes in the past, but also still in developing countries at present, the production process of building materials, elements and components takes place on the building site and thus is integrated in the stage of actual realisation of the planned building. The lack of alignment between the parties working side by side on construction projects translates into dysfunctional teams, poor levels of cooperation and lost opportunities for the optimum use of resources, innovation and industrialisation.

Industrialisation is expected to reduce costs through faster construction, to increase construction quality, to eliminate dependence on weather conditions at the construction site, and to improve coordination of planning and construction. Viewing building construction as a total production system, sub-divided in a number of individual production processes, implies that each of these processes has a potential to be industrialised. This means that innovations can be applied in (a) the process of design, engineering and specification of the construction; (b) the process of project execution, i.e. the actual building process; (c) the process of building materials, elements and systems production as well as integrated in the total construction process. CIB W24 (International Council for Research and Innovation in Building and Construction, Work group 24) defined Industrialised Building as "a building technology where modern systematised methods of design, production planning and control as well as mechanised and automated manufacture are applied". Industrialised building, following the views applied to industrialised manufacturing, should relate to the application of accumulated knowledge and technologies in construction processes that become increasingly mechanised, rationalised, systematised, standardised, automatised and flexible. Industrialised building does not necessarily equate with mass production. Mechanisation in parts of the construction process on site and prefabrication of building materials and elements were the first phenomena of industrialisation in the construction industry with the purpose to reduce costs of manpower and time-consuming activities. What actually has happened in the construction industry in the course of time is that combinations of innovative solutions based on accumulated technological and knowledge advances were adopted in attempts to move from largely craft-based construction to a systematic construction process where resources are utilised efficiently. In fact a *convergence of technologies and knowledg*e from different areas and disciplines has taken place. By drawing parallels between industrialisation in manufacturing and construction like Girmscheid and Hofmann (2000) did, the sequence of accumulated knowledge and technology advances as well as their impact on the construction process characteristics can be noticed as outlined in Table F.1.

Table F.1: Innovation and changing construction process characteristics, based on Dicken (2000) and Girmscheid &Hofmann (2000)

era	construction process characteristics	cumulative technology & knowledge advances
craft based construction	location-bound labour + division of tasks building materials and constr. system determined by availability of natural resources	Materials Product engineering
Mechanisation	Labour substituted by machines New materials Prefabrication of building materials & elements	Materials Product engineering Energy Transport
Rationalisation Systematisation Standardisation	New materials and composites Standard bld elements & engineering solutions (e.g. components, methods, processes or dimensional standardisation and modularisation) Pre-assembly (materials, prefabricated components and/or equipment are joined together for subsequent installation); Modular and dimensional coordination Work process organisation further division of tasks More control and supervision	Materials Product engineering (based on applied mechanics & building physics; new materials & tools) Energy Transport Production management
Table continues on next page		

Specialisation Automisation	New and engineered materials, (e.g. high strength concrete, fibre reinforced materials, glass, ceramics) Assembly line production processes of standard bld elements with flexibility in design More control on pace of production Mass production: large volumes of standardised products Large span and tall buildings Building systems (product system with an organised entity consisting of components with defined relationships, including design rules) Construction management Optimisation of procurement & logistics Lean construction Concentration on market segments	Materials Product engineering Transport Energy Production management Process engineering
Flexibilisation Integration	Utilisation of programmable machines (e.g. robots-performing tasks; computerised tools for planning, design and operation; computer added management) Flexibility in standardised elements and bld systems Intelligent buildings Interaction of design, engineering, planning, production, construction and marketing Integration of planning, construction, manufacturing and marketing Response to dynamic market demand: (mass customisation) >relation/communication suppliers-producer-user	Materials Product engineering Transport Energy Enterprise management Process engineering ICT

Hence innovation in the construction industry refers to the process of development, distribution and application of technologies -a new or improved product, process or service- and knowledge with the purpose to improve productivity and to suit the customer's requirements. Construction industry innovations are mostly incremental and thrive on accumulated technological and knowledge advances and took place in various areas: materials, engineering, transport and equipment, ICT, computers, robotics and management. As construction evolves into an industrialised process, new construction methods and building systems are also being developed to assemble prefabricated components. "Prefabrication" existed already in the ancient world; in Egypt, Greece, and Italy, where famous buildings were erected with prefabricated components made of stone (Warszawski, 1990).

The past decennia have seen the popularity of prefabrication rise and fall. At present it still gets a mixed acceptation. Despite this it is widely applied in modern construction and became almost normal practice. The benefits of prefabrication, or off-site fabrication, as making a significant contribution to construction performance, are increasingly recognised by the construction industry. The advantages of prefabrication include a reduction of (time-consuming) on-site activities and an elimination of some of the construction peculiarities such as suboptimal (climatological, locational) site conditions. On the other hand the introduction of prefabrication in the construction process tends to make the total process more complex. Prefabrication means investing in preparation, so that things proceed smoothly. Planning and organisation must be intensified, of interaction, cooperation and co-ordination in a multi-trades context has to be optimised (Koskela, 2000). This also implies a need to have a quality control system for all activities during the whole process since the requirements on dimensional tolerances are more severe.

The degree of industrial prefabrication has an impact on competitive prices. A higher degree of prefabrication on the other hand, requires more work on the part of planners, which means that more time must be invested in planning processes. There is a necessity of making precise commitments in certain instances in the planning process. According to Warszawski (1990), the main problem of prefabrication today is the lack of a system approach to its employment among the diverse parties involved. What could be seen is that industrialised building did not automatically imply increased productivity, reduction of man-hours, or economic growth. To provide high performance buildings to the consumer, profit maximisation, cost minimisation and output maximisation to builders, production theories and management tools were used in order to know how to manage their operations in all phases. Koskela and Vrijhoef (2000) note that direct application of radical managerial innovations such as mass production or lean production from manufacturing. to construction has been limited due to different context in construction in correspondence to manufacturing. The question is whether the evolutionary theoretic approach will offer a better understanding of the major factors that are impeding or stimulating industrialisation, innovation and prefabrication in the construction industry and thereby a better insight in the strategies to be followed to industrialise.

5 Paradigm Shifts for Industrialisation and Innovation in Construction

When the lines of thought of the theories that were discussed in the foregoing are applied to describe innovation and industrialisation in the construction industry the assumption is, that the innovation system comprises conditions for innovation and paradigm shifts. These are provided (or constraints formed) by the technological regime, i.e. the economic and regulatory environment, the internal capacity of firms to seize market and technological opportunities; cumulativeness and nature of technological and knowledge advances; accessibility of critical inputs and the way new technologies and knowledge is protected for imitation. *The innovation system of the construction industry* includes a variety of actors. It is the network of more or less interrelated enterprises, organisations and institutes which jointly and individually contribute to innovation, i.e. to the development, diffusion, application and use of new technologies. *Long term linkages* between the various actors are critical for innovativeness and for the efficiency in terms of speed and costs at which projects and technological inventions in these are realised, handed over and used by and among the actors. It counts also for the efficacy at which clients' requirements are met with the project. Linkages in the construction industry however are mostly project bound and of temporary nature. It is not only the linkage that counts it is also the *size and nature of the knowledge base* within the distinct institutes, organisations and firms that is considered determining for innovation and industrialisation.

The construction industry is characterised by a high percentage of small and medium sized firms. Much of the technology and knowledge – at least in the contractor business- is tacit, not codified and project experiences are often not documented, which makes diffusion more problematic. Building product and material manufacturers have been the major sector of the construction industry to actively develop or look for new technology to improve their products, given the fact that they can profit from scale economies, which forms a *technological opportunity*.

Another industrialisation *stimulating factor* concerns the aging and shrinking construction labour force in many Western countries as progressively fewer young people enter the industry. If demand for labour remains the same and the supply decreases, costs will increase. This pressure will lead builders to innovate and apply industrialised construction, which requires fewer specialised trades and people.

Impeding factor is the tendency to conservatism making that diffusion of technological developments - a new or improved material, building element, process component or procurement method - generally faces quite some constraints within the construction industry. The array of regulations and standards -often unduly conservative and prescriptive- as well as the variety of contractual agreements and the separation of responsibilities among those involved in a construction process can be blamed for this (Nam & Tatum, 1988; Ofori, 1990). The reluctance to change is enhanced by risks of unforeseen failure and damage during the project execution and a marginality of profits. Acceptance, application and implementation of technological developments, inventions and improvements in the construction industry therefore slowly come to pass.

An important role for Governments is to improve the efficiency of innovation systems and facilitate their formation. Innovation stimulating is the fact that people become more educated and know more about for instance energy conservation, lighting, indoor air quality, and other health and comfort related issues, consumers (homebuyers and commercial property owners). These customers put pressure on firms to deliver better quality goods and services. The uniqueness of each construction project provides an impetus for innovation. Moreover *appropriability in construction is low*; construction operations are rather transparent, easy to copy and have the opportunities for job-site training; the industry has an extensive scope for diffusion of inventions and technological improvements from other projects and industries (Hillebrandt, 1984, Tatum, 1986).

Although there are incentives to innovate and industrialise, there are factors impeding innovation and industrialisation which in majority appear to be the deficits in the innovation system such as cooperation between planning and construction as well as characteristics of the technological regime such as the reluctance to accept and adopt new technologies.

6 Conclusions

In this paper the theories that could underpin our understanding of industrialised manufacturing have been discussed as well as how these can be utilised to improve our understanding of what happens regarding industrialisation in the construction industry. The innovation system approach as developed by economists (Malherba, Nelson and Winter) seems to offer an interesting opportunity to get a grip on the processes of industrialisation in the construction industry. The basic assumption that is adopted here is that the technological regime of the construction industry sets the boundaries for innovations, which applied in this industry stimulates or are a constraint for industrialisation processes.

The construction industry has continuously developed during the years. Innovations could develop by accumulation and convergence of technologies and knowledge from various areas and different parties in the construction industry in the course of time. Despite this the technological regime and the innovation system seems to adversely affect innovation and industrialisation. More transparent forms of planning cooperation could be a way forward as well as innovative forms of communication and/or exchange between planners and builders. The development of integrated production management in the construction industry - of which development prefabrication is a part- supported by ICT development and application, is expected to lead to industrialised building and at the same time will bring about radical changes for the involved firms. It still is point for discussion what exact type of paradigm shifts is needed for real successful industrialised construction.

7 References

BRESCHI, S., MALERBA, F., ORSENIGO, L. (2000). „Technological regimes and Schumpeterian patterns of innovation". *The Economic Journal*, 110.

DICKEN, P. (2000) Global Shift: Reshaping the Global Economic Map in the 21st Century, London: Sage Publications Ltd. pages 656

DOSI, G. (1982) Technological paradigms and technological trajectories. *Research Policy* 11

EGMOND, E. VAN (1999), *Technology Mapping for Technology Management,* Delft University press, Delft , pages 410

FINN D.W (1992) Towards Industrialized Construction, in *"Construction Canada"* 34(3), May 1992, p. 25-26, 28

GIRMSCHEID, G. AND E. HOFMANN (2000), "Industrielles Bauen-Fertigungstechnologie oder Managementkonzept?" *Bauingenieur Band 75*, Sept, http://link.springer.de/link/service/ journals/94194/papers/0075009/00750586.pdf.

HILLEBRANDT, P. (1984) *Economic Theory and the Construction Industry*, Second Edition. Macmillan, London

KOSKELA, L AND VRIJHOEF, R (2000) The Prevalent Theory of Construction is a Hindrance for Innovation in *Proceedings Eighth Annual Conferece of the International Group for Lean Construction*, IGLC-6, Brighton, UK, July 17-19

KOSKELA, L. (2000). An exploration into a production theory and its application to construction. VTT Publications 408. VTT, Espoo.

KUHN, THOMAS S.,(1962) *The Structure of Scientific Revolutions.* Chicago, IL: University of Chicago Press.

MALERBA, F AND ORSENIGO, L (1996) "Schumpeterian patterns of innovation are technology specific". *Research Policy,* 25, 451-478.

MARSILI, O AND VERSPAGEN, B (2002) "Technology and the dynamics of industrial structures: an empirical mapping of Dutch manufacturing". *Industrial and Corporate Change*, 11, 791-815

NAM, C.H. AND TATUM, C.B. (1988). "Major characteristics of constructed products and resulting limitations of construction technology." *Construction Management and Economics*. 6, 133-148.

NELSON, R.R. AND WINTER, S.G. (1982): *An Evolutionary Theory of Economic Change*. Cambridge, MA: Harvard University Press.

OFORI, G. (1990). The construction industry: Aspects of its economics and management, Singapore University Press, Singapore.

ROGERS, E.M. (1995). *Diffusion of innovations* (4th ed.) New York: The Free Press.

ROSENBERG, N. (ed.) (1976) *Perspectives on Technology.* Cambridge: Cambridge University Press.

SCHUMPETER, J.A. (1934): *The Theory of Economic Development*. Cambridge, MA: Harvard University Press.

STIGLITZ, J. (1999) *Knowledge as a global public good*, World Bank http://www.worldbank.org/knowledge/chiefecon/articles/undpk2/

TATUM, C. B., (1986) "Potential Mechanisms for Construction Innovation," Journal of Construction Engineering and Management, ASCE, Vol. 112, No. 2, Paper No. 20641, June, 1986, pp. 178-191.

TURIN, D.A. (2003) Building as a process. *Building Research & Information*, 31, (2), 180-188.

WARSZAWSKI, A. (1990). Industrialization and robotics in building: a managerial approach. Harper & Row, New York. 466 p.

WINTER, S.G. (1984), 'Schumpeterian Competition in Alternative Technological Regimes', *Journal of Economic Behavior and Organization*, Vol. 5, 287-320.

CHAPTER II:
STRATEGIES OF INDUSTRIALISATION

There is a constraint between the big series of identical products from industrialised suppliers and the clients' aim for individualism. Roger-Bruno Richard proposes a production strategy of Flexibility on 4 levels. Caspar van den Thillart (Ministry of Housing, Netherlands) and Mieke Oostra (TNO Research, Netherlands) advocate mass customisation to meet the same constraint.

Gerhard Girmscheid proposes also a production strategy with factors like Standardisation, Rationalisation and Mobilisation but he also advocates an external strategy based on Outsourcing, Subcontracting and communication of strength.

Industrialisation requires a cultural change or paradigm shift. Limburg and Rutten studied the strategies applied in other industries to achieve acceptance of change. Girmscheid states that market orientation and user oriented adaptability are essential elements of the paradigm shift. In a contribution by Lunze and Girmscheid this market orientation is further specified as a two dimensional approach.

A) Four Strategies to Generate Individualised Buildings with Mass Customisation

ROGER-BRUNO RICHARD[1]

1 Introduction

Individualisation is a fundamental feature of human nature: everyone is different from the neighbour and different from him/herself over time. Accordingly, most manufacturers have learned how to introduce individualisation within their industrialised production lines without any significant additional cost. Four strategies can be extrapolated and applied to the delivery of individualised and adaptable buildings: Flexibility of the Product, Flexibility of the Tool, Multipurpose Framework and Combinability. Some of them are already applied, notably in Japan and within the European Community.

2 User Friendly Production

Contemporary products are affordable mainly through the strategies and technologies of industrialisation: aggregating the participants in a continuous operation serving a market large enough to break an investment down into very small fractions. The goal of that investment is to support a process capable of simplifying the production and thereby reducing the cost while achieving quality at the same time (Richard 2003).

To be appropriate, a product has to offer different configurations in order to meet the needs and personality of the various targeted users: that is precisely the purpose of Individualisation. For instance, the shoe manufacturer has to offer the whole spectrum of sizes and a diversity of models to respond to the demand.

Manufacturers are obviously aware that a standardised product would never reach a market large enough to justify an innovative technology. They have learned how to play on different keyboards to introduce individualisation and adaptability within their industrialised production lines without any significant additional cost.

---

1 Prof., M.Arch. (Berkeley), Architect (OAQ), Head of the graduate Design & Systems for Construction (DSC) profile, School of Architecture, Université de Montréal, P.O. Box 6128 Centre- ville, Montreal (Quebec) H3C 3J7 CANADA, Phone +1 514 343 7968, Fax +1 514 343 2455, roger.richard@umontreal.ca

In the case of buildings, individualisation is related to adaptability, since a functional program very often becomes obsolete even before the building is completed. An appropriate building system would therefore need to allow for change not only over space but also all along the whole lifetime of the building.

3 The Strategies

Four strategies can be extrapolated from the various industries presently successful in providing individualised products (Fig. A.1):

1. Flexibility of the Product;
2. Flexibility of the Tool;
3. Multipurpose Framework;
4. Combinability.

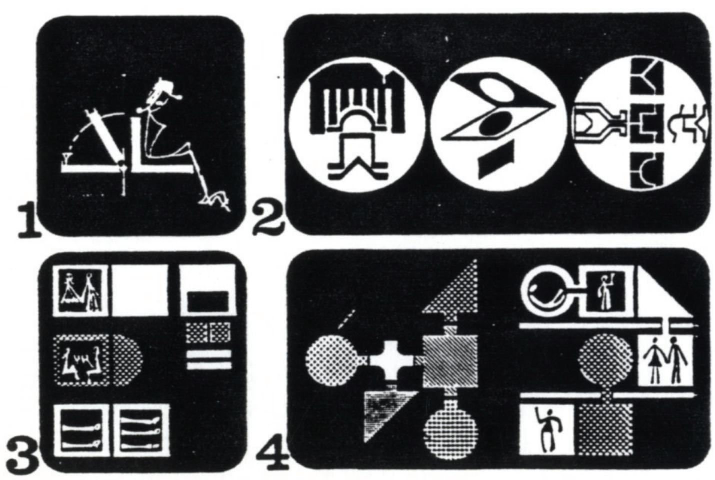


Fig. A.1: Schematic representation of the four strategies to generate individualisation

Separately, each strategy may seem limited, but they are more or less complementary to each other. Together, they offer a wide range of options and there is no reason not to apply them to architecture. Therefore, with imagination and ingenuity, these strategies can lead to the generation of individualised buildings over space and time.

3.1 First Strategy: Flexibility of the Product

Flexibility of the Product implies that the product itself is capable of geometrical variations while in use, in order to respond to different needs over space and time.

For instance, the bedrooms of young children should normally be visually close to their parents whereas the contrary will be preferable when they become teenagers (Fig. A.2). A flexible partition or modular shell sub-system (with provisions to integrate the wiring) would permit a reverse planning layout using the same components.

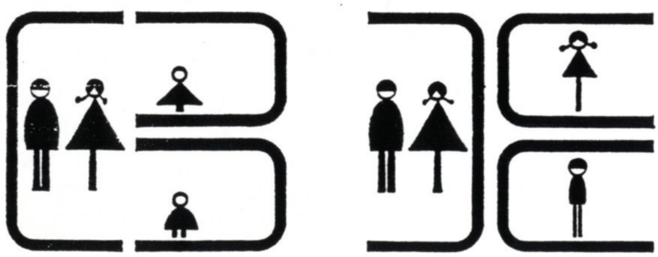


Fig. A.2: Young children / Parents / Teenagers scenario

Various factory made building components are already applying the Flexibility of the Product strategy:

- Demountable partitions, where the panels are supported by notched studs.
- Movable partitions, only requiring a ceiling channel and dismantled in a single operation.
- Mobile 3D functional modules, lightweight shells corresponding to the main functions, like the individual booths in a landscaped office floor. For instance, Shigeru Ban has recently designed "personal rooms on casters" which can be moved freely according to the scenario of their users.
- Raised access floor, to allow for mechanical and electrical relocations.
- Interchangeable exterior envelope panels.

The flexibility offered by interchangeable exterior envelope panels responds not only to the positioning of the flexible partitions, but also to the personalities of the users: some will ask for large windows, others will prefer more discretion; some will want to identify themselves with vivid colours, others will seek anonymity.

3.2 Second Strategy: Flexibility of the Tool

With Flexibility of the Tool, the tool itself becomes the generator of diversified products. Variations can be generated from the same machines (Fig. A.3) by operating at the level of:

- the CONTROLS i.e. feeding a digital model to a CNC (Computer Numerical Control) machine in order to generate diversified components or diversified moulds to cast the components, notably by milling blanks or using robotics to install various layers of material (e.g. contour crafting, etc.);
- the LAYOUT i.e. modifying the pilot pattern governing a pantographic tracer or transforming a master mould with "reservations" (e.g. inserting blockers or spacers);
- the MATRIX i.e. a simple interchangeable form-giving apparatus governing the output of a large / complex / expensive machine (e.g. changing the "die" of the extrusion machine or the "mould" of an injection machine, etc.).

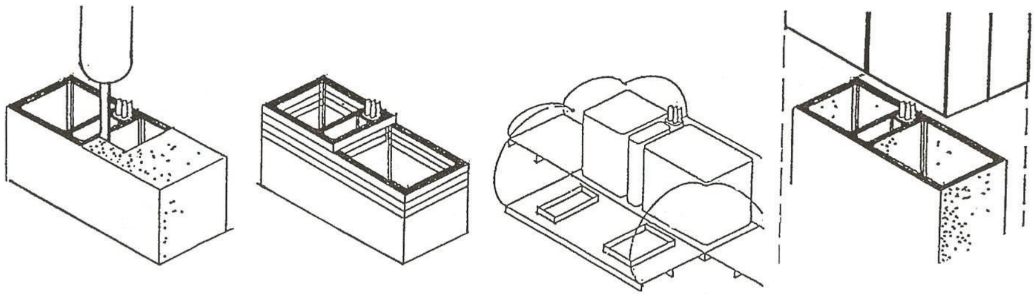


Fig. A.3: Examples of Flexibility of the Tool: CNC Milling, CNC Contour Crafting, Introduction of "Reservations" and Extrusion.

In Thailand, Preuksa Real Estate Public Co., developer / manufacturer / builder / of residential real estate, operates a fully automated plant (delivered by Weckenmann) where each precast concrete panel is produced according to a different and specific layout, notably by using laser plotters and magnetic shutters to configure the formwork (Fig. A.4).

Fig. A.4: Laser plotter on a Preuksa precasting table

3.3 Third Strategy: Multipurpose Framework

Multipurpose Framework is a situation where the same basic product acts as a framework to accommodate different options. These options are obtained through:

- the addition of specialised components or
- the introduction of secondary modifications on the production line.

The automobile industry has adopted the "specialised components approach" out of a framework called «platform», a shared set of components common to a number of different "models". These components normally include the chassis, the engines, and various other mechanical features. Most housing manufacturers adopt a similar approach by offering different types of kitchens and bathrooms within their basic shell. They also offer "personality" kits to individualise the external look of the house, like the addition of dormers, bay windows, porticos, skylights, etc.

The aircraft industry is acting somehow differently, mainly opting for the "introduction of secondary modifications" at the production stage, notably by offering "stretched" versions of the basic design. However, options are the rule for key subsystems like the engines and the avionics.

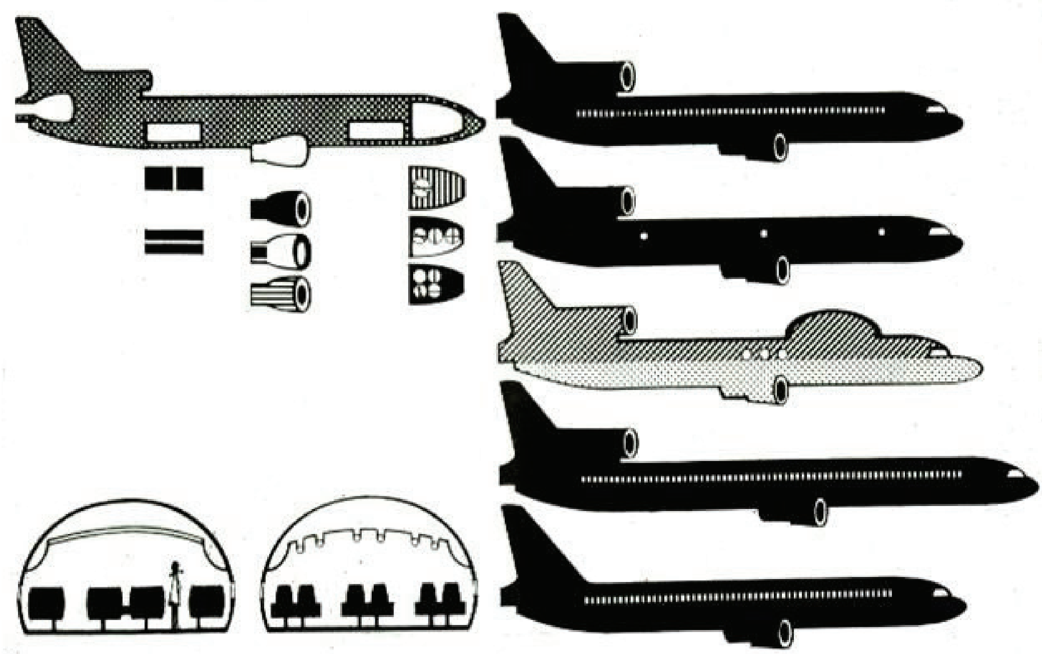


Fig. A.5: Optional subsystems and Secondary Modifications to a basic aircraft design

In Architecture, the Multipurpose Framework approach was initiated forty years ago in the Netherlands under the leadership of John Niklas Habraken: a collective "Support Structure" is open to a variety of "Detachable Units", also called "Infill", which can be modified over space and time by the occupants of each unit according to their needs and resources (Habraken 1976).

The "Support" would normally be limited to the structure, the collective circulation spaces and the wet services; as such, it is regulated by the collectivity. The "Detachable Units" ("Infill") include the external envelope panels, the partitions and the equipment sub-systems; as such, they are controlled by the occupants themselves. The objective is to design standard interfacing details and ensure that those Detachable Units ("Infill") become widely available on the building supply market.

Habraken's SAR approach is now pursued by the "Open Building" movement, rallied under the Working Commission "W-104" of the CIB (International Council for Research and Innovation in Building and Construction).

The Kodan Support & Infill (KSI) R&D program, developed by the Urban Housing Technology Research Institute (Japan), is similarly promoting skeleton and infill type housing systems to respond to diversified lifestyles (Fig. A.6). The structure is in concrete whereas the service shafts are running in the collective zone. Each dwelling unit is served through an under-floor distribution network (Fig. A.7). Full flexibility is provided: the kitchen and bathroom can be relocated anywhere in the apartment and fit in with the relocation of the flexible partitions.

The KSI program has a large influence on the new and remodelled residential building market in Japan. High rise apartment buildings are more and more designed according to that approach. It is the case for two recent buildings of ± 42 stories in Yokohama and Fukuoka.

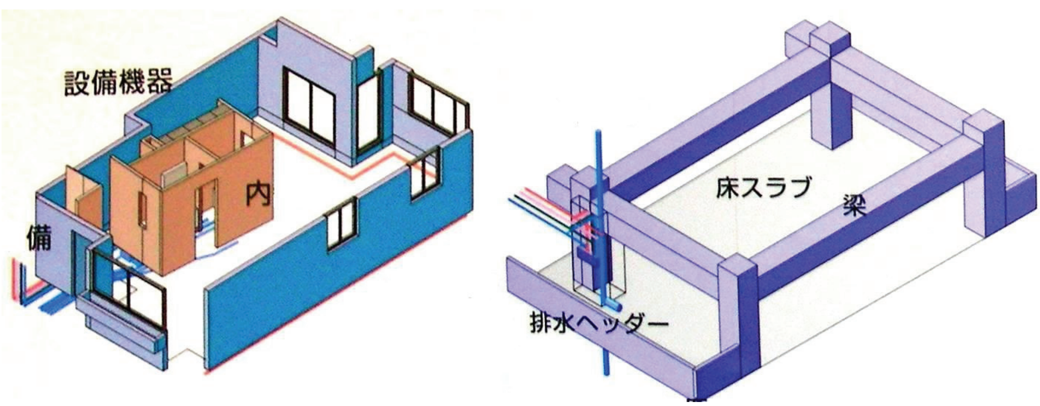


Fig. A.6: Distinction between the Infill and the Support proposed by the KSI approach

Fig. A.7: KSI Under-floor piping and wiring distribution

3.4 Fourth Strategy: Combinability

Combinability means generating a multitude of combinations from a set of basic components produced in large quantities. Combinability operates through modular co-ordination and interfacing rules for the joints.

The most obvious application of Combinability is music (Fig. A.8): the same eight notes modulated on a stave have been used billions of time by hundreds of composers and interpreters for many centuries and yet we are still amazed by new melodies that come up almost every day.

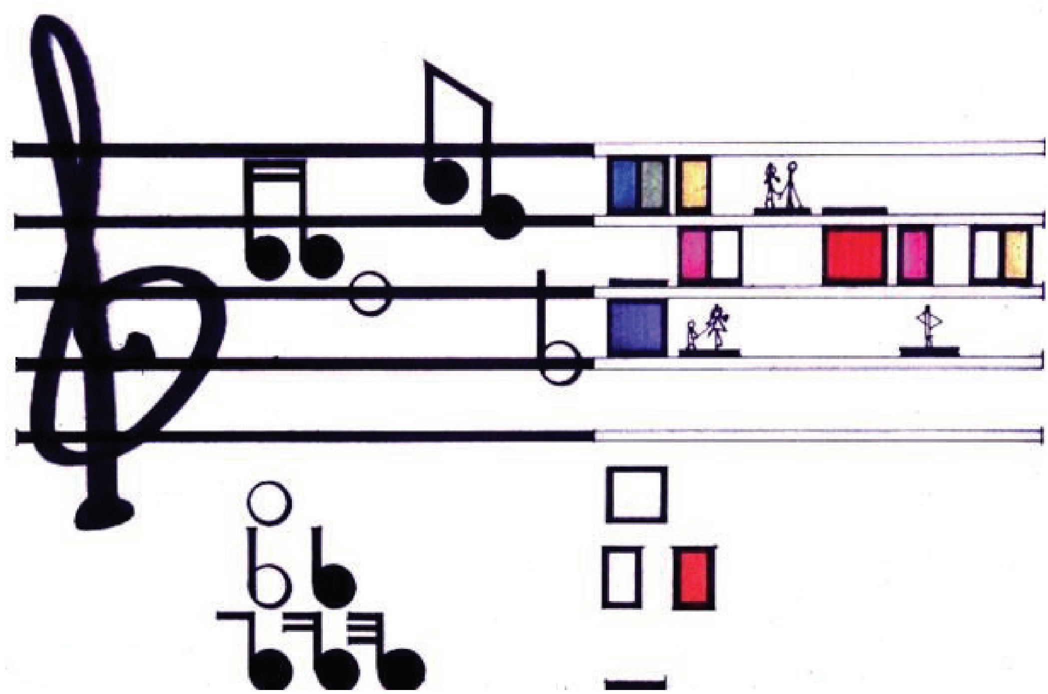


Fig. A.8: Schematic representation of the analogy between music and Combinability.

The "Meccano" kit is the iconic example of that approach: numerous types of variations can be obtained using the same basic parts, the prerequisites being the same modular spaces between the joints (modular coordination) and the same type of nuts and bolts (interfacing rules). Building systems adopt an identical approach; notably the Post & Beam kits (Fig. A.9). It is then up to the architect to be as versatile with such a discipline as the piano player is with the notes on his/her instrument.

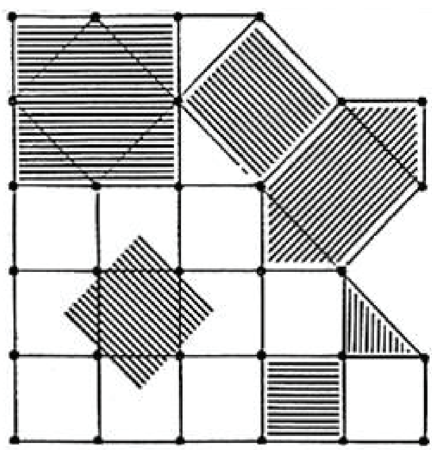


Fig. A.9: Variations generated by two typical beams, an orthogonal one and a diagonal one.

As long as they share common modular coordination and interfacing rules, different components from different manufacturers can thus be combined within the same building. In the European Community, an organisation called ManuBuild is bringing institutes and manufacturers together from 10 countries around the goal of producing open systems out of interchangeable components: "*…customers will be able to purchase high quality, manufactured buildings having a high degree of design flexibility and at low cost compared to today. For the first time, inspirational unconstrained building design will be combined with highly efficient industrialised production…* (ManuBuild, 2006).

Combinability is systematically applied by the Japanese housing manufacturers. Sekisui Chemicals, Misawa Homes and Toyota Housing are producing 3D housing modules on assembly lines similar to the ones found in the automobile industry. Using a standard framed-at-the-edges 3D steel skeleton, they generate different geometrical combinations as well as various interiors through diverse arrangements of their standardised components to a point where no two houses are similar. "*Each manufactured house in Japan is designed and produced according to the buyers' needs and demands, while the design components are fully standardised or mass-produced*" (Richard and Noguchi 2006).

4 Industrialised / Flexible / Demountable (IFD) Systems: Individualisation merging into Sustainability

Due to the very high quality and precision present within most industrialised technologies, factory produced dry joints are designed to simplify site installations (nobody wants to invest in factory production and carry expensive site installations). Industrialised construction systems then become Flexible and Demountable (IFD) as the same precision that allows for easy and fast installation can also be applied to easy and fast modifications, reconfigurations and even dismantling.

IFD systems stand as appropriate vehicles to integrate the four strategies: whereas Flexibility of the Tool is offering individualised components right off the production line, the adaptability inherent in the IFD approach coincides with the changes over time implied by Flexibility of the Product, Multipurpose Framework and Combinability.

IFD Systems are also paving the way to a high level of Sustainability in construction as they are offering major changes with a minimum of efforts and without any loss:

- construction waste are eliminated at the outset since *Industrialised* components are made modular and never need to be crafted at the site;
- in a renovation phase, construction waste or destruction of material is avoided through the use of *Flexible* components;
- when the building becomes obsolete, demolition is replaced by reconfiguration or relocation as the system is *Demountable*.

Dry jointing is the fundamental condition to provide flexible and demountable components. The situation is easy with precast concrete as the material is by definition offering fireproofing and soundproofing: an easy-to-crush lightweight grouting allows for re-opening the steel connection nests where the bolts have been precoated with a lubricant. In the case of a steel structure, a simplified type of fireproofing has to be provided, like intumescent paint, instead of the usual gypsum cladding. For the exterior wall panels and the partitions sub-systems, bolted or clipped joints can be sealed with an "easy to peel off" compound.

5 Interaction with the User / Occupant

No one is able to predict the requirements, desires or tastes of the same user over time or space, as well as the requirements, desires or tastes of the eventual new occupant of a specific space. Adaptable systems are there to meet that challenge, to generate "user friendly" buildings open to change: freedom of choice for the first- users and opportunity to modify the layout for successive users, evolution of layout through space and time, and elimination of renovation waste.

Most of the time, the variations are produced by the user him/herself or by a technician directly contacted by the user without going through the service of a design/engineering professional. However, some complementary relationship between the manufacturer and the occupant will also take place, either directly or indirectly. That relationship is desirable at any one of the four stages: Planning, Acquisition, Modification and Reconfiguration / Dismantling.

When new components are required long after the initial building is delivered, two options are available as far as the role of the manufacturer is concerned:

- asking the manufacturer to maintain a "Service Centre", as it is done by most housing manufacturers in Japan (to accommodate major changes, Sekisui Chemicals offers to dismantle, recycle and even relocate the units),
- distribute easy to install sets of components on the large scale public market (± the "IKEA" approach).

All over Japan, the general approach to housing is to leave the interior space completely open and offer a kit of raised floor supports and panels, relocatable partitions, and kitchen / bathroom / closet modules in order to allow for full flexibility. NEXT-21, the prototypical residential building in Osaka designed under the leadership of Professor Yositika Utida (Osaka Gas, 2000), is an outstanding example of total Flexibility of the Product, including interchangeable exterior envelope panels (Fig. A.10).

Fig. A.10: The NEXT-21 prototypical project in Osaka.

6 Conclusions

Flexibility of the Product, Flexibility of the Tool, Multipurpose Framework and Combinability are strategies favouring an evolutive architecture specific to each individual, dealing with space and time all together and preparing the buildings for unpredictable but obviously very different futures.

To be effective, the four strategies must be understood and promoted by all the participants involved in the building process. The architects and the designers should be the first to study and understand them as they are positioned to lead their implementation. The four strategies can become strong marketing features for manufacturers, builders and building operators. Properly applied, the strategies will allow for change without any destruction or demolition, thereby directly and appropriately meeting the Sustainability agenda.

7 References

Habraken, Niklas John (1976). *Variations: The Systematic Design of Supports*, Laboratory of Architecture and Planning, M.I.T., Cambridge Mass., U.S.A.

ManuBuild (2006). *Open Building Manufacturing*, www.manubuild.org/summary

Osaka Gas (2000). *NEXT21: Osaka Gas Experimental Residential Complex*, www.osakagas.co.jp/rd/next21/htme/reforme.htm

Richard, Roger-Bruno, and Noguchi, Masayoshi (2006). *Japan Solar Photovoltaic Manufactured Housing Technical Mission 2006*, CANMET Energy Technology Centre, Varennes (QC Canada), 38 p.

http://cetc-varennes.nrcan.gc.ca/fichier.php/codectec/En/2006-166/2006-166e.pdf

Richard, Roger-Bruno (2003). *Industrialised Building Systems: Reproduction before Automation and Robotics*, Automation in Construction Journal, Elsevier, Amsterdam, No 14, 442-451.

B) Mass Customisation a new Challenge for the Building Sector – Concepts and Networks for the European Market

CASPAR VAN DEN THILLART[1] & MIEKE OOSTRA[2]

1 Mass Customisation, the Solution for Market Saturation in Europe

Many sectors of industry are faced with market saturation and businesses are struggling to survive. Customer behaviour has become unpredictable and major companies' classic marketing strategies seem increasingly incapable of reaching today's individual consumer. One of the sectors affected by this development is construction. The Dutch housing market is changing rapidly as a result of privatisation and declining production. A downward trend in housing production started in many European Union Member States before it did in the Netherlands. Housing occupancy in Europe is falling to 2.2 people per housing unit and the ageing of the population is accelerating rapidly (see Fig. B.1). Generally speaking turnover in the maintenance and refurbishment sector is higher than that of

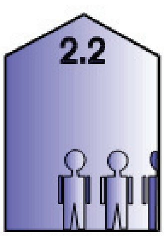


Fig. B.1: Saturated market: *Housing occupancy Europe*

new build. The problem of selling products in saturated markets is found in many other industries. The same economic laws of decreasing consumer appreciation for standard products and subsequent pressure on product quality and differentiation apply in such market conditions in all industrial product sectors. In a free market the private actors - the customers - are in the driving seat. Sights on value for money in this type of market also have to be set higher in order to cope with the competition.

---

1 Dr. Ir., Universities of Delft, Eindhoven & Twente and Esprit huis, Javakade 504 1019 SC Amsterdam www. Esprithuis.nl, Phone +31-204191241, c.thillart@xs4all.nl

2 Dr. Ir., Netherlands Organisation for Applied Scientific Research (TNO), Built Environment and Geosciences, PO Box 49, NL-2600 AA Delft, Phone +31-15 2673110, Fax +31-15 2763024, mieke.oostra@tno.nl

There is a general tendency to use mass customisation (MC) production technologies - the paradox of satisfying individual customer wishes and producing at a profit.

Table B.1: Comparison of substitution of dwellings in Japan and Europe

Europe	Japan
• Decline of new build • Rehabilitation / maintenance sector are growing • Average age of dwellings > 50 year • Average new dwellings / 1000 inhabitants: 5	• Average age of dwellings 25 years • High prefabrication rate (2000,000 dwellings) • Average new dwellings / 1000 inhabitants: 10 • Dwellings sold are predominantly new buildings (90%)

In Japan customer driven industrialisation is the normal practice. The Japanese building industry demonstrates that a high degree of substitution is perfectly possible in a saturated market. The degree of substitution in the housing sector in Japan is at least twice as high as in Europe (see Table B.1). This industry is highly customer driven, represents a large share of the GDP and is skilled at persuading consumers to replace their existing homes by new build. Japanese people do not buy existing dwellings and are proud of their new homes. They also don't like doing odd jobs in their homes, as do Europeans (often out of necessity). The European building industry, with its fragmented and competitive medium sized enterprises and its adherence to tradition, appears to be very different from the Japanese approach.

2 Building Systems, the Appropriate Product Level for Mass Customisation (MC) in Europe

The question is what MC techniques are suitable for Europe to reverse the downward trend. If we look at the current status of industrialisation in the European building industry, we notice major differences within Europe between the northern and southern Member States. The emphasis in the southern Member States is on the traditional processing of building materials on the construction site like hollow bricks and concrete structures poured in situ. In the northern part of Europe there is rather a hybrid mix of industrialisation and traditional building methods. In view with this hybrid mix of prefabrication and / or traditional building, dependant of the various building cultures in the European regions, large scaled centralised production of complete houses is not an option. Moreover, this kind of production has not been very successful in the past, due to its monotonous architecture and its association with cheap mass-produced housing built after the Second World War.

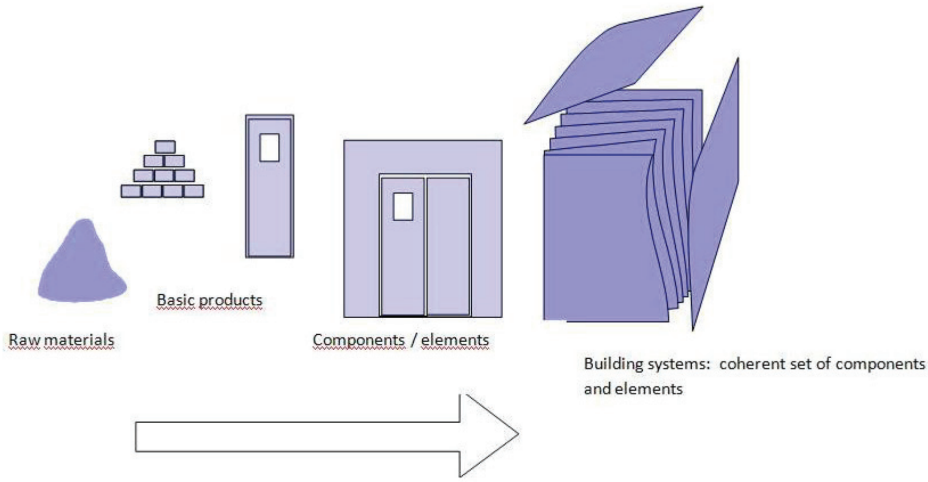


Fig. B.2: Upgrading to customer driven industrialisation (van den Thillart, 2004)

Industrialisation of the building industry is a broad concept. It can apply to both basic building products and building systems (see Fig. B.2). For example, the brick industry has seen dramatic labour substitution (90% approximately over a period of 50 years). However, basic building products delivered from stock - despite its high industrialisation degree in the factory - are not suitable to perform customer driven industrialisation.

Adaptation to customers' wishes somewhere in the production process of the factory is simply not possible. Processing of basic products at the construction site still takes relatively large amounts of time. Each of these activities is carried out by a different party, which results in poor logistics and a lot of inefficient intervals between the successive processing steps. Customer driven industrialisation should therefore preferably be focussed on the higher level of the product chain: the quick assembly at the construction site of transportable, flexible and tailor made building systems. Moreover, tailor made and just in time delivered systems create added value for the supplying industry, compared to the delivering of cheap basic products. The question is how to market these systems all over Europe.

This is not an easy job, considering the different building cultures and regulations, which exist in the 27 Member States. The first condition to trade building systems without barriers is that they comply with the various building regulations on the European market. Complying with building regulations is not enough. The systems must be able to perform flexible buildings, tailored to customer's individual wishes and last but not least, gain a substantial market share to survive. The marketing of tailor made systems in a direct way to customers is being made increasingly feasible through the support provided by information technology (IT), contrary to supply on anonymous markets (which is the case for basic products). Networks of co-makers in the supplying industry are therefore necessary, to make arrangements on the junctions of building systems and the 'just in time' delivery of these systems.

Table B.2: Industrialisation by expanding markets (via supplying industry)

- Stained glass windows gave way to prefab window frames;
- Larders gave way to refrigerators;
- Inbuilt store cupboards gave way to ‘freestanding’ cupboards;
- Earthenware sinks gave way to kitchen units;
- Thatched roofs gave way to roof tiles, chimneys to roof ducts, fireplaces to stoves and boilers, sculleries to washing machines etc.

An important observation is next that the market exposure of building systems can be enhanced through the concept of disentanglement. This process started a long time ago, fed by innovations in the supplying industry (see Table B.2). It is striking that these innovations became possible because the products developed from built-in elements into separate components. This stimulates substitution and increases exports. A higher degree of industrialisation is made possible by expanding the market; a pantry cannot be exported, whereas a refrigerator can be. The root cause is that disentanglement is able to break down logistic complexity. Substitution of adaptable components and systems during the lifetime of buildings becomes an easy job. For new build it creates, through the combination of adaptable systems, easy and manageable enhancement of variants, to suit customers’ wishes.

Last, but not least, the concept of disentanglement can be applied to the building process itself. This paper advocates customer driven industrialisation in fragmented markets (like the European market) by working in networks.

3 The Concept of the Virtual Kit as a Basis for Mass Customisation (MC)

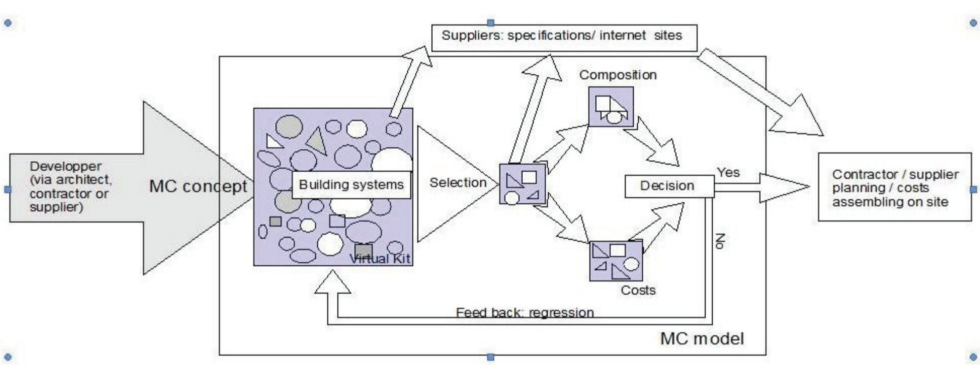


Fig. B.3: MC model based on a virtual kit (van den Thillart, 2004)

A first step to customer driven industrialisation on the European market is to market building systems, which comply with the different building regulations in the European regions. The usual European terminology for prefabricated multi-component products or building systems is ‘kit’. A kit consists of a set of building components, which is marketed as one product. A kit is based on a harmonised European technical approval (ETA). Kits, based on ETA’s bear the CE-marking to indicate that the product can be traded on the European market and can be used in buildings without any barriers (Construction products Directive (89/106/EC) and Guidance paper C).

The European kit proves to be a perfect basis to elaborate MC concepts (van den Thillart, 2004). Kits are based on ‘non physical’ design systems. For MC purposes the notion of ‘design system’ is extended to ‘design concept’. A design concept can be looked on as a flexible prototype that is considered by the market to represent a good opportunity. ‘Flexible’ means in this respect that the prototype can generate many variants.

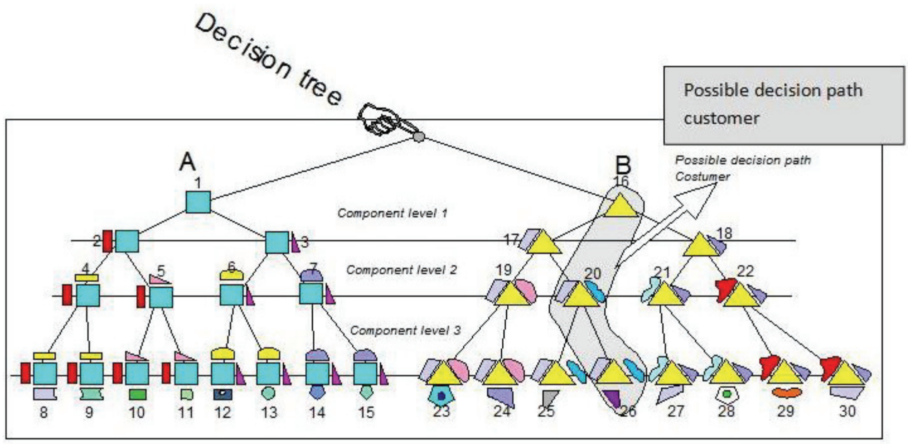


Fig. B.4: Variation by disentanglement: shifting components to the other nodes in a decision tree of a virtual kit (van den Thillart, 2004)

Imagine next that such design concepts form the virtual basis for kits. Those ‘virtual kits’ extend beyond individual projects and can be used at various different locations. A virtual kit encompasses all of the many candidate building systems that jointly, after selection by buyers, form a series of different dwellings. The building systems in the virtual box are ranked in layers. Every selection in a layer adds a building system to the building system selected earlier from the previous layer.

A virtual kit is turned into a MC model by organising building systems in decision levels on the basis of a particular marketing concept, supported by IT costing programs and programs for drawing component assemblies and three dimensional presentations (see Fig. B.3). The number of variants that consumers are free to choose from is a yardstick for how consumer-driven the plan is. Virtual kits can easily generate thousands of ‘end variants’ and even adopt completely different appearances. Creation of variants is not a goal in itself. The variants are manageable by the disentanglement of the different systems in the kit. Disentanglement makes it possible to freely attach variant components to any branch of the decision tree (see Fig. B.4). If 10 suppliers are each responsible for 10 variants this results in 1010 end variants. This many ‘end variants’ is feasible by spreading the logistic complexity over the participants. The customer only needs to take 10 decisions! For the different techniques to create disentanglement, such as morphological transferability and techniques to postpone the order penetration point, see the publication 'Customised industrialisation in the Residential sector and its references to other authors' (van den Thillart, 2004b).

4 Aspects of Chain Integration, Based on IT and Virtual Kits

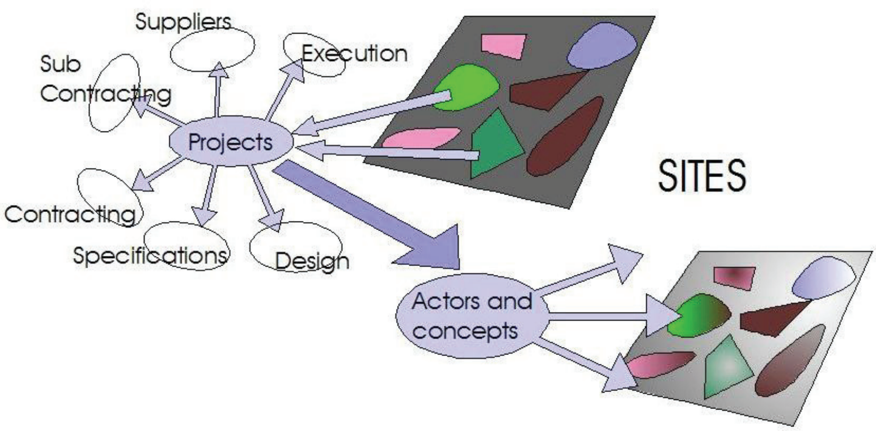


Fig. B.5: From traditional tendering to proactive (van den Thillart, 2004)

IT has increasingly becoming an information carrier linking the different disciplines in the building industry. The ongoing advance of IT can stimulate collaboration between the many different parties involved. Co-operation in networks is important for the marketing of tailor made building systems, as we indicated above. The basis for co-operation is a flexible prototype, based on a virtual kit. Its flexibility allows for location-independent pro-active marketing to customers. The direct marketing to the customer supposes chain integration.

The participants are not tied anymore by traditional tendering and constraints by the specifications of the contractor, but are able to offer their variant-options directly to the customer. For this to be achieved chain management is an important issue. The architect's new design challenge lies at the start; the development of a successful concept that can be used in several locations. This concept is based on the technical possibilities of the different suppliers in the kit. The contractor has the role of managing the whole process.

The suppliers play the role of co-makers. They make arrangements in advance, to guarantee that all the relevant components fit together and are delivered just in time at the building site. All supporting IT software programs, such as customer's choices, costs, virtual reality systems, E-commerce and technical specifications are interconnected in the MC model and designed to economise in a simple way the whole supply chain (chain shortening). This can be achieved in practice by means of a uniform electronic dossier that digitally stores documents such as design and drawing software packages, reports etc. that are identified by author, revision date etc, and known as the back-office software. The IT software to market the products to the customer is the 'front office' software (see

Fig. B.6). Individual customer wishes require careful monitoring of changes, which have to be horizontally transferred to all IT programs. The link between the front office and back office software is the last step in chain shortening.

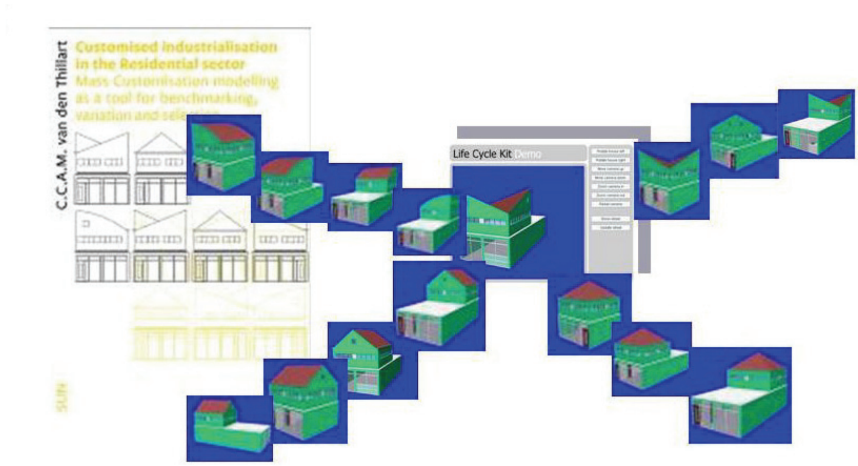


Fig. B.6: An example of the front office program, the life cycle kit, elaborated for the TUD symposium in 2004 on mass customisation, (van den Thillart, 2004)

5 Practical Application of MC

At the moment there are several initiatives regarding to the practical application of MC in Europe. There are different kinds of initiatives emerging; (a) virtual networks in the construction industry, which are organizing their supply chain in such a manner they are able to design, engineer, market, produce and deliver virtual kits, (b) initiatives from the demand side, such as municipalities demanding customer choice for new housing developments and end-users, ordinary citizens, organizing themselves to realise housing that fulfils their personal demands and (c) an European research project to promote the adoption of MC on a European scale. An example from a virtual network in the Netherlands will be given in this chapter as well as a short description of the European project. Examples from initiatives on the demand side can be found in Oostra (2007).

5.1 Pilot Projects in the Esprit Network

As we indicated above, co-operation between the building parties and working in networks - even over long distances - is a condition ‘sine qua non’ to improve customer driven industrialisation in fragmented Europe. By IT, customers can be reached all over Europe, but marketing houses without co-operation of local authorities and industry is an illusion. The threat of possible elimination of the local industry is the main barrier to market entire industrialised houses. The network model permits foreign companies to join virtual kits and vice versa. The advantage of the network model compared with centralised production is that it is suitable for all categories in the residential sector, and the manufacturers do not need to be completely dependent on their production under this network model for their survival. The distribution of the logistical complexity makes participating in the network an easy job.

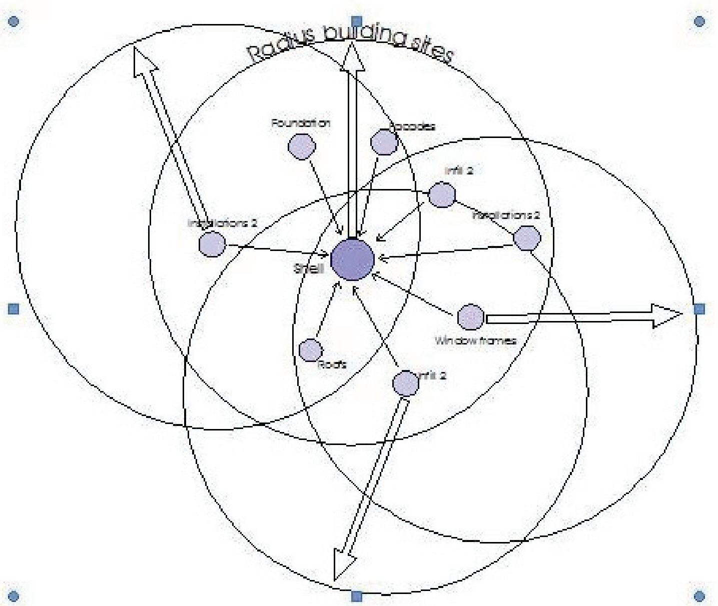


Fig. B.7: Network model with different radius, (van den Thillart, 2004)

As all participants have an interest, there is therefore greater certainty of timely delivery than in the case of traditional public tendering. The MC concept, based on virtual kits has been adopted by Esprit, a network of companies in the Netherlands with special interest in customised industrialisation. Esprit covers all professional building parties like developers, consultants, architects, contractors, and supplying companies in the construction sector. In the next years to come, three Dutch universities of building technology and architecture in Delft, Eindhoven and Twente are co-operating within the Esprit network to develop and monitor real MC projects, based on the virtual Kit concept.

The Esprit supplying companies are able to market their variants direct to the customer, made possible by the disentangled building systems of the virtual kit. The first pilot project deals with supply chain integration, comprising aspects like marketing, chain management and chain shortening (front office / back office), as discussed above. Other aspects of chain integration like quality chain control and sustainability will be exercised in following projects. Together these five aspects represent the Esprit method of supply chain integration.

5.2 ManuBuild, an European Project on MC

The European Committee has co-funded ManuBuild, a European consortium with representatives from 10 individual countries to develop, test and demonstrate MC in the building industry based on the principles of Open Building (see Fig. B.8). This research programme, with the main focus on the supply of housing, stretched out over a four-year period from April 2005 until March 2009. It aimed a realizing a step change in construction on four different aspects:

- From technology push towards market pull
- From mass production to mass customisation
- From production on the building site towards off-site production in combination with clever mechanised (near) on-site production
- From a project market towards a service centred market.

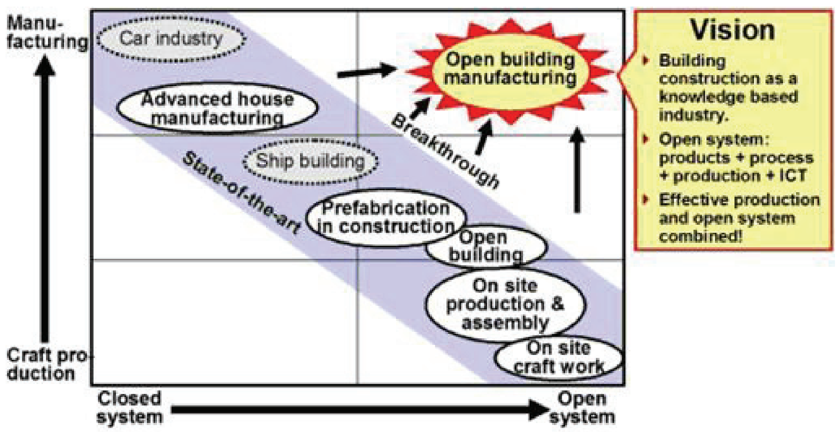


Fig. B.8: Current state in relation to Open Building Manufacturing, EICHERT (2007)

In order to realise the envisioned step change, five key elements were addressed within the project: building concepts, production technologies, business processes, ICT support and training. Building concepts with a high degree of design flexibility and adaptability were developed tailored to the need of stakeholders. Architectural quality and customer choice were used as starting point. Smart components and multi-function integrated modules were developed for which easy maintenance and replacements were an important criterion. Special attention was given towards connections and interfaces enabling rapid and easy 'plug and fix' assembly on and off site.

On the part of production techniques off-site (automated) manufacturing techniques were combined with pre-assembly offering a highly flexible, scalable and efficient production process. Mobile factories were developed to bring manufacturing and pre-assembly operations to or near building sites, providing safe and clean working environments while reducing transport. Logistical systems were developed for lean handling and delivery of components and modules within supply chains from all production units to the final assembly of buildings. On site assembly methods and systems for rapid, safe and precise handling and assembly were developed. Safety, quality and the reduction of environmental impact were given special attention while developing these production techniques.

New outlines for business models were developed to suit the new customer centred approach. A performance model with criteria on every aspect of the process was developed in order to monitor overall quality. Concepts and scenarios for value driven business processes were developed by involving and working in collaboration with key stakeholders. Organisational models for networked and virtual cooperation ('virtual factories') were developed, including identifiers for incentives and barriers for new contractual relations. Service models were developed covering the full life cycle requirements of buildings including an evaluation of approaches to switch towards a new business model.

A lot of effort was put in developing supporting IT technology to enable the envisioned business processes. An open system for IT systems was adopted, essential to integrated all the different information from stakeholders during the entire life cycle of buildings. Intelligent component catalogues were developed based on standardised description languages for categorizing, encapsulating and publishing product related data and knowledge. A market assessment tool was developed as well as three configurators: (1) a sales configurator to assist customers in making their choices, (2) a design configurator as a tool during the design of the building including the preconditions for the infill which will determine the amount of choice for customers and (3) a manufacturing configurator to support the production process. Logistics management and assembly planning were addressed including the monitoring and coordination of supply and assembly of the different components on site.

These new developments were combined, tested and demonstrated in the context of 4 pilot projects in Spain, the UK and Sweden. To disseminate the required new knowledge and skills beyond the project a multicultural and multidisciplinary training plan was made. To support training and education a mobile and portable construction site training simulator was build, to provide a virtual environment in which people can experience the effects of decisions made during the realisation process. More information on the ManuBuild project and its results can be found at www.manubuild.org.

6 Conclusions

Saturated markets force industries towards a customer centred approach, in which value for money and differentiation will be pivotal to withstand competition. For these industries mass customisation (MC) production technologies allows satisfying individual customer wishes, while still earning a profit. In Japan this is already common practice, while in the European building industry the first initiatives are now emerging. Question is what MC techniques are suitable for Europe. There are major differences between the northern and southern Member States, which form a barrier to simply market complete systems across Europe. Industrialisation of building products and complying with local building regulations and building cultures is simply not enough.

Transportable, flexible and tailor made building systems are needed which create value for the customer as well as for the industry. In order to make this profitable a considerable turnover is necessary. Costs can be reduced if businesses co-operate to place these systems on the European market. Information technology (IT) makes it possible to communicate in a direct way to customers. Networks of co-makers in the supplying industry are necessary to make arrangements for building systems and their 'just in time' delivery. An essential concept is disentanglement, in order to break down logistic complexity. This will allow for adaptable systems, easy and manageable enhancement of variants which will suit customers' wishes. The European internal market policy aims at eliminating barriers to trade by harmonizing National requirements for construction products. Under the European Construction Products Directive not only simple intermediate products are harmonised but also multi-component prefabricated building systems which can thus be marketed without barriers across Europe. They are referred to with the term ‘kit’. This European kit proves to be a perfect basis to elaborate MC concepts. The next step will be to work with design concepts which form the virtual basis for kits. Those ‘virtual kits’ extend beyond individual projects and can be used to realise a series of different dwellings. This virtual kit functions as a MC model by organizing building systems in decision levels, supported by IT costing programs, programs for drawing component assemblies and three dimensional presentations.

The saturation of the building market in combination with the possibilities of MC and IT technologies is bound to instigate a fundamental change in the European building industry. More choice and value is to be created for customers, while at the same time effects of decisions on performance, appearance and costs will be made transparent. Suppliers co-operating in networks are no longer tied by traditional tendering and constraints by the specifications of the contractor, but are able to offer their variant-options directly to the customer. Supply chain integration and partnering will become the new norm as a result.

7 References

Construction Products Directive (CPD) 21-12-1988, Council Directive 89/106/EC, Guidance paper C: the treatment of Kits and Systems under the CPD. Constr. 96/175 Rev 3

Eichert, Jochen & Abdul Samad Kazi (2007), Vision and Strategy of ManuBuild - Open Building Manufacturing, in Open Building Manufacturing, Core Concepts and Industrial Requirements, Abdul Samad Kazi, Matti Hannus, Samir Boudjabeur & Adrian Malone, ManuBuild www.manubuild.org

van den Thillart, C. (2004a), Customised industrialisation in the Residential sector, Mass Customisation modelling as a tool for benchmarking, variation and selection, Sun, ISBN 90 5875 128 7, www.uitgeverijsun.nl *See for a broad survey of MC techniques the reference list in this publication*

van den Thillart, C. (2004b), ‘Customised industrialisation in the Residential sector and its references to other authors’

Oostra, Mieke, Elke Nieuwenhuijzen & Amelie Veenstra (2007), User participation in residential design, *Unpublished paper.*

C) Industrialisation Procedures in Construction Companies Rationalisation and Systematisation of Processes

GERHARD GIRMSCHEID[1]

1 Industrialisation – Strategic Measures

1.1 Industrialisation – Benefits from a client perspective

Industrial construction measures are not just suitable for reducing costs and striving for the strategic option of cost leadership, various measures also offer means of differentiating from the competition or successfully processing certain market niches.

For each product and each group of clients, companies need to identify which aspects offer clients particular benefits and play a role in the decision-making process, above and beyond just the prices of the products. The main aim of industrialisation is cost reduction in the companies. But industrialisation needs in today's construction industry that the client is also convinced that this method is also beneficial for him, even if the product is not different in use if it would built by handcraft. Therefore the industrialised construction must offer also potential benefits for the client to motivate the architects and clients to request such produced construction products from the market. From a client perspective, industrial construction can offer the following benefits:

- Parallel performance of construction workflows, shortened construction time.
- Increased cost certainty by using standardised methods or products, companies might even offer cost guarantees or reduce the overall costs compared with execution using conventional construction processes.
- Product quality improves.
- Prefabrication ensures higher speed on-site construction workflows.
- The construction site is dry, i.e. can be immediately utilised in full.
- Environmental impacts on the construction site (e.g. noise, dust) are reduced by shifting production to prefabrication factories.
- Billing and project management are more transparent and thus easier to plan and track and more reliable for the property developer.

[1] Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch

- The integration of interior works into prefabrication production leads to lower cost and higher speed for the client.

These benefits from a client perspective need to be identified by the company and implemented using strategic and operational industrial construction measures. They offer the opportunity of differentiation from the competition or of occupying specific market segments or enabling cost leadership.

1.2 Industrialisation – Creating strategic business units (SBUs)

Since most companies have several product and service areas and several client groups, industrialisation requires a professional breakdown into various strategic business units (SBU). Each business unit or division should have a business unit strategy aligned to its relevant client groups. Since, from a client perspective, there are several means of differentiating the various products and client groups, various industrial construction measures could be suitable for implementation in the units. Generally speaking, those business units that are ideal candidates for industrialising the organisation of processes and works are those where

- the workflows can be standardised,
- the volumes of similar work processes are quite high,
- manual work can be reduced by machines of different processes

are ideal candidates for industrialising the organisation of processes and works.

The following criteria serve as an aid to identifying such business units:

- The rate of repetition of works and workflows is high, or similar processes can be standardised together.
- The administrative burden of modularisation and standardisation reduces the general business costs.
- The interfaces to other trades and processes are defined.
- Information processing and distribution expertise is available or can be obtained.
- The volumes of construction materials or components are high, or similar elements can be standardised using a platform concept, for example.
- Manual works can be significantly reduced by using equipment.
- Prefabrication generates time and cost savings or other benefits from a client perspective.
- Rationalisation, prefabrication or automation can be used to structure processes more safely and transparently (e.g. performance of works regardless of the weather, controlled capital investment using information systems, control systems for quality and malfunctions including operating procedures for different scenarios).
- Standardisation lowers the costs of setting up the construction site.
- The work safety of the employees is improved.

The next step is to implement appropriate industrial construction logic and measures in line with the identified criteria.

1.3 Industrialisation – Communication of its strengths

Initially, the price of a building seems to be easily comparable for many property developers and owners. But evaluating both the performance that can be expected at the relevant prices and the risks inherent in the various bids is more difficult than just comparing the price. If the contractor wants its industrialisation competence to be evaluated by the clients not only in terms of price, it must clearly communicate the soft facts relating to industrial performance potential that inspire trust. This can be immensely important when work contracts are being awarded. Seemingly cheap bids can quickly result in cost increases if the relevant ratio of price to risk is taken into account. Rational clients will first analyze the risks and performance overall before opting to accept those bids that offer a more favourable ratio of price to performance and risk, despite the fact that these might be more expensive. The communication of the strengths of controlled industrialised processes with a strong client focus will set the company apart from others, which is crucial for influencing the client's decision.

By implementing industrial construction measures, construction companies can use various approaches to create a competent and trustworthy impression and to set themselves apart from otherwise similar competitors, provided that they focus on communicating those performance potentials arising from professional industrial systematisation and standardisation and from the company's very own expertise. These include, for example (Girmscheid, 2006):

- Structured, systematic work preparation processes
- Command of specific construction and production methods
- Networks for exchanging resources and expertise
- Control processes to manage the execution processes

These benefits need to be communicated and must differentiate a company from its competitors. The aim of the communication process must be to convince customers of the balance between price, performance and risk and of the company's ability to provide the desired quality on the agreed date at the agreed price.

1.4 Industrialisation – Outsourcing and cross-company cooperation

Entrepreneurial actions always focus on client requirements. These client requirements differ, however, depending on the strategic business unit or market segment. But many situations reveal that customers wish for a single point of contact who can offer to reliably perform a comprehensive range of services at low cost.

The problem for a construction company which is departing from individualised crafts work to industrialised work is that its proprietary and basically limited resources do not allow it to offer an all-encompassing range of services at low cost. One means of expanding resources in the interests of optimizing a company's own range of industrialised services offered with a view to creating complementary competitive advantages is to provide the products and services in cooperation (Girmscheid 2006).

The **goals** of cooperation are as follows:

- Qualitative expansion of the range of products and services
- Quantitative expansion of the range of products and services
- Allowing each individual company to focus on its relevant core competencies
- Spreading risks and costs
- Making optimal use of internal resources

These goals are achieved by the following measures:

- Individual activities that are not being optimally used or do not form part of core business are outsourced to other companies, whereby the following points must be observed:
  - Availability of the product or service in the marketplace
  - Creation of dependencies on external companies
  - Security of the information outsourced from the company
  - Means of controlling external companies in terms of quality and improvement of the product or service to be purchased
  - Costs of purchasing the product or service, consisting of the price of the external product or service and the internal costs of purchasing the product or service/transaction costs
  - Flexibility for purchasing the product or service
- The company's resources that are freed up by such outsourcing can be used to improve the company's abilities in its core competencies. These can be human or financial resources. Outsourcing also enables an improvement in the balance sheet structure, which offers benefits when it comes to company ratings.

Outsourcing can be achieved by sourcing or carving out individual corporate tasks or units which have not the volume or capacity to be industrialised in their performance.

Any decision to outsource or cooperate must be preceded by the definition or identification of proprietary **core competencies**. Core competencies are those competencies of a company that generate a competitive advantage in the relevant market segment from a client perspective but cannot be easily imitated by other companies.

Focusing on core competencies creates cost saving potential for a company. Proprietary resources can be put to optimal use and processes improved on an ongoing basis. This continual process improvement minimises costs, ultimately resulting in a comparative competitive advantage and, if marketed properly, to increases in turnover.

The optimal utilisation of proprietary resources requires a consistent flow of orders resp. processing. And yet demand generally fluctuates. Aligning proprietary resources to maximum demand, which only occurs over limited time spans, is less cost effective that ensuring sufficient resources to cope with less than maximum demand and outsourcing orders that exceed this optimal level of utilisation (Fig. C.1). Each company must determine its level of provision of proprietary resources individually, taking the aforementioned outsourcing determinants into account.

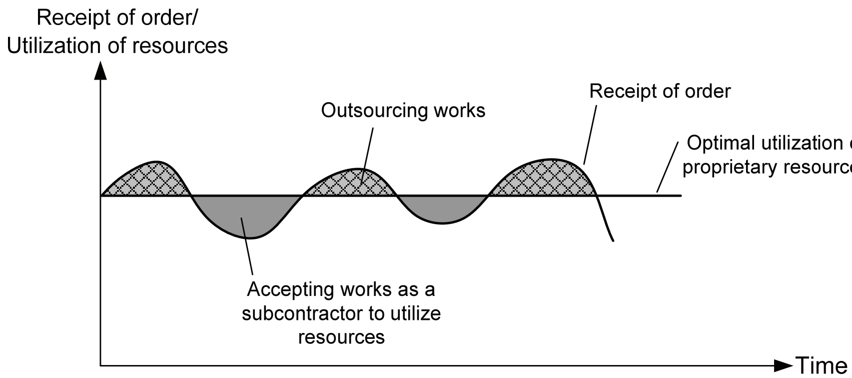


Fig. C.1: Optimal utilisation of proprietary resources

Although focusing on core competencies results in cost reductions, it also causes the overall range of products and services to be spread over various companies. This contradiction to a customer's demand for a total or system solution can be addressed by forming market-oriented cooperations without negatively impacting the benefit arising from focusing on core competencies. Complementary core competencies on the part of the involved companies can be linked to create new, market-oriented and above all customer-oriented total and system solutions. Various forms of cooperation can be considered, depending on the product or service in demand (Girmscheid, 2006) (Fig. C.2). Cooperations can increase the range of products and services offered, both in terms of quantity and of the products and services themselves.

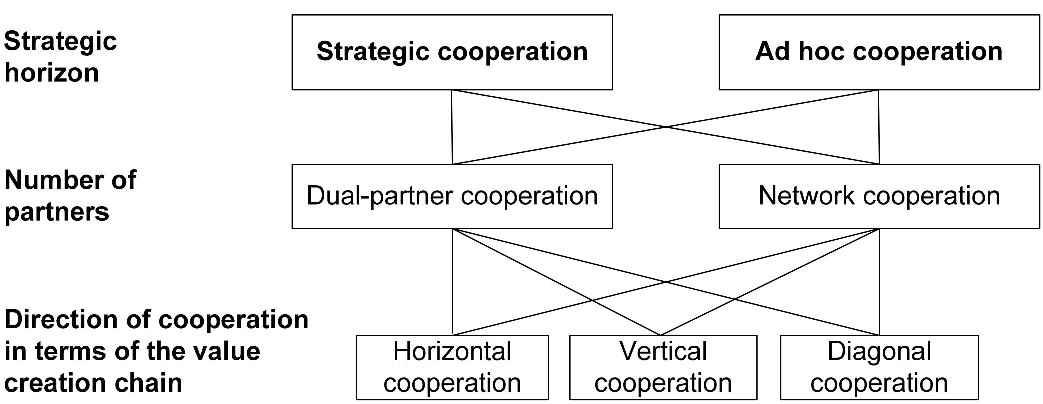


Fig. C.2: Generic structure of cooperations

Strategic cooperations actively pursue common goals in one or several business divisions over the long term. Usually these cooperations are managed by a focal company. By contrast, ad-hoc cooperations pursue situativ or project-related goals and generally do not have a proprietary or long-term management structure.

The vertical cooperations shown in Fig. C.2 refer to cooperation agreements along the value creation chain, i.e. generally supply and purchase relationships. In the construction industry, they refer to cooperation agreements among planning, execution and operating companies. The benefit is the harmonisation of the interfaces between the individual life cycles of the building through cooperation among the relevant companies in the interests of the client. Horizontal cooperations, by contrast, refer to cooperation agreements among companies with similar entrepreneurial objectives, or among companies operating on the same level of value creation. The aim of these horizontal cooperations can be to optimally utilise resources or to acquire and perform large-scale contracts. Cooperations that extend beyond industrial segment boundaries are referred to as diagonal cooperations. These are particularly beneficial when the range of products and services enhance each other and common target groups exist.

The paradigm shift from purely optimizing the costs of constructing a building toward investment-oriented and life cycle-oriented planning and construction requires an increase in the knowledge of the individual companies. Cooperations also enable the transfer of knowledge among the individual trades and offer opportunities to expand a company's own range of products and services to include integrative cooperational services over the long term.

Examples of cooperations include:

- Higher utilisation of resources:
    - Shared use of works yards
    - Merging of purchasing departments to produce more purchasing power or enable the companies to benefit from bulk discounts
    - Outsourcing human resources, accounts, legal or IT departments
    - Project-related temporary procurement of equipment
- Joint acquisition of larger contracts
- Complementary enhancement of products and services
    - Joint marketing and provision of system provider services by cooperating with insurance and financial companies (financing services) or service companies (operation and maintenance of buildings), provision of services relating to the external facilities
    - Development of new products and services (e.g. cooperation among chemical companies and construction machinery manufacturers to produce and market special equipment like a concrete spray robot)
    - Provision of total construction solutions (e.g. bathroom: instead of the property developer awarding the individual works, as has traditionally been the case (various contracts with different companies, interface management and coordination obligations), companies can cooperate to offer the works as a total service [professional management and coordination, common project goal])

2 Industrialisation – Operational Measures

Since a sustainable and long-term increase in competitive ability due to industrialisation can only be achieved by combining strategic and operational approaches, the following operational clusters also have to be implemented, together with the strategy measures:

- Standardisation of materials, components and construction methods
- Systematisation and rationalisation of the integrative execution planning and production planning processes
- Rationalisation of inventory management by making specific use of “all-round” equipment to increase the level of utilisation or temporarily renting equipment that is optimally suited to the task
- Rationalisation by utilizing standardised information technologies for the internal and external exchange of data
- Rationalisation and standardisation by prefabricating components

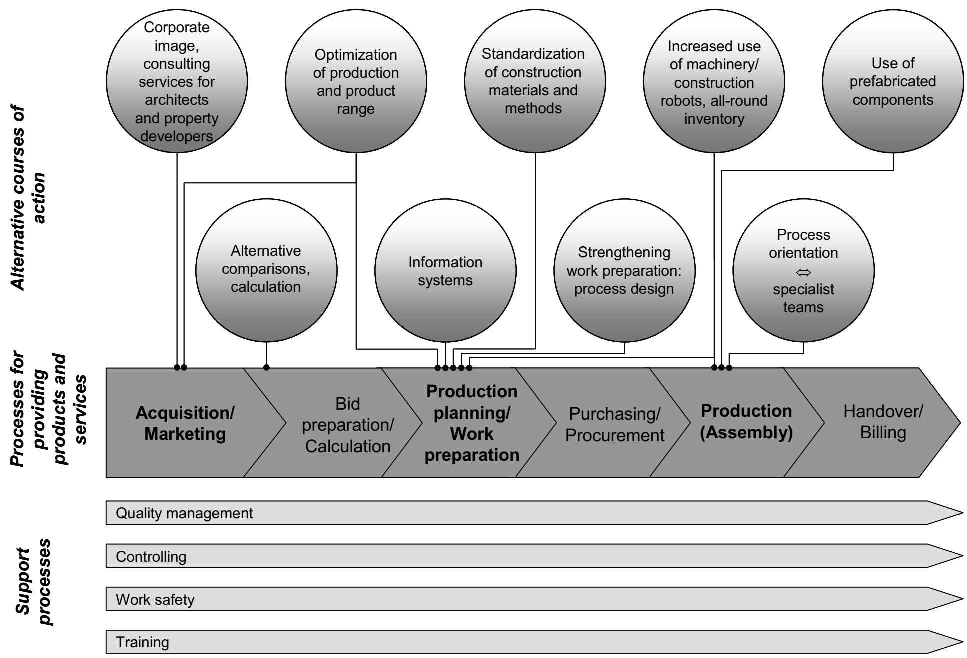


Fig. C.3: Means of industrialising the business process of in Construction Companies

Each individual construction company has to define specific courses of action in order to qualitatively structure and implement the individual solution clusters for industrialisation. These include, for example, an analysis of the production and logistics processes and the flow of information within the company. The relevant approaches to industrialisation and their allocation to the primary processes within the value creation chain can be seen in Fig. C.3. As already explained, these courses of action form the operational cornerstones to implement the strategy targets of the relevant business unit for everybody in day-to-day business.

2.1 Rationalisation – Optimizing Processes

Rationalizing the processes within a company is the key step to industrialising the performance of a company. According to Girmscheid (2004), rationalizing processes within a company encompasses the entire value creation process, together with the support processes, and also includes bid management and execution management.

To rationalise processes within a company means focusing on value adding activities and eliminating non-value adding activities by means of continuous improvement processes (CIPs). Rationalisation also means motivating the workforce to become actively involved in the process of continual improvement. CIP is especially suited as a bottom-up approach.

Process optimisation starts with market observation, acquisition and selection of the tenders in the marketplace. The company must define clear selection criteria derived from its risk-based strategy (Girmscheid, 2004). Bids must be processed efficiently and in a systematic manner, which requires a clear, risk-based analysis of the contractual, economic and technical aspects of the tender together with a dedicated cost analysis to include cost quality-efficient procurement in the marketplace. Examining alternatives is crucially important, where checklists can be particularly helpful for a systematic and quick procedure, as can systematic, market-aligned databases relating to

- approaches to offering products and services
- procurement costs of subcontractors
- internal cost estimations
- subcontractor evaluation lists

The aim must be:

- to only work on bids that optimally match the company’s range of products and services and expertise in order to generate comparative competitive advantages
- to draw up the bid in a quick and result-oriented manner with relatively low transaction costs
- to raise the success ratio in the marketplace and achieve the targeted margins.

The processes are optimised during the execution phase by means of systematic work preparation on the basis of the cost calculation. As such, work preparation is the fundamental starting point for rationalizing and optimizing processes during execution. Work preparation can be standardised or systematised for the individual strategic business divisions in most companies, e.g. for building single-family or multi-family homes. Systematizing work preparation ensures that nothing is forgotten and all construction sites are prepared to a consistently high degree. The use of checklists should not however prevent, but should instead support the development and use of alternative innovative construction methods. Process optimisation also includes the standardisation of all containers, from construction site management cabins down to small equipment containers. The formwork systems for on-site production should be systematised to suit the types of load-bearing structure on buildings. The use of semi-prefabricated parts and prefabricated components also needs to be systematically examined in relation to the construction workflow plan, the construction work itself and the parallel performance of workflows.

During the execution, the processes need to be systematically and continually improved, by examining means of optimizing the time spent on repetitive workflows right from the start. This optimisation is achieved with the help of time studies that classify and subsequently eliminate the non-value adding activities. This also requires a weekly planning schedule at group level that is then implemented by the construction manager and supervisor based on the workflow plan. The supervisor must draw up and daily adjust the daily planning schedule based on the weekly planning schedule. The monthly, weekly and daily planning schedules take the place of the cost-intensive improvisation by a supervisor equipped with a cell phone, since the workflows on today's construction sites are still guaranteed to a large degree by improvised, short term material and equipment requisition orders, which incur considerable supplementary costs and raise doubts about the positive performance of the construction site. Ongoing reporting systems that capture both performance and costs enable the processes on the construction site to be managed in such a way as to ensure that the target is reached. This also includes the use of on-site and off-site production facilities.

2.2 Standardisation – Using Information Technology to Exchange Data

Usually a very large number of companies and trades are involved in the planning and execution of a construction project. Clear **communication** and the exchange of data **among the project parties** are especially important when it comes to coordinating the various interests and individual works. A uniform or compatible data system offers the following advantages:

- Simple and fast exchange of data among the project parties
- Avoidance of multiple capturing of data
- Avoidance of losses of data and findings from earlier project phases
- Simple updating of cost estimations and calculations
- Simple preparation of target-actual comparisons
- Utilisation of the data for production planning, including purchasing

Enormous potential still exists within most companies to increase the efficiency of **intra-company communication**. Although traditional communication forms and IT systems generally exist in companies, the possibilities offered by information processing systems are constantly increasing, making it necessary for each and every entrepreneur to ask himself whether optimal use is already being made of all these possibilities. IT can simplify and structure workflows and processes more cheaply and transparently at every stage of the project. Some examples are listed below:

- The company's employees can access relevant contractual and execution documentation
- Communication and documentation of intra-company agreements and agreements among construction companies and clients
- Creation of common formats and files to reduce each individual's workload
- Automation of various work steps
- Classification and access to relevant data, even using external platforms
- Acquisition of new contracts via electronic media
- Controlling and cost control
- Prompt billing and reconciliation with procurement systems

2.3 Standardisation – Materials and Components

If similar construction methods, materials and components are used from one construction site to the next, intra-company standardisation could be implemented. This standardisation of construction components and materials should and must not, however, impair the individual characteristics of each building. On the contrary, the aim of standardisation is to simplify the complexity of the production processes in order to reduce execution deficiencies, minimise induction and start-up times and benefit from cost savings and efficiency improvements in repetitive works (e.g. improved ability to plan the construction workflows, better utilisation of special machinery).

For example, **brick walls** are currently frequently made from small-size bricks although the actual size of each brick is nearly always irrelevant for the final product. Since the use of small-size bricks is extremely labour-intensive, the option of using large-size bricks should be examined together with the relevant labour savings. This places more stringent requirements on the work preparation to ensure that the savings from using large-size bricks are not eaten up by labour-intensive fitting and follow-on works on the construction site. As such, it might be necessary to first determine the use of special laying aids/lifting equipment or the sequence of delivery and installation (cf. section Fig. C.16). As such, prefabricated walls made from bricks or other materials could be delivered to and installed on the construction site, which would reduce the weather-dependent workload on the building site and shorten the construction time. The coordination of both the materials used and the workflows undergoes a continual improvement process as construction management and work preparation are continually exchanging information.

Ancillary materials could also be standardised, where any substitution of the same could greatly impact work performance without affecting the work result. The following could be agreed, for example

- to minimise the number of different diameters of reinforcement bars
- to avoid the use of scarcely compatible concrete formwork
- to simplify interfaces for the choice of interior fittings systems.

2.4 Rationalisation – Prefabricating Components

Prefabrication plays a particularly important role in industrialisation since it allows circumvention of the construction site conditions that do not favour industrial production, such as changing production locations and the negative impact of the weather. The production processes can be much more easily mechanised and automated in a prefabrication plant than on a building site. Building using prefabricated parts unravels construction workflows. Prefabrication concepts can extend beyond the production of structural components and can combine various types of work (e.g.: integration of insulation, installation fixtures and surface treatments). Certain construction and finishing works (e.g.: more complex shell systems or stringent accuracy requirements) can only be economically ensured by prefabrication.

The cost efficiency of prefabrication increases in line with platform conformity and the ensuing size of series that have a pre-defined degree of variability. As such, preparations for the use of prefabricated components should be started back at the planning stage. Companies that practice industrial construction therefore need to establish contact to planners at an early stage (Fig. C.4). Once a project has been put out to tender on the basis of execution plans and detailed job descriptions, the potential for using prefabrication is limited. In this case, the Construction Company can only suggest the use of prefabricated parts for individual construction components. The intensified utilisation of information technology for prefabrication production could offer a means of escaping this dilemma. If the production process is largely automated and a CAD design is provided that is compatible with the prefabrication plant's CAM system, it is also possible to cost efficiently manufacture individual architecturally sophisticated components on the basis of platform systems. Fig. C.5 outlines the flow of information needed for integrated production planning.

Fig. C.4: Rationalisation through the use of prefabricated components (e.g. hollow reinforced concrete walls and semi precast elements)

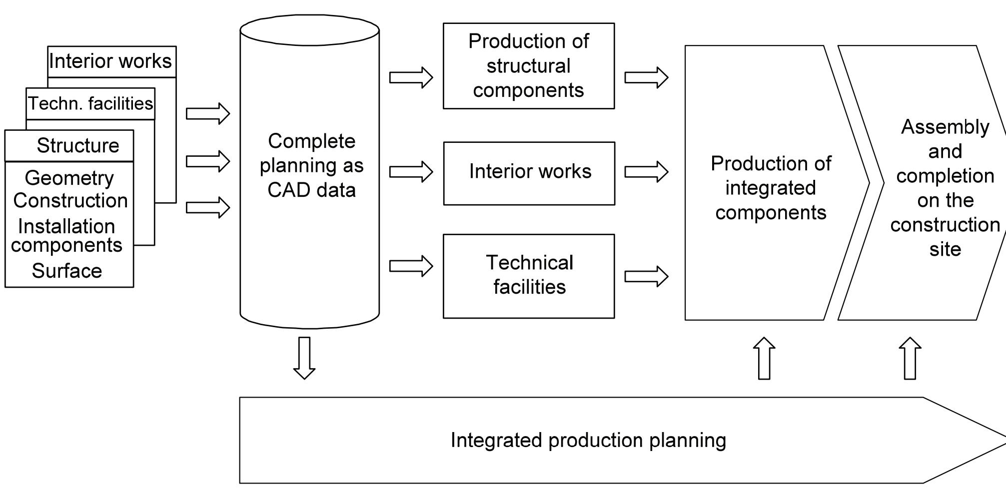


Fig. C.5: Flow of information as the basis for integrated production

It is not always possible to prefabricate entire components. But the prefabrication of intermediate products, such as reinforcing cages, can also be automated. There are meanwhile a large number of reinforcing machines in the marketplace (Fig. C.6) that can be used to produce the common types of reinforcing mats and cages. In addition, automated laying equipment for reinforcing mats and rods is also available for plant in line production.

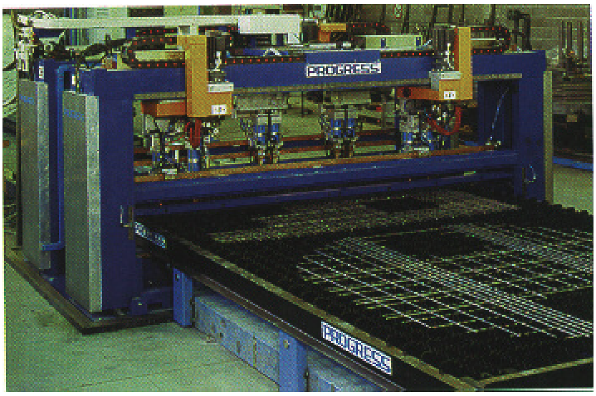


Fig. C.6: Automated (robotised) reinforcement welding plant (Betonwerk+Fertigteiltechnik, 1999)

2.5 Standardisation – Modular Construction

Modular methods of construction enable the use of identical components both within a project and for different construction projects. Such repetition involves designing in small series on a so-called platform basis with the ensuing benefits arising from a standardisation and optimisation of the processes. The production of a series of identical components on a platform basis enables more cost efficient prefabrication and automation, and justifies the investment of more time in detailed planning and work preparation, resulting in advantages, not only in terms of construction schedule and costs, but also quality.

On the one hand, the use of modular platform systems increases the flexibility of the production processes while on the other hand clients do not perceive the final product as being modular. As such, modular construction presents a challenge for planners, above all, whereas construction companies are faced with the task of offering modular methods of construction and actively communicating with planners.

2.6 Standardisation – Construction Methods

The aim of standardizing construction methods is to produce the work result more efficiently. Generally speaking, the standardisation of construction methods harmonises workflows and reduces non-value adding activities on the building site. This can be achieved both by standardizing work steps, e.g. by using special equipment, and by adopting alternative construction methods.

The use of the following construction methods is an example of how standardised construction methods can enable the elimination of individual work steps and the related labour costs:

Self-compacting concrete (SCC) is a self-compacting and self-levelling concrete, the use of which offers the following advantages:

- Easily cast into complex shell shapes or close-meshed reinforcements
- High pouring performance

- More consistent quality of the concrete throughout the entire cross section
- Improved quality of the concrete that can result in reduced dimensions of the components
- Reduced noise exposure
- Shortened construction time

The use of SCC eliminates the work steps of compacting and levelling, while still allowing the production of highly-reinforced components.

Steel fibre concrete (SFC) contains fine steel fibres added to enable the absorption of tensile forces. Given the corresponding dimensions or for simple components, the use of steel fibre concrete eliminates the need for conventional reinforcement. Steel fibre concrete is nowadays mainly used to produce industrial flooring (Fig. C.7), as shotcrete in tunnel construction or to minimise crack widths. It can, however, also be applied onto filigree ceilings or used to produce prestressed ceiling panels (Grad et. al., 2006). In addition, it can be used for components that only require crack reinforcement.

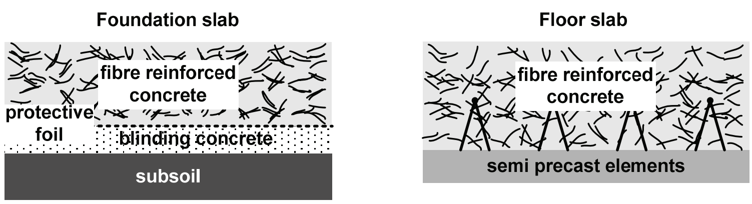
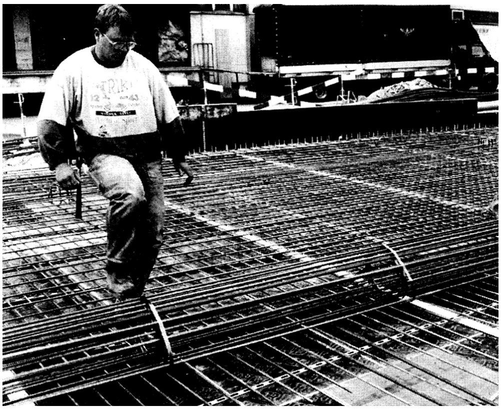


Fig. C.7: Rationalisation through the use of standardised building materials (e.g. use of steel fibre reinforced concrete in foundation and floor slabs) and prefabricated components (e.g. semi precast floor slab elements

Rolling out **prefabricated reinforcement mats** on large scale components is more efficient that laying individual reinforcement bars on the construction site. These reinforcement mats are prefabricated at the plant using a parallel system of reinforcement bars and mounting bands. The mats are incredibly easy to lay (Fig. C.8). Once the crane has lifted the mat to its starting point, the workers can easily roll it out, thus minimizing the time spent on installing the reinforcement while at the same time ensuring high degrees of positional accuracy and execution quality (SFS Locher).



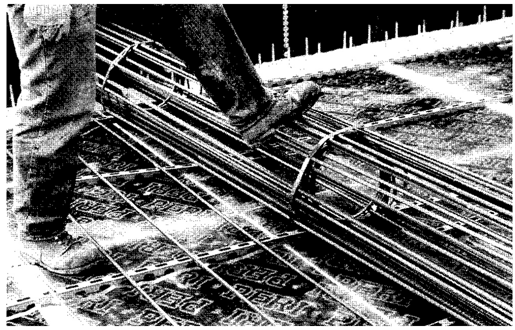


Fig. C.8: Installing/rolling out of prefabricated individual reinforcement mats, detail of a mat (SFS Locher)

The use of **self-climbing platforms (SCP)** (Bärthel, 2002) (Fig. C.10) or **sliding formwork (**Fig. C.9**)** is especially suited to high or tower-shaped components. Both methods eliminate the need to erect scaffolding up to the full height of the building. On the contrary, SCP climbs independently to keep pace with construction progress; sliding formwork does the same, yet continuously, without producing concrete joints in the structure.

Fig. C.9: Stairwell/elevators cores built using sliding formwork (Gleitbau GmbH, 2006)

Fig. C.10: Self-climbing formwork, SCP (DOKA)

2.7 Mechanisation of Construction Site Production

Numerous activities have to be performed on the construction site that

- are simple and monotonous,
- frequently involve repetitious work steps,

- require consistent levels of quality, and
- incur high expenditure to protect the worker performing the task, and
- cannot be shifted to prefabrication.

Raising the degree of mechanisation and automation, i.e. using appropriate machinery or robots, can increase the work productivity of construction sites. Frequent repetitions of workflows mean a higher capacity utilisation of special machinery. Moreover, construction machinery and robots are frequently able to produce more accurate work than humans (e.g. consistent thicknesses when painting or coating), especially over longer periods. The need for expensive work safety measures for tasks involving health-hazardous substances (e.g. solvent-based paints) or working at great heights (e.g. façade works) can be eliminated if the use of machinery means that the workers do not need to be exposed to the danger.

For traditional reasons, many construction companies still try to perform all works themselves. As such, they buy inventory, such as formwork, cranes or other equipment, and tie up huge amounts of capital. Once they have purchased the inventory they are faced with the problem that it is frequently not utilised to full capacity.

Taking the purchase of all-round equipment as an example, it often results in a less than optimal utilisation in terms of the required and the available performance of the relevant equipment. Generally speaking, this incurs higher costs from using purchased but not optimally deployed inventory.

In the case of specialised equipment, in particular, it frequently makes more sense to hire or lease it specifically to perform the relevant work task. In addition to the more efficient utilisation of the individual piece of machinery or equipment, the temporary procurement of the inventory also makes it possible to improve cost allocation to the individual projects. Since these procurement models generally include service contracts or warranties, companies can minimise their fixed costs of equipment maintenance.

Many labour-intensive and repetitive works have to be performed on the building site. The working conditions on construction sites are, however, not always the most favourable for the use of automated and therefore technically sophisticated and possibly sensitive fabrication methods. On-site production means that the equipment is permanently exposed to external influences, such as the weather, dirt, dust, and vibrations. In addition, the equipment itself has to be mobile and therefore requires an extremely advanced and accurate navigation system that has to be coordinated with the navigation within the actual work area. This produces a much higher need for control than with stationary equipment.

The logistics and operating conditions also need to be adjusted to reflect these special requirements. For example, sufficient open space must be made available within the structure, material feeding must adhere to exactly defined specifications, and a hitherto unnecessarily accurate degree of planning of the structure is essential.

The following machinery and automated equipment is used on construction sites:

- automated rollers for compacting floors (Fig. C.11)

- GPS-controlled and/or laser-supported bulldozers, rollers, scrapers and graders for digging ditches and trenches (Fig. C.12) (Hampton, 2005),
- mechanised, semi-automatic self-climbing formwork systems and concrete casting, compacting and levelling equipment

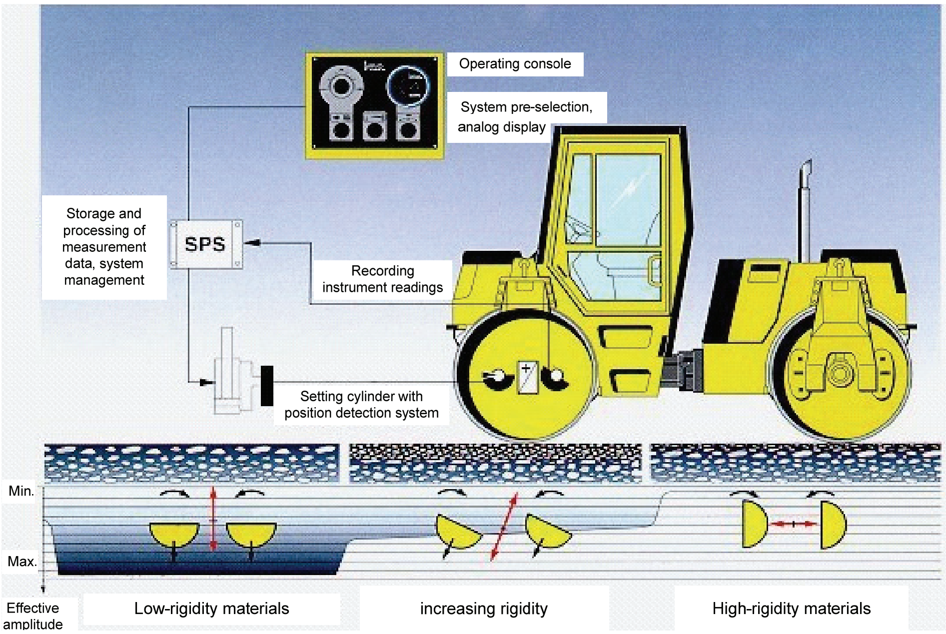


Fig. C.11: Earthworks: Vibration roller with automatic compact control (BOMAG-MENK GmbH)

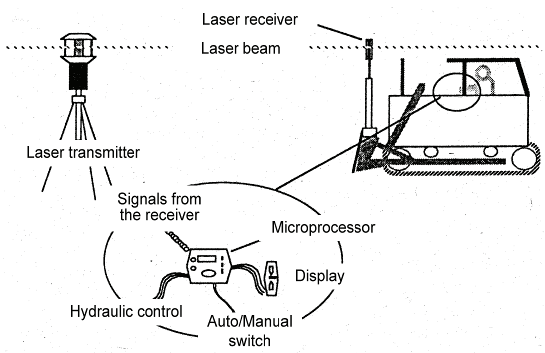


Fig. C.12: Earthworks: Principle of laser-supported bulldozing (Girmscheid, 2006)

Table C.1: Service robots for building construction applications (Schraft and Volz, 1996)

Area of Application	**Brief description**	**Country**
Structural engineering	Computer-controlled stationary concrete spreader	Germany Japan
	Robot for leveling and compacting concrete	Japan Sweden
	Autonomous systems for smoothing concrete surfaces	Japan
	Autonomous systems for reinforcing concrete surfaces	Japan
	Brickwork robot	Germany Great Britain
	Automated construction systems for structural engineering	Japan
Interior works	Autonomous material transport on construction sites	Japan
	Robot for laying tiles in interior rooms and on facades	Finland Israel Japan
	System for applying ceiling lining	Japan
	Partially automated system for spraying fire-retardant paint	Japan
	Robot for external painting	Japan

As described in Table C.1, some Japanese companies have made sufficient progress in automating equipment for concrete construction that it can be used under construction site conditions.

The equipment in question is always standard equipment (concrete spreaders, surface treaters and surface planers) that has been fitted with automated control mechanisms and navigation systems. Its deployment requires large surface areas and uniform operating cycles, however, as can be seen from Fig. C.13, Fig. C.14 and Fig. C.15. The equipment has not yet been optimised for use in existing small-scale structures in conventional residential housing.

In addition to the possible improvement in productivity and the purchasing costs, any entrepreneurial decision to purchase a new machine must take into account any logistics expenditure possibly related to the machine.

Since the manufacturers of construction machinery are constantly expanding their range of products on offer, machinery will become available to perform ever more works and steps. Further automation will depend, above all, on the technical stability and low costs of purchasing construction site and prefabrication robots.

Fig. C.13: Concrete spreader (Takenaka Corp, 2006)

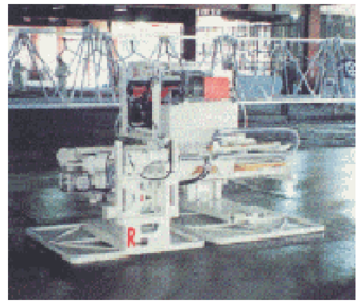


Fig. C.14: Surface treatment and water extraction (Takenaka Corp, 2006)

Fig. C.15: Surface planers (Takenaka Corp, 2006)

For example, special offset machines for large-size bricks and mortar spreaders have been developed to increase the degree of mechanisation in **brick construction** (Fig. C.16). This equipment does not work autonomously or fully automatically, but is operated by hand. Compared with manual production, the equipment offers higher levels of efficiency in combination with large-size bricks that improve performance but cannot be laid manually because of their size. Together with the use of large-size bricks and appropriately trained personnel, this equipment can streamline the process by up to 40 % (Bilfinger+Berger AG, 1998).

Fig. C.16: Offset rig for large-size bricks (Bilfinger+Berger AG, 1998)

3 References

Bärthel, J., Girmscheid, G. 2002) Industrielles Bauen. Leitfaden für KMU-Geschäftsführer. vdf Hochschulverlag ETH Zürich

Betonwerk + Fertigteiltechnik (1999) Ausgabe 3/99

Bilfinger+Berger AG (1998) Rationalisierungsmöglichkeiten im Mauerwerksbau, Mannheim, 1998

BOMAG-MENK GmbH, Boppart, Produktinformation

DOKA Schalungstechnik GmbH, Maisach, Produktinformation

Girmscheid, G. (2004) Angebots- und Auftragsmanagement im Baubetrieb. Verlag Ernst & Sohn, Berlin

Girmscheid, G. (2006) Strategisches Bauunternehmensmanagement: Prozess-orientiertes integriertes Management für Unternehmen in der Bauwirtschaft. Springer-Verlag, Berlin

Gleitbau GmbH (2006) http://www.gleitbau.com/images/product/telekom_1_m.jpg (30.03.2006)

Grad, J.; Grad, Th.; Kassner, U. (2006) Vorspannung ohne Verbund und Flachdecken aus Stahlfaserbeton. In: Beton- und Stahlbetonbau 101, Heft 02/2006

Hampton, T. (2005) 3D Grade Control Puts Designers Right in the Operator's Seat. In: ENR Engineering News Report, McGraw-Hill Construction, 03. October 2005

Schraft, R., Volz, H. (1996) Serviceroboter, Springer Verlag, Berlin

SFS Locher: Prospekt: Bausysteme

Takenaka Corp. (2006) http://www.takenaka.co.jp, 08.06.2006

D) Framework to Facilitate Process Innovations

S.M. LIMBURG [1] & P.G.S. RUTTEN[2]


1 Introduction

The construction sector has difficulties in realising buildings that adapt to the changing user demands during the building's lifecycle. This leads to early obsolescence and partial rebuilding, high vacancy levels or even demolition of buildings that have not technically depreciated yet. This is, on the one hand, due to a lack of collaborative design in the early design phase (Rutten & Trum, 2000). On the other hand a system approach to building design is missing which gives consideration to the differences in lifecycles of the various systems in a building (Brand, 1994) and stakeholder involvement (Habraken, 1961). New design approaches introduced a more central role of the end-user and distinguished disconnected building layers with a support and infill (open building) (Habraken, 1961). Later Rutten & Trum (2000) introduced a design approach with integrated functional levels and value domains that also supports the design team in a focussed attention to a dynamic future use of the building (strategic design).

Yet these design approaches are barely adopted in the building industry despite a wide promotion. The construction sector is dominated by a conservative culture, the market is fragmented and the continuous changing design and construction collaborations hamper technological innovation. The many specialised participants make coordination of complex buildings difficult and inefficient. Due to the fact that the building industry doesn't welcome and stimulate changes, pilot projects experience difficulties in implementing innovative design strategies or design partners continuously fall back into the traditional and safe working methods. It is obvious that there is a need for an implementation strategy of the above mentioned innovations in design processes. In this paper a framework is recommended to facilitate the successful introduction and implementation of innovative design processes.

2 Innovation Research

Some other industries are similar to the building industry, yet they are more innovative. Research was conducted to find the underlying reasons for their successes in an attempt to learn from their approach

[1] Ir., Delft University of Technology, P.O. Box 5043, 2600 GA Delft, The Netherlands, S.M.Limburg@tudelft.nl
[2] Prof. Ir., Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands, P.G.S.Rutten@bwk.tue.nl

towards innovation (elegant stealing) (Van Loon, 2002). According to the typology of Botter (1974) we have selected industries with similar characteristics as the building industry (see Fig. D.1).

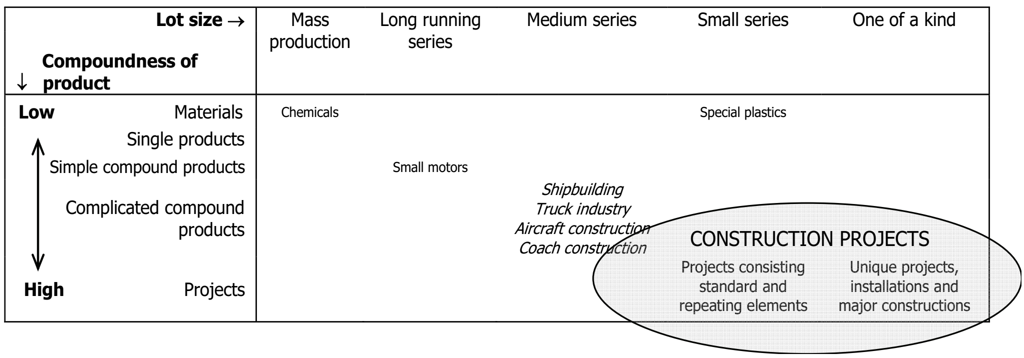


Fig. D.1: Botter´s typology (Source: Botter, 1974)

The following industries were part of this research; the shipbuilding, the truck industry, aircraft construction and the coach construction industry. In interviews with key representatives of companies in these industries insights were gained in key success factors in innovation trajectories. These insights were subsequently tested in a case study that was conducted in a building project by a large health care organisation in The Netherlands. This project centered around the introduction of adaptable ICT-technologies in dwellings (ambient care). The main aim of the project was to further the quality of life through custom-made support services for care and well-being. As this project involved the need to introduce technological innovation in existing organisations, it was a suitable test bed for the insights gained from the non building industries in terms of organising the innovation trajectory and defining desired interventions. Finally, the construction sector has been analysed so that implementation of the key success factors gained from research in the non-building industries and the case study will be more efficient.

3 Research Results

Some generic lessons learned from the research, the case study and the analyses of the construction sector are:

- When endeavouring change in a human system expect resistance. To overcome the resistance it is important to let people experience the advantages of the innovation and the opportunities it offers for them and, most importantly, to involve them in the process as early as possible so that the change comes from within themselves and is not being forced upon them by others.
- To change the culture of a company or industry is extremely difficult. Often outsiders can help to bring the necessary change about. Consider therefore involvement of professionals from non-building industries or with a different educational background.
- It is important that people are conscious of the need for innovation and its implementation. Communication to all layers of the organisation is an ongoing basic necessity.

- One requires a framework that structures the various phases in the innovation process together with key success factors and desired interventions in each of these phases. The phases that non building industries distinguish are as follows:
    - Initiative
    - Trial phase
        - Preparation
        - Realisation
        - Evaluation
    - Consolidation
- In the construction sector, implementation of process innovation is most effective at cluster level, where all companies involved in design, construction and operation of the building decide to bring about innovation in the building industry. Realizing process innovation at company level is not very effective because of the equal basis of collaborations in construction projects and the need for an integrated approach. Furthermore, initiatives at sector level often fail as a dominant player or coordinating organisation is missing.

The following explanation is given of each of the phases (mentioned in 4 above) in the innovation process together with specific key success factors and interventions.

I. Initiative

Organisations will initiate innovation processes when they become aware of the advantages and opportunities of alternative processes. External events such as technological innovations or changing societal demands can give extra impulses to change. By dissimilating the advantages and opportunities that alternative design approaches offer, organisations will become more conscious of the need for change and are more likely to participate or to start innovation processes. Knowledge centres and universities may play a role in this dissemination.

Intervention:

- Disseminate the advantages of innovative design strategies.

II. Trial phase

To experience the collaboration between the participants a trial phase is defined. In this phase one or more pilot projects will be executed. The sequence of the preparation sub phases is not strictly determined but may be carried out in parallel or overlapping time frames.

A) Preparation

Acquire a project

The initiator will search for a pilot project in which the cluster can deliver added value. By disseminating the opportunities of the alternative design strategy people should become enthusiastic for working with a cluster and implementing innovative design strategies.

Intervention:

- Disseminate the advantages of innovative design strategies.

Compose initial cluster

Starting innovation processes it is important to involve all knowledge domains from the beginning of the process. Part of the selection criteria for organisations is the willingness to participate for a longer period. During the selection process, selection criteria should be used in order to create a balanced team as the participants should complement each other. An external, independent project manager can be involved to stimulate and guide the team according the principles of the innovation strategy. Moreover, to guarantee and persuade the people to work as an integrated team, professionals from. Besides the architect, technical specialist and project manager, the end-user has to be part of the cluster as well. If the initiator has not found a pilot project yet, delegates from formal user-organisations can participate in the cluster.

Interventions:

- Create a multidisciplinary cluster
- Involve end-users
- Involve an extern, independent project manager,
- Involve professionals from non-building industries.

Anchor the organisation

In workshops the differences in expectations should be addressed, where awareness, insight and respect for each other can be reached, the barriers between specialists can be broken down and a common ground is built in terms of attitude, behaviour, practices and perspective. People get enthusiastic and get a drive to succeed as a team. Besides the creation of cohesion within the design team, the organisation structure is formalised in a project plan and consensus about the objectives is formalised in a 'gentlemen's agreement'. Somebody is being held responsible for the success of the process innovation's implementation. Experts can pass on the principles of innovative design strategies and adaptable technologies to create consciousness by the participants.

Interventions:

- Create shared attitudes, values and enthusiasm in workshops
- Formalise organisation structure and objectives in a gentlemen's agreement
- Hold project manager responsible for implementation innovation
- Education.

B) Realisation

The cluster will execute the project, implementing the principles of innovative design strategies such as open building and strategic design. This aims to realise adjustable buildings which are flexible and adaptable to future changing demand dynamics.

Interventions:

- Apply innovative design strategies.

C) Evaluation

To close the learning cycle and continuously improve the cooperation within the cluster, the innovation process and the project should be evaluated. Possible evaluation outcomes can be reassigning interventions or changes within the composition of the cluster.

Interventions:

- Apply evaluation tools.

III. Consolidation

The participating parties can decide to consolidate the collaboration. Through long-term collaborations and further formalisation the developed knowledge can be further improved for other interested owners. The cooperation has to adopt the principles of a learning organisation to be able to continuously react on future demands. Recommended methods are Kolb's learning cycle (1984) and the five disciplines of Senge (1995).

Interventions:

- Apply principles of a learning organisation.

Total process

Interventions, critical during all phases of the process, are open communication and applying intermissions. Communication is essential to create awareness over the project's goals and the method of working. Intermissions are needed to control the project, to create a learning organisation, establish short term successes and to evaluate interventions.

Interventions:

- Communication
- Apply intermissions.

4 Process innovation framework

The results of the research in the various industries, the case study and the analysis in the construction sector can be combined in a process innovation framework, see Fig. D.2.

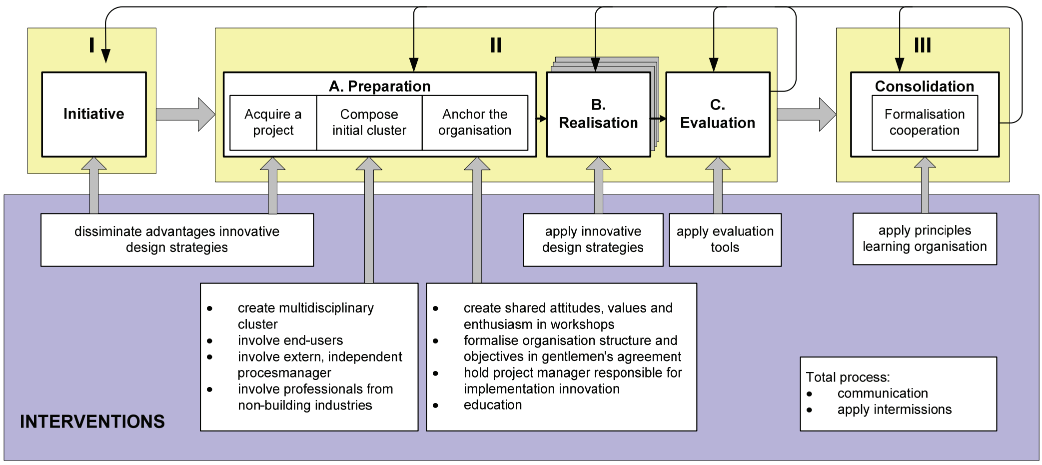


Fig. D.2: process innovation framework

5 Conclusions

This paper has introduced a framework to facilitate process innovation. The following conclusions can be drawn:

- The construction industry should become more conscious of the fact that innovation involves both process innovation and technological innovation.
- In the construction sector, process innovations can only be reached by cooperating teams from the whole spectrum of the building industry. Creating clusters and long term collaborations is essential to bring about and successfully implement process innovations and continuously improve technologies. In addition to a business opportunity, every project provides an opportunity to innovate together.
- The cluster should continuously consider external societal and technological dynamics. Creating a learning organisation and closing the learning cycle are essential elements.
- The construction sector can learn from other industries. More research is needed in non-building industries or more regular application of research done in other industries to the construction sector.

To start process innovation within the construction sector this paper recommends the adoption of the proposed framework.

6 References

Botter, C.H. (1974). Industrie en organisatie. Philips technische bibliotheek. Kluwer/NIVE ISBN 90-267-0442-9.

Brand, S., 1994. How buildings learn. R.R. Donnelly & Sons Company, Ohio, USA.

Habraken, 1961. De dragers en de mensen, het einde van de massa woningbouw. Amsterdam: Scheltema & Holkema N.V.

Kolb, D.A., 1984, Experiental Learning; experience as the source of learning and development, Prentice Hall, Englewood Cliffs.

Loon, S.M. van, 2002, Veranderen naar een consumentgericht ontwerpproces; onderzoek naar de ontwikkeling van veranderingsstrategie, Technische Universiteit Eindhoven / TNO.

Rutten, P.G.S., Trum H.M.G.J. (2000). On innovation of buildings. Int. Building Physics Conf. (IBPC 2000). Univesity of Technology Eindhoven.

Senge (1990). The Fifth Discipline: the art & practice of the learning organization. New York: Currency Doubleday.

E) Paradigm Shift and Client Focus on Industrialisation

GERHARD GIRMSCHEID[1]

1 Introduction

The construction industry nowadays mainly focuses on various single paradigms of industrialisation to increase cost efficiency and/or differentiation. But this narrow focus on single industrial paradigms must be expanded holistically to meet the client requirement for individual solutions.

2 Paradigm Shift

The various paradigms of Industrialisation in construction with their appropriate market strategies and areas of application are illustrated in Fig. E.1. The classic action paradigms, which are still very common, designate exclusively the orientation toward single operational processes. Such single actions in construction processes are necessary but do not sufficiently exploit fully the efficiency potentials.

A paradigm shift is needed to achieve holistic optimisation within a company that also encompasses the corporate strategy. The only companies that will be able to survive long term in the marketplace are those that:

- operate in those areas of business that generate sufficient margins
- adopt an investment-oriented or life cycle-oriented approach, depending on the scope of the project,
- focus on their core competencies,
- improve the internal processes to maintain competitiveness and
- implement continuous improvement and innovation processes

This can only be achieved by focusing on those market segments where the core competencies generate comparative competitive advantages for the client. Furthermore internal processes have to be systematically industrialised and continuous improvement process must be organised. Implementing such a paradigm shift might well necessitate working with external planners and specialist companies, whereby new project delivery and business models also need to be structured and implemented

[1] Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch

(Girmscheid, 2006). A corporate strategy aligned to this paradigm shift must be implemented in the companies.

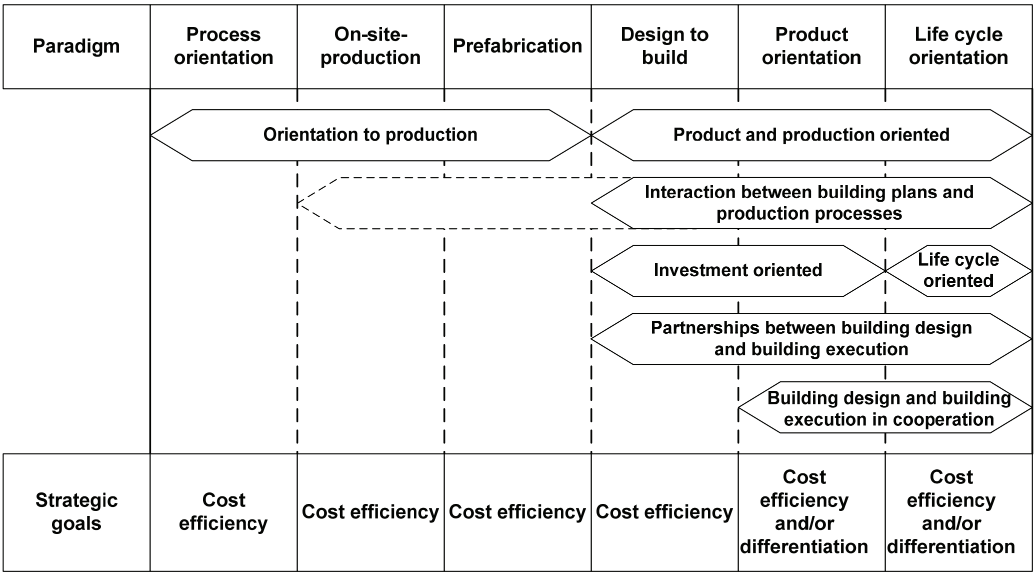


Fig. E.1: Industrialisation paradigms with corresponding strategic objectives

According to classic management doctrine (Porter, 1999), the following market oriented strategy options exist at corporate level:

- **Cost leadership**: Differentiation from the competition solely on the basis of the price of the products and services offered
- **Focus strategy**: Occupying and processing particularly attractive partial markets (market niches)
- **Differentiation strategy**: Processing selected customer groups with the aim of generating USPs that set the company apart from the competition

According to Porter (1999), each company, respectively each area of business within a company must opt for one of these strategies if it wants to survive long term in the marketplace.

Implementing Industrialisation in construction companies is resource oriented and not just restricted to reducing internal costs and, as such, to a strategy of cost leadership. For example, a shortened construction schedule enabled by the use of prefabricated components can be a decisive module of a differentiation strategy relating to the customer group of "property developers".

Above and beyond Porter's strategy options, **mass customisation (client-individual mass production)** has been a further resource oriented strategy option that has been under discussion since the mid-1990s (Pine, 1993, 1998, Piller, 2003). A mass customisation strategy aims to ensure that the product meets the individual needs of each client while at the same time offering virtually the same efficiency levels as mass production. The idea behind the development of the mass construction strategy is, on the one hand, the ever growing need of clients for individual products and, on the other hand, the fact that new technologies are no longer forcing the two parameters of quality and price to opposite ends of a value scale, but rather enabling the two to be linked to each other. And the fact remains that USPs arising from differentiation or cost leadership can only be sustained for a limited time as imitators emerge in the marketplace and, as such, the introduction of a further USP offers added value on an individual client basis. When pursuing a strategy of mass customisation, the following four levels need to be weighed against each other:

- Cost level: Additional costs arising from processing information and individualised design must be minimised through cost savings achieved by eliminating development and sales risks.
- Differentiation level: Creating non-monetary USPs generates comparative competitive advantages for the client
- Relationship level: Individualised design for each client and the strong focus on the client minimises sales risks; innovations are initiated by the clients
- Scope: Designates the framework to be determined by the producer that establishes the balance among the 3 other levels and, in doing so, the limitations to individualisation of the products (e.g. production based on platforms or modules)

The following criteria are generally deemed to be crucial for successfully implementing a strategy of mass customisation:

- High sales volumes of the products
- Modular design approach, i.e. products can be adapted to suit customer requirements within predetermined limits or from a predetermined choice of individual components/modules
- An interface exists between the client and producer that is simple for both sides
- The flow of information from the customer's request entered in the system to production right up to delivery must be continuous, simple and transparent
- A control system is installed to analyze the customer's request, for example, in terms of statutory and technical production requirements
- Lean production, i.e. production on demand, lean and flexible work processes, incl. support processes
- A learning system with regard to improving customer loyalty and production workflows

When applying this strategy option to construction production, this involves streamlining, rationalisation and standardizing processes and products with the aim of reducing costs and at the same time securing the freedom of architectural design. The industrial production of client-specific wall panels as a prefabricated platform-based component is one example for the implementation of a mass customisation strategy in construction production.

The consequences for processes relating to project delivery are shown in Fig. E.2. In the case of mass customisation, full-scale requirements management is important to catch all customer requirements and financial restrictions to provide value for money. The integration of building design and production planning process are, however, equally important.

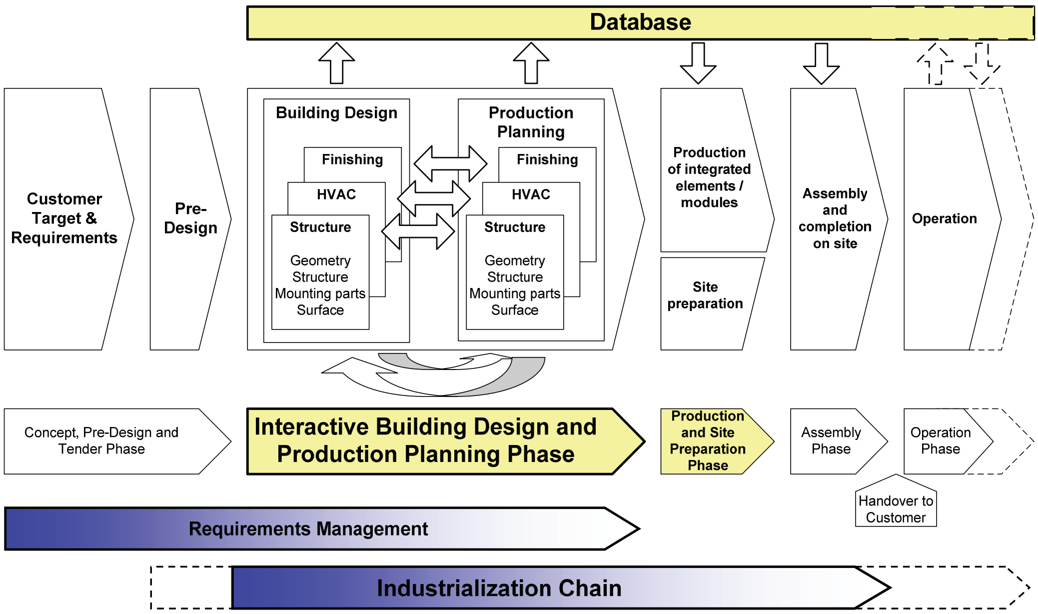


Fig. E.2: Mass Customisation production and required project delivery process

3 Client Focus on Industrialisation

Pushing ahead with the Industrialisation of construction production necessitates a paradigm shift in construction processes. It is absolutely essential to maintain freedom of architectural design when industrialising production and processes. Nevertheless, Industrialisation must be systematised and standardised if cost efficiency is to be achieved. Success will be an optimum combination of individuality, customisation and standardisation.

In order to simultaneously ensure high levels of variety when manufacturing and using elements, modules and systems, the planning and production processes need to be highly adaptable in terms of the design variance of the elements, modules and systems. As such, systematisation and standardisation also necessitate flexibility on the basis of so-called platforms to ensure the adaptability of the industrial construction processes and products and the design variance of the elements.

With regard to Industrialisation, a distinction must be made in the **design adaptability** between production-related and use-related adaptability.

Production-related adaptability relates to the manufacturer's flexibility during the planning, production and execution phases. Platform and module systems are based on this concept. For example, various wall elements etc. can be prefabricated using adjustable magnetic formwork. The use of optimised standard details is also linked to planning and production on the basis of platform or module systems.

Industrialisation requires production-related flexibility to enable design versatility using individual elements, modules and systems manufactured in line with Industrialisation concepts. Manufacturing in line with Industrialisation concepts also means producing large volumes, whereby platform or module systems can be used to individually design each separate product for the user in the given variety of the platform system.

User-related adaptability ensures the flexibility for easily adapting the use of the structure to individual needs. For example, building elements and modules can be substituted as needed (e.g. facades) or moved (e.g. interior walls).

In order to simultaneously ensure high levels of variability when manufacturing and using elements, modules and systems, the planning and production processes need to be highly adaptable in terms of the design variety of the elements, modules and systems within a platform. As such, systematisation and standardisation also necessitate variabilisation on the basis of so-called platforms to ensure the adaptability of the industrial construction processes and products and the design variance of the elements.

Planning and manufacturing modules and elements, i.e. defining components and interfaces, offers options both for prefabrication and for user-related adaptation. The interrelationship between product-related and process-related adaptability and design variability is illustrated in Fig. E.3.

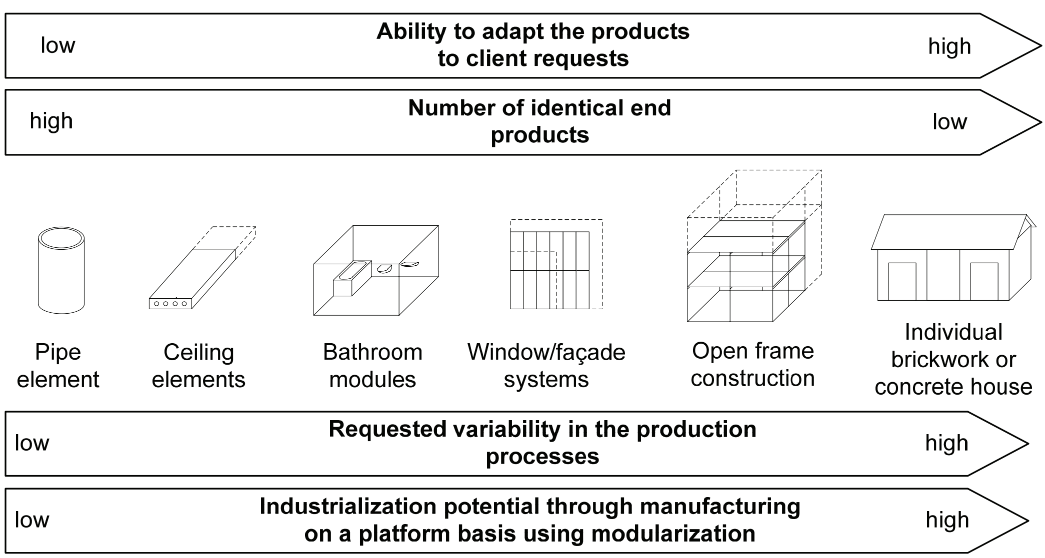


Fig. E.3: Interdependency of design variety and process-related and product-related adaptability

Fig. E.4 illustrates the specific characteristics of the various business models common to the construction industry, together with their Industrialisation potential. On the one side, there is client-specific individual manufacturing, where all processes and partial elements are manufactured and designed specifically for one client. On the other side, by contrast, is the mass producer who always manufactures the same components and elements using standardised processes and methods. This type of fabrication requires the ability to sell large unit volumes. Various interim levels exist between these two extremes that differ in terms of the varying degrees of streamlining and standardizing products and processes. Generally speaking, the higher the degree of standardisation, the better is also the Industrialisation potential and, as such, the potential to achieve cost leadership.

Business model	Supplier of unique products one-off customization			System provider mass customization		Mass product supplier mass production
Type of fabrication	Single fabrication			Production based on platform or module systems		Mass production
Products	Individual system			Building system	Partial systems	Mass product elements
Product examples	Individual building	Individual building	Individual building system with system elements	Individual building system	Individual system windows	Brickwork, profiles
System	Single fabrication	Single fabrication	Single fabrication	System-specific single fabrication	System-specific single fabrication	Mass system
Processes	Product-specific	Cross-project standardization of processes	Cross-project standardization of processes	Cross-project standardization of processes	High degree of cross-project standardization of processes	Highest degree of cross-project standardization of processes
Partial elements	individual	adapted to a specific project	Project-specific standardization of elements/ modules	System-specific standardization of elements/modules	System-specific standardization of elements/modules	Highest degree of standardization
Number of partial systems	single	single	low/medium	medium	high	very high
Influence on design	Client					Manufacturer
Industrialization potential	low					high
Variability in the design of individual products	high					low
Process streamlining and standardization	low					high
Cost leadership potential	low					high

Fig. E.4: Specifics of individual business models

Standardisation is best implemented where the parameters are stable and the support and manufacturing processes can also be better standardised. In order to ensure sufficient flexibility in manufacturing while at the same time meeting the individual architectural requirements, the fabrication methods need to be designed along the lines of modular or platform systems. Both require the prefabrication of components.

4 Conclusions

In the construction industry the strategy field above and beyond Porter´s market oriented strategies of cost leadership, focus strategy and differentiation is the mass customisation approach as a resource based strategy option. The strategy of mass customisation has four different goal levels, the cost level, the differentiation level, the relationship level and scope. All strategies chosen in the construction industries must focus on the clients' requirements of individual but valuable solutions. Production-related adaptability and use-related adaptability are the key functions in the design adaptability of any industrialisation in construction. These functions must balance standardisation, rationalisation and prefabrication to maximise the value for the client and by doing this increasing the competitiveness.

5 References

Girmscheid, G. (2006) Strategisches Bauunternehmensmanagement: Prozess-orientiertes integriertes Management für Unternehmen in der Bauwirtschaft. Springer-Verlag, Berlin

Piller, F.T. (1998) Kundenindividuelle Massenproduktion: Die Wettbewerbsstrategie der Zukunft. Carl Hanser Verlag, Wien, München

Piller, F.T. (2003) Mass Customization und Kundenintegration: Neue Wege zum innovativen Produkt. Symposion Publishing GmbH, Düsseldorf

Pine II, B.J. (1993) Mass Customization, The New Frontier in Business Competition. Harvard Business School Press, Boston, Massachusetts

Porter, M. (1999) Wettbewerbsstrategie, Methoden zur Analyse von Branchen und Konkurrenten. Campus-Verlag, Frankfurt (Main)

F) Two-dimensional Cooperation Network for System Precast Construction


DAVID LUNZE[1] & GERHARD GIRMSCHEID[2]

1 Introduction

Due to the structural change and the globalisation of the construction markets (Russig et al., 1996) in reaction to the tense earnings situation of the construction industry, both in German-speaking countries and internationally, both construction engineering practice and research are striving to industrialise construction production processes (Girmscheid, 2005a, Bärthel, 2002). In the field of building construction, these efforts at industrialisation are causing a renaissance of precast reinforced concrete elements, modules and composite systems (Zürcher Hochschule Winterthur (Hrsg.), 2002), based, above all, on improved materials technology (Jachmich, 2001) and efficient production processes (Girmscheid, 2000, Ballard et al., 2003). Although the method of construction with precast concrete elements is used to focus primarily on the low-cost and rapid "serial production" of affordable housing (Bongers, 1998), the potential for manufacturing individual buildings with individual shapes and functions and made from individual materials but using precast elements, modules and composite systems has meanwhile been recognised (SwissBeton (Hrsg.), 2004). Because of the lack of established and suitable market instruments, the industrialisation potential of pre-fabrication has, so far, not been sufficiently exploited in practice.

The construction industry is increasingly seeing the opportunities offered by partnerships and cooperations as a means of synergetically exploiting not only tangible, but also intangible resources, in a competitive market (Girmscheid, 2005b). The principal architecture of such partnerships and cooperations for forming strategic networks (Sydow, 1993), enhancing each company's own specific competencies (Friedli, 2000) and the utilisation of marketing and sales synergies (Maier, 2002) are part of the research being conducted by neighbouring disciplines, such as economics or business management.

Cooperative distribution systems as an instrument of growth for SMEs have so far scarcely been able to gain a foothold in both the national and international construction industry (Watson and Kirby,

[1] Dipl.-Ing., Chair of Construction Process and Enterprise Management, Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3370, Fax +41 44 633 1088, lunze@ibb.baug.ethz.ch

[2] Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch

2000), since the idea of selling construction services right through to the client will only generally gain ground once customer orientation has been established. The ancillary construction trades are showing first signs of cooperative sales forms (Dornach, 2004). In this case the ambivalently structured construction market with its strongly local or in other cases supraregional markets is used for cooperative networks to distribute products and services efficiently and profitably.

Embedded into the presented scientific environment, the following issues have been identified:

- Outsourcing services that are not part of the construction company's core competencies is increasing in the construction industry. The research examines the reasons for the lack of a suitable form of cooperation that transfers the diametrical interests of the partners into a win-win situation.
- There is only a latent motivation to cooperate in the construction industry. The research takes the differing expectations of potential partners into consideration when developing suitable incentive systems that would allow them to perceive acting in cooperation as a win-win situation.
- Based on the findings of the aforementioned issues, the two-dimensional cooperation structure with its associated, necessary system or cooperation partners will be developed, and the interactive, integrated process and organisational structures that are needed will be derived.

The cooperative business model with its two-dimensional cooperation network will substantially contribute towards achieving the economic goals of the cooperation partners:

- Increase in sales by increasing the market share of precast concrete elements in the considered market segment "individually designed single-family and multi-family homes"
- Increase in profits from offering customer-oriented system services with unique selling propositions that set them clearly apart from the services and products offered by the competition

2 Research Methodology

The constructivist research paradigm and methods of qualitative and quantitative social research will be primarily used to reveal findings relating to the issues mentioned in the introduction. In addition, the logical models and empirical results will be validated and rehabilitated using a theoretical reference framework. The research methodology is based on Yin (1994), Mayring (1999), Stier (1999) and Girmscheid (2004).

The economic and organisational parameters required for the two-dimensional cooperation network will be identified by adopting the interpretavistic research approach using qualitative expert interviews and quantitative empirical studies. On the basis of this, the logical-deductive business model is being developed by applying the constructivist research approach, give it a theory-based structure by applying the theory of structuration (Giddens, 1985) and respectively the principle-agent theory and test its academic quality by means of triangulation.

3 System Prefabrication Business Model

The fundamental structure of the system prefabrication business model comprises the two cooperation dimensions within which the players needed to successfully establish this method of prefabrication cooperate in the form of a strategic partnership. In the case of the business model outlined here, this cooperation focuses on the construction market segments for individually designed, integrated precast modules (e.g. prefabricated bathrooms and dormers) and precast systems for single-family and multi-family homes (SFH/MFH)). The initiative to form strategic partnerships in the two cooperation dimensions, which will be described in more detail later, stems from a manufacturer of precast elements, whose strategic interest centers on the integration of the competencies needed for the system service. In return, the cooperation partners involved in the two cooperation dimensions benefit from the market-strategic potential of the cooperation networks, which only arises through the strategic cooperation and with the help of innovative precast technologies that enable the manufacturers of precast elements to prefabricate virtually any element independently of serial production (mass customisation).

The core organisation is formed by the system- and plant production-oriented cooperation (1st cooperation dimension) consisting of the manufacturer of precast elements, the system architect and electrical and HVAC companies as a focal organisation. This focal system and plant production organisation is organisationally linked in a kind of franchising system to the supraregional, locally focused sales- and assembly-oriented cooperation network (2nd cooperation dimension). The system competency that is cooperatively integrated into such a cooperation structure is passed on to the locally sales- and assembly-oriented cooperation network (2nd cooperation dimension) (e.g. via a licensing agreement).

The locally operating sales- and assembly-oriented cooperation network, which involves the local architect and the necessary players for construction site preparation, assembly and fitting (construction entrepreneur, electrical and HVAC companies), can use its proximity to the customers and the ensuing trust to efficiently market the system service. The organisational link to the first cooperation dimension is institutionalised by means of a focal company "Building construction system service". The cooperation partners from the local sales- and assembly-oriented cooperation network are organisationally linked to the focal system and production cooperation due to a franchising organisational structure. The client benefits from the advantages of prefabrication (defined manufacturing conditions/high level of finishing quality, efficient processes for building the structure/shorter delivery times, lower financing/investment costs) without having to relinquish his desire for an individual building, while at the same time receiving this system service from a single source. This approach enables the cooperation partners to achieve the customer-oriented strategic goals mentioned above.

3.1 System- and Production-oriented Cooperation Network

The focal system- and plant production-oriented cooperation network integrates the competencies needed to develop and produce an individual, customer-oriented system service (Fig. F.1). It comprises a manufacturer of precast elements and the system architect, who cooperates with the fastening technology company, (partial) system suppliers and planning experts to plan the prefabrication.

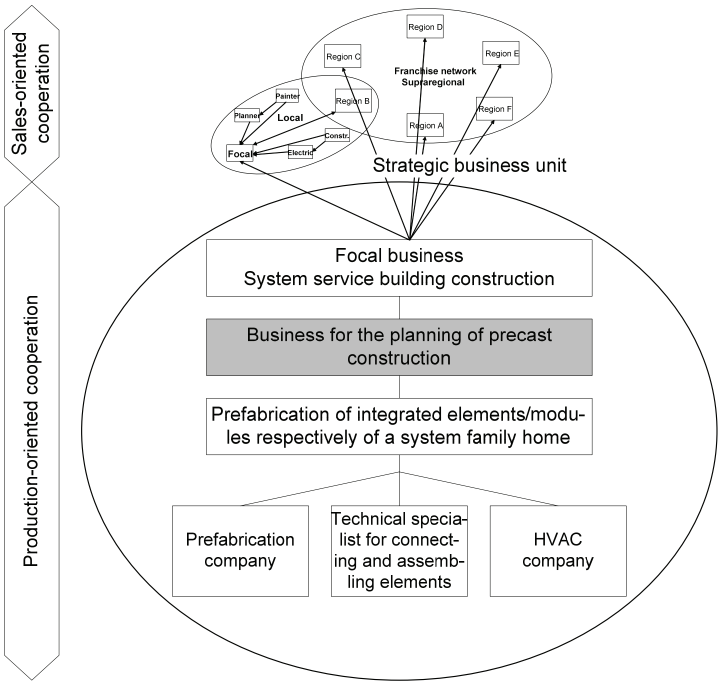


Fig. F.1: 1. Cooperation dimension – System- and production-oriented cooperation network

The focal system- and plant production-oriented cooperation network provides the following output:

- the technical and creative design of the system concept
- a suitable supraregional marketing concept to support the distribution of the system concept
- technological planning competency for the customer-oriented individualisation of the system concept in the form of precast planning consulting, check lists, internet based customer design planning tools and other planning tools to support the use of precast systems, modules and elements
- a suitable incentive system to control the synergetic business interests and competencies of the involved partners in a target-oriented fashion

3.2 Sales- and Assembly-oriented Cooperation Network

The sales- and assembly-oriented cooperation network provides the expertise for distributing and assembling the system. It is comprised of a local architect, who is responsible for the individual, customer-oriented architectural and functional design, a local construction company to prepare the building site, excavate, build the foundations and assemble the precast elements, and a local electrical and HVAC company to finish the installations (Fig. F.2). Additional necessary services will be carried out by subcontractors. The sales- and assembly-oriented cooperation network provides the following contributions towards successfully establishing the business model in local markets:

- detailed knowledge of local market structures in the segment of SFHs and MFHs
- established informal local networks for acquiring suitable cooperation partners
- comfortable market access for acquiring potential clients
- operative tasks relating to preparation, assembly, commissioning and warranty works.

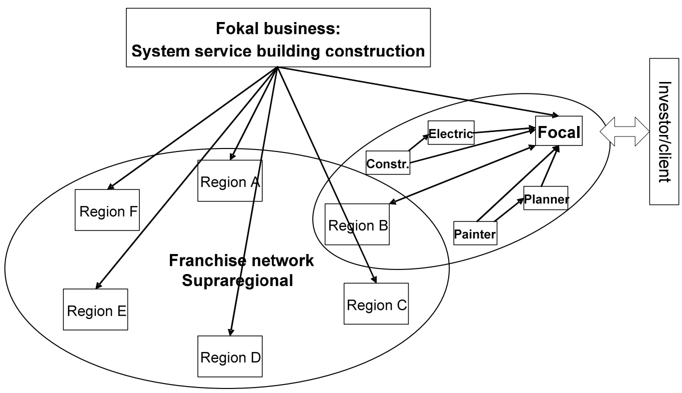


Fig. F.2: 2. Cooperation dimension – Sales- and assembly-oriented cooperation network

4 Conclusions

The business model presented here comprises the production- and sales-oriented cooperation concept to develop and penetrate the local housing market with mass customised precast houses. The structure of the business and management concept is to develop the virtually individualised service offering for customers, and the marketing of the overall product as a one-stop service and warranty. The core of the business model for mass customised precast houses is the two-dimensional cooperation network comprised of:

- focal system- and plant production-oriented cooperation among the system architect and companies to develop and produce an individualised, customer-oriented system service
- locally focused sales- and assembly-oriented cooperation among local/regional/supraregional partners to ensure proximity to the customers and exploitation of local connections

The partners involved in the cooperation networks are given the unique opportunity of sustainably increasing their sales through the specific use of mass customised precast (partial) systems, modules and elements that are tailored to the needs of potential clients in the market segment of single-family and multi-family home construction, and of consequently improving the capacity utilisation of their company resources. These results in a reduction of the specific overheads relating to a project, and companies have a better chance of obtaining an improved, positive project or operating profit. In addition, mass customised prefabrication allows the participating companies to reduce their non-value adding work hours by producing in a defined local manufacturing environment and, in doing so, to generate much higher profit margins.

Clients obtain the commercial benefit of the business model from the efficient delivery of the building or facility within a considerably reduced construction time, since the building is then available for utilisation much earlier, allowing, for example, a reduction in financing costs. In addition, clients benefit from the quality advantages in terms of less material and production variation and qualitatively optimised standard details and construction elements (learning system concept).

5 References

BALLARD, G., HARPER, N. & ZABELLE, T. (2003) Learning to see work flow: an application of lean concepts to precast concrete fabrication. *Engineering, Construction and Architectural Management,* 10**,** 6-14.

BÄRTHEL, J. (2002) *Industrielles Bauen Leitfaden für KMU-Geschäftsführer,* Zürich, Vdf Hochschulverlag AG an der ETH.

BOENERT, L. & BLÖMEKE, M. (2003) Logistikkonzepte im Schlüsselfertigbau zur Erhöhung der Kostenführerschaft. *Bauingenieur,* 78**,** 277-283.

BONGERS, I. (1998) Europa-Haus - Vorfertigung als Wohnungsbau der Zukunft. *BFT Betonwerk + Fertigteil-Technik, Concrete Plant + Precast Technology,* 63**,** S.31-36.

DORNACH, B. W. (2004) Geld verdienen mit (Franchise-)System. Mega-Trend: McDonaldisierung im Handwerk. *sbz Sanitär-, Heizungs-, Klima- und Klempnertechnik,* 59**,** S.50-53 (3 S.).

FRIEDLI, T. (2000) *Die Architektur von Kooperationen; HSG Disss. 2407,* Bamberg, Hochschule St. Gallen (HSG).

GIDDENS, A. (1985) *The constitution of society: Outline of the theory of structuration,* Cambridge, Polity Press.

GIRMSCHEID, G. (2000) *Herausforderungen und Perspektiven für das Bauingenieurwesen. Baumagement der Zukunft - Neue Chancen nutzen oder auf alte Rezepte bauen?*

GIRMSCHEID, G. (2004) *Forschungsmethodik in den Baubetriebswissenschaften,* Zürich, Eigenverlag des IBB an der ETH Zürich.

GIRMSCHEID, G. (2005a) Industrialization in Construction – Product Technology of Management Concept? *Proc. 11th Joint CIB Int'l Symposium "Combining Forces".* Helsinki, Finland, 13-16 June 2005, section VI.

GIRMSCHEID, G. (2005b) Partnerschaften und Kooperationen in der Bauwirtschaft - Chance oder Irrweg? *Bauingenieur,* 80**,** S.103-113.

JACHMICH, W. (2001) Elementierte Planelemente aus Leichtbeton für den Wohnungsbau. *BFT Betonwerk + Fertigteil-Technik, Concrete Plant + Precast Technology,* 67**,** S.128-130.

MAIER, H.-D. (2002) *Marketingorientierte Kooperationsmodelle für kleine und mittelständische Unternehmen in der Bauwirtschaft; HSG Diss. 2589,* Bamberg, Hochschule St. Gallen (HSG).

MAYRING, P. (1999) *Einführung in die qualitative Sozialforschung eine Anleitung zu qualitativem Denken,* Weinheim, Beltz-Psychologie Verlags Union.

NARDI, G. (1997) *Angelo Mangiarotti,* Rimini, Maggioli Editore.

RUSSIG, V., DEUTSCH, S., SPILLNER, A., POPPY, W. & GREFERMANN, K. (1996) *Branchenbild Bauwirtschaft Entwicklung und Lage des Baugewerbes sowie Einflussgrössen und Perspektiven der Bautätigkeit in Deutschland,* Berlin, Duncker & Humblot.

STIER, W. (1999) *Empirische Forschungsmethoden,* Berlin etc., Springer.

SWISSBETON (HRSG.) (2004) *Handbuch für Planung und Entwurf von Betonfertigteilbauten,* Gütersloh, Bauverlag BV.

SYDOW, J. (1993) *Strategische Netzwerke Evolution und Organisation,* Wiesbaden, Gabler.

WATSON, A. & KIRBY, D. A. (2000) Explanations of the decision to franchise in a non-traditional franchise sector: the case of the UK construction industry. *Journal of Small Business and Enterprise Development,* 7**,** 343-351.

YIN, R. K. (1994) *Case study research design and methods,* Thousand Oaks etc., SAGE publications.

ZÜRCHER HOCHSCHULE WINTERTHUR & BRÄM, M. (2002) *Konstruktives Entwerfen mit Betonelementen,* Winterthur, Zürcher Hochschule Winterthur.

ZÜRCHER HOCHSCHULE WINTERTHUR (HRSG.) (2002) *Konstruktives Entwerfen mit Betonelementen,* Winterthur, Zürcher Hochschule Winterthur.

CHAPTER III:
PRODUCTION METHODS AND TOOLS FOR INDUSTRIALISATION

The methods and tools already available to help industrialisation in the construction sector a step forward are numerous. They vary from robotizing of traditional craftwork to completely new techniques especially designed for application in industrialised construction.

Prof. Thomas Bock from Munich University performed a number of inventories of automated tools for traditional work. We include three of his papers. One on brick laying, another on precast concrete elements and a third one on wooden elements. Prof. Alistair Gibb from Loughborough made his inventory at the other end of the spectrum. He reports on completely new methods and even futuristic tools such as 3-dimensional printers and Contour Crafting.

Industrialisation is expected to solve problems inherent to traditional construction such as occupational health issues and waste generation, but it also causes new problems typical for industrialised construction such as a need for standardised measurements methods and the observation of strict tolerances for prefabricated components, produced by a variety of suppliers. Anne Landin from Lund University reports on the demands on the tolerances when industrialising the construction sector.

Another constraint to industrialisation is the lack of suitable IT-technology and the reluctance among the labour force to adapt emerging IT-technology. Frits Scheublin – from Eindhoven University of Technology – investigated the available IT-tools and their acceptation.

In the last paper in this chapter Thomas Bock reports on the state of the art in robotics for construction. Especially robotic for high rise construction is discussed. Apart from construction tasks also the developments in robotic deconstruction was inventoried.

A) Applying Future Industrialised Processes to Construction

R.A. BUSWELL[1], A.G.F. GIBB[2],
S.A. AUSTIN[3] AND A. THORPE[4]

1 Introduction

In the manufacturing sector, automation using industrial robots and machines that used direct numerical control took hold in the 1960s. The development of microprocessors delivered computer numerical control in the 1970s and the IT revolution in the 1980s brought computer aided design software. In the 1990s advanced parametric modelling was introduced and the industry has enjoyed the development of the integration of design and analysis tools and machine control. All these technologies can be found in construction (Howe, 2000; Kolarevic, 2003; Schodek, 2005). The introduction of CAD/CAM for the creation of large structural components for freeform buildings is driving the development of digital manufacturing technologies for construction. However, cutting edge designs for buildings are becoming increasingly unrealisable using the current state-of-the-art methods - new processes are required (Egan, 1998; European Construction Technology Platform 2005). The control of material placement and reducing the number and quantity of materials will play a key role. The manufacturing sector is turning to Rapid Manufacturing (RM) for solutions, especially for the production of highly personalised products (Invisalign, 2006). The construction industry is waking up to the potential that automated additive technologies offer for solving these problems. Ultimately, it is feasible that such new processes will drive down the cost of existing construction, while raising the bar of achievable construction design solutions. New technologies are most likely to find niche applications initially and will eventually filter down to the domestic sector; exemplified by the Tunnelform system (The Concrete Centre, 2004).

Over the last ten years there have been attempts to selectively bond sand and cement to create freeform structures from traditional building materials (Pegna, 1997). RM has developed large mould making processes (The American Foundry Society, 2005) and the first viable large-scale freeform process for construction, Contour Crafting (CC), has been demonstrated in the laboratory at the

1 BEng, PhD, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 223783, r.a.buswell@lboro.ac.uk
2 PhD BSc CEng MICE MCIOB, Professor of Construction Engineering Management, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 223097, a.g.gibb@lboro.ac.uk
3 BSc PhD CEng MICE, Professor of Structural Engineering, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 222608, s.a.austin@lboro.ac.uk
4 CEng CITP BSc MSc PhD FICE FBCS FCIOB FRICS MIMgt, Professor of Construction IT, Department of Civil & Building Engineering, Loughborough University, UK, Phone +44 (0)1509 223771, a.thorpe@lboro.ac.uk

University of Southern California (Khoshnevis, 2002). Khoshnevis is pushing for the commercialisation of this process in the US. It is capable of producing full scale, freeform wall structures that would replace the structural concrete block wall similar to that found in UK house construction.

Contour Crafting, however, cannot take full advantage the extended functionality that can be embedded within the wall structure if the principles demonstrated by existing RM processes are applied. Precise control of very small volumes of build material would allow the wall to be constructed, ground up, with all the internal pipework, conduits and channels in place, removing structurally redundant material. The implications of such an approach would lead to: clever design solutions using geometric freedom; a smaller number of build materials and a reduction in the material resource required for construction process; simplify on-site operations with a reduction in complex trade coordination; force the resolution of interface issues, hence reducing part count. Design would be complete up front and would mean that the structure could be designed to be more easily disassembled and recycled at the end of life. In addition, the acoustic, permeability and thermal characteristics can also be modified by ‘printing’ appropriate, optimised geometry (Buswell, 2006).

A concept domestic wall structure, designed using Freeform Construction principles is depicted in Fig. A.1.

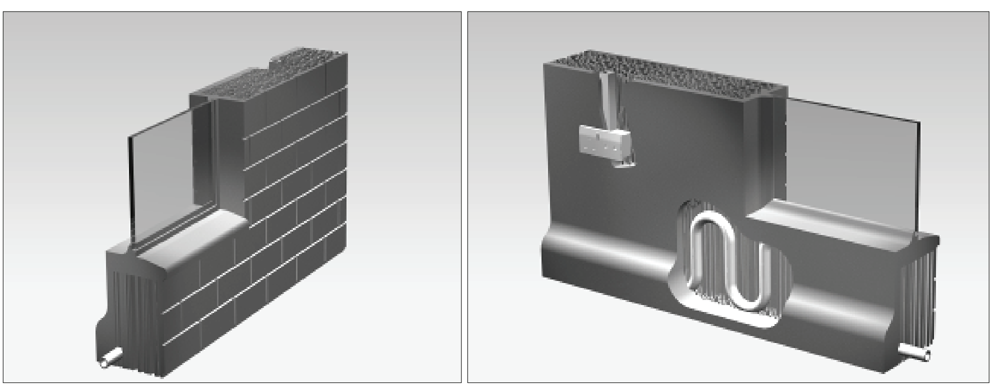


Fig. A.1: A concept application for Freeform Construction – 'WonderWall'.

New UK research at Loughborough University, is developing a process capable of delivering the concept ‘Wonderwall’ at full scale. This paper gives details on additive processes and a discussion of the differences between traditional and Freeform Construction is given as background information. The issues surrounding design practice, design tools, and data and information protocols are highlighted.

2 Additive Technologies

There are a family of names used to describe essentially the same type of fabrication technology; Additive Manufacturing, Rapid Manufacturing, Rapid Prototyping and Solid Freeform Fabrication. This method of making physical components is delivered by many types of process; Thermojet, Selective Laser Sintering (SLS), Stereolithography (SLA), 3D printing (3DP), Fuse Deposition Modelling (FDM), are a few (Wohlers, 2004). Typically each of the processes can use a range of materials and all have advantages and disadvantages, suiting them to particular tasks. They all work 'print' 3D structures typically up to 500mm in the *x*, *y* and *z* directions. A design is usually created using 3D CAD solid modelling. A model is first tessellated in much the same way as a Finite Element Analysis mesh is generated then sliced into layers according the specific machine parameters. Each slice is sent to a machine. The machine builds the component by sequentially creating and bonding each layer to its predecessor to reproduce the 3D artefact. Applications vary and can be found in the literature and on the web sties of companies offering Rapid Manufacturing services. A good source of further reading can be found at Castle Island (2006). Many classification methods exist for current RM processes. Application descriptions of common RM processes are offered here for discussion of the differences of these in a construction context. Parallels are drawn between these process, traditional construction methods and both existing and conceptual Freeform Construction technologies.

2.1 Comparison of Additive Process

Fig. A.2 depicts the process of slicing the CAD model and gives diagrams illustrating the principle features of mentioned processes. Each works on a layer-by-layer basis. The SLA and SLS processes employ a laser; the latter cures a liquid photo-sensitive resin, the former uses the laser to melt a small area of powdered material that then sets to form a solid. The surface finish and fine-ness of detail is dependent on the material properties and the width and intensity of the laser. The laser 'rasters' across the build area with a fine laser. To speed up the build process, both processes outline the solid/liquid or powder boundary on each layer with a fine laser beam profile and then 'fill in' the area with a de-focussed laser or open hatching strategy. As with any process, control of operating parameters is crucial for a successful build. SLS requires a balance of laser intensity, traverse speed penetration and time required to either melt or sinter powder particles into a solid. These parameters are similar with SLA but the phase change mechanism is different. Even when these parameters are tightly controlled, issues arise. For example; the heat generated during the sintering process leaves solidified components embedded in a hot but loose powder 'cake'. If broken open too soon then thermal distortion will affect dimensional tolerances. Table A.1 compares the various processes.

The 'drop-on-demand' processes of 3DP and multi-jet deposition epitomise the idea of three dimensional printing. All employ raster based deposition of either phase change build materials or binder systems onto powders and use standard inkjet printer technologies (both PZT and bubble). Fused Deposition Modelling (FDM) refers to a family of processes which extrude a range of thermoplastic polymers to build up a component in much the same way squeezing a tube of toothpaste would.

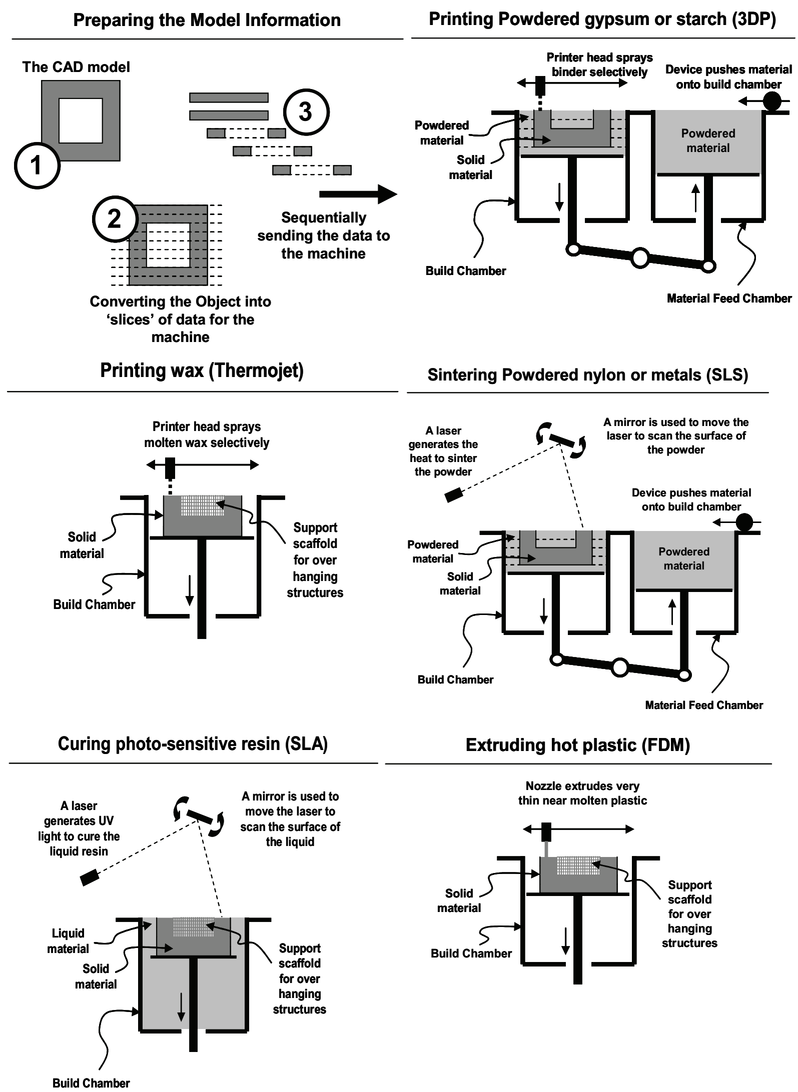


Fig. A.2: Diagrams depicting several of the most commonly used Rapid prototyping processes.

Table A.1: summarises the similarities and differences between the mentioned processes.

		3DP	SLA	SLS	ThermoJet	FDM	CC
Support Strategy	Placement of permanent lintel						■
	Second material					■	
	Scaffold system		■		■	■	
	Powder cake	■		■			
	Self supporting capability		■		■		
Material Delivery	Vat	■	■	■			
	Through deposition device				■	■	■
Phase Change	Thermo set				■	■	
	Curing						■
	Laser melting			■			
	Binding	■					
	Light activated		■				
Post Processing	Removal of scaffold		■		■	■	
	Removal from powder cake	■		■			
	Surface curing (liquid systems)		■				
	Infiltration (part strengthening)	■					
	Surface finishing (scaffold attach)		■		■		
Feature size	Very Fine (< 0.01mm)		■				
	Good (< 0.1mm)			■	■		
	Reasonable (< 1.0mm)	■				■	
	Construction (>19.0mm)						■

Rapid Manufacturing machines are designed to build miniature, hand held and desktop sized items. A site based construction process is unlikely to use a laser augmented approach (SLA/SLS). In addition, the 'vat of material' approach is unattractive, because of the impractical issues associated with post-processing what would be very large components (SLS/3DP). This leaves processes that deposit material through a deposition device (Thermojet/FDM). A key point is that as you increase the build scale, the volume flow of material will force the design of a new process; it cannot simply be scaled up.

For build sizes in the order of 1mm →10mm, the build material can be deposited by a printer head and still maintain a reasonable build speed. Using the printer head to control deposition of a curable liquid allows incredibly fine feature sizes, up to 600dpi (Objet Geometries, 2006). Between part sizes on the scale of 10mm→100mm it can be cost effective to use a matrix material that has a larger particle size; the ZCorp 3DP process uses powdered gypsum (Z Corp 2006). Instead of passing the build material through the printer head, only a liquid binder is deposited which binds the matrix material. The volume of liquid passed through the head is a fraction of the part volume and hence the build speed is maintained. Larger processes (100→1000mm) cannot get enough binder through a printer head and so only print a curing agent onto a matrix material pre coated with an epoxy based compound (Prometal 2006).

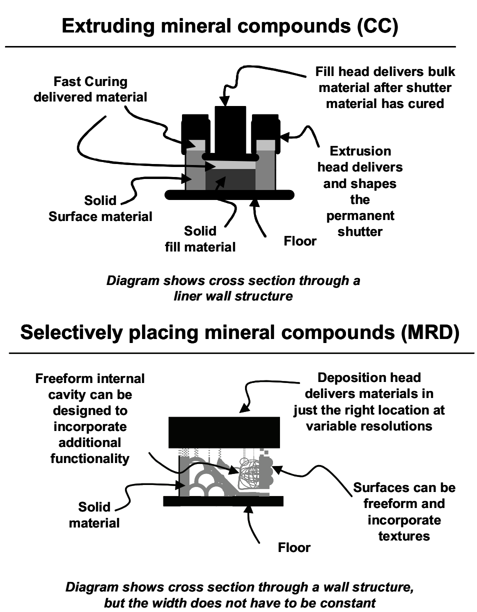


Fig. A.3: Diagrams of existing and conceptual Freeform Construction processes.

For conceptual larger scale parts, say 1000→10000mm, a special (non-existent) agent would be required so that minute quantities could be used to reduce the print volume flow.

2.2 Additive Processes for Construction

The top diagram in Fig. A.3 depicts the Contour Crafting process and the process features are in Table A.1. Contour Crafting has been tailored for the production of domestic housing wall components. The intention is that a large gantry system will be able to ‘print’ the entire structure for a house. The process has been demonstrated to produce large structures in the order of 3m long by 1m high by 0.1m wide. This volume is many times that of the conventional RM processes. In order to deliver these volumes of material an extrusion and back fill approach has been adopted: An inner and outer 'skin' is extruded (~19 by 19mm) and forms a permanent shutter. The machine then backfills with a bulk compound similar to concrete. One of the key issues is how the build material maintains its desired form once it is deposited while it is curing: Contour Crafting uses thixotropic materials with rapid curing and low shrinkage characteristics. The process avoids post-processing by depositing the material using similar principles as the Thermojet technique. So far the process has not been developed to handle overhanging sections, although the strategy for creating openings for doors and windows will be affected by robotic placement of lintels that the deposition head can build off.

The shutter extrusion dimensions limits the feature size that can be created and the process is given to producing long, thin walls that can be curved arbitrarily. The surface finish is towelled as part of the process and can achieve very high degrees of smoothness. The practical wall system that the Contour Crafted structure would be a part of, would also need to be clad, insulated, finished internally, have doors and windows fitted and mechanical and electrical services, etc. added to it. Currently the intent is to leave out sections of the wall as it is ‘printed’ and post fit services modules that could be either accessible from the outside (flush with the surface), or internal, being built into the wall.

Contour Crafting represents the first generation of Freeform Construction processes. The next generation of technologies will be capable of printing at variable resolutions. A Multi-Resolution Deposition (MRD) device is depicted at the bottom of Fig. A.3. MRD will build objects at comparable scales and speeds to Contour Crafting, but will be capable of fine detailing that gives RM technologies their strength. The likely specification and process features will be:

- mineral based compounds (cost);
- selective deposition of material (minimising post processing);
- feature size down to ~1mm (control of surface texture);
- variable deposition resolution (high speed fill in);
- material shape holding (allow additional layers while curing);
- high degree of self-supporting features (minimises post processing);
- inclusion of internal voids and channels (adding value through function);
- varying material properties through additives (e.g. for moisture control);
- more freeform surfaces (greater design freedom for free); and,
- more reliable build time and precise tolerances (machine control).

3 Implications for Construction Design

The MRD Freeform Construction process has been defined. This section discusses implications for construction design and issues associated with design process and information handling. A conventional UK domestic dwelling wall is cited here to highlight differences with the concept wall depicted in Fig. A.1. This wall might comprise (typically, from the inside out): 3mm coat of finishing plaster to create a hard smooth finish; 12mm render to remove imperfections from the block work in preparation for the finishing plaster; 100mm load bearing concrete block wall bedded using a sand cement mortar; 50mm cavity filled with an insulation e.g. glass fibre; 100mm clay brick bedded in mortar, tied to the internal leaf with steel ties.

There are 8 materials listed here and typically 2 trades required to erect and finish the wall; the brick layer and plasterer. A complete ‘fully functioning’ wall could include timber and glass for the doors and windows, employing a combination of glaziers and joiners; a joiner would also finish the wall with timber skirting boards and sills; plastic conduit for electrical wiring, usually embedded beneath the plaster, requiring an electrician and labourer; pipe work and panelled heating devices, usually surface fixed by a plumber. The design now uses nearer 13 materials and 7 trades. In addition, damp-proofing introduces another material and openings in the structure require lintels and usually some sort of temporary former, made in timber, to guide the brickwork. Scaffold is needed to elevate the site operatives to access higher sections of the wall safely. The design becomes a complicated series of interface resolution issues: Damp proofing location and draining round windows; closing cavities; lintel placement; cutting bricks for openings and defining space; weatherproofing round windows and doors.

The MRD process would aim to handle many of these issues with a single operation, utilising reduced numbers of materials. In the example given, this process would replace the original 13 materials with 5; the primary build material, glass, a framing material, probably an insulating material and some additive to the primary material for moisture control. In addition, the thermal performance could be enhanced (Buswell, 2006) and material resource could be minimised by simply not printing structurally redundant sections; and there could be more variation in design because it takes no more effort or expense to print a curved section that it does a straight one. The only costs are; design time, machine setup and run time and material consumption. It is also likely that self supporting structures like arches will be employed to form openings which would reduce the requirement for post processing. Glazing these can be achieved using well established CAM/CAD and CNC technologies. This affects the design of space and form and would mean more client choice and greater use of freeform surfaces.

Designing functionality into the interior of the wall is the real benefit. Designers, architects and engineers would be required to rethink how performance can be achieved and enhanced using solutions based on geometry; using a single material to realise the design goals. The process would need to be integrated and increased use of automated optimisation to derive design solutions would become more likely. In order to achieve this, it is conceivable that CAD software tailored for Freeform Construction design would design rules. These constraints would ensure that the designed structures could be successfully built within the process operating parameters. A process like MRD simplifies the elemental operations to achieve a construction component and limits material options.

The key is that functionality is not compromised, just realised in a different way. By simplifying the elemental operations of the construction process, building design criteria and optimisation routines into such software are realisable and therefore greater design variety is afforded with a single process.

3.1 Implications for Design Process

The design process for a part produced using RM and construction are similar. Table A.2 highlights this, comparing RM, construction and MRD design process. All three processes describe how to make a physical object and the stages for all are similar. The actual operations and the way in which information is transferred are different. The real difference between traditional construction design process and that used by MRD is how the building information is gathered, stored and utilised. Traditional approaches typically use an 'over-the-wall' approach between design experts. The MRD approach will require simultaneous design because the design of the material placement will affect the integration of structure, function and services while having to satisfy the desired outer form. It is possible that the outside form could be determined by the wall internal structure and the space requirements, rather than working the space design and services integration around a given wall shape.

Table A.2: Design process comparison between Rapid Manufacturing, Freeform Construction and traditional construction.

Rapid Manufacturing	MRD Construction	Traditional construction
Specification and brief	Specification and brief	Specification and brief
Concept and ideas	Concept and ideas	Concept and ideas
CAD model	CAD model	Design
STL conversion	STL conversion	Drawing production
STL testing (buildability)	STL testing (buildability)	Analysis of site programme
STL Slicing	STL Slicing	Temporary works
Fabrication	Fabrication	Build
Post processing	Post processing	Remove temporary works
Assembly with system	2nd & 3rd fix	2nd & 3rd fix

3.2 Implications for Information and ICT

The MRD process will require a digital representation of the component to be built and assumption here is that this will be a 3D solid CAD model. The control of RM machines often uses a the common interface Standard Triangulation Language (STL) file format. STL describes a faceted surface representation of the CAD model. Each triangle has a normal associated with it that indicates which face in 'inside' the component. Simply, the original CAD model is a geometric representation of a shape that defines what is solid and what is not. The format only carries the object information and is not capable of carrying other information, such as *how* to build it. This can be important because the layers created in the vertical direction during a part build in RM can result in non-uniform part material properties, which can be undesirable. The debate over standards continues in the manufacturing sector and the suitability for MRD has yet to be established. Likely issues include:

- size of data required to define large structures;
- quality of representation of surfaces;
- how to handle multiple materials;
- the transition from 2D to solid 3D modelling;
- the effort in design and analysis;
- machine control;
- build information;
- distribution of build 'knowledge' to machine;
- interfacing with existing design tools; and,
- units and tolerances and repeatability.

4 Conclusions

Automating construction will deliver benefits as has been demonstrated in the manufacturing sector. There are two options, one of which is to automate human processes. This approach is flawed for all except very specific tasks because encoding the complexity of handling materials coupled with the highly complex decision making process exhibited by craftsmen is difficult. The second option is to simplify the elemental operations controlled by the computer (Pegna, 1997). Many of these simple operations can be carried out in such a way as to produce a very complex product. This is the essence of Rapid Manufacturing and why the process is so suited to the construction automation issue.

The industry will have to rethink how components are designed to maximise the benefit that a process such as MRD can deliver. The design process will be computer based which is a goal the industry is already moving towards. The MRD device is the focus of ongoing research at Loughborough University.

5 References

Buswell, R.A., Soar, R.C., Thorpe, A. & Gibb, A.G.F., 2007, Freeform Construction: Mega-scale Rapid manufacturing for Construction. In Automation in Construction, vol. 16, no. 2, 222-229.

Castle Island, 2006, 7/6/06-last update, Castle Island's Worldwide Guide to Rapid Prototyping [Homepage of Castle Island Co.], [Online]. Available: http://home.att.net/~castleisland/ [2006, 21/6/06] .

Egan, J., 1998, Rethinking Construction, Department of the Environment, London.

European Construction Technology Platform, 2005, Strategic Research Agenda for the European Construction Sector: Achieving a sustainable and competitive construction sector by 2030, European Construction Technology Platform, www.ectp.org.

Howe, S. 2000, Designing for automated construction. In Automation in Construction, vol. 9, 259-276.

Invisalign, 2006, Invisalign home page [Online]. Available: www.invisalign.com/generalapp/gb/en/ [2006, 03/21] .

Khoshnevis, B., 2002, Automated Construction by Contour Crafting: Related Robotics and Information Sciences. In Automation in Construction Special Issue: The best of ISARC 2002, vol. 13, no. 1, 2-9.

Kolarevic, B., 2003, Architecture in the Digital Age: Design and Manufacturing, New York & London: Spon Press - Taylor & Francis Group.

Objet Geometries Ltd. 2006, Objet Home page. Available: www.2objet.com/ [2006, 06/23] .

Pegna, J., 1997, Exploratory investigation of solid freeform construction. In Automation in Construction, vol. 5, no. 5, 427-437.

Prometal, 2006, Prometal Home page. Available: www.prometal-rt.com [2006, 06/23] .

Schodek, D., Bechthold, M., Griggs, K., Kao, k. & Steinberg, M., 2005, Digital Design and manufacturing: CAD/CAM Applications in Architecture and Design, First edn, Wiley and Sons, Hoboken, New Jersey.

The American Foundry Society, Modern Casting [Online]. Available:
http://www.moderncasting.com/archive/ProductInnos/2005/Prod_099_01.asp [2006, 03/21] .

The Concrete Centre 2004, High Performance Buildings: Using Tunnel Form Concrete Construction, The Concrete Centre, Camberley, Surrey, UK.

Wohlers, T. 2004, Rapid Prototyping, Tooling & Manufacturing: State of the Industry, Wohlers Associates, Colorado, USA.

Z Corp 2006, Z Corp Home Page. Available: www.zcorp.com/ [2006, 06/23].

B) Industrialisation of the Building Construction Industry – From Early Trials to Advanced Computer Integrated Prefabrication of Brickwork

THOMAS BOCK[1] & THOMAS LINNER[2]

1 Actual Stage of Construction Automation of Brickwork

Since the end of the 70’s, due to a lack of apprentices in construction jobs and to an increasing discussion about the high costs of buildings, rationalisation developments in the construction industry have been started. In Europe rationalisation innovation mainly took place in the brickwork and the formwork/concrete sector, where no ready solutions from other countries were available. In Germany and also in other parts of Europe this innovation was supported by the fact, that brickwork has been an often used and loved building material. Due to the availability of this material and also due to climatic factors, a high percentage of building projects in Europe has been and still is constructed with this advantageous building material.

In the last three decades activities to develop machines and automated solutions that support the laying of brickwork have increased. Brickwork layering is a physically hard work, which can lead to severe physical impairment, early retirement and enhanced cost for health insurances and welfare systems in a long-term perspective. Moreover, only a small number of skilled workers able to do high quality brickwork layering are available nowadays. This, in turn, is reflected in ultimately high prices and wages, which make labour intensive brickwork construction rather expensive. In order to summarise the development in the industrialisation of brickwork construction and to give incentives for further approaches, this chapter presents devices and systems which have tried try to rationalise, mechanise/automise and/or robotise brickwork construction. Therefore trials to rationalise industrialise and systemise brickwork construction been divided into four different groups outlining the gradual development:

- Early trials of robotic assembly of modular blocks
- Industrialised Prefabrication (Manufacturing Plants for individually planned brickwork panels)

1 Prof. Dr.-Ing./ Univ. Tokio, Chair for Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.bock@bri.arch.tu-muenchen.de

2 Dipl.-Ing., Scientific Assistant, Building Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.linner@bri.ar.tum.de

- On-site rationalisation by mechanisation (Brickwork handling devices and simple manipulators)
- On site industrialisation by robotics (Masonry robots for customised construction on site)

2 Early Trials of Robotic Assembly of Modular Blocks

One of the basic ideas of Robot Oriented Design (ROD, Bock, 1988) in building construction is to transform and re-design conventional construction processes so that construction systems/components and advanced automation and/or robotic systems can be co-adapted. According to the guidelines of ROD a structural system for the wall erection named SMAS (Solid Material Assembly System) was developed already in the 80's in Japan. The system can be seen as an early trial and a predecessor of more complex systems developed in the 90's in Europe.

2.1 Solid Material Assembly System "SMAS"

SMAS is a reinforced masonry construction method involving both building components and production system. A standard building component of this system, 30cm x 30cm x 18cm in size and 20kg in weight, is made of pre-cast concrete and includes cross-shaped steel bar inside each component for the reinforcement of structural walls. Components are positioned automatically by the robot one by one. Following the positioning of each component, steel bars are connected to those of adjacent components also by the robot. The joint type of steel bar for vertical direction is mechanical, and that for lateral direction is overlapping. Concrete is subsequently grouted from the top of the wall which is erected one story in height (about 3m). The complementary operating hand is fixed to the mother robot (6-articulation-type robot) which had been designed for a wide variety of applications in factory use and a series of experiments for wall erection.

Robot-oriented Construction System and Structural Design

The rapid progress being achieved today in the modernisation and industrialisation of building construction technology has triggered a trend to reduce the complicate works at construction site and to increase building component production in the factory. It is obvious that prefabrication has been successful in up-grading the quality of the buildings and in shortening the construction period. Moreover, sizes of prefabricated building components such as structural members or wall elements are also becoming larger in to simplify and reduce work processes on the construction site.

However, this development is not necessarily advantageous for the introduction of robots on the construction site. Heavy and large components are often difficult to handle by a construction robot and complicated assembly processes are also difficult to be performed by those systems. On the contrary, compact and highly modular lightweight components can be processed by robotic on-site systems with a high degree of efficiency. Therefore SMAS building components had been designed as robot-oriented small sized components. Although masonry structure had not been considered as a major structural system in Japan because of earthquakes before, SMAS being properly reinforced became recognised as a flexible structural system applicable to customised building designs.

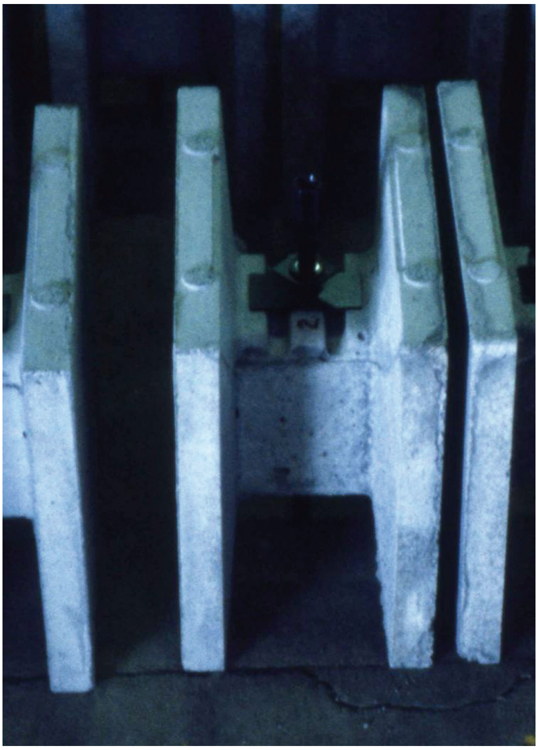


Fig. B.1: building component developed by guidelines of Robot Oriented Design (ROD);

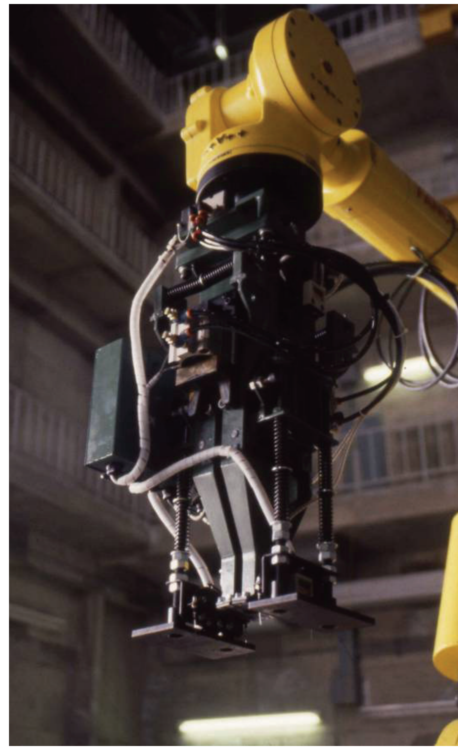


Fig. B.2: complementary robotic gripper/system

A basic solid component (Fig. B.1) is fitted with steel bars for the reinforcement to be assembled to a components-stacked wall. For the verification of adequacy of the proposed over-lap type joint in lateral direction, wall specimens had been designed and a horizontal loading test had been carried out. The result showed that the strength of the proposed joint is comparable to a ordinal lap-joint, when properly fabricated.

SMAS Complementary System Components

The SMAS had been designed as modular systems. Fig. B.2 - Fig. B.6 show SMAS's basic system components. All system components including stones (Fig. B.1), robotic system (Fig. B.2) and serving logistics (Fig. B.5, Fig. B.6) had been developed as complementary parts integrated with the performance of the total system (Fig. B.3).

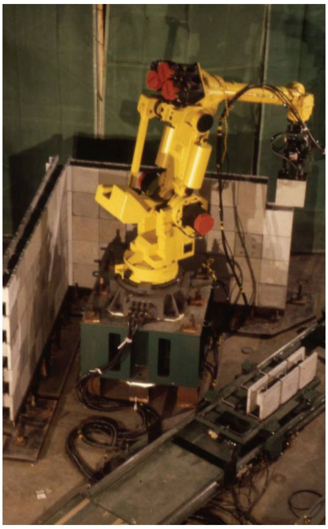


Fig. B.3: Total system in operation

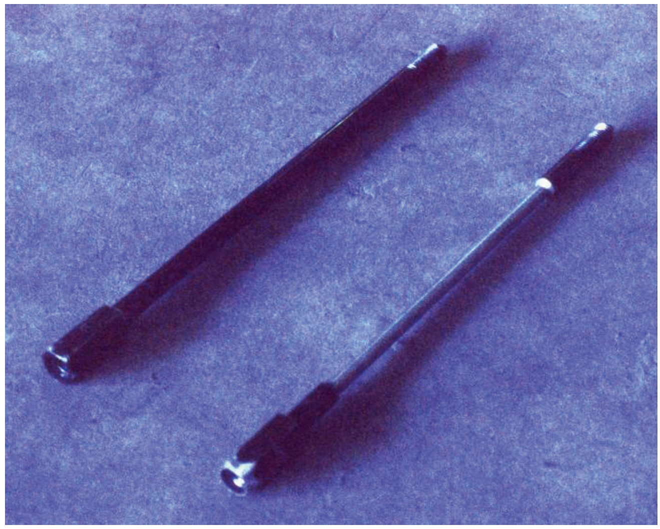


Fig. B.4: Components of the joining system

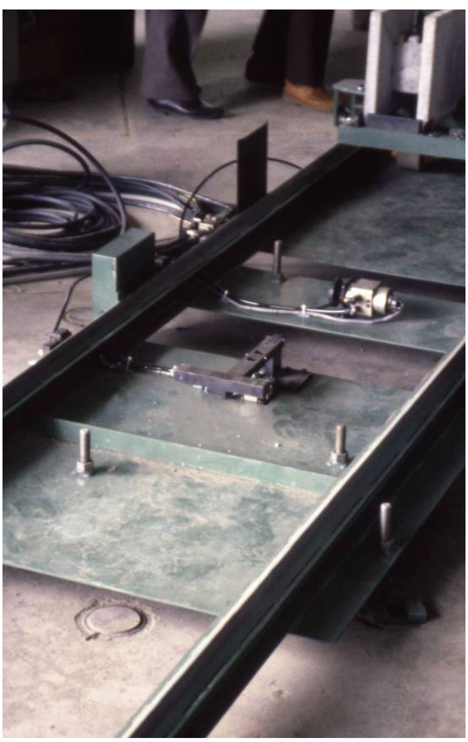


Fig. B.5: Robotic pallet system, complementary with robotic system, stones and operation performance of the total system

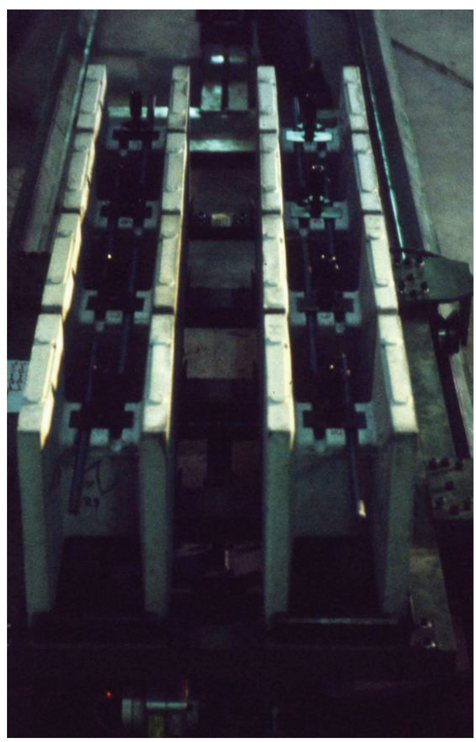


Fig. B.6: Complementary pallet delivering 8 elements

3 Industrialised Prefabrication (Manufacturing Plants for Individually Planned Brickwork Panels)

Individually planned brickwork panels can be produced in manufacturing plants through semi-automatic production lines or fully automatic brickwork robots under industrialised and highly controlled factory conditions. The capacity of this production method accounts with 3,5 m2 to 50 m2 prefabricated brickwork per person and hour. Further, automated and robotic plants have basically following advantages in contrast to a fixed-site production:

- weather-independent and constant working conditions
- ergonomy/healthy conditions for workers
- productivity increase
- modularity and flexibility of production
- quality control

3.1 Mechanised Brickwork Plants

Mechanised brickwork plants are based on shop floor fabrication with a rather low degree of controlled and interconnected processes and thus also deploy a low degree of automation or robotics. Nevertheless, in mechanised brickwork plants various assistance and handling devices are used:

- stationary bricklayer workstation with lowering platform
- stationary bricklayer workstations with lifting platform
- mobile floors with lifting platform
- mobile pallets with lifting and sag platforms
- various auxiliary equipment to shift the stones

Some advanced mechanised workstations/platforms are described in detail in this section.

Highly Flexible Stationary Lifting Platform: Rimatem

The Rimatem stationary lifting platform (Fig. B.7) is a highly flexible system for manual mechanised bricklaying in simple factory environments. Economic production is combined with the possibility of ergonomic handling. Rimatems hand–guided manipulators support flexible production and are moreover designed for interconnection with palletizing and other logistic systems. Similar to the Layher balancer (section 4.2) the Rimatem handling device could be equipped with various grippers and every position on the platform could be reached to position stones with minimal physical effort and high accuracy. Additionally, the platform itself could be adjusted in height to various use cases.

Fig. B.7: Highly flexible stationary lifting platform, Rimatem

Fig. B.8: Multistone platform, Anlicker GmbH

Multistone 8000 Anliker

The "Multistone" (Anliker GmbH) automatic masonry machine (Fig. B.8) consists of a rectangular steel frame with a rotating turning table. The blocks are placed onto a table, which automatically moves them to the correct position and height. Integrated ICT ensures that the mortar is applied properly and all that all subsequent operations are carried out with high accuracy. All in all the “Multistone” can be operated by two persons. One person is responsible for controlling the machine and the other one for various preparations, finishing work and organisational tasks. The blocks, which are coming stacked on pallets, are placed by the machine operator onto the turning table using a gripper arm. When the blocks have reached their correct position, they are set into the mortar bed applied beforehand by the machine. The cut-outs for doors and windows were made before. After the desired wall height has been reached, the steel frame is moved on in order to build the next wall. One or two days later, when the drying process is finished, the electrical wiring is installed. Afterward the walls are plastered and the sills and windows are fitted. With a low-bed truck the walls are carried to the construction site and a mobile crane installs them where they are required. With the "Multistone" automatic masonry machine used in a simple factory environment walls can be built up to ten times faster than on the construction site.

3.2 Automated Brickwork Plants

The adoption of CAD/CAM systems combined with the implementation of advanced Enterprise Resource Planning (ERP) solutions has made the implementation of highly/fully automated brickwork plants possible. Highly automated brickwork plants can be characterised by following items:

- high degree of interconnected processes/logistics
- CAD/CAM system integration
- ERP solutions and supply chain management
- Subsequent processes/production line

Brickwork Robot Plant SÜBA: A Prototype

A prototype of the automatic brickwork plant had been deployed by SüBA company in Hockenheim and the Windhoff AG in Rheine during the 90's. The production of brickwork panes is appropriate for a capacity of 300 m2 net area of brickwork panes - without windows and door recesses - in a shift of eight hours. The employment of CAD in the architect's offices made it possible to transfer the large data set needed for the production of brickwork panes directly without manual input over CAM to the brickwork fabrication system. Fig. B.9 - Fig. B.15 give an overview over the most important SüBA factory modules and automation processes.

Fig. B.9: cutting device

Fig. B.10: decollating station

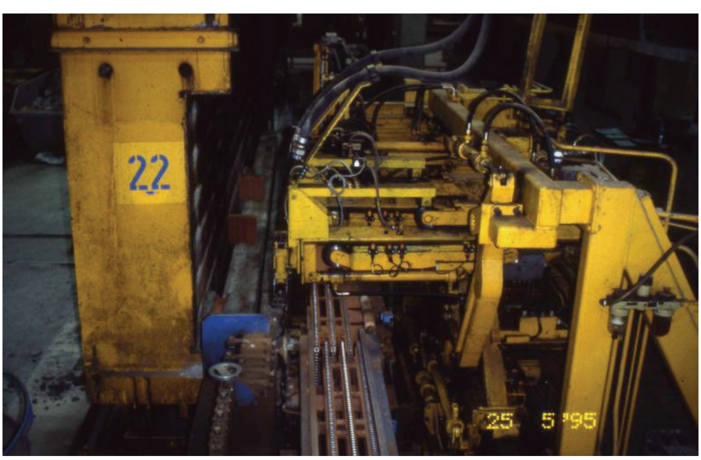


Fig. B.11: automated reinforcement (horizontal) station

Fig. B.12: motar dispensation

Fig. B.13: brickwork positioning

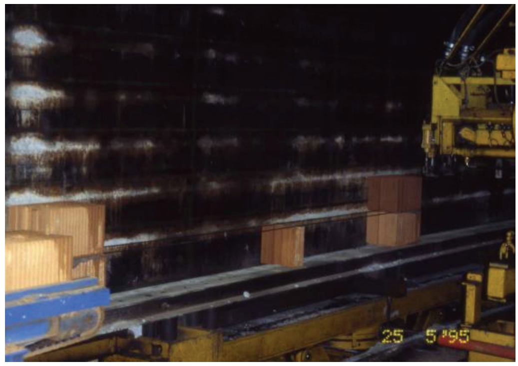


Fig. B.14: brickwork alignment

Fig. B.15: run-dry station

Brickwork Robot Plant Winkelmann (*Horizontal* Brickwork Panel Production)

Today's fully automated and highly robotised brickwork plants can be distinguished into two basic types: horizontal and vertical brickwork panel production. The brickwork robot plant Winkelmann is a characteristic example for horizontal panel production (Fig. B.16 - Fig. B.23). All single devices are equipped with Microsystems, interconnected and part of a systemic logistic network. CAD/CAM guarantees efficient data processing between planning section and production. After the delivery, standard bricks on standard pallets are brought into the factory's required processing order by an automated palletizing system with a robot for the distribution and arrangement of bricks. After that the bricks are taken up by automated de-palletizing system which supplies the horizontal brickwork layering robot station. Also insertion of reinforcement and in-house infrastructure and plastering are done stationary in the factory and finally a dried-out and finished brickwork panel is delivered to the construction site.

Fig. B.16: automated palletizing system with robot for distribution of bricks

Fig. B.17: automated de-palletizing system

Fig. B.18: automated horizontal brickwork layering robot station

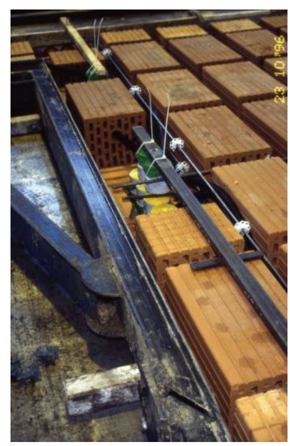


Fig. B.19: insertion of reinforcement and cable ducts

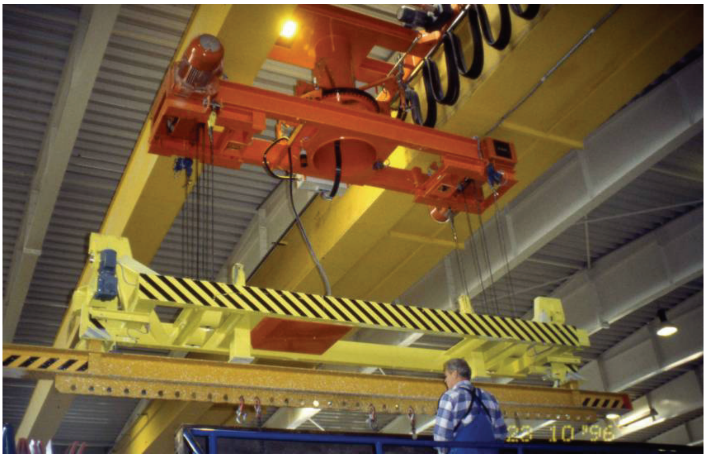


Fig. B.20: factory logistics indoor

Fig. B.21: bare brickwork floor panel

Fig. B.22: brickwork panel with plaster

Fig. B.23: logistics/transportation

Brickwork Robot Plant Leonhard Weiss (*Vertical* Brickwork Panel Production)

The brickwork robot plant Leonhard Weiss is a characteristic example for vertical brickwork panel production (Fig. B.24 - Fig. B.30). Many processes as for example the palletizing and de-palletizing processes needed to bring the bricks into factory order are similar to the horizontal brickwork production type. Yet the basic process of positioning the bricks in given order is done *vertically* layer by layer. High accuracy robots combined with linear axis systems are in charge for the accurate positioning. The automated vertical brickwork layering has particular advantages concerning the efficient use of factory area. Moreover, the firmness and quality of the wall could be improved through vertical processing. On the contrary the horizontal processing has advantages in terms of exact positioning of reinforcement.

Fig. B.24: supply with standardised pallets

Fig. B.25: de-palletizing system

Fig. B.26: sequencing station

Fig. B.27: robotic assembly system for vertical brickwork layering

Fig. B.28: robot end-effector / gripper

Fig. B.29: final brickwork panel product

Fig. B.30: Factory logistics indoor

4 On-site Rationalisation by Mechanisation (Brickwork Handling Devices and Simple Manipulators)

Brickwork handling devices and simple manipulators are mechanical systems which can support the bricklayers work. This mechanical aids range from a crane for stone handling, over a working platform that allows the brick layer to operate in an optimised working position to devices that provide the operator with mortar and other applied materials. Because of mechanised systems for moving, displacing and laying of stones the working place of a bricklayer gets safer and more humane. Additionally companies can increase productivity and become more competitive. When using mechanised systems the logistics of the construction site is important and must be taken into account. Moreover, arrangement, organisation and load capacity of the masonry scaffoldings, quality of the mortar, space conditions must be synchronised with the mechanised system. When a construction site's organisation considers these prerequisites, improved working routine and rationalised processes can be achieved.

4.1 Assistance System Steinherr

The Assistance System Steinherr is an example for a mechanised on-site assistance device supporting the ergonomically best working position, speed of work processes and accuracy/quality with a very simple and flexible solution. Furthermore, assistance sub-devices as stone saws, measuring instruments, stone shifting grip arms, equipments to apply mortar and transport carts for materials to facilitate the work and increase the production are part of the system (Fig. B.31).

Fig. B.31: Platform elevator with balancer and mortar kit

4.2 Layher Balancer and Handling Device for Masonry Construction

Various flexible Layher balancers (Fig. B.32, Fig. B.33) can be distributed over the whole construction site as they can easily be assembled, displaced and serviced by construction site's main cranes. The articulated multi-joint arm supports every working position and also exculpates highly frequented larger cranes from minor working processes. Further, the system is self-balancing and allows a free-moving stone positioning without any physical effort. The multi-joint arm has a overhang of 4,5 m for loads up to 400 kg. The vertical working position is sleeplessly variable up to 5 m and can wirelessly be adjusted by an electronic lifting-unit a remote control device. The balancers can be equipped with various mechanical grippers depending on the type of brickwork or stone used. Du to advantageous transport dimensions (2,20 x 2,20 x 2,35) the Layher balancer offers high flexibility and could easily be shifted or moved between different construction sites.

Contrasting to more interconnected, automated and robotised solutions, brickwork handling devices and simple manipulators are highly mobile and flexible stand alone solutions which are not integrated in overall planning or logistics networks. Therefore in many cases they are applicable to support small company's work process but they do not influence the efficiency of whole construction site. Also they are not applicable for efficient mass production or mass customisation.

Fig. B.32: Layher balancer with mechanical stone gripper

Fig. B.33: Scissor type gripper on sacra balancer

5 On-site Industrialisation by Robotics (Masonry Robots for Customised Construction On-site)

Two robot systems for erecting brickwork on the construction site (on-site) have been developed during the past decades: the SMAS in Japan and a highly mobile and more advanced bricklaying system developed later at the University of Stuttgart: Rocco system. Both of these approaches have following characteristics in common:

- Mobility of the robot system
- Sensor system for determination of the robots positions and its environment
- Off-line generation of the robots motions
- Automatic grappling of the stones from the pallets
- Automatic application of mortar
- Automatic positioning of the bricks

5.1 Mobile Brickwork Robot ROCCO (EU ESPRIT 3 6450 Project)

ROCCO is defined as a Robot Construction System for Computer Integrated Construction (CIC). The consortium under the project name ROCCO developed through a research project a system, which enables fully automated and robotised masonry construction on-site. Companies and institutes joined in the EU funded project in an inter-facultative and international team with experts in the fields of construction technology, mechanical and electrical engineering and information technology from Germany, Spain and Belgium. Goal of the project was the development of a computer integrated robot system, which also contains a continuous solution in the ICT for all steps from the architectural design to the automated assembly of the components on the construction site. The goal was a integrated total solution.

ROCCO System Components

The main task of the project was the realisation of a mobile robot system for construction site operation. Further, the integration of a computer based system for supporting working preparation, logistics and quality control was intended. Based on the CAD-representation of the building, first the walls are broken down automatically into the necessary blocks. In a next step, the optimal working positions of the mobile robot are calculated automatically. Moreover, the positions of the pallets and the arrangement of the blocks on the pallets are recognised and reported to the main system. With this information the necessary non-standard and standard blocks can processed. Finally, the robots motion is generated automatically out of the synchronised information. The graphical user interface used on the construction site is intuitive interactive and enables the user to re-program the system without the necessity to learn a specific robot programming language.

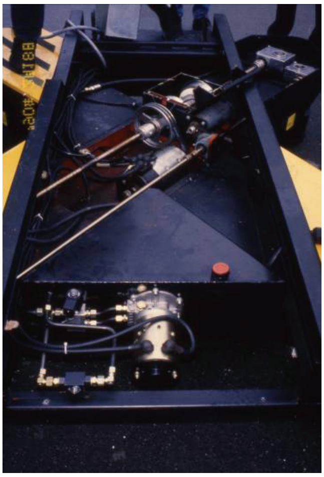


Fig. B.34: Autonomous mobile platform type 1

Fig. B.35: Autonomous mobile platform type 2

The mobile robot system executes the generated programs on the construction site. To test different approaches concerning the application (industrial and residential buildings) and the sensor integration (autonomous vehicle contra large reach), two systems for mobile platforms (Fig. B.34, Fig. B.35) were developed within the project: On one hand an autonomous vehicle together with a manipulator without extensive sensors and a reach of 4 meters, on the other hand a manually operated vehicle with fewer sensors together with a manipulator equipped with sophisticated sensors and designed for a reach of about 8 meters. Both systems had as basic requirements a payload of 300kg together with a cycle time of 100 seconds respectively a payload of 100 kg together with a payload of 30 seconds.

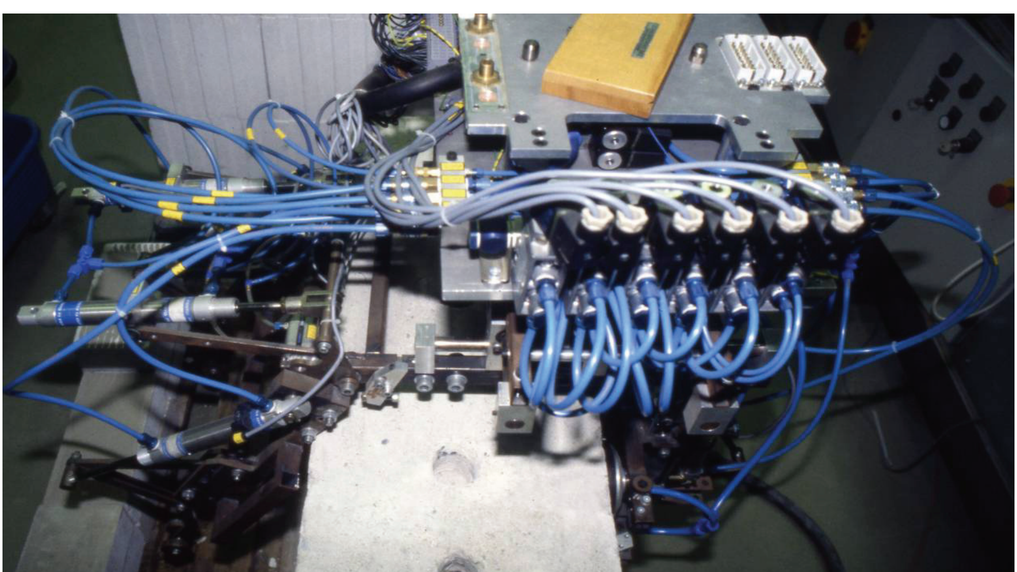


Fig. B.36: pneumatic end-effector for limestone blocks / gripper type 1

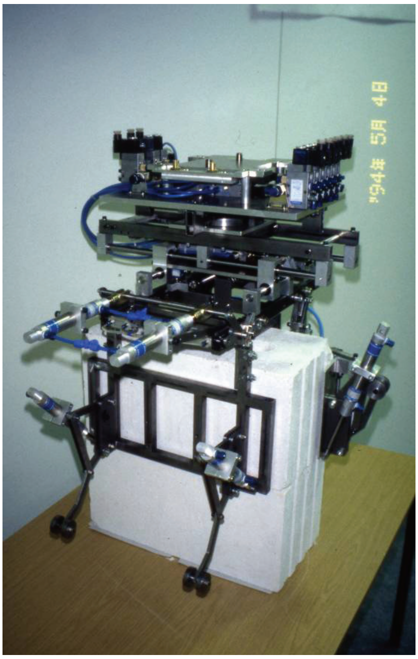


Fig. B.37: robot end-effector / gripper type 2

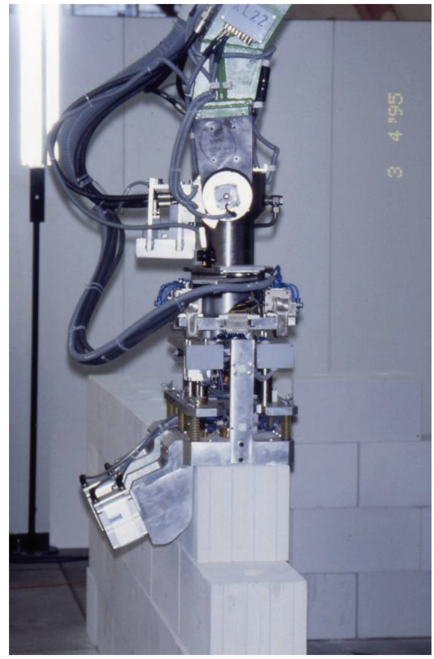


Fig. B.38: robot end-effector / gripper type 3

In contrast to a factory based approach, the ROCCO partners calculated with a significantly higher inaccuracy and positioning faults using a mobile robot on the uncontrolled construction site. Therefore a positioning tool had been developed, which compensates the inaccuracies of the system through feasible sensors, actors and compliant/complementary elements (Fig. B.36 - Fig. B.38). The positioning tool consists of the actual gripper and a fine positioning device. During the development of the gripper the requirements were considered to grip standard as well as adjusted blocks from the pallet and to assemble them in different configurations to a wall. Further, the possibility to handle different block materials as sand-lime or clay bricks or cellular concrete block examined. Finally, different quality control mechanisms have been integrated to detect damaged blocks and inaccuracies etc.

Fig. B.39: System type 1 Bauma 95

Fig. B.40: System type 2 for commercial buildings with long reach manipulator

Fig. B.41: System type 3 for housing construction

Construction Site Sequences and Process Integration

With the system outlined (Fig. B.39 - Fig. B.41) following working sequence (Fig. B.42) on the construction site evolves: The mobile robot system and the block pallets are placed on the floor by the crane in the rough initial positions determined by the working preparation. After referencing and measuring the position of the vehicle, the robot moves into its working position. After positioning and supporting the vehicle, the actual position will be measured and compared to the planned position. The determined difference will be used as a compensating value inside the robot control system, which compensates off-line programmed commands. The pallets, positioned with the construction site crane quite inaccurately, will be fine-positioned manually in the first step. After gripping of the respective block from the pallet, the block will be placed by the manipulator in a rough position on the wall. Finally the fine positioning could be executed by the gripping and assembling tool. All in all, the gripping tool is designed to compensate the occurring small inaccuracies of the whole system.

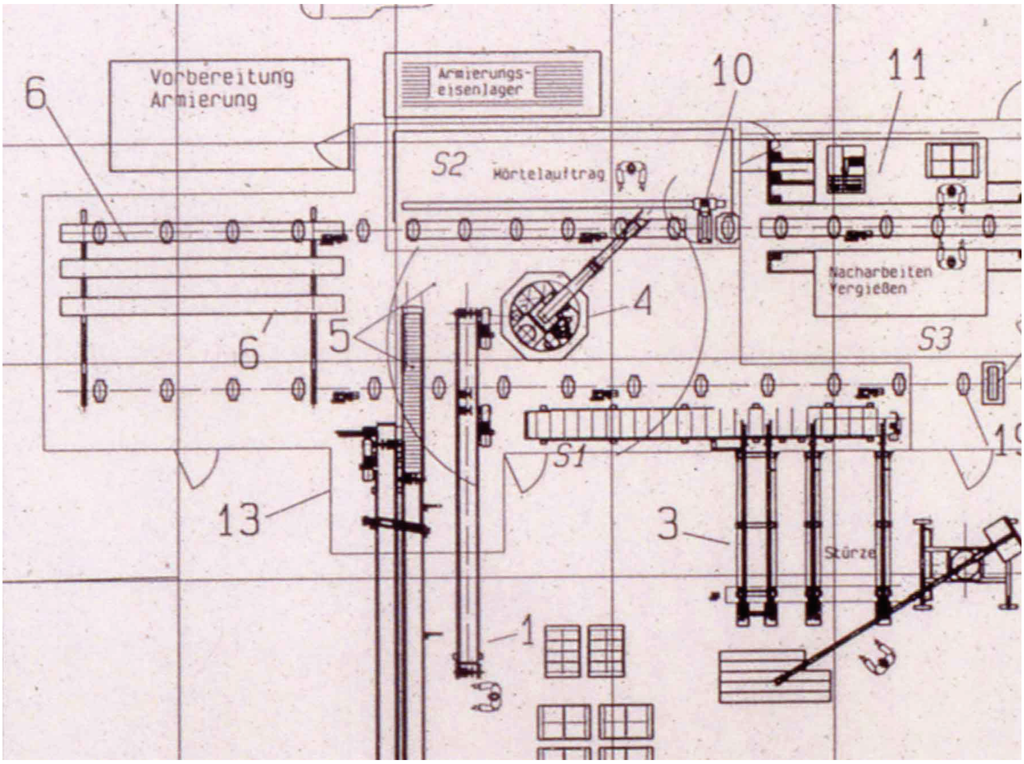


Fig. B.42: On-site brickwork panel production with Rocco system

Computer Integrated Brickwork Manufacturing

The ROCCO approach also was based on the idea of Computer Integrated Manufacturing (CIM), which is today already successfully implemented in various industries. The basic idea was to create a continuous information flow from the architectural design to the automated execution of construction process on-site. CIM makes it possible to automatically process all collected data without loosing the data consistency. This enables all participants to stay as flexible as necessary despite possible short-term changes. Until the introduction of CAD-systems for designing buildings, all information necessary for masonry construction was included in the manually drawn architectural design plans. These plans where send to the executing construction company, who ordered with then the necessary building materials as a non-customised prefabricated standard product, adapted it according the plan in a handicraft manner on construction site and assembled the walls manually based on the information of the architectural plans. This complicated process was significantly simplified in the ROCCO approach through CAD/CAM and subsequent robotised processes.

6 Conclusions

Naturally brickwork layering is a construction method based on mathematical and systemic repetition of similar elements. Therefore today advanced and integrated computation can easily serves as basis for automated applications and robot supported systemic on-/off-site production of brickwork. Thus, especially in the area of brickwork fabrication the concept of the computer integrated construction allows the continuous automation of the construction process. Following systems requirements can be identified:

- **Wall Partitioning Tool:** Tool which divides the architectural walls into the necessary blocks under the consideration of windows, doors, lintels, etc. The outputs are the dimensions and positions of each block in the respective walls. During the segmentation procedure, optimisation criteria have to be considered under hard boundary conditions. The number of non-standard blocks should be minimised to keep the costs low and the dimensions should be well balanced to keep the waste during cutting low. Simultaneously official and technical prescriptions should be kept concerning the bearing capacities, the joints' positions, the walls' connection, etc.
- **Sequence and Task Planning Tool:** Tool which is responsible for different calculation and optimisation procedures. In the first step, the software has to determine the possible assembly sequences of the blocks, that is to generate an assembly precedence graph. In the second step, the optimal sequence has to be determined concerning the optimisation criterion of minimizing the number of vehicle movements respectively of maximizing the number of blocks built from one working position.
- **Palletizing Tool:** Tool which helps to determine the position of the blocks on the pallets and the sequence and positions of the pallets on the construction site. Necessary information are the assemble sequences related to the perspective working points, the dimensions of the blocks and pallets, the position and dimension of the free storage space around the robot and the specific properties of the gripper, i.e. the gripping direction and for that the free reachable block surfaces. The main intention of the tool is to minimise the number of pallets.

With the CAD-data of the designer, it is possible to automate the huge amount of similar working steps being typical for brickwork construction. Through a careful definition of the necessary processes, system components, modules and interfaces a maximum flexibility could be achieved. A consistent database handling throughout the complete construction process avoids errors during execution, increases the quality and is able to react flexibly during short term changes. Combined with the outlined principles of Robot Oriented Design (ROD) which allow a complementary integration of co-adapted brickwork components, re-engineered gripping systems and manipulators, the production of brickwork could be high performance.

7 References

Fig: Fig. 1-6 copyright T. Bock;
Fig. 7 copyright Rimatem; Fig. 8 Anlicker GmbH;
Fig. 9-30, 34-42 copyright T. Bock;
Fig. 31, copyright Company Steinherr, Germany;
Fig. 32-33, copyright Company Layher, Germany

ANDRES, J. & BOCK, T. (1994) *First results of the development of the mansonry robot system ROCCO: a fault tolerant assembly tool*, Proceedings of the eleventh International Symposium on Automation and Robotics in Construction, Elsevier, Amsterdam

BALAGUER, C., ABDERAHIM, M. (2008) *Trends in robotics and automation in construction,* i- tech education and publishing KG Vienna, Austria

BOCK, T. & BLASER, C. & GEBHARDT, C. (1992) *Planning and designing for computer integrated construction suitable for automation,* Bautechnik Vol. 69, No. 3, March, pp. 118-124, Germany

BOCK, T. (1988) *Robot Oriented Design*, Shokokusha, Tokio

BOCK, T. (1996) *The Current Status and Key Issues in the Future on Automation and Robotics in Construction in Germany*, Division for Automation in Construction; Institute for Machinery in Construction; University of Karlsruhe (TH); Germany

BOCK, T. (1998) *Comparative Design and Technology Management for the Development of robotic prefabrication and on site construction systems in Japan and Europe*, Design Research Society Conference; Germany

BOCK, T. (1998) *On automation and robotics in building construction*, 15th ISARC, Germany

BOCK, T. (2000) *Integrierte Planung als Voraussetzung für roboter- und automatisierungsgerechte Gebäudeerstellung'*, in: Bauiniformatik JOURNAL 6/2000, S. 33-37, Germany

BOCK, T. (2001) *Time is Money: Schneller Bauen mit Robotern,* in: Bauingenieur Bd. 76, S. 130-134, Germany

BOCK, T. (2004) *Construction robotics and automation: past-present-future*, in: World Automation Congress, Tenth International Symposium on Robotics with Applications; Seville, S. 1-7, Spain

BOCK, T. (2007) *Construction robotics*, in Vol. 22:3 of Autonomous Robots. USA: Springer Science + Business Media, 2007

BOCK, T. (2009) *Das Dach wird zuerst gebaut und das Erdgeschoß zuerst rückgebaut*, in: Volume 84, Bauingenieur, Springer ed., Germany

DALACKER, M. (1997) *Entwurf und erprobung eines mobile roboters zur automatisierten Erstellung von Mauerwerk auf der Baustelle, Fraunhofer IRB Verlag,* Schriftenreihe Planung, Technologie Management und Automatisierung im Bauwesen, Germany

MATSUMURA, S. (1985) *Mokuzo chikugumi buzai no precutka to kanri taisei*, Dai ikai kenchiku seizanto kanri gijitsu symposium, Tokio

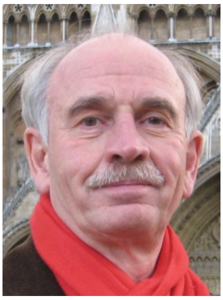
PUENTE, E.A. & ARACIL, R. & BALAGUER, C (1986) Sistemas *'CAD/CAM/CAE: Robots Industrials`* Marcombo

SCHRAFT, R.D. & VOLZ, H. (1995) *Service Roboter,* Springer-Verlag Berlin Heidelberg

VAN GASSEL, F. (2008) *mechanizing, robotizing and automating construction processes,* i- tech education and publishing KG Vienna, Austria

C) Strategy to Enhance Use of ICT in Construction

FRITS SCHEUBLIN[1]



1 Introduction

The construction industry is rather slow in adopting ICT technology. Stand alone applications for bookkeeping and 2-dimensional drawings are generally accepted. But more advanced applications such as 3- and 4-dimensional modelling, GPS and internet technology are still only incidentally applied.

For the development of the construction industry ICT is of major importance. This paper presents research to find why construction is such a late adopter and what ICT can do to enhance the industrialisation of construction.

The most important findings are: Suppliers claim that they offer a range of tailor made ICT tools, while clients report that little suitable software is available. Other constraints are the requested return on investments within 3 years, a traditional culture and a lack of a drive for innovation. Another major problem is the lack of standards required for an effective exchange of data between parties.

A follow-up study found that, for construction, the most promising development is mobile internet combined with GPS-technology. A guide was produced to facilitate successful development and introduction of ICT solutions.

In 2004 the Dutch research institute Stichting Bouw Research (SBR) initiated a research project on ICT in Construction. The first goal was to assess what type of ICT-based technologies are available for the construction industry and to what extent these technologies are already used. In a second stage it was investigated which of the identified technologies were likely to be applied on a larger scale and why this had not already happened.

SBR was founded and is governed by the Dutch construction industry. The SBR foundation is primarily an editor and a publisher and is not a research institute. The board of management and the program committee comprise representatives of contractors, designers and consultants.

---

[1] Prof. Ir., Eindhoven University of Technology, Eindhoven, The Netherlands, Faculty of Arcitecture, Building and Planning, chair of Construction Technology, Director of Engineering Bam Construction Group, Swedish Concrete Award 2005, Phone +31 653.33.84.53, Frits.Scheublin@live.nl or F.J.M.Scheublin@tue.nl

One of the aims of the research project was to benefit from experience and innovative insights from other industries. The methodology consisted primarily of data collection through questionnaires sent to suppliers and users of ICT in construction. The addresses were selected from the data base of Vereniging Grootbedrijf Bouw (VGB), the Dutch association of big contractors. After evaluation of the questionnaires, the leading experts in the VGB data base were also interviewed for a more in-depth picture of the researched field.

2 Definitions

To prevent misunderstanding, it is useful to define first the stages of development of the construction industry and the characteristic of the tools and tasks. An overview of the production systems as seen from the view point of the personnel and their tasks is shown in Table C.1.

Table C.1: Types of production systems (van Gassel, 1997)

Tasks / Systems	Physical tasks	Brain tasks in execution of the work	Brain tasks in organizing the work
Traditional	People Equipment	People	People
Mechanised	Equipment	People	People
Mechatronised	Equipment	Computers Telecom	People
Automated	Equipment	Computers Telecom	Computers Telecom

Table C.1 has a clear focus on the employees on the construction site. The development from physical tasks to brain tasks is characteristic for the ICT-enabled development.

Another point of view is from the equipment perspective. The development goes from traditional construction, through industrialisation to integration. The move from on-site to off-site production is characteristic here. This development is shown in Table C.2 below with the building site as a central focus point.

Table C.2: Relations between traditional construction, industrial construction and integrated construction.

Traditional construction	Industrial construction 1st generation	Integrated construction 2nd generation
Most activities on the construction site. On-site production, traditional assembly of construction materials.	Mechanised production of components off-site Mechanised assembly of components and materials and mechanised finishing on construction site	Automated production of components and large elements off-site. Mechatronised assembly and finishing on construction site. Integrated design, optimised production and logistics.
Hand craft	Mechanised	Automated

3 Constraints to the Introduction of new Technologies

The research project started with an investigation why ICT Technology is not more often and more widely used in construction. The most noticeable finding was the discrepancy between the view of suppliers and users of software for construction. Where the suppliers appeared to be convinced to propose a tailor-made line of software products, the demand side stated that little suitable software was available. Among both parties there was a 100 % consensus that, in the near future, the construction industry cannot continue without adopting the available ICT tools. It is also remarkable that most client respondents were of the opinion that their company was falling behind. A majority of 55 % found that their company had a low level of ICT use, while they thought that, among their competitors, 69 % was at a medium level of ICT use.

Table C.3: opinion of experts on status and potential of ICT in construction

Opinion of peer group	**Supply side**			**Demand side**		
	high	**med-ium**	**low**	**high**	**med-ium**	**low**
To what extent are ICT-technologies already applied in construction companies?	16	50	34	6	69	25
To what extent are ICT-systems applied in <u>your</u> (construction) company?				22	23	55
How important is increased introduction of ICT technology for construction?	75	25	0	75	25	
How important do construction companies consider the increased use of ICT?	75	25	0	62	25	12
What is the suitability of the actual supply of ICT tools for construction companies?	75	25	0	0	94	6
To what extent should construction companies adopt ICT solutions in the near future?	100			100		

The reason why available ICT technology was not fully introduced in construction companies was not only because of a lack of perceived suitability of the software. Factors in the organisation of the industry were also identified. A listing of all major factors is given in Table C.4.

Table C.4: the constraints to introduction of ICT in construction

Reasons why ICT was not (fully) adopted.	**percentage of respondents**
Investment too high	78
Return on investment too uncertain	56
Lack of flexibility of new technologies	55
Uncertain economic situation	48
Risk of technical malfunction	42
Difficult to integrate in existing process	37
Lack of reliability	36
Maintenance cost	35
No innovative culture	32
No market information	31
Limited technical life cycle	30
No acceptance by employees.	24

4 The Most Promising Technologies

Before searching for tools to enhance the application of ICT in construction, the researchers tried to identify the technologies that were most promising as these are the technologies to be promoted the strongest. A technology is considered promising if the technology is already available, affordable and easy to handle. Affordability is defined as the ability to provide a return on investment within 3 years. This is considered rather short by the standards of most other industries, but it is general practice in construction. The found technologies can be divided in three main groups.

- Modelling technologies, ranging from the generally accepted 2D-CAD via the emerging 3D-CAD to the futuristic 4D-CAD. Document management systems and model based planning and estimating are part of this group.
- Satellite enabled positioning such as GPS and Galileo.
- Integrated software such as ERP-systems. Better known under the brand name SAP.
- Internet based data exchange such as Project web and E-commerce.

5 The Introduction of new Technologies.

In management literature the introduction of new technologies and processes is divided in five stages. The research team investigated the extent of the introduction of the most promising ICT technologies in construction. Table C.5 presents the current status.

Table C.5: the most promising technologies and their five stages of introduction

Technologies / Stages	2D CAD	3D CAD	4D CAD	Mobile data & GPS	Doc. Man. Syst.	ERP	Proj. Web	E- commerce
Idea			X	X	X			X
Investigation		X					X	
Decision		X			X	X	X	
Introduction	X					X		
Daily use	X							

For the newest technologies, a reference group was asked if they were already in the idea stage and, if they were not, they were asked if they expected to be in that stage in the foreseeable future. Their responses are shown in Table C.6.

Table C.6: How soon will latest technologies reach the idea state.

Systems	Already in idea stage	Soon in idea stage
3D modelling	16 %	38 %
4D modelling	3 %	32 %
Mobile data	8 %	31 %
E- Commerce	9 %	38 %

6 Mobile Internet

6.1 Activities Supported by Internet

The last two technologies mentioned, Project Web and E-commerce are impossible without the enabling internet technology. Document management systems may be used on their own, but gain value if used in combination with internet. Mobile internet was indicated by the respondents as the most promising technology of all technologies identified. For that reason a more in-depth study of the possibilities offered by mobile internet was performed.

Mobile internet may support a number of other activities. The most important options found by the project team were clustered into seven main groups:

- Exchange of drawings
- Exchange of planning
- Time registration and worksheets
- Material identification
- Equipment identification
- Access to experts knowledge
- Registration of inspections.

6.2 Penetration of Internet in the Construction Industry

At the same time that the research project reported here was carried out another Dutch institute investigated the use of the internet by construction companies. This report by EIB, (Economic Institute for the Building industry) the findings were that, in 2004, over 90% of all construction companies used the internet. The non-users were almost exclusively small companies with less than five employees. Of the internet users, most companies used the internet only for E-mail and only 8% had internet connections installed on building sites. About 30% of the companies uses internet also for E-commerce and 25% used internet for communication with external parties in the building process. EIB concluded that the use of the internet in construction was growing dramatically over the period 1999 to 2004, but that the use is still rather limited when compared to the potential.

CPB, another Dutch research institute, found that where internet technology is adopted, the profit margin initially increases, but that lasting improvement only occurs where the organisation of the work is adjusted to the new technology.

To introduce a new ICT technology, a carefully managed process is needed. Ripper (2006) developed the step by step procedure shown in the Table C.7.

Table C.7: The intervention steps (from Ripper, 2006).

Stage	Activity	Tools	Focus
1	Define motive	Step analysis SWOT-analysis	Environment
2a	Attunement between organisation and personnel	ICT Scan of organisation	Application
2b		SWOT-analysis for personnel	User
3	Decision making	7S model	Organisation
4	Introduction	Implementation square	Management
5	Routine	Intervention wheel	Management
6	Optimisation	Evaluation model	Management

7 References

Beereboom, Drs H.J.A., Internetgebruik door Bouwbedrijven, EIB, Amsterdam, 2006

Centric, Bent u de Draad al kwijt?, Final report of the committee on Mobile internet in Construction. SBR, Rotterdam, 2006

Gassel, F. van, Maas, G., Robotiseren en Mechaniseren op de Bouwplaats, Researchschool Bouw, Delft, The Netherlands 1997

Ripper, B., ICT in de Bouw, De ontwikkeling van het interventie-stappenplan ter bevordering van de verdere invoering van ICT systemen in de bouw, TU/e master thesis, Eindhoven, 2006

Willems & van den Wildenberg, Reader Robouwtech, SBR, Rotterdam, 2004

D) Integrated Design and Production – Decision-making Tools for Optimal Industrialisation of Housing Construction

JUAN MONJO-CARRIÓ[1] & IGNACIO OTEIZA[2] & JUAN QUEIPO DE LLANO[3]

1 Introduction

Some of the most representative facts and figures in connection with the present status of industrialised housing in Spain are:

- Housing accounts for a substantial portion of building construction (>70% in 2007).
- Today's construction systems and procedures can be regarded to be obsolete and inefficient. They have remained essentially unchanged in the last 50 years, with a low level of "rationalisation" and a high percentage of "in situ" work.
- Most "in situ" construction techniques deployed in housing are based on the use of an abundant supply of generally low-skilled labour ("crafts without craftsmen"). One outcome is the need for frequent demolition and rebuilding of newly finished units of work, with all that entails in terms of rubble, technological impoverishment of the industry, large numbers of building failures and inevitably higher costs. According to the latest figures, over 15% of construction costs is devoted to correcting on-site errors.
- At present, nearly every block of flats is a prototype in which the initial design takes insufficient account of the construction system to be used. This leads to work-site adaptations not necessarily suitable for the building, whose implementation detracts from overall efficiency.
- The result is that new production and control techniques in place in other industrial processes have not been instituted in housing construction, reducing the quality, efficiency and, in short, the sustainability of the process as a whole.

In this vein, the specific issues that may be cited in support of the need for a change in the present approach include:

---

[1] Prof. Dr.-Arch., Full Professor, Escuela Técnica Superior de Arquitectura, Universidad Politécnica de Madrid, Av. Juan de Herrera 4, 28040 Madrid, Phone +34 91 336 6570, Fax +34 91 336 6560, juan.monjo@upm.es

[2] Dr.-Arch., Científico Titular, Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC), c/ Serrano Galvache 4, 28033 Madrid, Phone +34 91 302 0440, ioteiza@ietcc.csic.es

[3] Arch., Titulado Superior, Instituto de Ciencias de la Construcción Eduardo Torroja (CSIC), c/ Serrano Galvache 4, 28033 Madrid, Phone +34 91 302 0440, jqueipo@ietcc.csic.es

a) High prices, that in turn depend on a number of factors, namely:

- *High construction costs*, due to an excessive reliance on “in situ” labour-intensive work resulting in relatively long turnaround times.
- *Construction errors* that necessitate repeat work in many units, as well as a substantial amount of correction work prior to final product delivery.
- *Pathological processes* in the first five years of use, and the concomitant additional cost.

b) *Low quality* leading to excessively high maintenance costs, normally due to:

- *Poorly suited designs* from the standpoints of the:

    - general approach (preliminary design), hampering construction rationalisation and sustainability both.
    - technical specifications (final working construction design), leading to improvised worksite decisions and changes and hindering quality control of the various units of work.

- *Poor quality construction*, for several reasons:

    - poorly trained workers,
    - overly large number of units of work erected on site,
    - insufficient emphasis on quality control.

c) *Scant operational and sustainable rationalisation* of housing, with no particular emphasis on:

- *Energy savings*, for the failure to envisage bioclimatic and co-generation (CHP) solutions in the design.
- *Domotics* for all building services as a whole, without which the use of bioclimatic energy saving systems is particularly difficult.

d) Difficulties encountered to design housing at least partially based on (industrialised) “*assembly*” techniques for greater overall efficiency in building production.

Essentially, then, the situation is characterised by:

- *Ingrained traditional housing construction techniques*, which hinder the change in professional (both designer and builder) mindsets and habits required to adapt to new techniques and procedures.
- A *need for a new focus in design and construction* to rationalise the various phases involved (design, materials, construction and maintenance) and benefit from the advantages of the industrial approach.

Fig. D.1: Traditional "in situ“ construction techniques

2 Objectives

In light of the foregoing, a need has been identified to define and design the tools required to reach two basic objectives:

- *To integrate design, production and maintenance.*
- *To maximise sustainability in housing production and use.*

Moreover, account must be taken in this context of the pressing need to integrate housing design and construction in a single process to ensure smooth and efficient industrialisation.

2.1 Integration of Housing Design, Production and Maintenance

This requires viewing housing construction as a global process covering everything from building design and final construction to maintenance throughout its service life, including items such as energy consumption in keeping with the intended use and the manufacture of materials and components for framing as well as building services.

Learning Process to Foster Industrialisation

Construction is an “*additive process*” and traditionally, building involves the on-site handling and joining of materials to erect members, units and so on. This tradition envelopes designers, contractors and workers alike.

The huge amount of “in situ” work entailed in this approach lowers general productivity because process *rationalisation* is particularly difficult under such circumstances.

Setting industrialisation trends requires a break from this traditional approach in the *learning process* of all the agents involved:

- **Designers** should be trained to think in terms of building solutions that rationalise *additive processes* and reduce “in situ” labour, from the earliest phases of design.
- **Contractors** should organise their works around products and components *as fully finished as possible*, and hire workers with *suitable know-how and training* to correctly “*join*” different

components and ensure the quality of the final product. Expertise must be assured in techniques such as:

  - The most traditional of "in situ" skills, when indispensable.
  - Prefabricated component assembly, adjusting for geometric and functional tolerances.

Integrated design and production

The industrialised approach should be adopted from the design phase, for if provision is not made for the appropriate techniques and processes early on, the result will be poor construction processes throughout. Consequently, works should be designed using construction products and techniques that:

- *Rationalise* processes to make them more efficient.
- Reduce *labour* to a minimum in "in situ" construction, by:
  - Designing for construction systems and techniques that intensify the use of "assembly" and reduce on site "construction".
  - Rationalizing space and dimensions to adapt their construction to such techniques and systems.
  - Preferably using modular prefabricated components in building design, possibly in combination with others erected "in situ", depending on market demands at any given time.
- *Eliminate improvised on-site technical decision-making.*

Contractors, in turn, must hire only *suitably qualified employees*, able to work efficiently with such products and use techniques that *maximise construction process rationalisation*, introducing:

- *On site prefabrication shops* for modular adaptation to specific buildings.
- Appropriate *quality control* systems.
- *Robots* for efficient and high quality "in situ" construction.

Decision-making Tools

Such integration can be achieved through the deployment of a series of *decision-making tools*:

- ***Design rationalisation of housing solutions*** (at the expense of their possible uniqueness), which calls for specific analysis in both stages:
  - Preliminary design to optimise operability and facilitate industrialised building, establishing the necessary design guidelines for what might be called a "design for rational building" as well as a "design for sustainable habitation".
  - Final construction design, defining the technical specifications and conditions for such industrialisation.

- ***Coordination and classification of market products and techniques*** to attain:
  - Ready adaptability of their mechanical and geometric properties to rationalised design (modular coordination and attachability).
  - Possible inclusion in the industrialised housing construction process, via one of the following two formulas:
    - *Closed schemes*, involving the use of specific designs and components.
    - *Open schemes*, with component and technique interchangeability for coordinated designs.
- ***Design of an IT tool for:***
  - *Entry and updating of the various rationalised designs of the housing solutions* obtained.
  - *Entry and updating of the market products and techniques* obtained.
  - *Interactive use of the tool by the different actors participating in the process*, to seek industrialised solutions for real-life situations:
    - *Designers*, in particular, for their project designs.
    - *Developers*, to optimise buildings
    - *Material manufacturers*, to specify product qualities and geometries.
    - *Builders,* to rationalise construction.
    - *Tenants,* to optimise use and maintenance.

This tool, in short, would be an **integrated computer-aided design system to facilitate the tasks of the players involved in the housing design and construction process** (designers, engineers, builders, suppliers, public authorities, tenants) **and further interaction among them**. This in turn entails the development of computer software that "improves" (automates and optimises) normal design and construction tasks in the framework of existing practice, and the implementation of measures to begin to upgrade such practice through the resourceful use of information and communication technologies. Other aims include the integration of design and construction processes and the incorporation of bioclimatic solutions.

Fig. D.2: Integrated design process

2.2 Maximum sustainability in housing production and use

To erect more modernised buildings, attention must also be paid to the *automation* techniques and systems and focus on *sustainability* already in place in other industries that build environments intended for human occupation, such as automobiles, ships, trains and airplanes. This will call for establishing clear and precise *maintenance* procedures and their implementation throughout service life to:

- Increase component *durability*.
- Maintain the *quality of use* in housing.
- *Reduce repairs and replacements* to save on material and energy.

In order to do so, a series of goals would have to be defined as a corollary to the design tools specified in the preceding item. These goals include:

- ***Improved efficiency of construction techniques and procedures*** (materials, components, workmanship), which entails *rationalisation of the entire process*, to achieve:
    - *a high degree of industrialisation,*
    - *shortened overall construction times,*
    - *lower total costs as a result of time savings.*
- ***Improved quality of the final product and durability of its components***, to lower building use and maintenance expenses.
- ***Reduced maintenance needs***, in all respects:
    - *Reduction of energy consumption* by using, among others, bioclimatic design solutions, natural energy collectors, low energy generators and so forth.
    - *Reduction of replacement and repair needs* thanks to higher quality materials and components with longer durability.
- ***Improved housing operability*** while ensuring effective environmental control in interiors through, among others, *automated operating controls (home automation)* that cover all aspects of habitability.

Fig. D.3: Reduction of energy consumption

E) Demands on the Tolerances when Industrialising the Construction Sector

ANNE LANDIN[1]

1 Introduction

At present, organisations within the building sector in Sweden are endeavouring to develop a more effective process than hitherto available for achieving a combination of high quality, economic advantage and gains in terms of time.

The building sector is moving towards industrialised construction procedures (Winch 2003, Landin 2004, Svensk Byggtjänst 2006) and there is a strong trend today internationally to industrialise the building process. This term has been given a variety of definitions, all of them probably justified. One area of discussion concerns *on site* versus *off site* production and when production procedures should best take place on site.

- The discussion of off-site versus on-site production has focused on the demand that increasing emphasis be placed on prefabrication. Building sites are taking on, to an increasing extent, the character of locations where components and parts are assembled.
- Strategies concerning the technical approach to be taken in efforts to achieve greater industrialisation are directed increasingly at developing robust and standardised processes and procedures for the manufacture of products of different types, regardless of whether production takes place on-site or in a factory.

Other areas of discussion have to do with the need to develop technical platforms of various kinds. These can be directed both at processes and at physical entities. The overall goal is to produce better products at a lower cost, for the benefit of society.

The term building system refers here to the basic system on which a building's construction is based. What system is most appropriate is determined, in part, by the technical characteristics of the building and the methods of manufacture involved (Lindgren 1995). Prefabrication involves a product being ready to be assembled when the parts of it arrive at the building site. There are different degrees of prefabrication, the most common being that frame components and wall elements are ready to assemble, but volumetric elements are also used. In Sweden the degree of prefabricated house

1 Prof. Dr.-Ing., Head of the Division of Construction Management, Lund University, Faculty of Engineering, PO Box 118, 221 00 Lund, Phone +46 46 222 74 17, Anne.Landin@Construction.LTH.se

production that has taken place has been rather low. For example, one can cite the fact that around the middle of the 1990s only about 15% of the apartment houses in Sweden were produced industrially, whereas, in Finland and in Denmark, some 70% of houses were industrialised (Fernström, 1998). It has been shown that prefabrication results in house production being more effective, leading to a reduction in costs. It is important that at early stages in the process, those producing prefabricated parts work closely with the other parties involved, since all technical problems need to be solved on the drawing board, before site work begins (Redlund, 2004).

It is difficult, using conventional building and production methods, to develop both the building sector effectively and enable building costs to be reduced. According to the Swedish Building Delegation's directives, a reduction in costs can be achieved by ”promoting new ideas within the building sector, initiating research and development concerning new building techniques and building products, and introducing new forms of planning, competitive bidding and purchasing of services aimed at furthering competition and quality” (SOU 2000:44).

The systems and production methods employed have not developed in the building industry at the same pace as in other industries. This may be due, in part, to structural factors within the building industry and to the presence of many small organisations with only limited possibilities of developing new systems and new methods themselves or of testing them. Earlier investigations have shown a far too large portion of the production costs within the building industry to be due to mistakes and defects, to loss of working time, to materials being rejected and the like. Experience also shows that directing work at a building site effectively can be difficult, partly because of the individual craftsmanship which is involved in so many stages of the work.

The aim of this paper is to use the result of a case study for a discussion that points out specific problems that the construction industry has to deal with in order to continue its ambition towards an increased industrialisation and innovative culture. The research project described here is concerned with how quality, expressed as a desire for precision, and is an important factor throughout the different stages of the construction process.

2 Method

A case study was conducted to evaluate a new construction system from three aspects that are economic, production technique and environmental. This study was used for gathering data that pin down specific problems on a general level for the construction industry. In short the aim were to

- Describe and evaluate the functions of the new system in a housing project with the following considerations:
    - Production process with adaptation to other construction and installation parts
    - Production time and production economy
    - Effectiveness for entire project economy
    - Influence on project quality – appraisals on occurrence of failures and shortfalls
    - Environmental influence in respect of production and transportation
    - Transportation economy.

- Propose a continuous development of the system based on the results derived from these assessments.

The case study served as an example to illustrate possible ways to cope with problems during the production stage when new systems are tried out. The research project was limited to the part of process performed on construction sites and no study was carried out on the manufacturing of the elements at the factory. With financial support from the Development Fund of the Swedish Construction Industry, the project was undertaken by Lund Institute of Technology. The study was based on a case study of a pilot project where the new system was in use.

The case study included: continuous site visits with observations concerning KBS-system; interviews with relevant personnel; collection of relevant data to aid the economic and production evaluation of the system; literature study; gathering of comprehensive price and cost concerning similar projects under the adjacent time period in order to perform a comparison study to the actual housing project; and life cycle analysis.

The project results are presented in a report where the analysis and evaluation of a construction system are demonstrated.

3 Results

The goal for the innovation and development of the new construction element is to produce a building element that could fit into the future construction method. A new light construction system was developed and named KBS-system. The KBS-system consists of corrugated sheet forms with sheet material on both sides filled with lightweight concrete (containing expanded polystyrene). By creating an element which is lightweight (160kg/kvm), it is possible to lower the transportation and construction costs. Furthermore, building materials that are lightweight are easier to handle during assembly.

The lightweight element means freight volume and not freight weight determine how much can be loaded on every vehicle. This result means that it is possible to transport around 200 m^2 of element area. This is three to four times more than the complete prefabricated element on every vehicle.

No large machines or equipment are required to handle the elements at construction sites. Additionally, it reduces the dependency of other machines and equipment such as workers accommodation, formworks and concrete equipment which will not only reduce machine cost but also reduce the number of transport trips to and from construction sites. This simple assembly method allows assembly to be implemented without special and expensive machines and tools.

The lightweight elements also give a lower total weight for the building framework. This reduces soil pressure which in turn allows for simpler foundations and thus reduces foundation cost.

The KBS building system has a high degree of prefabrication which means the time consumption will be reduced considerably. A weather independent manufacturing of element, weather proof storage for the finished element and weather proof transportation container to construction sites will guarantee a high quality finished product. Reduction of transport cost, material waste and construction time both during production and construction are undeniably advantages both economically and environmentally through reduction of environmental pressure from vehicle and material waste.

Innovations need ‘running-in’ time and the framework system is no exception. Pilot project that this report is based on was undertaken to prove the manufacturing and construction technique so as to eventually identify any faults or shortfalls. Failure during fabrication, failure in management of the product during transport at construction sites are factors that were given extra attention at construction sites.

During the construction stage, details were tested and problems were solved objectively. The results helped to improve the manufacturing and assembly at the work place. A necessary improvement, which was called for during the production phase, was in gaining better control at anchoring an element. The tolerance levels were not achieved which caused delays and the remedial activities cost far too much and could not be accepted. The solution that was chosen was to change the anchoring devices to adjustable ones instead. This control allows adjustment during assembly and thus avoiding misalignment between elements.

In the first project, windows were assembled traditionally but this procedure could be avoided at the construction site by a raised level of prefabrication. Today customers are offered elements with inbuilt windows. This is an advantage where assembly of these elements made it possible for buildings to be sealed much earlier.

KBS wall system gives an added advantage in relation to traditional curtain wall with bolt framework in terms of dampness and fire resistance, density and sound insulation. Life cycle costs are also reduced together with a prolonged life span.

Environmental advantages also exist, with the prefabrication of the construction system. Logically, with the consumption of less energy, this results in less harm to the environment. Thus the construction sites will be cleaner and safer with less material requiring storage.

4 General Conclusions

The results from the section above are specific in their content. However, the results could, and should be communicated more closely between special conditions and general conclusions. We feel it is appropriate to let the special content in the case study serve as a platform for pointing out some research directions anxious for the progress of the industrialisation of the construction industry.

4.1 Tolerance Levels

Differences between different building materials concerning the traditions that have developed in connection with them can make it difficult to determine within a building project as a whole what tolerance levels should apply to various components. Firms dealing primarily with concrete, steel, wood and glass, respectively, can differ in the practices and measurement techniques they consider to be appropriate, which can complicate planning of how the transition of one material to another or the joining of materials can best be dealt with.

4.2 Planning of Dimensions and Measurements

There is nothing new in pointing out that computational mistakes, carelessness and lack of clarity during the planning stage can lead to difficulties during the production stage. There are many reasons for this and various models to explain it. It is not at all unusual for those designing a building or parts of it to not be familiar with certain details of the building site and the production techniques that can be called for. The labour assembling the building may not be aware of the reasoning of those who designed the building with regard to the measurements and the tolerance levels decided upon, knowledge of which could be of help in deciding how production would best proceed. In the case study this was a large problem, see Fig. E.1, and the solution was to develop new devices that did not demanded tight tolerances. The problem with tolerances could have been solved by changing the measurement techniques and gaining better control of anchoring which would be the most cost effective way of solving the problem. The building industry should be well aware of the important role of measurement techniques, since poor measuring quality can have very negative consequences (Swedac, 2006). Having access to clear dimensional competence is important for enabling sound construction work. However the production culture that has to be generated in the construction industry must consider the importance of the measurement techniques used at the construction site.

4.3 Production Techniques

The putting together and joining of the different parts and components of a building on site can be carried out in different ways, using a variety of different tools and methods of joining parts together. If there has been a failure to communicate adequately, the different dimensions that should be used, there is a definite risk of problems that could have been solved already at the planning stage being encountered during the production phase.

Prefabricated building production can achieve shorter construction time and less waste on sites. With the help of prefabrication, construction methods can be more effective which eventually will lead to lower cost. On the contrary, with the old production method, it is difficult to develop the construction industry and lower the production cost. According to the Swedish Building Construction Delegations director, change can be achieved through promoting new thinking within the construction industry and initiating research and development around construction techniques, and construction products, initiating new planning, entrepreneurship and procurement forms that promotes competition and quality.

If we look into the future desiring a better and more effective construction industry, we must pay attention to the future lower labour supply. Future labourers are expected to have a more sceptical attitude towards heavy, hazardous and dirty element that will exist in the future work place. Instead of reducing the exposure time to such types of work in the construction industry, there exist bigger possibilities in making the construction work more attractive. With the KBS-system, the construction time will not be shorter but, instead, hazardous and unattractive work conditions will be reduced significantly. On the other hand this future construction process will demand labour educated in “tolerance thinking” which will provide the adequate circumstances for solving the problems according to tolerances between different materials with preventing routines.

The installation of parts of a construction project must also be considered. Prefabricated installation parts can reduce construction time and building cost.

5 Discussion

5.1 Attractiveness and precision

The concept of industrialisation is difficult to define here unambiguously. There are two major dangers in interpreting its meaning. One has to do with precision and the other with attraction or attractiveness.

Regarding the first of these, there are increasing demands being placed on precision. This concerns both the details of individual components and the manner of coordinating the functioning of the system as a whole, whatever the major direction is that building activities may take.

As the end users and the general public tend to associate industrialised buildings with the building company who ‘own’ the system, attractiveness is important in order for the company to retain its share of the market and maintain its competitiveness. The design of a building should be attractive to the contractor, the builder and the customer alike. An important issue in connection with the industrialisation of building activities and the attractiveness of the product is to be seen in the unique and often highly attractive characteristics of a house designed by an architect, as compared with the monotonous dreariness that buildings often have that have been mass-produced. Many examples of failures of this sort can be seen in the apartment house building program set into motion in countries such as Sweden during the 1960s and 1970s. Industrialisation should obviously not take a direction of this type.

Precision, in a very broad sense, has to do with knowledge of the characteristics of components and of systems that enables one to develop and to utilise these to produce end products that function as they should, both in their entirety and in their individual parts, in relation to the use to which they are to be put. Within the auto industry, for example, precision is a fundamental quality which is aimed at. Precision is important for achieving effectiveness in terms both of time spent and of costs, making it very much of a challenge to the building sector. Efforts to achieve precision are a sign of quality and a necessity for industrialisation.

Since obtaining precision involves close knowledge of the characteristics of the product in question, its contribution to the customer’s interests is considerable, the product gaining in terms of intellectual value, so to speak. (For a building firm, this means the price attached to the product being a function of more than simply the sum of the value of the parts of which the product is composed.)

For both off-site and on-site building strategies, a building firm should adopt an approach conducive to both attractiveness and precision.

The building sector as a whole is one of the most capital-intensive sectors in the Swedish economy, despite the fact that the average profit that the individual building firms obtain is fairly low.

Fig. E.1: The lack of experience with the new and stricter tolerance requirements led to extra and unnecessary work at the building site (LANDIN) 2004. The manufacturing industry can be a source of inspiration to the building industry through its far stricter tolerance requirements.

5.2 The tolerance dilemma

The tolerance level prescribes the maximum deviations from the dimensions foreseen for a given building component that can be regarded as acceptable. The tolerance levels used at a building site thus specify the largest deviations – from what was planned originally – that one is willing to accept. The deviation in the individual case is the summed effect of the manufacturing tolerance, the storage and transportation tolerance, and the installation tolerance involved (ISO 3443 Tolerances for building).

In the present context the concept of tolerance is used in the somewhat broader sense of being concerned with how matters of precision can best be anchored within the framework of each of the steps involved in the overall manufacturing process and be communicated from those engaged in the one process to those engaged in another.

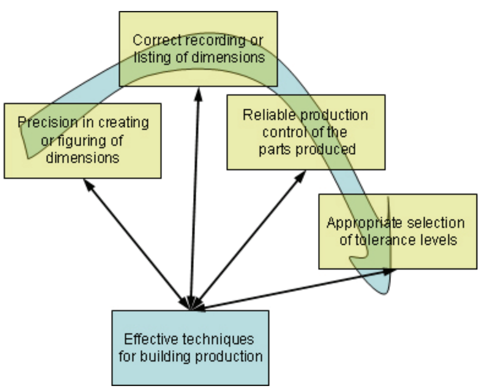
The latter can appear simple enough, yet problems appear when differing materials or types of objects are involved and differing cultures in connection with the level of tolerance meet, at any point ranging from the designing phase to the building site and the time pressures connected with the latter.

Decisions of what form products are to take are made in consultation groups in which the aim is to bring about an industrial type development of the processes involved and create an approach to products and production appropriate to such a task. Although goals of this sort have long existed, the ability to coordinate all of this seems to have been lacking. The industrial type processes that the building sector is now trying to incorporate into its work call for deeper and more adequate insight into the degree of tolerance which the components and systems one has require in being fitted into, or confronted with, other systems or components.

In endeavouring to increase the effectiveness of the building industry, it is important that building components, regardless of their size, be optimised in terms of their performance or functioning. The consequences of measurement errors can be difficult to predict and can depend on a variety of factors, such as the following:

- The chain of events in the building process being held up by the work needed to modify some part while installing it or putting it into place, resulting in an increase in the resources needed, and possibly making it difficult to complete the whole building task in time.
- The goals of the architect in terms of the building's appearance not being fulfilled.
- Adjustments made in components that have been put in place or been installed causing strains in the structure through its being loaded in an unplanned or undesirable way.
- The performance of the structure being impaired, such as by cold or heat bridges or by acoustical problems being created.

There are different sources of error that lead to the dimensions that have been decided upon not matching exactly those found at the building site.



.

Fig. E.2: Sources of error that have consequences for building production.

The greater the degree of industrialisation of the building process is, the more serious the consequences of building parts being given the wrong dimensions when they are produced. Fig. E.2 displays four important parameters that need to be in proper relation to each other in order for building production to function properly

6 References

Byggkostnadsdelegationens betänkande (2000) Från byggsekt till byggsektor, SOU 2000:44, Stockholm.

Fernström. G, Kämpe. P. (1998) Industriellt byggande växer och tar marknad, Byggförlaget, Stockholm.

ISO 3443 (2004) Tolerances for building.

Landin. A, Fransson. H, Öberg M. (2004) Lättbyggnadssystem – en analys av en ny byggmetod, ISRN LUTVDG/TVBP—04/3079-SE, Lund

Näringsdepartementet, Miljödepartementet, Bygga/Bo (2000) Tänk nytt, tänk hållbart! – att bygga och förvalta för framtiden. Miljövårdsberedningen, Stockholm.

Persson. M, Landin. A, Andersson. A. (2006) Kunskapsuppbyggnad och erfarenhetsåterföring i byggföretag – en fallstudie, ISBN 91-85257-96-6, Lund.

Redlund. M. (2004) Prefabstommar för bostäder, Byggindustrin, 35.

Svensk byggtjänst, (2006) Det nya byggsverige, Stockholm, 2006.

Svensk byggtjänst. (2006) Industrialiserat byggande, Stockholm.

Swedac kvalitetsaktuellt, No 2, juni 2006.

Winch. G. (2003) Models of manufacturing and the construction process: the genesis of re-engineering construction, Building research and information, 31,107-118, Spon Press, United Kingdom.

F) Off-site Industrialisation – Process and Production Technologies – Towards Customised Automation and Robotics in Prefabrication of Concrete Elements

THOMAS BOCK[1] & THOMAS LINNER[2]

1 Introduction and Task Description

In Europe several hundred concrete element factories have been installed and existing ones are being gradually automated. In the years to come there is a demand for numerous engineers that can run these kinds of automated factories. This technology described here is a solution for high wage countries where also a lack of skilled labour and construction quality fluctuation is further aggravating the situation. This article is exemplary, describing the state of art in Germany, but there are other advanced factories of a similar kind in Europe.

Development in the field of construction being predominantly-characterised by increasing shortage of skilled labour, this shortage will have to be compensated for by an increase in the level of prefabrication to be achieved in the manufacture of precast concrete building elements.

Market demand will force the expansion from precast concrete flooring elements and precast concrete wall elements to precast concrete columns and beams. On the basis of the development of the European market for these precast products, the intention to invest in them can be regarded as farsighted and promising of future success.

This chapter presents the application of the most advanced computer aided design (CAD) and computer automated manufacturing (CAM) technologies currently available in the manufacturing of double wall elements, solid walls, flooring and roof elements, column and beam elements. Recently one of kind design of precast concrete components can be realised by CAD/CAM technology..

[1] Prof. Dr.-Ing./ Univ. Tokio, Chair for Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.bock@bri.arch.tu-muenchen.de

[2] Dipl.-Ing., Scientific Assistant, Building Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.linner@bri.ar.tum.de

2 Why Precast Element Production?

The advantages of the precast (PC) product, namely:

- shuttering-less construction;
- no wear and tear on shuttering material;
- any openings, recesses or other special features are provided during manufacture;
- no plastering or rendering required, ready for painting as soon as the joints have been filled;
- homogenous structural components, achieved by means of concrete pouring;
- individual customisation
- reduction of building costs
- continuous and constant construction quality

On the other hand, there are also some disadvantages, which, however, are largely offset by the aforementioned advantages:

- minimal tolerances and allowances
- just on demand concrete and reinforcement supply
- monolithic structures cast in situ still offer the highest degree of flexibility achievable on a building site;
- difficulties with joints, e.g. pressing water, can be solved more elegantly by in-situ construction;
- due to the insertion of an additional lattice girder, there is a weight increase of approx. 1.9 kg/m2 ;
- as the precast concrete element is reinforced with round steel from a coil, this may in some cases result in a slight increase in steel consumption as compared to the reinforcement by bar mats;
- depending on costing procedures followed and/or on uses made of shuttering (e.g. large-area shuttering) a concrete wall cast in situ may, given optimal conditions on the building site, prove less costly to erect. However, the surface of a concrete wall cast in situ will never reach the quality of the surface of a precast concrete hollow wall element not to forget the shortened construction time.

Due to the steadily rising labour costs, precast elements offers the opportunity to reduce labour costs by increasing added value. With wage costs accounting for a considerable portion of today's total building costs and the product making it possible to reduce wage costs significantly, future possibilities for the double wall element are very good indeed. The wall elements can be placed by unskilled workers, who, under the direction of a supervisor, will also be able to carry out all assembly work required.

The current shortage of skilled labour in the construction industry can, at least in parts, be compensated by this method of construction. The comparatively few carcass specialists available up to now can then be assigned to more demanding tasks.

The existing trend towards higher levels of prefabrication is enhanced by the fact that, for economic reasons, construction time will have to be reduced still further, so that the market-share trend of the precast elements will continue to be on the increase, and should this hold true, in the case of a decline in the volume of private construction. The share of the total market for precast concrete elements being still very small, it will be possible to arrive at increasing their share of the market even in case of a general decline in the volume of construction.

Price changes in basic materials are the same for both precast concrete building elements and insitu concrete construction. This applies to cement, aggregate, steel and other materials needed. Wage changes are also identical both for manufacturers of precast concrete building elements and for the construction industry in general. However, as the percentage of total costs attributable to wages is lower with manufacturers of precast concrete building elements than in construction in general, this factor should also help to further improve future sales possibilities for those products.

In traditional manufacturing in high wage countries the share of labour cost increases faster due to low mechanisation rate. Applying mechanised manufacturing methods allows labour cost share reduction by increasing mechanisation rate. According to the mechanisation ratio a minimum lot size of about 30 elements is required. Most gains can be achieved by automated manufacturing using robots, CNC machines and FMS in order to further reduce the significance of labour costs. Traditionally automated factories required a minimum lot size of 1000 or even 10.000 pieces to guarantee the Return On Investment (ROI). Through the use of FMS (Flexible Manufacturing Systems, robots, off line programming methods, hybrid control systems etc.) it became possible to run a one of a kind production efficiently. Most present day CADCAM factories reach their ROI point after 3-5 years. They can run 1-3 shifts, producing 1500 to 2000 square metres of floor-wall panels per shift.

Another substantial advantage in favour of the precast concrete elements consists in the job efficiency of the workforce. As the building site personnel is to a far lesser extent concerned with somewhat more complicated tasks, such as formwork, insertion of reinforcement steel, etc. than is normally the case with regular construction workers, job efficiency at the plant level reaches an optimum that cannot possibly be arrived at on a building site. In addition the costs of transportation are approximately the same both for the prefabricated elements and for corresponding quantities of site-mixed concrete.

3 Installation of CADCAM

In terms of hardware, CAD requires two powerful work stations, one controlling the existing manufacturing process and the other controlling the manufacturing process planned. Further hardware requirements include 1 size-A-0 plotter, 1 laser printer and 1 wire matrix printer, all of which were available and will be integrated via a network.

The software used is a highly specialised product specifically designed for the manufacture of the precast concrete elements. Program capacity permits complete control of the entire manufacturing process.

Program features include:

- transformation of geometric data from architectural drawings transferred directly into the manufacturing process of elements.
- generation of:

- steel list
- list of cuts
- stacking list
- computation of mass
- invoices

- operation scheduling
- pallet configuration planning
- formwork scheduling
- list of parts to be inserted/installed
- reinforcement according to specifications laid down.

The CAM system also includes both hardware and software components. Hardware consists in a master computer on the basis of a PC using the OS/2 operating system by IBM. If certain requirements are met, the possibility persists of merging the required two computer based processed into one single computer process, meaning merging the existing manufacturing process with the planned manufacturing process.

In addition to the master computer, CAM hardware components comprise control units for both the automatic concrete distributor and the automatic formwork setter. Moreover, special interface cards for control of steel working and manipulation have been installed in the master computer.

CAM software installed on the master computer includes programs for data preparation and transfer of data to the different devices and machines as well as logging programs for status and error messages from the processing plant. It also includes programs for conversion and further processing of production data and status messages into statistical lists and performance reports. Those lists and reports are prerequisites for plant efficiency surveys, which, when used in combination with registration of equipment operating times by means of a time-recording device that is interconnected with the master computer, reflect the sensitivity of the different devices and machines. In controlling the costs of a specific order data requests concerning the course of manufacture can be made per pallet and, starting from there, for any other larger period of time desired, up to 4 weeks of production data.

Documentation includes:

- operating time
- consumption of steel
- consumption of concrete
- produced square meter
- operating times of individual stations
- error messages
- error duration
- inventory of parts to be inserted/installed
- inventory of finished products.

In addition, the afore-stated data can be used to request, for any observation period desired, additional performance data and/or other indicators, such as, for example, h/m2, kg of steel/m2, pallet occupancy rates or percentage of space/pallet occupied by spacing panels. Setting a target value for concrete consumption serves the automatically requested distribution of a corresponding quantity of concrete from the mixing plant. Interconnection with the mixing plant is checked automatically.

The software product described above will be an innovation. Pallet configuration as established by the CAD system is considering automatically within the master computer to account separately for each of the two shells that comprise a hollow wall element. The circulation of pallets that, as a result of this, have doubled in number will from now on be managed by the master computer, so that the first of the two shells can be manufactured with a definable intervening interval of time prior to manufacturing the second shell. In one-shift operation this intervening interval will normally extend over approx. 24 hours.

After that period of time has elapsed, the second shell is manufactured in a second cycle. In due time, the master computer will transmit the circulation plant relevant data to the control unit, rendering it possible to identify the matching first shell in the curing chamber and, as a result of this identification, to have it moved out of that chamber.

Consumption of materials required for manufacturing is also managed by the master computer. Supplies will be registered by input of relevant data to be gathered from the accompanying supply notes, while deliveries of finished products will, upon leaving the storage facilities, be automatically registered, based on corresponding set values stored in the CAD system.

With each delivery of precast concrete elements, a request for establishment of the corresponding bill of delivery is directed to the master computer with an immediate effect on the inventory of finished products in stock. On the other hand, manufactured wall elements are automatically added to the inventory of finished products in stock.

4 Description of Plant Equipment and Manufacturing Sequence

The circulation plant is designed for a maximum capacity of 50 pallets with individual shells. Multiple-shift operation is possible with a heated curing chamber.

Fig. F.1: Insert Robot – Setting of a screw socket

4.1 Production Facilities

The plant for the combined manufacture of two- and three-dimensional precast concrete elements is installed in a hall with a required floor-to-ceiling height of 8 metres.

4.2 Bridge Crane

An overhead travelling crane integrated in the hall structure and equipped with 2 electric hoists with a lifting capacity of 10 tonnes each and transports any produced element with a span of at least 17 metres.

Functions:

- Transport of consumption materials supplied:
    - lattice girders
    - steel coils
    - parts to be inserted/installed
- Lifting off elements from the concreting station into the storage facility or onto a transport crate.

Technical Data:

Two-rail overhead travelling crane:

- span: 17 metres
- rail lifting capacity: 2 x 5 tonnes
- two-rail travelling crab with 2 rigidly installed electric hoists.

4.3 Pallets, Moulding System

The pallets (portable platforms) are designed for use in the manufacture of both two-dimensional precast concrete ceiling elements and three-dimensional precast concrete elements.

Technical data:

- External length: 10,600 mm
- External width: 3,310 mm
- Clear width: 3,000 mm
- Dead load: approx.: 4.5 tonnes
- Maximum load: 350 kp/m2 = 10.5 tonnes (total load capacity)

Pallet formwork consists of two solid surrounds.

Due to the use of magnetos, which are automatically attached by a gantry type robot on the pallet any two-dimensional precast element can be produced. As far as three-dimensional elements are concerned the flexible pallet formwork has a minimum width of 300 mm. Depending on which of the shells is manufactured, additional longitudinal magnetic anchors must be installed on the side of the pallet where they are needed. The various longitudinal moulds are put in place by a robotic moulder.

4.4 Demoulding, Depalletizing Device

Pallet circulation starts at the discharging station, from where it proceeds via the pallet cleaning station to the first workstation. There, by means of a depalletizing device attached to a panel stacking crane, the finished flooring elements are lifted off the pallets and stacked directly within the working range of the discharging vehicle.

Due to the fact that the lattice girders of wall elements are rotated at a 90-degree angle as compared to those of flooring elements, a special type of depalletizing device has been developed for wall elements. Two electric motor driven slewing gears, each equipped with 4 separately movable hooking beams equipped with 4 spring-loaded hooks, are installed on a spreader bar. This mechanism permits the simultaneous hooking of up to 8 lattice girders of a first shell of a double wall element.

The operator attaches the panels to the telecontrolled hooking device and then lifts them up just slightly. The longitudinal moulds released by that slight lifting of the panels are placed on a roller conveyor that is located at the side of the first workstation and leads up to the station where new formwork is positioned. In manufacturing double wall elements, the panel stacking crane will put the first shell of a wall element on a special turning device. The shell will be fixed to that turning device from below, by means of vacuum suction plates mounted on traversing glides that can be moved by telecontrol in linear direction.

Demoulding of double wall elements and solid walls will be done by means of the in-hall overhead travelling crane specifically designed for that purpose. Following demoulding, the pallet moves into the depalletizing station, where it is tilted in an 85-degree angle. The wall element, which is now in an almost vertical position, is lifted off the pallet by the in-hall crane and put either in intermediate storage or on a transport crate. The pallets can also be used for "on-edge" manufacture of precast concrete building elements, which method, however, requires the use of a specific moulding system. Elements manufactured in this particular manner are depalletised by a swinging crane and then put on storage tables. Here, latitudinal moulds will remain on the pallet after demoulding.

4.5 Cleaning, Measuring and Oiling with a great Rationalisation Effect

The set-up times for production lines and pallets are reduced decisively. This means an increase in production capacity. Intensive cleaning, precise measuring and even oiling mean that better results are archived in a shorter space of time. The magazining, cleaning and plotting (MCP) robot is used for a variety of tasks: picking up, magazining (term explained in 4.5.1.), insertion of latitudinal anchors, cleaning of pallets, full scale plotting of elements, installation of latitudinal anchors. The robot, the development of which was based on experience gathered in manufacturing precast concrete ceiling elements, has been equipped with a number of additional functions. Any concrete waste resulting from the cleaning of the pallets is immediately dropped in a sunk container. Cardboard waste is collected and disposed of separately.

- "M" stands for magazining. Fully automated collection of latitudinal anchors and their subsequent insertion into interchangeable magazines will start upon arrival of a pallet to be cleaned.
- "C" stands for cleaning. Cleaning of pallets starts upon removal of the latitudinal anchors. Any resulting waste materials will be moved into their respective containers.
- "P" stands for plotting. After the pallet is clean, fully automated plotting of the new panel geometry is initiated by transfer of corresponding data from the CAD-system. Latitudinal anchors are positioned as specified. Oil will be applied to those sections of the horizontally oriented pallet surface the anchors are placed on as well as to any vertically oriented surface. This requires a maximum of precision, which differentiates this method substantially from those applied in on-floor manufacturing.
    - At this point, the new panel geometry as well as any special features (e.g. outlines of additional parts to be installed) have been plotted on the surface of the pallet now moulded with latitudinal anchors. On account of the very high level of precision required in the manufacturing of wall elements, the following innovations have been integrated: A longitudinal travelling mechanism with servo control for the whole device, based on two parallel toothed racks in minimum tooth clearance design with an accuracy of +/- 2 mm and, in addition, automatic realignment of reference edges of pallets with the MCP device.

- o The MCP-device can store up to 48 latitudinal anchors at a time. Three pull-out magazine tables at the side of the device allow the use of interchangeable magazines each providing for 2 x 8 magazining locations permitting the application of different moulding profiles (with or without triangular chamfer, with or without surrounds).

4.6 Robotic Shuttering Systems Increase Speed and Produce Precision Elements

The wide ranges of slab geometries are of no difficulty to the systems. There are transversal shutters made of light plastic and longitudinal shutters as reusable steel profiles, with magnets for simple fixing. The result: precise shutter edges and good optical impression of the slab.

Shutter Robot System Description

This fully automatic robot system was developed for:

- Positioning magnets and shutter units
- Plotting all geometrical slab inf. as required

Comprising the following components it can carry out these tasks independently:

- 4 axes gantry robot
- Feeding belt for shutter profiles and magnets
- Cleaner for shutter profiles and for magnets
- Identification belt for shutter profiles
- Congestion roller conveyor for magnets
- Magazine for shutter profiles

Description of a Robot Procedure

The cleaned pallet is conveyed to the robot station.

- Transmission of the geometric data from the master computer directly to the robot system.
- Inscription of the pallets and plotting of the slab geometry that has to be manually effected (e.g. opening for window).
- Positioning of the magnets. They are removed from the congestion roller conveyor at the discharge stations by the double gripper and are set down at pre-determined spots.
- Set the shutter profiles over the magnets.

For this purpose the control first checks whether and which of the shutter profiles are available on the identification belt. If the robot needs a shutter profile that is lying on the identification belt, it will take it. Otherwise, it will turn to its magazine and pick out the respective profile. Set the profile at the pro-determined position. When all the shutter profiles are in place, the pallet is convoyed out of the robot station and the next cleaned pallet is transported into it.

If the cycle time of the pallet system is longer than the robot system needs to put the pallets in place, the portal robot uses this time to fill the magazine with the shutter profile on the identification belt.

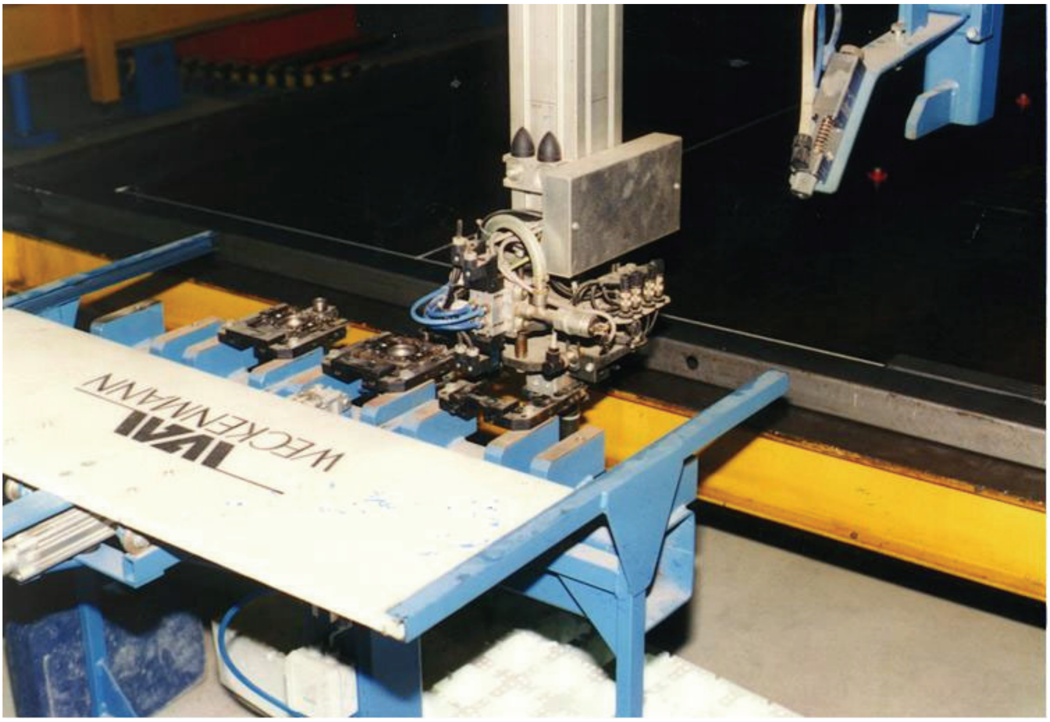


Fig. F.2: Insert Robot – Exchange of the gripper

Description of the Single System Components of a 4-Axes Gantry Type Shutter Robot

The gantry robot has one axis for each X-, Y-, Z- and C-direction, whereby the C-axis is used as the rotating axis of the robot gripper. The X and Y- axes consist of a double linear unit and the Z-axis of a single linear unit. These linear units guarantee a very high positioning accuracy and are truely easy to service. The C-axis consists of a rotating module with identical characteristics. All axes are equipped with a servo drive and the necessary low-play transmissions. The gripper unit consists of a double gripper ensuring the safe gripping, conveyance and placing of the shutter profiles and magnets. The plotting and oiling devices of the robot system are to be found on the gripper. The current is supplied via energy supply chains and highly flexible cables. Limiting switches protect all the axes and the gripper. The computer control of the robot is installed as stationary unit and equipped with a power control as well as manual control part.

Technical Data

X- and Y-axes:	Max. travelling speed:	2.4m/s
	Travel	according to customer requirements

Z-axis:	Max. travelling speed:	1.5m/s
	Travel	according to customer requirements
C-axis:	Max. rotating speed:	120°/s
	Rotation range:	270°
Gripper:	Gripping force:	2 x 700 N
	Compressed air pressure:	min. 6 bars
Cycle time:		4-5 min(as of June 95)

Feeding lines for Shutter Profiles and Magnets

The feed conveyors allow the quickest possible transport of the shutter profiles and magnets from the striking station to the robot system. These lines are set up along the entire striking station. This allows the staff to work under pleasant conditions as there are no long transport distances.

Automatic Cleaning Machine for Shutter Profiles and Magnets

The shutter profiles and the magnets are automatically conveyed through the cleaning machine. They are not only cleaned but also oiled immediately after cleaning.

Identification Belt for Shutter Profiles

An identification belt is necessary to recognise the cleaned shutter profiles. It registers the length and form of the profiles.

Congestion Roller Conveyor for Magnets

The congestion roller conveyor transports the cleaned magnets to two integrated discharge stations. Two dischargers reduce the necessary travel of the robot.

Magazine for the Shutter Profiles

A magazine is required to provide the portal robot with shutter profiles. The volume and division of the magazine are designed according to the customer requirements.

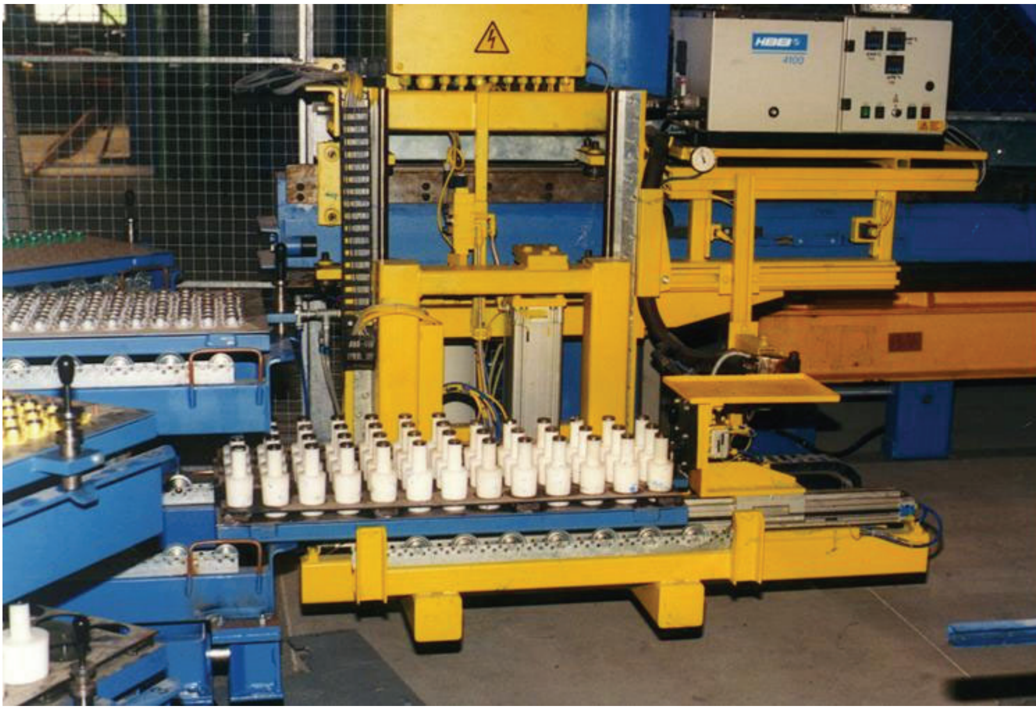


Fig. F.3: Tray on the shuttle

4.7 Moulding – Work-Station System

This section is a fully equipped workplace system designed for manual completion of moulding. This work-station system is composed as follows:

- one rack system for the storage of insulations and other materials of consumption. This rack system extends over the whole length of the pallet and is 1 m deep.
- a second rack system is located on the opposite side and is used for intermediate storage of longitudinal anchors and of other auxiliary material, and this is also the place where the roller conveyor ends.
- a suspended monorail car equipped with the following devices:
    - a hand oiler used for oiling of longitudinal anchors and spacers
    - a hot-melt adhesive dispenser used for bonding moulds

Fig. F.4: Round sparing, reusable

4.8 Automatic Oiling and Reinforcement Station

A stationary automatic oiler is oiling pallets while passing to the reinforcement station. Previous first generation CADCAM precast plants used articulated robots for rebar positioning. The present innovative reinforcement station is essentially based on the use of 2 linear robots. As it has been designed to serve in the manufacture of wall and ceiling elements the reinforcement station permits longitudinal reinforcements, latitudinal reinforcements and lattice girders to be inserted in parallel with either the longitudinal or the latitudinal dimension of the pallet.

The data required for manufacturing to be fully automatic will be compiled by the master computer on the basis of CAD-reference data on pallet configuration and then transferred via a direct data link to the control unit of the reinforcement station. All reinforcement work required is performed directly on the pallets for the inner and the outer shells, respectively. With this method, the first shell (inner shell) is manufactured with insertion of a lattice girder, while there is no insertion of lattice girders into second shells at this stage of the manufacturing cycle.

Installation of the First Layer

Latitudinal reinforcements and spacers are (with ceiling elements) automatically put on when the pallets travel back to the previous station. As the positioning device is installed in parallel with the longitudinal dimension of the pallets, latitudinal reinforcement bars are, prior to being inserted, rotated at a 90-degree angle.

However, when manufacturing wall elements, it is, at this stage, longitudinal reinforcements combined with spacers that are inserted. In this case, the pallet moves at a clock-pulse-controlled rate of travel from station to station. Insertion will be carried out automatically by a linear robot. On the other hand, wall elements that exceed standard maximum heights are at this stage of the manufacturing cycle treated like ceiling elements, since they are provided with latitudinal reinforcements instead of longitudinal ones.

Installation of the Second Layer and Insertion of Lattice Girders

In the following station flooring elements are provided with longitudinal reinforcements, while wall elements are provided with latitudinal reinforcements. Insertion of reinforcements is carried out automatically by the second computer-controlled linear robot. The position required for insertion of the lattice girder in parallel with the longitudinal dimension of the pallet is achieved by moving the pallet in the direction of a buffer station.

In the manufacture of wall elements both the second layer and the lattice girder (the latter only with "first" shells) must be inserted in parallel with the latitudinal dimension of the pallet. To achieve this, the inner grip of the inserting robot has been equipped with a slewing mechanism. At this stage, precise positioning is especially important, in order to prevent the lattice girder being immersed into the freshly mixed concrete of the second shell from colliding with any part of the latitudinal reinforcement of that shell.

Intermediate storage of lattice girders commercially available in lengths of 14 m is effected by inserting them into the appropriate slots of a partitioned box-type magazine that is installed at the side and can be moved up and down. Up to 13 different types of girders can be magazined as many different boxes and can also be removed from those boxes without any difficulty - by simply moving the whole magazine up or down until the box to be dealt with is at the required level. In moving out of the box the girder will be pressed through hydraulic shears until it contacts a CAD-controlled measuring point. Upon contact, the girder is cut to the specified length. Remaining pieces of girder steel can be welded together with a butt-welding machine.

4.9 Installation of Additional Parts and Re-positioning of Reinforcement

The two stations following the buffer station are used for manual readjustment of reinforcement and/or installation of additional parts, e.g. window cases, door cases or cantilevered elements. A further workstation system could be installed in this area in the future if more complex and value added elements have to be produced or if a higher degree of automation should be achieved. An overhead travelling crane is equipped with 4 chain hoists and a working platform is used for transport of additional parts to be installed from the intermediate storage facility directly to the pallet.

Fig. F.5: Screw sockets and sparings

4.10 Examples of Semi Automated and Robotic Concrete Distributors

Various examples of semi-automated concrete distributors are:

- Gantry concrete spreader for feeding precasting lanes (also with lightweight concrete): 6.5m3 capacity. Lane width 2,700 mm subdivided with 23 valves.
- Production of bar-shaped precast concrete parts with tandem screw spreader of bridge construction with integrated lifting gear.
- Concrete spreader, sealing and surface smoothing system for manufacturing concrete garage floors.
- Sliding production of fully insulated, prestressed bedplates in the following production stages: preconcreting of walkways, sealing of walkways, concreting and screeding of surface layer. The edge walkways are trimmed with a slip form.
- Crane concrete spreader for areal flooring and wall elements, also for use in the production of load-bearing precast parts.
- Concrete Spreader, bridge construction and transverse bucket moving gear with screw discharge and filling nozzle for the production of ceilings and walls.
- Concrete spreader with detachable crane stabiliser, spiral roller discharge, slewing and lifting gear as used in a plant that manufactures facade elements, columns and trusses.
- Concrete spreader with detachable crane stabiliser, gravity discharge, lifting and slewing gear as used in the production of prefabricated stairs.

- Concrete feeding and compacting of prestressed brick headers.
- Circular shuttering concrete spreader for feeding round shutterings. The feed chute is adjustable in height and radius and rotates continuously 360¦ for filling in layers. Used in the manufacture of subgrade products such as pipes and rain-water tanks.
- Concrete spreader in use on precasting lanes for manufacturing single-element ceilings and facade elements.
- Concrete spreader system with 2 alternating buckets for feeding columns and trusses. The two alternating buckets are removed from the filling station by a bridge and transported to the shutterings. In order to fill the shutterings which vary in height as exactly as possible, the alternating buckets are equipped with a lifting device. The concrete spreader system is designed for fully automatic 4-axial operation.
- Bridge type spreader(3m3) in a rotation unit for manufacturing single-element ceilings.

Facade production in exposed-aggregate concrete with a concrete spreader on precasting lanes. Equipped with lane vibration, internal vibrator, screed and smoothing device.

Fig. F.6: Pallet in concreting station

Various examples of Robotic Concrete Distributors are:

- *Equipment:* Transverse moving gear, stepless spiral roller drive, distribution roller, local lighting, central lubrication unit, screed, roughening device, lined bucket interior, lane vibrator, hydraulic valve width adjustment.
- *Screed*: Screed bar for smoothing the surface during the concreting of solid walls. The bar has two external vibrators for producing an extremely smooth surface.

- *Valves:* Can be opened separately or in groups according to the pre-setting. All construction parts(e.g. bearings, hydraulic components) are situated outside the concrete discharge thus ensuring durable, maintenance-free construction.
- *Discharge Unit:* The interaction between the distribution roller(at the top) and the porcupine roller(at the bottom) ensures the even discharge of concrete that is characteristic of the Weckenmann-type concrete spreader.
- *Control positioning:* The ergonomic design of the workplace enables full exploitation of this efficient machine.
- *Drive:* Stepless, powerful drive motors in conjunction with an automatic central lubrication unit ensure a first-class concrete discharge and high operational reliability of the concrete spreader.
- *Moving/Slewing Gear*: Transverse movement: in order to feed more than one parallel lane.

4.11 Automated Low Noise Vibrating Station

The vibrating station is located in the noise control area. The automatic concrete distributor is installed above the vibrating station. The concrete distributor must be innovated, as the existing distributor will not meet the exceedingly high precision standards as to thickness of elements required for the manufacture of two-leafed solid walls. The design of the new distributor to be developed shows a linear charger functioning very much like a plotter. Operation and/or monitoring of the fully automated new concrete distributor is to be carried out from a wall-mounted control board that is located in front of the windowed noise insulation gate. Vibrating time is approx. 30 sec/pallet, with operating cycles to extend over approx. 10 min. each. Requests for distribution of concrete are transmitted automatically from the control unit of the concrete distributor to the control unit of the mixing plant.

4.12 Low Curing Chamber, Rack-storage Crane

The curing chamber is composed of 4 racks with a maximum total of up to 50 pallet storage boxes. The storage area facilities are in the form of racks and are used for hardening of finished precast concrete building elements. Up to 12 pallets can be "stacked" at different levels in each rack. Pallets are manipulated with the rack-storage crane by means of a special spreader bar attached to that crane.

In the manufacturing sequence for double wall elements, the first shell, which has already hardened, is placed with the demoulding device on the grillage of the turning device. The shell being safely attached to the grillage by means of 36 vacuum suction plates rotates 180 degrees. Each of the vacuum suction plates can hold up to 140 kg. 18 suction plates can be moved in 2 directions and rotated in a 90-degree angle. The remaining 18 suction plates are rigidly installed on the reference edge of the grillage. The mobile suction plates are moved by hand, on the basis of coordinates obtained from the CAD pallet configuration planning. Following rotation, the grillage travels to the rack station.

The rack-storage crane picks up the grillage and moves it transversely, where a pallet with freshly mixed concrete is located. The pallet in this station contains the matching counterpart of the shell fixed to the grillage and has been moulded and concreted together with the shell. The rack-storage crane lowers the first shell onto the second shell. The shells are then combined by means of vibrating the lattice girders of the first shell into the second shell. Following the release of the shells, the grillage is set down and then moved back to station. The finished two-leaf double wall element is picked up by the rack-storage crane and moved into one of the storage racks for hardening.

4.13 Transport and Storage System

Large-scale concrete slabs are lifted, transported and stacked quickly and safely - by one person. There are many varieties: portal vehicles, double-support bridges with longitudinal and horizontal running mechanisms, or an extra device for an existing crane. A pit located between the storage foundations is used for intermediate storage of double wall elements. Intermediate storage is inevitable as a manufacturing method that is primarily based on optimised pallet configuration will not necessarily meet assembly-oriented requirements at all times. Transport of double wall elements from the hall into the intermediate storage pit is affected by means of a special transport crate.

The transport stack (with ceiling elements) and/or the transport crate (with double wall elements) is moved out of the hall onto, or into, the corresponding intermediate storage facility by means of an electric motor driven, remote-controlled discharging vehicle. This discharging vehicle moves from the hall to the storage site. The transport stack and/or the transport crate can be put down directly on the storage foundations. By using a travelling platform on the storage site, it would be possible to discharge on several storage foundations.

4.14 Ecological Production through CADCAM of PC Element

With round steel from a coil waste is reduced to a negligible minimum as was shown by the experience to that effect gathered in the manufacture of flooring/ ceiling elements. The very little steel waste that still remains is collected in a container and eventually sold to a scrapyard.

Owing to the computer-optimised moulding system, styropore waste could be reduced to a considerable extent. In the future, only longitudinal moulding will continue to require the use of treated cardboard-styropore for complementation, and even this will only concern small pieces of styrofoam measuring less than 10 cm. Apart from that use, openings and perforations that cannot be fully moulded by the computer-optimised moulding system, will continue to require styropore. Styropore waste is first collected in a separate container and then disposed of at a land-fill-site.

5 Customised CADCAM Designed and Built Projects

5.1 Example 1: Neuer Zollhof, F.O. Gehry, Düsseldorf

As an example we introduce the project „Neuer Zollhof“ by Frank O. Gehry in Duesseldorf. The total construction time of this project was three years (1996-1999). The complex consists of three buildings called House A, House B and House C. The perimeter walls of House A are plane and 4° to 6.5°

vertically inclined prefabricated elements. These elements proved to be the cheapest solution for these extraordinary shapes.

Fig. F.7: House A with clinker façade

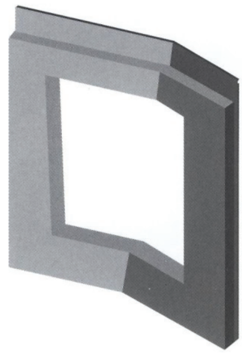


Fig. F.8: 3D-iamge of prefabricated element of House A

The geometry of the pieces was described digitally and then built in three dimensions. The 2D drawings for the formwork plans were automatically generated by CATIA-CAD, a software designed for airplane construction. According to those drawings the plant produced the pieces. Almost every part is unique. The precast elements had a thickness of 25cm and were approximately 6m high, 4m wide by a weight of 9t. All parts were assembled by crane. In a few exceptions a lorry mounted telescopic crane was needed.

Fig. F.9: conventional assembly of shuttering for precast elements house type A

The clinker facade required extensive details and good craftmanship. House B consists out of 355 prefabricated non-structural perimeter wall-elements carried by cast-in-place concrete ceilings.

Fig. F.10: House B stainless steel facade

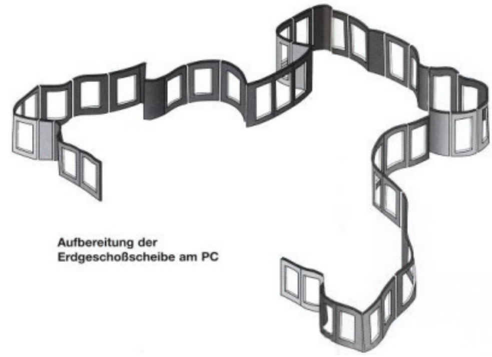


Fig. F.11: first floor “slice” in 3D

The new method, which was patented, allowed a widely computer-aided production of the prefabricated elements. With CATIA the complex geometry of the building was cut into single “floor slices” and then converted so that the data could be used in AutoCAD for further architectural planning. Each floor was split into single elements according to assembly and structural needs and then the data were reconverted into CATIA in order to be delivered to a milling shop.

These specific polystyrene-formworks were produced by CNC-milling machines.

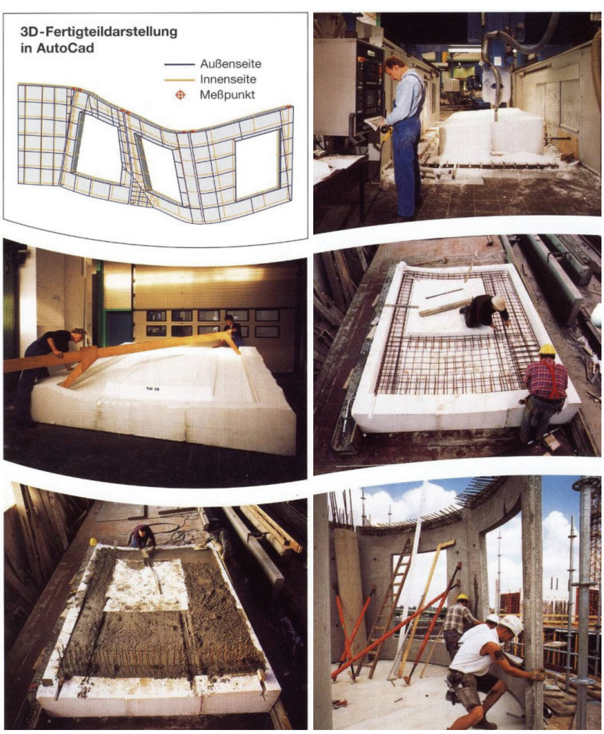


Fig. F.12: CNC-milling machine producing a polystyrene formwork

With the formworks the 18cm thick precast-concrete elements were manufactured and then delivered to the construction site "just-in-time".

Fig. F.13: first floor: just-in-time assembly of the elements

In comparison to House B the perimeter walls are made of masonry due to reduced curvature.

Fig. F.14: House C white plaster

The freeform inclined surface of the cast-in-place walls of House C were built in a similar way as the prefabricated elements of House B. The concrete parts were digitally generated so that the CNC-milled and form defining polystyrene pieces fit in between the plane formworks. The milling process for the polystyrene-formwork was similar to the one in House B. On site the pieces were integrated into the regular formwork. The walls are all cast-in-place concrete.

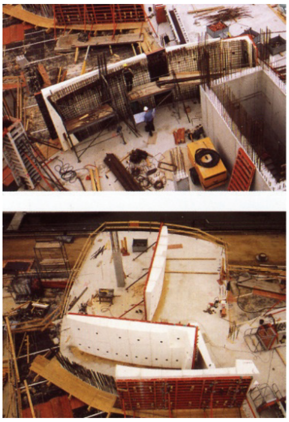


Fig. F.15: The reinforcement is placed in front of a formwork element, prepared wall formwork

Fig. F.16: structural works House C

5.2 Example 2: Bodenkiesel Media House

The organic shaped convention space was developed using a highly complex and currently unique construction method. The unusual building with 3-dimensional bending walls is based on a wood-steel structure clad by 124 glassfiber-concrete facade elements with a maximum height of 5,30m and a maximum width of 4m by 25mm thickness.

Fig. F.17: The „Bodenseekiesel“

The facade elements out of thin, flexible and at the same time stable glassfiber-concrete are fixed to a glued-laminated timber girder combined with a steel frame structure.

Fig. F.18: House within a House – the convention space by 2/3 inside the mediahouse

To be able to manufacture the facade elements the specialists decided to build a styrofoam model in 1:1 first. On the base of the digital model the heights and sections for the realisation were calculated.

Fig. F.19: model of the Styrofoam-igloo und the 1:1 realisation

The production of the prefabricated glassfiber-concrete elements was a highly complex procedure. The styrofoam-igloo was digitally scanned and then split into 124 pieces. The single pieces simultaneously became formworks for the manufacturing process.

Fig. F.20: ready prototype of the igloo

The conventional realisation with steel-reinforcement would indeed have been impossible, however the 2,5cm thick glassfiber-concrete and the unconventional method of the engineers made it possible.

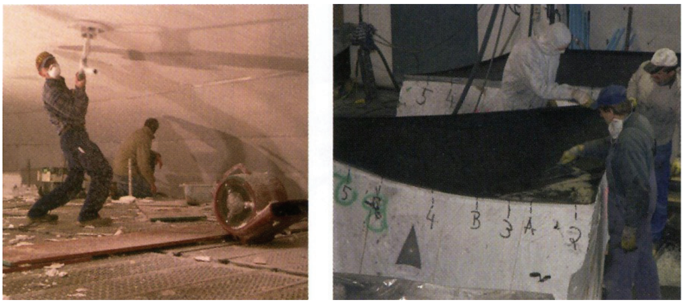


Fig. F.21: modelling of the pebble-form in the igloo; production of the fiberglass-concrete elements

Every facade element became unique. To ensure the same colour for each element the manufacturer needed to take special care of the sequencing of the mixture, the temperatures and the machined mixing in the production facilities.

Fig. F.22: production of the glassfiber-concrete elements

Fig. F.23: assembly of the wood structure

Fig. F.24: interior view of the wood structure and construction of the facade-elements

Fig. F.25: construction of the facade elements connection detail facade – structure

6 Conclusions

The research, development and application of industrialisation in construction during the last 3 decades suggests that by using robotic technologies in prefabrication, on site construction and services, we are able to achieve customised building products at affordable construction costs under constant quality and human oriented working conditions. Recent advances in CNC technologies enable us to design and produce highly individualised precast concrete elements of very complex geometries at reasonable costs and constant quality.

7 References

Fig: Fig.1-6, copyright, H: WECKENMANN, Germany;
Fig. 7-18, copyright, P: HOLZMANN AG, Germany;
Fig. 19-20, copyright, CONNE VAN d'GRACHTEN, Germany;
Fig. 21-26, copyright, SCHMIDT Bauunternehmen and RUDOLPH Baustoffwerk, Germany;

BOCK, T. & LINNER, T. (2009) *Structural Changes and Technology Utilization in German Construction,* in JCMA, Japan Construction Mechanization Association, Japan

BOCK, T. (1988) *Robot Oriented Design*, Shokokusha, Tokio

BOCK, T. (2008) Digital *Design and Robotic Production of three dimensionally shaped precast concrete elements*, Keynote 25th ISARC, 27th., Vilnius, Lithuania

JOHNSON, R.E. & CLAYTON M.J. (1998) *The impact of information technology in design and construction: the owner's perspective*, Automation in Construction, Vol.8, Nr. 1, Elsevier.

MATSUMURA, S. (1990) *Precut Koho no gensai to sono tokucho*, Tokio

PILLER, F.T. (2006) *Mass Customization,* Deutscher Universitätsverlag, Wiesbaden, 2006 , ISBN-10 3-8350-0

PUENTE, E.A. & ARACIL, R. & BALAGUER, C (1986) Sistemas *'CAD/CAM/CAE: Robots Industrials`* Marcombo

VAN GASSEL, F. (2008) *mechanizing, robotizing and automating construction processes,* i- tech education and publishing KG Vienna, Austria

G) Off-site Production Methods – Precast Plant Production

GERHARD GIRMSCHEID[1]

1 Industrial Concrete Product Prefabrication

In recent years, prefabrication methods have evolved ever more toward industrialised, i.e. mechanised and automated methods. Automation using the latest CAD/CAM technology is also now venturing into areas of prefabricated construction. The prefabrication industry is being forced to invest considerably to secure the market share of prefabricated construction against other methods of construction. Major focus is on the flexibility of the equipment to produce individual single components and small series, since large-scale serial production is virtually a thing of the past.

The majority of industrialised plant fabrication methods for producing prefabricated concrete components can be allocated to the following methods of production:

- Production methods using stationary single formwork
    - Short line production
    - Long line production
- Production methods using mobile formwork – production circuits or assembly line production

The following characteristics distinguish between the basic methods of production:

- Production methods using stationary formwork - stationary formwork, mobile workflows in the cycle process
- Production methods using mobile formwork - stationary work posts / workflows and movement of the formwork along the assembly line

The circuit production or stationary long line production methods are generally used in structural engineering. Stationary short line production is suitable for standard prefabricated components whose variability is usually restricted to their ability to adapt to the design variable "length". Circuit production offers better ability than long line production to adapt to design variability in terms of thickness, length, width and of incorporating notches and installations.

[1] Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch

1.1 Stationary short line production methods

Fabrication using stationary short single formwork requires that the tools and materials be brought to a specific point (single formwork) in a predefined time sequence (Fig. G.1).

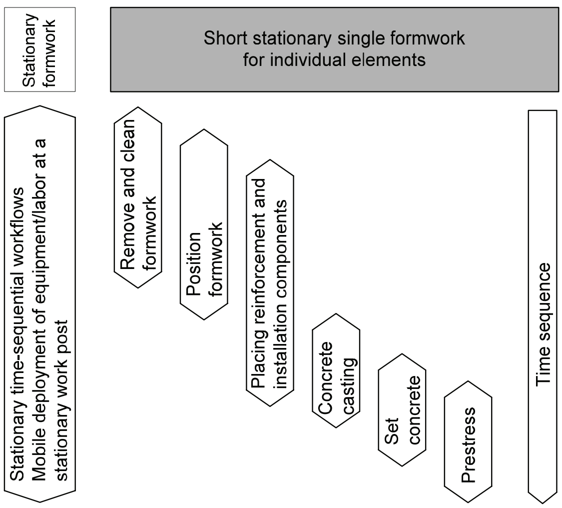


Fig. G.1: Plant production: Principle of short line production using stationary single formwork

The short line production methods include

- Short line production
- Battery formwork production
- Centrifugally cast concrete production

Short Line Production

In order to achieve continual production of **segments of a box girder bridge**, one segment per day and piece of formwork should be manufactured, thus allowing the concrete to set overnight. The segment can be removed from the formwork the next day and moved to the new match-cast segment location. Box bridge elements usually have to be partially laterally prestressed prior to relocation.

Fig. G.2 shows the individual work steps of the production cycle for one day for fabricating a segment of a box girder bridge, taking into account the measurement and control procedures. Production commences by controlling the measurements of the segment poured the previous day (N) and the match-cast segment (N-1) (Fig. G.2/1.). Depending on the design of the formwork, the interior formwork is then removed in one or several steps (Fig. G.2/2.). The match-cast segment (N-1) is subsequently picked up by a lifting device and moved to its storage space (Fig. G.2/3.). The segment that was last poured (N) is lifted out of the formwork and set to match-cast position (Fig. G.2/4.). The rear facing formwork is aligned at the same time. The next step is to measure the new match-cast segment (N) vertically and horizontally (Fig. G.2/5.). The lower and outer parts of the formwork are then put into place, their correct connection to the rear facing formwork checked and their position adjusted to the stipulated dimensions of the formwork using the adjusting and measuring equipment (Fig. G.2/6.). The reinforcing cage, which has already been prepared, can now be placed in the formwork (Fig. G.2/7.). The interior formwork then has to be moved in one or several steps to its position in the new segment (N+1) before the new segment (N+1) can be poured (Fig. G.2/8.).

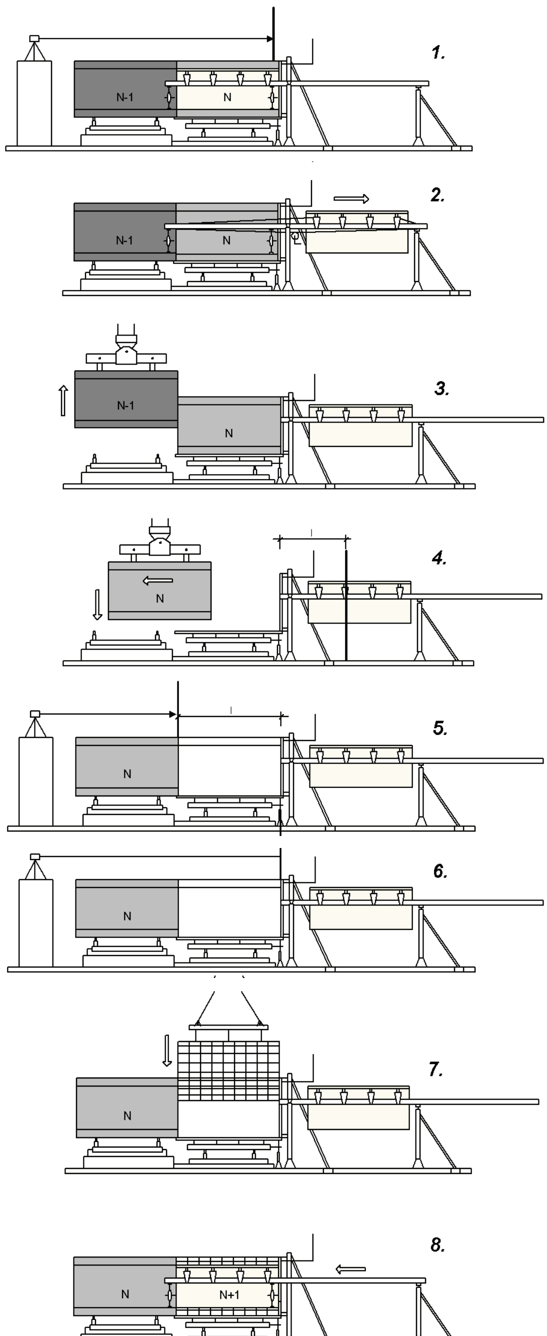


Fig. G.2: Stationary short line segment production cycle

The individual fabrication steps to produce the segments have to be performed in a specific technical and organisational sequence that determines the positioning of the individual pieces of equipment at the production location.

The basic elements of the prefabrication facilities are:

- Production hall for the reinforcing cages,
- Tower crane for lifting the reinforcing cage and pouring the concrete,
- Steel or steel-frame formwork for pouring the segments (Fig. G.3),
- Concrete mixing station and/or ready-mixed concrete,
- Gantry crane, shuttle lift, etc. for transporting the segments to their storage location, and
- Storage location.

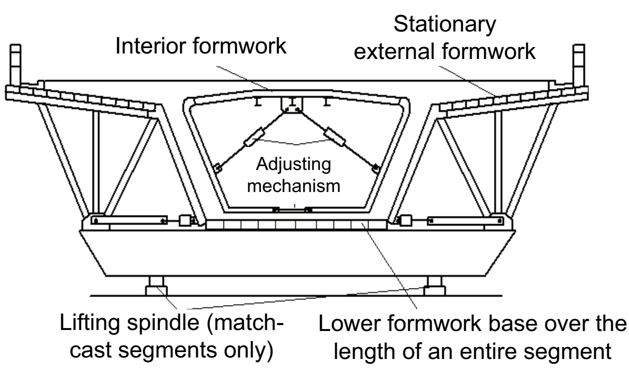


Fig. G.3: Basic formwork structure for short line production of segments

In order to minimise the number of fabrication steps, the reinforcement should be already pre-formed (bended) upon delivery to ensure that the reinforcing cage only has to be assembled using the individual elements at the segment prefabrication site.

When using the short line production method on construction sites, the fabrication of the segments therefore has to be basically organised along the lines of Fig. G.4.

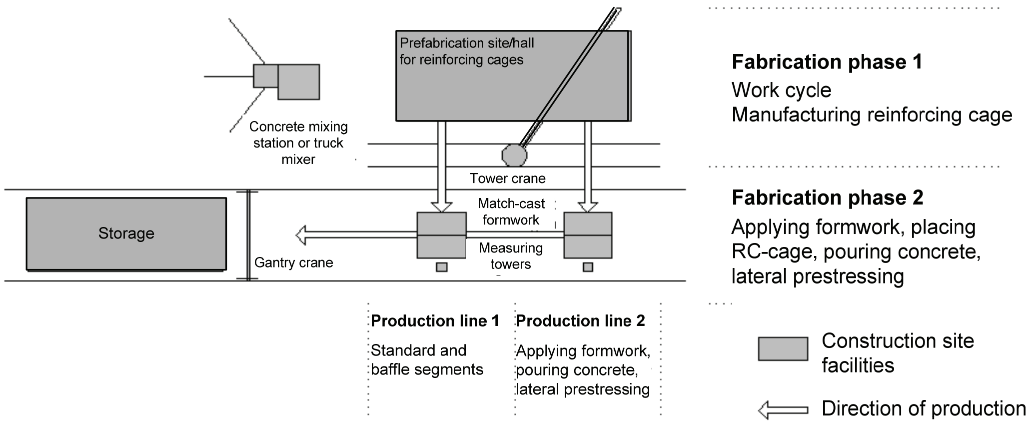


Fig. G.4: Basic short line segment fabrication organisation

Battery Formwork Production

Battery formwork production is also a production method that uses stationary formwork. This production method is especially suited for the fabrication of large-size slabs. Several prefabricated parts are arranged vertically side by side in the battery formwork to ensure that the surfaces of both sides of the slabs lie on and are flush with the formwork. Unlike horizontal formwork tables, where the upper face of the prefabricated part has to be smoothed or specially cured, battery formwork production eliminates the need for these work steps.

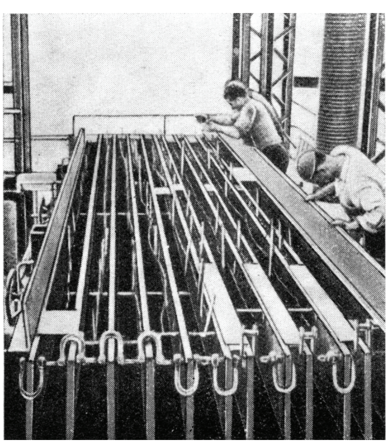


Fig. G.5: Battery formwork (Lewicki, 1967)

Centrifugally Cast Concrete Production

Centrifugally cast concrete production (spun concrete production) is a further short line production method using stationary single framework. Radial symmetric cross sections, such as columns, poles and pipes, can be produced using spun concrete. This method involves placing the reinforcement and the concrete into formwork which is then quickly rotated around its own axis. The centrifugal force presses and at the same time compacts the concrete against the formwork wall (Fig. G.6).

This method produces prefabricated concrete components with extremely smooth surfaces and high levels of concrete strength.

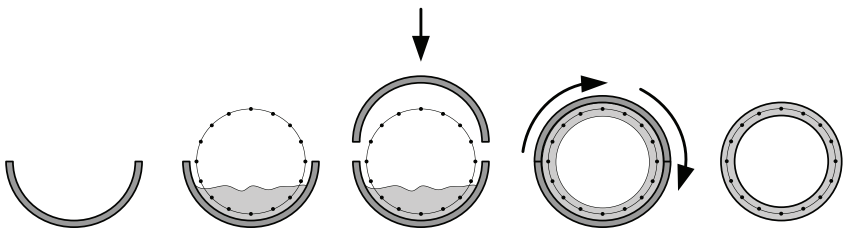


Fig. G.6: Spun concrete production (Lewicki, 1967)

1.2 Stationary Long Line Production Methods

When using stationary long lines of formwork, the equipment and materials have to be arranged in a specific time sequence with parallelisation options above or along the long production line. Fig. G.7 illustrates the principle of long line production in diagram form.

This production method using stationary long lines of formwork includes long line production

- where the individual elements are placed in the long formwork using facing formwork
- where the individual elements are cut apart (sawn) in the long formwork.

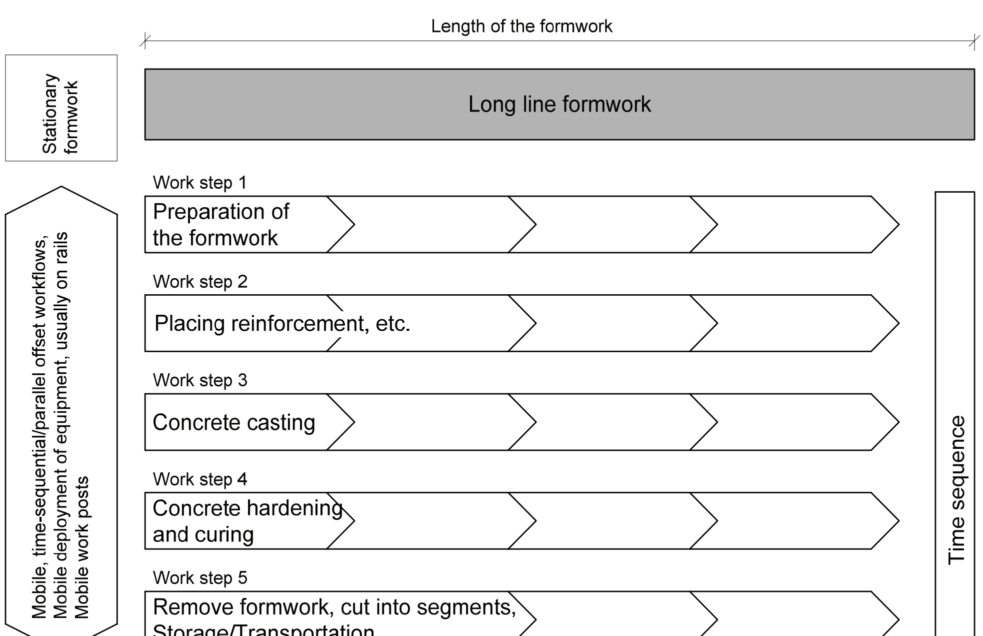


Fig. G.7: Plant production: Principle of long line production - stationary formwork, mobile workflows

Long line production - Cutting the elements apart

There are two different methods used for this type of fabrication:

The **sliding fabrication method** is executed in four steps:

- Stationary arrangement of face to face formwork along a long line, for example: slab elements
- Stationary placements of reinforcement cages, blockouts and inserts
- Movable automated concrete spreader pouring and compacting concrete and smoothing concrete surface
- Subsequent curing of concrete using heat and/or steam

The arrangement of particular formwork for wall and slab segments can be placed by robots with magnetic formwork tables. Reinforcement cages can also be positioned by robots, and the positioning of blockouts and inlets can be supported by automated laser systems.

Fig. G.8 shows an automated concrete spreader for use in long line production. It is used in producing both untensioned and tensioned ceiling elements or binding beams and bridge girders.

When using an **extruder**, relatively rigid concrete is poured by screw conveyors into the previously reinforced fabrication strips and then compacted under high pressure and high frequency vibration. Following the pressing and compacting processes, the concrete is rigid enough to allow the extruder to prop itself on the completed concrete strip and move itself forwards.

Fig. G.8: Automated concrete spreader (Weckenmann)

Once the ceiling or wall elements have achieved the required concrete strength - whether by sliding fabrication or using extruders - the concrete strips are cut into separate elements of variable lengths if no separation forms are used.

Since the stationary fabrication strips allow steel stressing bars to be incorporated into the prefabricated components, the method is frequently used to fabricate prestressed components. Fig. G.9 shows the formwork and reinforcement for such a prestressed girder. Transoms are used to apply tensile force to the tension strands before the concrete is poured (Fig. G.10 and Fig. G.11). The load can then be taken off the transoms after the concrete has hardened.

Fig. G.9: Prestressing strands in a stressbed (Element AG)

Fig. G.10: Using hydraulic presses and transoms to apply tensile force (Element AG)

Fig. G.11: Prestressing strands in a stressbed (Element AG)

Long line production - Facing formwork for the elements

In addition to the fabrication of wall and slab elements, long line production is also used, for example, to produce bridges with cambered soffits, where the individual segments are prefabricated using the match-cast method. Each production encompasses the segments of an entire bridge span, from one pier axis to the next. The base formwork rests on a cambered concrete bed (Fig. G.13). Concrete is poured into every second element between facing formwork that is also used for accurately placing the sheaths for the tendons. Once the facing formwork is removed the face of the segment is treated with an antibonding agent. In the next steps the reinforcement cage is placed, the interior formwork is relocated and concrete is poured into the remaining segments in-between using the match-cast method, thus ensuring that the joint surfaces fit perfectly together.

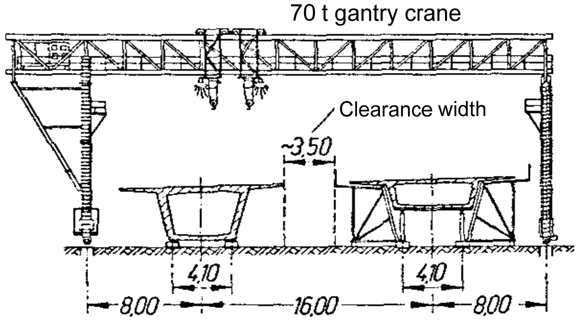


Fig. G.12: Long line production

For example, to manufacture a span measuring 80 m, the same length of formwork base and outer formwork must be available. Since the interior formwork is moved from segment n to n+1 and back from n+1 to n, and therefore used for 2 segments, only half the length is needed. The facing formwork has openings for connecting and fixing the sheaths.

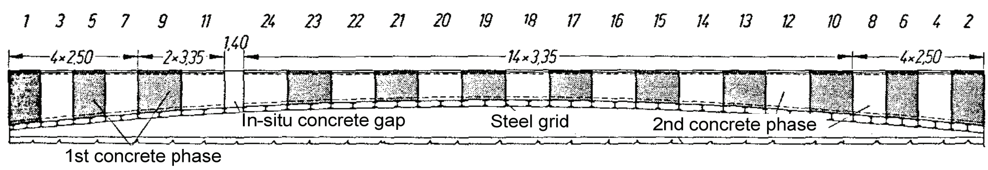


Fig. G.13: Long line segment production (match casting)

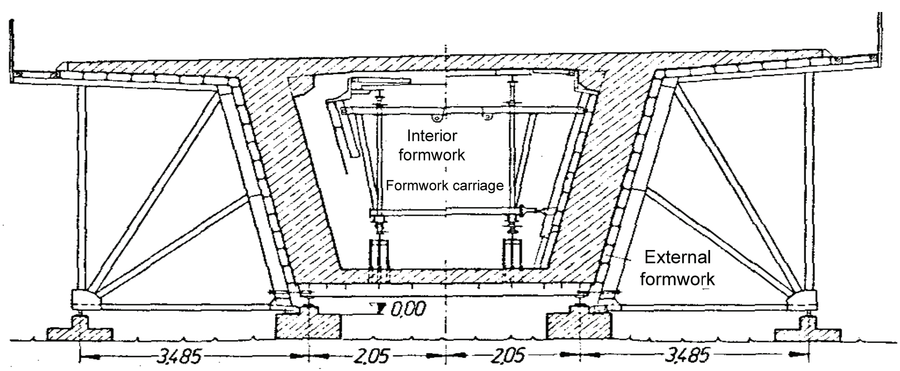


Fig. G.14: Long line formwork

The sheaths of the segments poured in the first phase must be securely protected against concrete and cement paste while the remaining segments are being poured. To this end, rubber hoses are drawn through the sheaths and inflated, thus also ensuring a perfect fit of the sheath axes to the segment joints.

A certain phase shift exists between the fabrication and assembling rhythms since the components are produced from one axis to the next, but laid from one cantilevered arm to the next.

1.3 Production Methods Using Mobile Formwork – Circuit Production (Assembly Line Production)

Circuit production moves the elements on roller conveyors or travelling platforms through the plant from one work step to the next. This method of production is used for large-scale elements, such as wall and slab panels or tunnel lining segments.

In terms of fabrication method, circuit production is classified as plant assembly line production since the machinery is stationary in a line with the production process while the prefabricated components are processed in a continual locational and time sequence.

Fig. G.15 shows the fabrication of slab elements using a circuit production method with horizontal formwork tables with variable side formwork. When using circuit/assembly line production, slab and wall elements are manufactured using the following process steps with moving formwork and at the following consecutive stationary work posts:

- Cleaning the formwork and positioning the side formwork for the individual wall element
- Positioning the lower mat reinforcement with concrete spacers, positioning the installation elements, such as power sockets/cable ducts, pipes, etc., positioning the , spacer cages for the upper reinforcement, and finally positioning the upper reinforcement
- Pouring and compacting the concrete using formwork vibrators, smoothing using smoothing boards or plates
- Hardening in a steam-hardening unit at 60 - 100 °C
- Removing the formwork, curing and storing the elements

The formwork tables are usually fitted with a hydraulic tilting system to ease the removal of the formwork. Fig. G.16 shows a diagram of the principle of circuit production.

Fig. G.15: Manufacturing ceiling elements using the circuit production method (Vollert Anlagenbau, 1992)

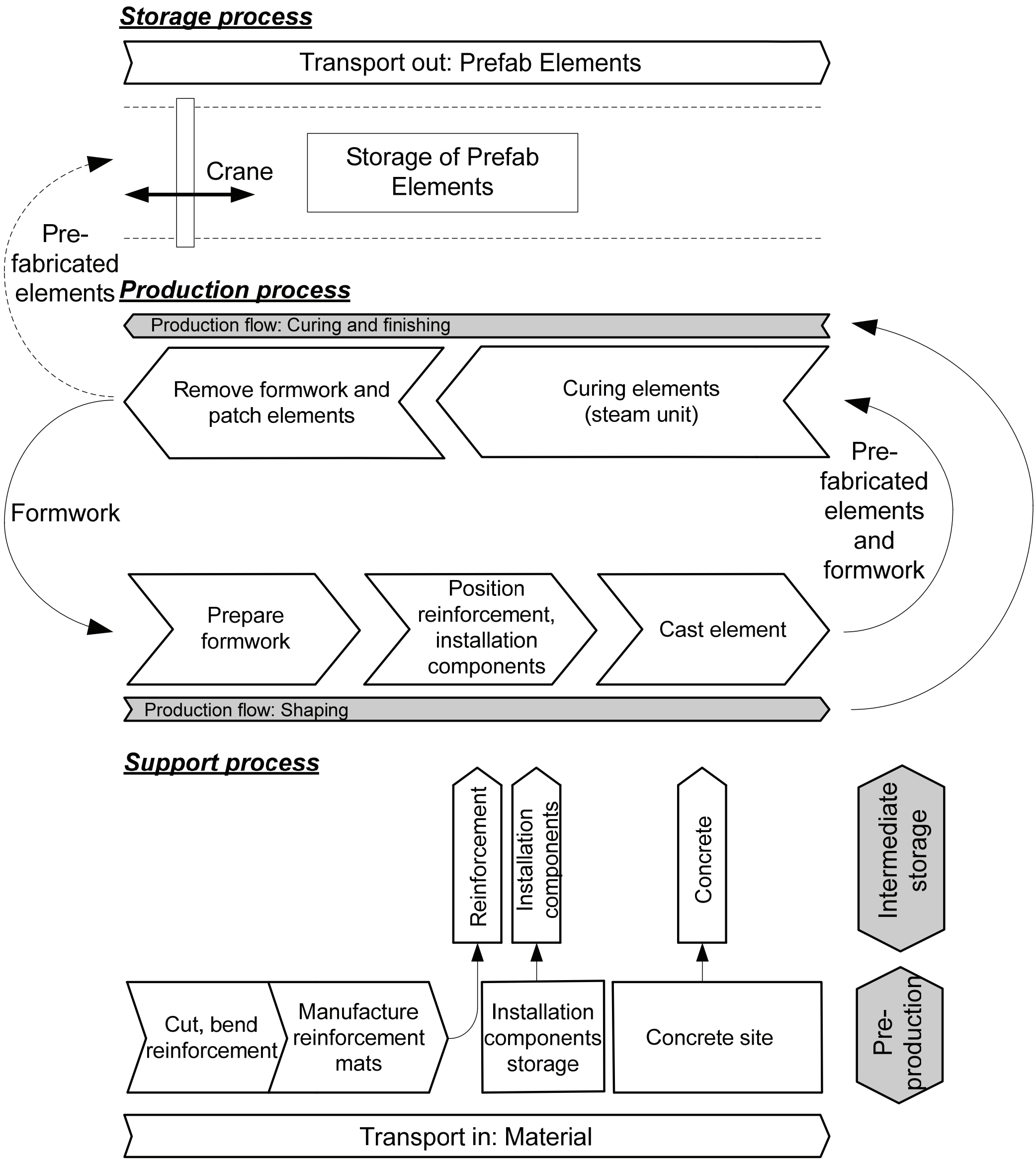


Fig. G.16: Plant: production: Principles of circuit or assembly line production

Because of the process constraints, the use of horizontal formwork tables produces only one smooth surface. Two smooth surfaces are achieved using battery formwork to manufacture prefabricated concrete components vertically (cf. section 1.1).

Nowadays, circuit production methods are designed to ensure high levels of flexibility in the production of prefabricated components. The use of appropriate formwork tables ensures that the formwork setting, reinforcement positioning and the pouring of the concrete are largely automated, which also enables the cost-effective production of small series or the production of single prefabricated components.

Fabrication using the circuit production methods offers the following benefits:

- Better organisation of the entire production process: The requisite materials can be provided without internal transportation issues (in terms of both location and time), and the same worker performs the same task at the same post (monotony)
- Reduced plant costs since the individual work steps can be optimally performed on specially equipped stations and, for example, the vibrators or tilting hydraulic system only have to be provided once, albeit with more convenient features (Steinle, 1998).

One typical field of application for circuit production is the manufacturing of tubbing for tunnel lining in shield TBM driven tunnels.

A tubbing production installation consists of the following partial fabrication units (Fig. G.17):

- Circuit production system (“carousel system”) with movable steel formwork on a production line on rails with sequentially consecutive work areas
- Cutting and bending station and reinforcing cage installation station
- Concrete mixing station with material storages
- Stream curing station
- Storage
- Neutralisation plant to treat wastewater polluted with binding agents (cement, additives)

The individual work steps in a circuit production system are as follows:

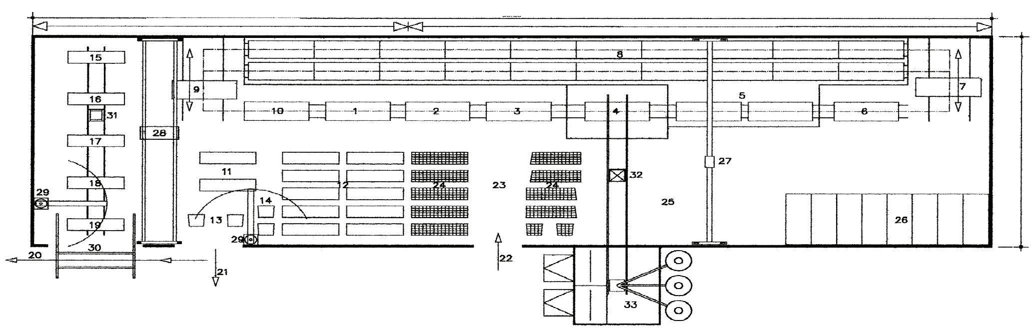
- Removing residual concrete from the formwork
- Spraying the formwork with formwork lubricant
- Positioning the reinforcing cages with spacers, installation components and blockouts
- Closing the sides of the formwork (if they are not already closed before the reinforcing cages are positioned)
- Pouring the tubbing concrete and compacting using external vibrators on the vibrating tables
- Meticulous smoothing of the concrete surfaces, e.g. using levelling or smoothing rollers that rotate inversely to the rolling direction
- Closing the top formwork cover in case of inclined concrete surface
- Moving to and curing in the steam unit
- Pushing out of the steam channel (unit)
- Opening the formwork, removing and finally curing the tubbing at room temperature and applying a sprayed water-impermeable sealing membrane
- Verifying the dimensional accuracy of the tubbing (each individual piece when using single formwork, random checks when using double formwork, e.g. every fourth sample)
- Storing the tubbing

The steam unit and steam channels serve to rapidly harden the prefabricated elements. Saturated steam at temperatures of up to 110 °C is used as the heat medium, which causes the temperature of the concrete during the steam treatment period of 4 - 5 hours to increase to 70 - 80 °C.

The following installations are needed for steam units:

- Steam boiler
- Steam collector
- Pressure regulation and control systems, etc.
- Steam tunnel

The steam-treated concrete should be cured to ensure that it does not lose too much steam during the cooling phase. If it is not cured, it could dry too quickly which would have a negative impact on the further strength. The surface should therefore be sealed with a sprayed water-impermeable sealing membrane.



1 Preparing the formwork
2 Positioning the reinforcement, closing the formwork
3 Final checks
4 Pouring the concrete
5 Preliminary storage (max. 2 hours)
6 Surface treatment
7 Moving to the hardening chamber
8 Hardening chamber (2 lines)
9 Moving to the disassembly line
10 Removing the formwork
11 Tubbing surface sealing
12 24 h intermediate storage of the tubbing
13 Surface sealing + fitting the cap stones
14 24 h intermediate storage of the cap stones
15 Patching the tubbing if necessary
16 Positioning for measuring the tubbing
17 Measuring the tubbing
18 Installation of accessories
19 Installation of accessories
20 Loading and transporting the tubbing
21 Loading and transporting the cap stones
22 Delivery of reinforcement + incidentals
23 Material turnover
24 Reinforcement storage
25 Incidentals and consumables storage
26 Office, workshop, lab, sanitary facilities, etc.
27 Single-beam travelling crane 5 to
28 Two-beam travelling crane 15 to
29 Swing crane
30 Turning and loading station for the tubbing
31 Lifting truck / straddle carrier
32 Skip transport (concrete spreading)
33 Batch plant

Fig. G.17: Tubbing circuit production plant for the Wesertunnel (Ceresola Tunnelbautechnik AG, 1997)

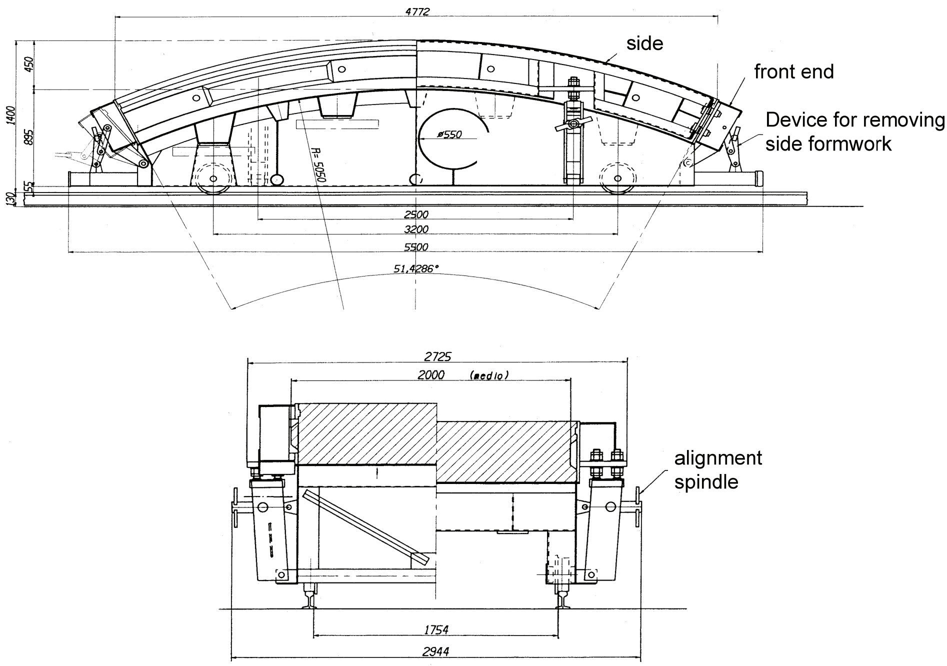


Fig. G.18: Circuit production formwork for tubbing (Girmscheid, 2000)

A typical circuit production formwork for tubbing on rails is shown in Fig. G.18.

Smaller prefabricated components, such as concrete roofing tiles, are also manufactured using the circuit production method. Fig. G.19 shows circuit systems for producing concrete roofing tiles.

Fig. G.19: Production of concrete roofing tiles (Vollert GmbH, 2006)

1.4 Use of CAD/CAM in Prefabrication

Computer aided methods have been in use for design purposes (CAD - Computer Aided Design) and to draw up execution and installation plans for the production of slab panels and wall elements for some time now. But CAM - Computer Aided Manufacturing - is now also being applied to the production of prefabricated concrete components or elements.

Remarkable progress has recently been made in prefabrication in the three classic areas of automation:

- Computer aided design (CAD)
- Production planning and scheduling (PPS) with materials management
- Process flow production (CAM – Computer Aided Manufacturing) and factory data recording (FDR)

Fig. G.20 shows a diagram of a formwork robot for plant fabrication. Magnets and various vertical formwork profiles for the required formwork are rigged and placed by means of process control tandem grabber robot on the base formwork table before the prefabricated component is reinforced and the concrete poured. By the same token, the rigging and placing of formwork to meet individual requirements, the positioning of the reinforcements and installation components and the pouring of concrete are nowadays controlled fully automatically using CAM (Steinle, 1998).

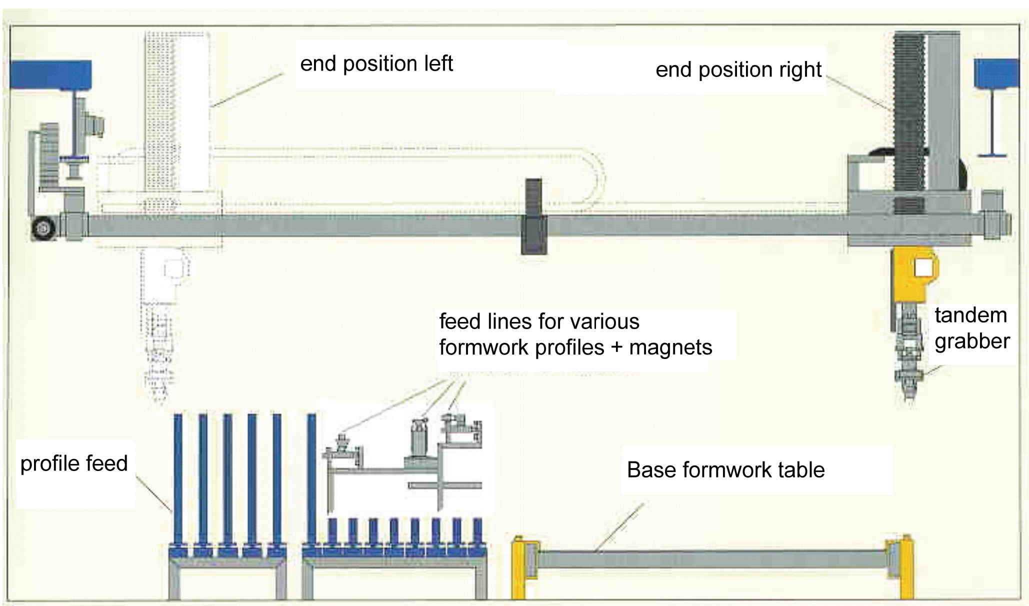


Fig. G.20: Formwork robot system (Weckenmann)

In former times, the construction of a prefabricated component was characterised by the extreme minimisation of material (adapting the cross section to the internal forces), whereas nowadays the shape of a prefabricated component is defined, above all, by state of the art production and assembly facilities that allow reductions in labour costs.

For example, formwork tables and production lines are cleaned mechanically and automatically, the tension strands are laid automatically, and a computer controls the concrete pouring process. In sliding fabrication or production using extruders, the fabricated slabs are cut apart using a fully automated concrete saw (Steinle, 1998). And last but not least, the dimensions are captured by optical gauges and measuring equipment and compared with the required target or design figures.

The cross sections of prefabricated components are adapted, depending on the formwork, by adjusting the settings for the edge formwork or by using corresponding inlays. Cavities, e.g. for cored panels, are created using pre-installed hollow profiles that are protected against floating during the concrete pouring process.

Fig. G.21 shows a formwork robot that fully automatically performs the tasks of marking out the position and installation of facing formwork and installation components on the formwork base table. The reinforcement for the prefabricated components is produced upstream and positioned in the prepared formwork. Fig. G.22 shows the reinforcement that is ready for use in producing a prefabricated component (in this case: element slab panel). Once the installation components and reinforcement have been positioned, the concrete is poured by a concrete spreader (Fig. G.23).

Fig. G.21: Formwork robot (Weckenmann Anlagentechnik GmbH+Co. KG, 2006)

Fig. G.22: Prefabricated reinforcement installed by handling robot (Vollert GmbH + Co. KG, 2006)

Fig. G.23: Automated concrete spreader (Weckenmann Anlagentechnik GmbH+Co. KG, 2006)

Fig. G.24: Automated lifting truss (Weckenmann Anlagentechnik GmbH+Co. KG, 2006)

Fig. G.25: Automated horizontal and vertical transport processes (Vollert GmbH + Co. KG, 2006)

Fig. G.26: Automated crane and rail transport (Vollert GmbH + Co. KG, 2006)

Once the concrete has been poured, the elements have to be transported to various other stations within the prefabrication plant (surface treatment, removal of the formwork, steam plant, etc). These processes are also fully automated. Cranes or rail wagons/transportation systems are used for both horizontal and vertical transportation. Fig. G.24 - Fig. G.26 show such installations.

Large-scale prefabricated components often have to be transferred from a horizontal position (fabrication state) to a vertical position to enable them to be transported to the construction site or installed in their final position. In order to eliminate any inadmissible momentary loads transverse to the slabs, tilting platforms are used to raise the elements into a vertical position (Fig. G.27).

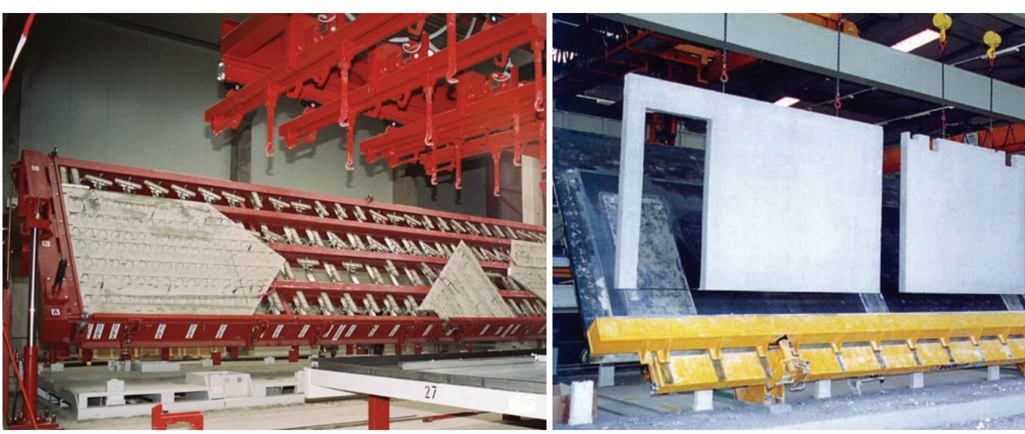


Fig. G.27 Automated tilting platforms (Vollert GmbH + Co. KG, 2006)

A production line for track sleepers is shown in Fig. G.28 and Fig. G.29. Here, again, the formwork for the track sleepers and the track sleepers themselves are moved from one work station to the next, while the individual fabrication units remain stationary. Plants, such as the production line for track sleepers, have a very high degree of automation, thus reducing the manual labour to performing monitoring and control tasks only. In the case of track sleeper production, the demand for huge volumes of identical components is advantageous but not absolutely crucial for such a high degree of automation.

Fig. G.28: Automated track sleepers production unit (1) (Vollert GmbH + Co. KG, 2006)

Fig. G.29: Automated track sleepers production unit (2) (Vollert GmbH + Co. KG, 2006)

Further interlinking of the planning and production processes for prefabricated components will make it possible to cost-efficiently manufacture small series or even single components using a circuit production method with appropriately designed automatic formwork and concrete pouring systems. Because of its process structure, long line production requires a sufficiently high number of prefabricated system components to make it cost-effective.

2 Assembling the Prefabricated Components

2.1 Logistics Planning

When using prefabricated components, logistics planning is one of the central success factors. The logistics include integrating the execution into the planning, with their

- static-constructional
- time-related
- production-related
- transport-related
- assembly-related

procurement-related and capacity utilisation-related constraints. Fundamental characteristics, such as the maximum measurements and dimensions dictated by transport constraints, need to be defined during the execution planning phase, together with the static and constructional requirements. The positioning of elements within the structure also determines the relevant time window for delivery resp. assembly. Production and delivery times need to be taken into consideration as well as the sequence of installation procedures on site.

The construction working drawing must be defined in advance with the sequence of installation / assembly. The transportation capacity relating to the lifting devices on site must be organised according to the assembly sequence in a timely manner to prevent intermediate site storage. Appropriate transportation means to the required installation site also need to be ensured on the building site itself. Access, turning bay and unloading stations on site for trucks with flat bed trailer must be sufficiently large and capable of bearing sufficient loads. It might also be necessary to provide intermediate storage for the prefabricated components on the construction site if the elements cannot be assembled immediately following delivery or if a reserve of prefabricated components is stipulated to guarantee a continuous sequence of assembly.

2.2 Transportation

The transportation of prefabricated reinforced steel components accounts for a share of the overall costs of the prefabricated components that should not be ignored. Transportation is taken to mean all the movements of an element and, as such, includes the following transportation

- from the production site to the construction site
- possibly from the intermediate storage facility or transport vehicle to the installation site

Transport costs are impacted to a major degree by

- the number of transport cycles
- the choice of means of transport
- the waiting times for loading and unloading

- the choice and load-bearing capacity of the crane
- the design of the transport anchorage
- transport routes and distances

A swing tower crane or truck crane with appropriate lifting equipment and capacity is generally needed to mount the prefabricated components.

The choice and positioning of the crane must ensure that the relevant prefabricated components can be safely moved from the flat bed truck or intermediate storage on site to the assembly position of the element on the building without moving the equipment. Moreover, the timing of the transport flows in this supply chain must be organised to ensure optimal capacity utilisation of the crane. Short hook-up times can only be achieved if the connectors for the prefabricated components are easy to mount and simple adjusting aids are used. Truck cranes are usually only hired for short periods whereas swing tower cranes (smaller load-bearing capacity) are frequently available for the entire construction period.

The permissible dimensions for road transportation dictate the widths of the elements between $w \leq 2.40$ resp. 2.50 m and the height of the elements of $h < 3.60$ m that are commonly used at present (permissible overall height of the vehicle 4.00 m). Special dispensation must be obtained to transport larger dimensions by road or if the total weight exceeds 40 t. When applying for these special permits the relevant transportation route and times must be clarified well in advance (it may only be possible to transport at night) (Steinle, 1998).

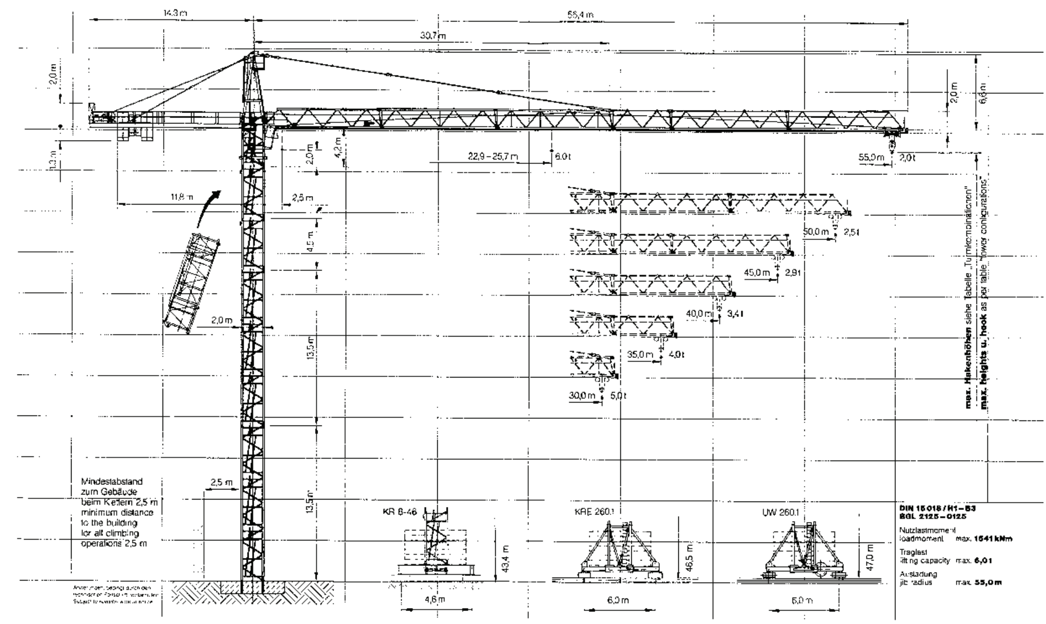
2.3 Assembly

The assembly sequence is dictated by the location of the element in the building and the dimensions, weight and interfaces of the elements defined during the planning phase.

Normal swing tower cranes can only lift relatively lightweight parts - albeit with a wide reach and full swing range (Fig. G.30). The largest swing tower cranes so far built in Germany can still bear a weight of 42 t at a reach of 100 m. A truck crane can move heavy elements if the stabilisers are extended, but must be stood on firm ground to do so. Caterpillar cranes are used to lift heavy loads, for example when assembling entire bridge sections. These can lift up to 1000 t with a reach of 12 m (Fig. G.31), for example. Mobile cranes are used when heavy loads need to be lifted for a short period only. As such, single and particularly heavy or large-scale prefabricated components are frequently moved and installed using mobile cranes (Fig. G.32). It is not cost effective to provide an appropriately large rotary tower crane for the entire duration of the construction works compared with the temporary use of a mobile crane.

Sometimes construction elements have to be assembled in regions that are difficult to access or cannot be reached on normal roads. The use of helicopters is then the cheapest and often only alternative for transporting and mounting construction elements without the need for roads (Fig. G.33).

Generally speaking, the entire assembly sequence must be designed to ensure sufficient **stability** of the structure at any and all times. The use of assembly struts may therefore be necessary for individual components.



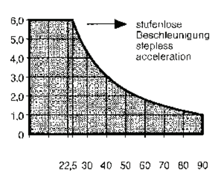
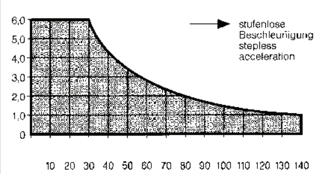
	Hw 628 FU (2-strängig / 2-rope falls)	Hw 637 FU (2-strängig / 2-rope falls)
Motor (kW)	28	37
Traglasten (t) loaddata (t)		
Geschwindigkeit speed (m / min)	22,5 30 40 50 60 70 80 90	10 20 30 40 50 60 70 80 90 100 110 120 130 140
max. Hakenweg (m) max. hook path (m)	190	190

Fig. G.30: Design and load-bearing capabilities of a rotary tower crane (Heuer et al., 1994)

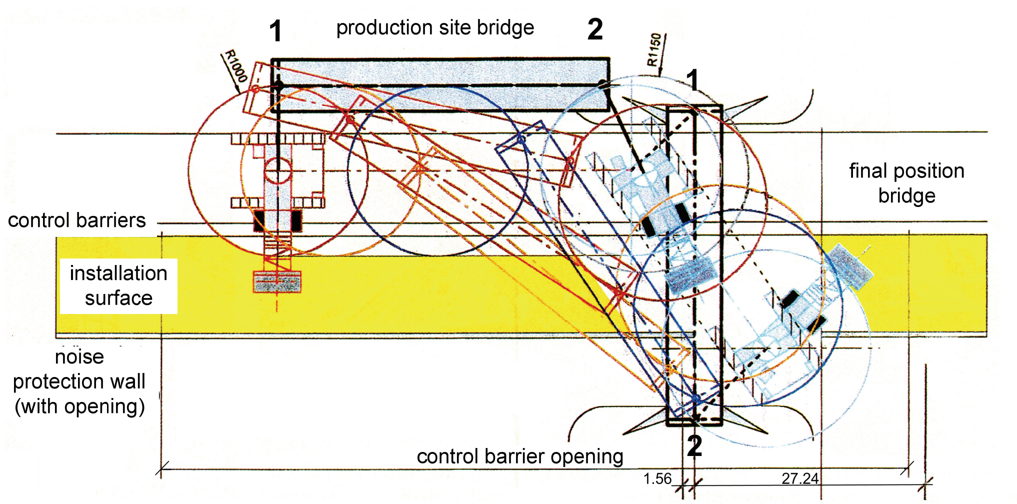


Fig. G.31: Using caterpillar cranes to move a bridge section (in layout)

Fig. G.32: Assembly using a mobile crane (August Bammer, 2006)

Fig. G.33: Helicopter transport (Wicki, 2001)

2.4 Implementing the Transportation and Assembly Logistics

Standardised, systematised logistics checklists are used to implement the overall logistics in a coordinated and goal-oriented manner. These logistics checklists were drawn up by the Institute for

Construction Engineering and Management as an internal means of optimizing the use of prefabricated concrete components for Small and Medium-sized Enterprises (SMEs) (Wicki, 2004). The use of checklists ensures that each project is approached in a standardised and systematic manner, thus creating routine processes that enable work to be performed efficiently and effectively. This helps to avoid errors and to transfer existing knowledge to new members of staff.

The following checklists have been developed for internal use by SMEs

- Work preparation checklist - for the general, project-specific preparation of measures
- Foreman's checklist - to control the implementation of project-specific measures.

Work preparation checklist

The work preparation checklist (Wicki, 2004) is a compilation of the information relating to the project, and includes:

- Project details

It contains a compilation of project details, including the name and internal number of the project, owner, planners, construction managers, foremen, etc.

- Assembly plan

Includes a definition of who draws up the assembly plan. It is either drawn up by the manufacturer itself or the drafting is purchased from external sources. If an external source is commissioned, it needs to be named together with a contact person.

- Assembly sequence, times and deadlines

A detailed schedule has to be prepared for the whole prefabrication contract. This prefabrication schedule has to fit into the overall schedule of the project. The prefabrication schedule has to be placed between the contract and the time window for assembly in the overall project schedule. The prefabrication schedule includes the element planning, material procurement, fabrication encouring, transportation and assembly on site. All concrete elements should be split into groups. Each group of elements should be allocated production and assembly time.

- Assembly equipment

The swing tower crane or truck crane which is specifically needed for the concrete elements should be defined in regard to operation radius and load capacity. The operation location of the crane, weight of the elements, size of the crane, space conditions and relevant capacities need to be coordinated.

- Assembly team

Either the company provides its own assembly team or the assembly is outsourced.

If the company performs the assembly work itself, the person in charge should name the relevant workers to ensure that thought is given in advance to those workers who are skilled in the assembly of concrete elements.

If assembly is outsourced, the commissioned company needs to be named, together with a contact person.

- Assembly materials

The relevant anchorage and assembly materials need to be defined and ordered prior to production and/or assembly. Moreover, if the company is performing the assembly work itself, it needs to ensure that the necessary tools are available in the construction site storehouse.

- Additional materials

Additional system-related materials need to be listed so that the foreman can use this list for preparing the assembly work.

- Ancillary conditions

The support conditions and special requirements need to be defined for each group of elements.

- Tolerance specifications

Compatible tolerances need to be defined for prefabricated components, connecting elements and the in situ frames and walls etc. Usually the on site in situ construction determines the tolerances (widest range of tolerance).

- List of recipients

The distribution list must contain all individuals whose subsequent work will be simplified by the compiled information. These include the assembly foreman and on site construction manager at the very least.

Foreman's checklist

The assembly foreman's checklist substantially comprises a list of controls to be performed. The controls are based on the work preparation checklist.

- Controlling the availability of the work preparation checklist
- Controlling the availability of assembly equipment, i.e. the availability and capacity of construction site or truck cranage, etc.
- Controlling the preparation of the crane locations for assembling
- Controlling the assembly process, times and deadlines in terms of amendments to the project, schedule and process due to site delays
- Controlling the assembly team. Confirming external assembly teams or informing the company's own workers about the forthcoming task.

- Controlling the assembly materials and tools. Are the requisite anchorage materials and required tools already on the construction site or do they still need to be ordered?
- Controlling the required additional materials, based on the work preparation checklist. If material is not yet available, it must be requisitioned immediately.
- Controlling the tolerances of the in situ structure after the concrete has been poured
- Reporting tolerance variances immediately to the prefabrication plant / Instigating corrective measures
- Controlling the ancillary conditions. If all ancillary conditions are not met for assembly, these must be instigated immediately.

Inspecting the construction site the day before assembly

To ensure that the assembly works can be performed on the construction site without any hindrances, the construction site should be inspected by a skilled member of the assembly team some days before.

There are two options if the ancillary conditions have not been met on the construction site: either the problem can be resolved prior to the assembly works commencing, or the assembly works have to be postponed to a later date.

This measure prevents the assembly team arriving at the construction site to find that it cannot work at all or can only perform certain works. This reduces the risk of non-value adding assembly times, thus preventing cost increases (Wicki, 2004).

Work safety during the assembly of prefabricated components

Given the rapid progress of assembly construction, the assembly plan must also define the work safety measures. The reasons for this integrative assembly and work safety planning are as follows:

- It ensures the safety of the workers during each phase of the assembly process (minimum requirement)
- The assembly works are performed efficiently since the workers are performing their tasks under factually and psychologically safe conditions
- The workflow is dictated by the target specifications since improvised on-site safety measures do not need to be drawn up.

The requisite safety measures include fall protection, in particular. Fall protection must be provided both inside the building with fall heights of approx. 3 m, and on the outside of the building. The following types of fall protection are possible (Fig. G.34):

- Mounting a side rail on the prefabricated component
- Erecting a safety scaffold on the building
    - Façade scaffolding
    - Semi-scaffolding
    - Safety nets

- Personal protective equipment consisting of a harness and catch rope in addition to hard hat and safety shoes, etc.

The mounting and anchoring of the fall protection must be planned together with the work preparation for the assembly. The following solutions are particularly recommended:

- Mounting the fall protection using lifting platforms
- Pre-mounting side protection posts on the edges of the prefabricated elements prior to assembly
- Incorporating assembly aids for fall protection into the design of the prefabricated components (Fig. G.34, Fig. G.35)
    - Threads
    - Bushes in the prefabricated component
- Designing the assembly process in such a way as to enable parapet elements on the façade to act as fall protection

Nowadays, system components (e.g. from Doka, Combisafe) are used for fall protection and allow efficient execution if planned properly.

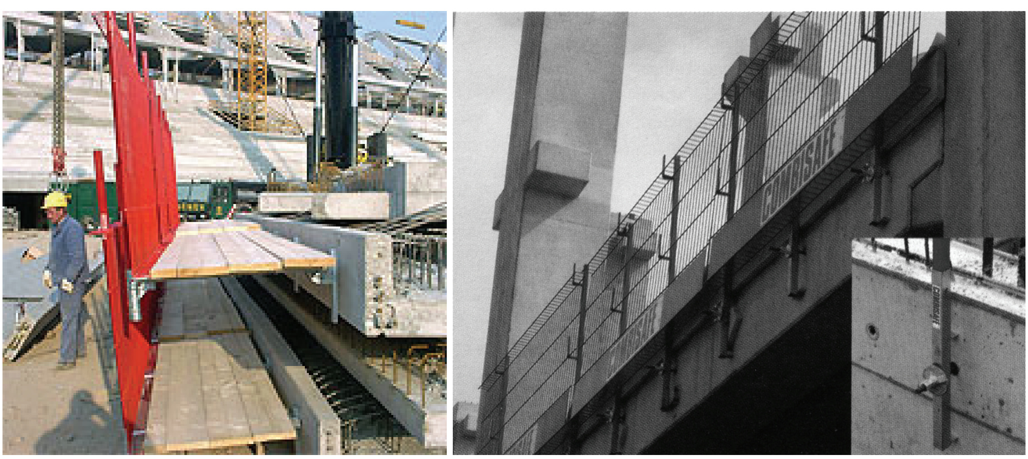


Fig. G.34: Safety fall protection in prefabricated construction (Combisafe Deutschland GmbH, 2006)

Fig. G.35: Safety fall protection following positioning of the prefabricated components (Leisering, 2006)

3 References

August Bammer (2006) http://atriumhaus.at/2004/fertigteil-bautechnik.htm (01.06.2006)

Ceresola Tunnelbautechnik AG (1997) Technische Unterlagen. Magden (CH)

Combisafe Deutschland GmbH (2006) http://www.combisafe.com/deu/index.asp (19.05.2006)

Email Element AG, Switzerland

Girmscheid, G. (2000): Baubetrieb und Bauverfahren im Tunnelbau. Verlag Ernst & Sohn, Berlin

Heuer, H.; Gubany, J.; Hinrichsen, G. (1994) Baumaschinen-Taschenbuch – Ratgeber für die Baupraxis. Bauverlag

Leisering, H. (2006) Schutzmassnahmen gegen Absturzgefährdungen im Fertigteilbau. In: Tiefbau 05/2006

Lewicki, B. (1967) Hochbauten aus grossformatigen Fertigteilen. Verlag Franz Deutige, Wien

Steinle, A. (1998) Bauen mit Betonfertigteilen im Hochbau. Ernst & Sohn, Berlin

Vollert Anlagenbau (1992) Prospekt: Vollert aktuell, Automatisierte Decken- und Wandfertigung, April 1992; Hrsg: Vollert GmbH + Co KG, Maschinenfabrik

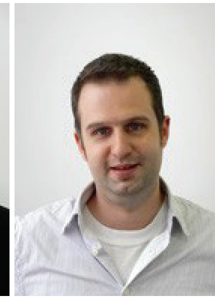
Vollert GmbH + Co. KG Anlagenbau (2006) www.vollert.de (15.06.2006)

Weckenmann Anlagentechnik GmbH+Co.KG (2006) www.weckenmann.de (15.06.2006)

Weckenmann: Prospekt: WeckenmannAnlagentechnik GmbH (D)

Wicki, K. (2001) Effizienzsteigerung in KMU durch Optimierung des Einsatzes von Betonfertigteilen. Diplomarbeit am IBB der ETH Zürich 2001 (CH)

H) Off-site Industrialisation – Process and Production Technologies – Towards Customised Automation and Robotics in Prefabrication of Wood Elements

THOMAS BOCK[1] & THOMAS LINNER[2]

1 Introduction

1.1 Prefabrication and Economic and Technological Influences

The concept of pre-fabrication and modularisation in building industry becomes more and more important in our increasingly industrialised, decentralised and networked economic structures. Not only in building construction industry but also in vehicle manufacturing, engine manufacturing and food supply we have seen an increase of the use of pre-fabricated ready-made elements being delivered by various suppliers throughout the last decades. Moreover, the factor time plays an important role in today's industry and therefore demands for rationalised processes. However, in the huge market of single-family, duplex, and terraced housing basic work is still being done by hand and without prefabricated components. A major aspect of pre-fabrication and rationalisation today is the improvement of processes and thus the increasement of efficiency. The term efficiency hereby can enclose various aspects since the goal is not only a pure cost reduction but also a upgrading of quality. Further, new customer integrating production strategies as "Mass Customisation" in combination with advanced and flexible production/automation systems enhance the value adding potential of prefabrication gradually.

1.2 Current State of the Technology in Timber Prefabrication

Pre-fabrication in conventional building construction industry today mainly focuses on the fabrication of standardised / normalised components. Standardised/normalised pre-fabrication aims at the prefabrication of various existing and well deployed construction components, thus reducing on-site

[1] Prof. Dr.-Ing./ Univ. Tokio, Chair for Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de

[2] Dipl.-Ing., Scientific Assistant, Building Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.linner@bri.ar.tum.de

construction activities. The advantage of this procedure is primarily a reduction of construction time. The second trend on today's building site is the mechanisation and automation of various construction activities. This als means the increased use of automated machines and robotic systems. Construction robots have mainly been developed in Japan to alleviate the construction progress in order to allow an increase of precision on the construction site.

2 Production Strategies

Production determining factors can be distinguished into "hard" and "soft" factors. "Hard" factors are related to decisions about production capacity, factory network, production technology and vertical integration. Personnel/labour management, supplier management, production plant control, accounting and management can be classified as "soft" factors. Both "hard" and "soft" production factors are influenced by the materials used. Brickwork, steel, concrete, carbon fiber composites, wood – every construction material has specific requirements and potentials concerning factory prefabrication. Additionally, depending on material availability and local specifics, different construction types have been developed. These construction types have to be synchronised with production strategies and mentioned production factors.

2.1 Wood – A Perfect Material for Customised Prefabrication

In Japan the prefabrication of timber elements for temples and later for houses has a strong culture. Also in some European and Scandinavian areas advanced fabrication of individual wood elements and wood houses has thrived. As mentioned above, wooden pre-fabrication brings along some advantages since the manufacturing of different components occurs nearly without manpower. The degree of automation in wood prefabrication has already reached a high standard in various countries. Basic methods of wood pre-fabrication can be distinguished:

- **Wooden Log Construction:** The oldest method of construction is the wooden log construction that due its massive construction method hardly finds its use in todays Germany. The pre-fabrication degree is fairly low and constricts itself to the addition of the individual beam.
- **Timber Frame Construction:** Timber frame construction deals with pure technical carpentered connections and a precise joinery.
- **Post Construction:** Post construction that characterises itself through several bar-shaped constructional components with the bracing accomplished through horizontally and vertically nailed boards. The pre-fabrication is also in this case limited to the manufacturing of single rods. A congener to this method is the wooden frame construction. This differs to the post constructional method in that it has a larger span width and a primary structure that is separate from the secondary structure thus allowing a freer arrangement of the floor plan. Indeed in this case the level of pre-fabrication stays the same.
- **Timber Panel Construction:** An important wood prefabrication method in Europe today is the timber panel construction. This method also works with the use of wooden framing however in contrast to the above named procedures the bracing occurs using externally placed wooden plates. This brings about a higher degree of pre-fabrication. Timber panel construction is moreover used by most European building prefabrication companies.

2.2 Multi level integration in timber prefabrication

In every production process different production levels have to be integrated to a general production strategy which is commonly based on a multitude of economic factors. Especially timber prefabrication which already implemented a high degree of CAD/CAM and IT-infrastructures, the production process is a complex set of sequential/parallelised techniques, processes and operations. Following determining and emerging operators for the next generation wood prefabrication systems can be identified:

Degree of Customer Integration

Customisation links the customer demand to the production processes. Continuous IT-infrastructures and network management are the basis for industrialised customisation. Industrialised customisation creates value by establishing company integration at early fabrication and assembly stages. Moreover, it is closely related to modularisation concerning product structures, logistics and production systems.

Product Structure and digitalisation

The product structure is essential for every advanced timber-prefabrication strategy aiming at customised and highly effective production. In general the properties of objects of the product structure can be described by attributes and parameters related to each object. These attributes and parameters have to be adjusted in respect of the expected performance of the following production process. Further, digitalised and parametric data can be used to control production scheduling, logistics, machinery, robots and shipping.

3D CNC Technology and automatic feeding

Many companies fabricating wood elements already have implemented CNC workstations with fully automatic feeding systems. A computer-controlled organisation of production processes in combination with latest feeding technology enables processing stations to be run with less staff meanwhile the product could be adjusted to individual use cases.

Modularisation of primary and secondary systems

The application of pre-fabricated elements to the construction of building's primary systems and secondary systems has spread in Europe over the last decades. Prefabricated primary and secondary elements can be found in concrete construction, steel construction and in wooden construction.

Modularisation of tertiary system

With the installation coordination system "Armilla" designed for the building systems MINI, MIDI and MAXI, Fritz Haller started already in the 60's one of the first attempts to systemise the tertiary structure for prefabricated buildings. This system has been developed further and ARMILLA5 is now a generic computer aided design system, which supports the cooperative design of complex buildings over multiple levels of abstraction. It follows the metaphor of a virtual building site. Especially in timber prefabrication the pre-installation of cables fittings and subcomponents plays an important role. In connection with CAD/CAM systems linked to 3D CNC production techniques the structuring of installations and installation cores according to the chosen type of construction (primary/secondary system) is important for the efficiency of customised prefabrication.

Mechanised and robotised assembly

Robots in the future will be more extensively used to support assembly work of prefabricated timber elements which are designed in respect of the automated off-site/on-site assembly and finishing work.

Maintenance

Robots can be deployed to perform inspections, surface treatments or repairs. However the employment is presently constricted to larger building objects due to the procedural complexity especially in performing sanitary tasks which are still easier to accomplish by hand. Robots currently have a wide application range in surveying tasks that continuously have to be accomplished.

Customer Relationship Management

CRM means the systemic long term management of the relation to the customer. In conventional construction a house is more or less handed over without the intent of a longer relation and in many cases a relation only is based only on managing warranty claims or similar construction related problems. Yet in modern product development a company uses CRM processes to strengthen its continuous contacts with its long term customers. Various informations about customers and customer interactions can beaccessed by employees in different company levels on demand. Typical CRM goals are to improve services provided to customers, use customer contact information for targeted marketing, and to establish a long term relation in order to generate additional products and services related to the main product.

Integration of subsystems/“smart” subsystems

Electronics and micro systems technology as own and separate disciplines more and more disappear and merge with other segments and building sub-systems. In car industry drive and gear are already highly integrated with electronics and distributed and interconnected cooperating sub-systems. Driving experiences of different models are often not generated by placing different drive and gear components but by changing the settings of electronics and software. Similar user-defined, intelligent house centered systems of the next generation will recognise its´ inhabitants moving through the living environment. Room configuration, multimedia systems, human- machine interfaces, climate and energy systems, lightning, height of tables or furniture can be dynamically configured on demand or automatically to changing circumstances. Similar to car industry the enhancement of the technology rate of the house could be used for both strengthening customer relations and offering additional services from energy management up to assistive technology and telemedicine services.

2.3 Automation and CAD/CAM

The manufacturing of pre-fabricated construction elements has for the most part been taken over by machines; this addresses the issue of how the data exchange between units can be optimised to achieve the designated goal. This exchange of information also plays a central role in the control of construction robots. Nowadays this is accomplished through CAD/CAM systems. This means, that data is transmitted directly from the drawing program (Computer Aided Design) of the planner and processed through so-called CAM programs to the individual machine to fabricate components or give a robot its orders. CAM stands for Computer Aided Manufacturing which means as much as computer controlled fabrication. Information is connected directly to CNC machines that obtain the needed information for the next step. CNC stands for Computerised Numerical Control. The goal behind this networking is the technical informational integration of all construction/production related processes.

3 Technologies and Production Processes

Production layouts, production technologies and production processes determine the overall product and prefabrication strategy. The knowledge about layouts, technologies and processes therefore is a prerequisite for any designer or/and engineer concerned with prefabrication. In the section we will outline basics about factory based wood prefabrication and required workstations.

3.1 Wooden Framing Method and Multi Level Automated Joining

The mechanical production of wooden components was introduced by the Japanese companies in the eighties. They developed a production system able to perform multiple working steps simultaneously. This system was in Germany later referred to as joinery machine (Fig. H.1). Joinery machines are CNC controlled and characterised by high performance meanwhile having low-level program complexity. The most well known multi level joinery machine in Germany is the K1 manufactured by the company Hundegger. It is able to process wooden profiles in various sizes ranging from 20x40mm to 300x450mm. This particular machine operates with the principle of a fully automatic single feeding mechanism in order to handle both high batches and single wooden parts without a loss of performance. However, this kind of machine is only suitable for bar shaped construction components meaning in this case only for timber frame construction, post construction and timber panel construction. The pre-fabrication is restricted to manufacturing of individual components for the carrying structure. The joinery machine, however, is able to perform numerous tasks including sawing, planning, drilling and molding. A sliding carriage is able to slides the baulks in the wanted position. The spectrum of fully automated processes covers a wide range of possibilities extending from normal rafters, arris rafters and valley rafters with hexagonal cross sections, end-grain and log house processing to molded and adorned fence posts. Also small sized carpentry firms rely on this technology today.

Fig. H.1: Multilevel automated Joinery Machine

Today, in Japanese factories a multitude of mono-functional machines are connected in a series to a multifunctional workstation. On the contrary in Europe production planners prefer flexible machines where multiple functions can be performed by a single machine. The Japanese method, however, has particular advantages in avoiding the complete breakdown of the production flow in case of a machine fault.

3.2 Fabrication Equipment in Timber Panel Construction

Prefab house manufacturers in Germany prefer timber panel construction due to short assembly times. Prefabricated timber panel construction does, however, need substantial investments in a variety of machines. Moreover, a major investment has to be done to develop the production layout and the specific combination of several subsequent processes and interconnected production subsystems. The end product coming from these interconnected workstations can be simple timber panels or completed fully functional and equipped modules. A production center with a rather high degree of automation and related machines/workstations are subsequently presented. To reach a high degree of automation in general a production line or at least a consequent subsequent processing order (Fig. H.2) are prerequisites.

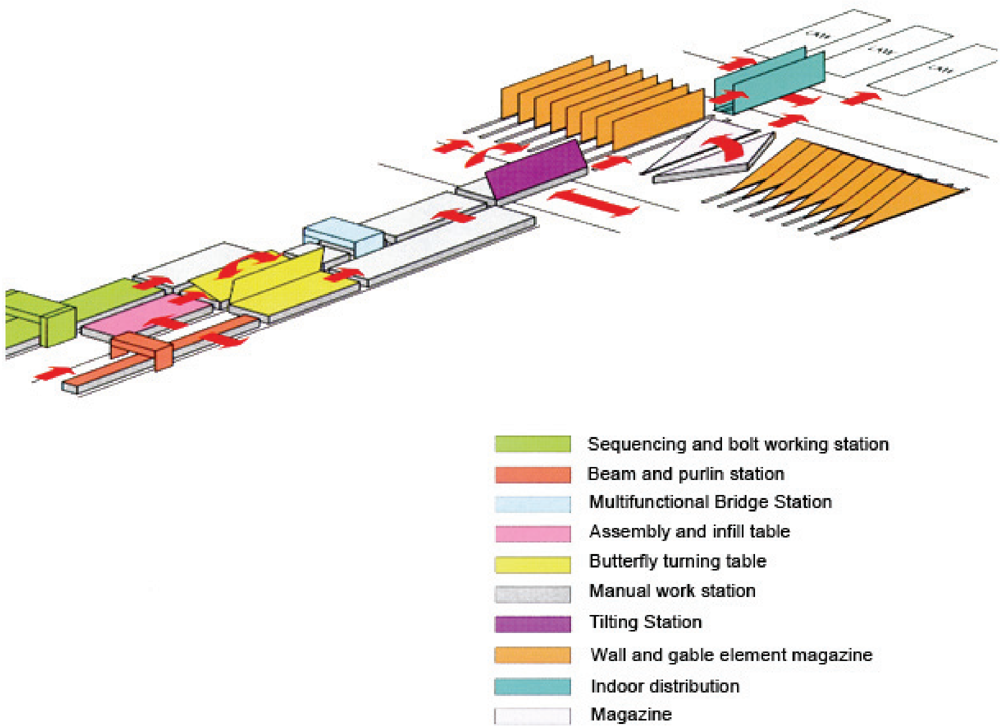


Fig. H.2: exemplary timber element prefabrication layout

Sequencing and bolt working station

This machine performs multiple tasks related to bolt working (Fig. H.3). Two supplying grabbers can place a wide variety of waling, shafts and wooden parapets upon the station and subsequently saw the elements into the proper dimension according to the required measurements. All necessary block-outs and holes are processed with an integrated milling and drill unit. Moreover the machine helps to bring the components into the desired order of processing.

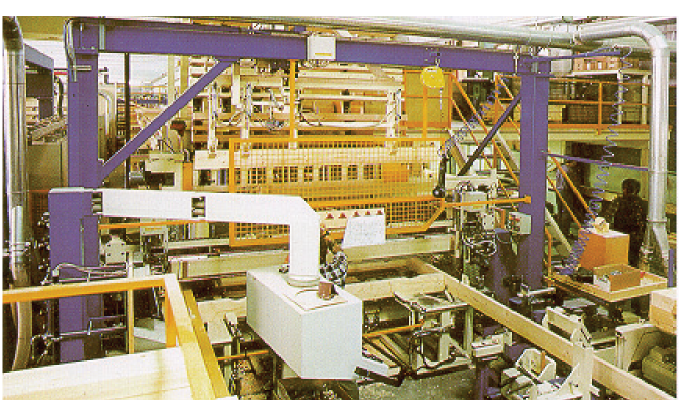


Fig. H.3: Sequencing bolt working station

Beam and purlin station

The wooden elements that are processed in this workstation are either manually or automatically placed on a roller conveyor. A CNC controlled grabber automatically measures the wood components whilst feeding them into the workstation (Fig. H.4). The processes in the beam and purlin station are fully automated and computer controlled containing scribing, drilling, milling, pressing of nail plates and angular sawing. The processed wood is subsequently transported to a magazine where it awaits the next step.

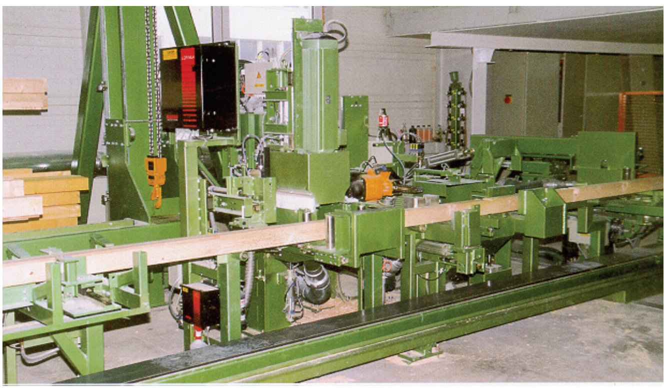


Fig. H.4: Beam and purlin station

Multi-functional bridge station

After the wooden frame has been fixed upon the table, it is taken up by the vacuum system equipped multi-functional bridge that places a desired batch of slabs into predetermined positions. Moreover, different slab sizes can be operated by the bridge station (Fig. H.5). The program controlled multi-functional portal performs the completion of the slab fixing including nailing, clamping, drilling and screwing.

Fig. H.5: Multifunctional bridge station

Assembly and infill

The wooden frame coming from a multi functional bridge station is placed and fixed upon the assembly and infill table. On the assembly and infill table (Fig. H.6) several worktasks can be performed including the infill of components and/or insulation.

Fig. H.6: Assembly and infill table

Butterfly turning table

After the assembly and infill procedure on table 1 has been completed it can be continued on table 2. Therefore the wall element is turned and further processed from the other side (Fig. H.7).

Fig. H.7: Butterfly turning table

Manual works station

The storaged lumber is manually placed and aligned. Integrated halve rails and measuring tapes help to improve the working precision. When a wood element has been fixed, the lumber is nailed and planked (Fig. H.8). The completed wood element can then be moved by a crane or placed upon a butterfly and rolled out.

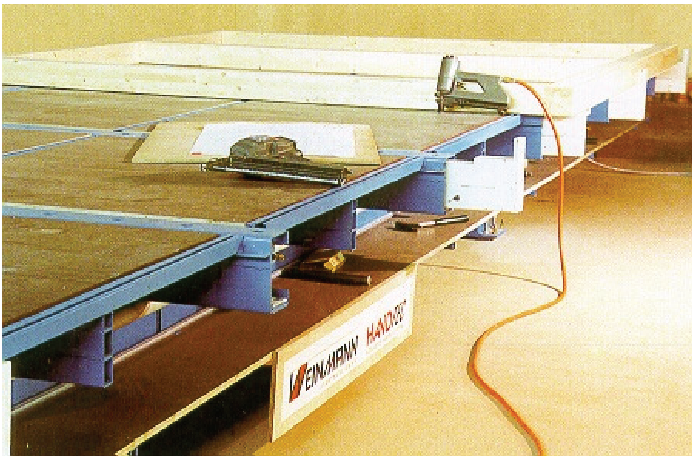


Fig. H.8: Manual works station

Tilting station

The wall and gable elements are transported from the prior tables to the tilting station (Fig. H.9), respectively, and the lateral procedure of the table is carried out on the chosen track where the wall or gabel elements are subsequently fitted into magazines.

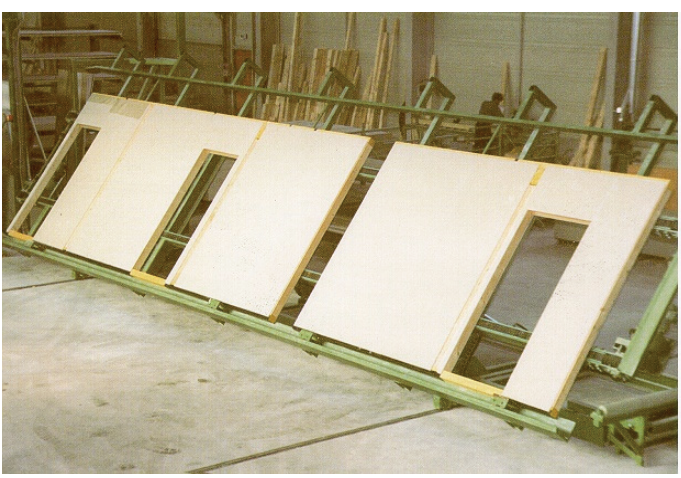


Fig. H.9: Tilting station

Magazine for wall and gabel elements

All wall and gabel elements are temporarily stored in magazines whilst the walls are being processed. The plastering work or the painting of elements as well as the assembly of doors, windows and shutters are also completed in the magazine (Fig. H.10). From the magazine walls or gabel elements can be directly loaded on a freight vehicle or a dispersing wagon.

Fig. H.10: Magazine for wall and gabel elements

Nailing unit for the production of board batch elements

Individual boards are loaded on to the nailing unit (Fig. H.11) using a conveyor belt or a cross conveyor, this can be done manually or automated. A lifting apparatus set up the boards which are then pressed together during the nailing process. During the automated nailing process a nailing image is rendered containing defined protected areas that simultaneously control the nail entry and depth. The length and width of the board batches are variable.

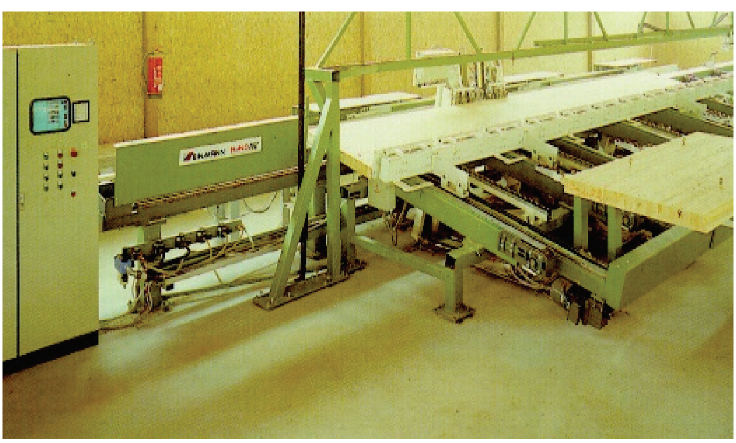


Fig. H.11: Nailing Unit

3.3 Modular Wood Unit Manufacturing

Although there is presently no company in Europe that specifically focuses on the wooden space frame unit construction, it is already being applied in Japan by the company Sekisui Heim which delivers steel frame units (Heim Line) and customised wood frame unit houses (TWO YOU Line). In the "TWO YOU" line system two-by-four and two-by-six construction systems are integrated with the legendary "Unit Method" originally developed for steel frame units. All units are finished in the factory by fixing surfacing materials to the timber frame in a production line based process arrangement. An expert System called HAPPS (Heim Automated Parts Pickup System) supports all levels of enterprise resource planning. Work in the factory is carried out both automated workstations and trained experts. After wood units have been completed in the factory they are delivered to the construction site and assembled just-in-time and just-in-sequence (Fig. H.12). The building is basically assembled and equipped with the prefabricated roof within 9 hours and at one day. Then it takes 45 days for completion and handover to be done. In Japan wood unit prefabrication in general can easily be used for buildings up to three stories. Wood unit buildings are about 5 % more expensive than steel unit buildings and they account for about 20 % of the prefabrication volume compared to about 80 % steel unit prefabrication.

Fig. H.12: Modular building construction Sekisui Heim, completed and packaged module leaving the factory

4 Emerging Concepts for Future Timber Prefabrication

4.1 Flexible Multipurpose Installation Systems

When the service nucleus is excluded mostly all there is left are non-crossing, two-dimensional and individual running cables in the wall and ceiling elements. Inserted, fixed or soldered connections of rigid pipes are not suited for an automated insertion as this process would simply be too complex.

When the necessary working steps are observed (cable path milling, cable insertion, cable trimming, cable clipping) it becomes clear that all actions have to follow the same path. An automated solution that simultaneously processes the paths could be ideal, especially in the case of more complex cabling such as radiant panel heating. Indeed a difference has to be observed between multi-conducting and single wiring water piping. In the case of water and especially heating it is an advantage when keeping the rolled goods churned in running metres since they aren't trimmed until they're inserted and afterwards simply connected a rapid connector using press fittings (Fig. H.13), press or sliding collars together with the sub-connector. In case of the fairly complex and serpentine piping of radiant panel heating, it is only profitable to having it fully automated. With a proper planning all uniform water bearing pipes could be simultaneously completed resulting in less reel changing on the robot and a more efficient piping process.

Fig. H.13: Easy press" connector for flexible multipurpose installation, Blansol Company

4.2 Pre-fabricated Installation Units

The insertion of pre-fabricated installation units (Fig. H.14, Fig. H.15) in newly built or existing buildings gradually increases in importance. There are currently a multitude of different compact modules that based on existing standards and norms offer the possibility of a simple insertion and fastening of installation items. A further development in regard to rapid connected electric and heating connections would, allow a completely automated, pre-fabricated functional interface with accurate geometric fitting. Using horizontal straight plates that simultaneously functions as an arrester would both allow automation and trouble-free connection. Thus pre-installed sub-modules from different sub-contractors could without a problem be docked to the interface.

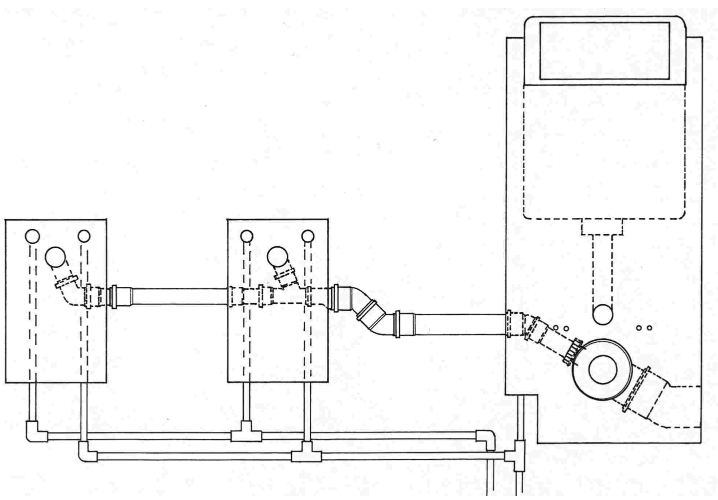


Fig. H.14: Schematic description of prefabricated installation module from the company Rövekamp

Fig. H.15: Geberit Frame – In-wall-system Duofix

4.3 Finishing

Using the possibility of „concealed" joining and installation a near 100% pre-fabrication could also be attained on the surface, since it's still dealing with beam or board/plane shaped work pieces and materials such as square timber, basic material boards, foils or paperboards. Finished wooden- and machine applied plaster surfaces are commonly used making finished inner surfaces feasible. Yet, there are two general "weak-spots" to be documented:

- First and foremost, delivering a surface finished component requires a higher amount of effort in packaging and transport security, respectively. Unlike the established surface-finished goods like furniture are these elements also put together outdoors, transported partly unsealed and due to the size shifted by crane. Even the slightest gust of wind could create inaccurate positioning and surface damage that would have to be repaired on site.

- Secondly, a problem emerges by ceiling splitting: Whilst the walls generally have floor-to-ceiling height and a length that can be delivered in one piece, the ceiling has to be split several ways within its area. Indeed the maximum measurement also depends on the maximum transport measurement, meaning a maximum height of three meters.

4.4 Fully Automated Sequencing, Sorting and Shipping

Prefabricated timber elements due to their structure and weight are advantageous components – compared to brick or concrete elements- especially in terms of logistics. Further, the gradual integration of all processes including logistics IT is one of today's main goals of advanced timber prefabrication industry. Gradually industrialised logistic networks are developing from centralised and hierarchical networks to highly flexible decentralised networks. If those networks are integrated in the "OEMs" IT-Structure, the supply chain management could support customised on-demand prefabrication enormously.

4.5 Integrated Ceiling/Flooring Elements

A newly developed ceiling system could allow 100 % pre-fabricated construction components. Up to now, the ceiling systems in wood construction have mostly consisted of wooden beams which become a planar building component with the plating of boards. The undersurface consists of wooden battens that for the most part are covered with either plaster or plasterboards on the construction site. The raw ceiling slab is after the erection of the walls covered with footfall sound insulation and floating floor with wet or dry treatment. A Pipe system is inserted into the floor pavement in order to install the floor heating system. In the case of dry paving the pipes are inserted into pre-milled fiber boards, however these types of pipe laying can only be done on-site. However, a new ceiling system should be developed with the usage of rapid connection technology which could be completely fabricated off-site. To be able to guarantee the fully automated production of pre-fabricated elements it is necessary to follow a prior determined assembly sequence. (Fig. H.16, Fig. H.17)

- The first step in this process hast o be the production of the structural layer, consisting of a solid wood board that for example could have been produced using the beam stacking or the nail system method. The decisive advantage compared to a beam ceiling is the fact that the elements contain a good storage property and can be fabricated with openings and flybacks without changing its properties much.
- The second step is the production of sound insulation. The mass of the elements is a positive factor in sound insulation however an additional insulation board has to be added in order to attain a constant value.
- Layers of fiber boards or chip boards are added with already integrated heating pipes. The boards are fixed together using a frame consisting of either U-rails or squared beams in order to install all elements simultaneously.

The following pictures exemplarily demonstrate a pipe insertion technique using a CNC unit:

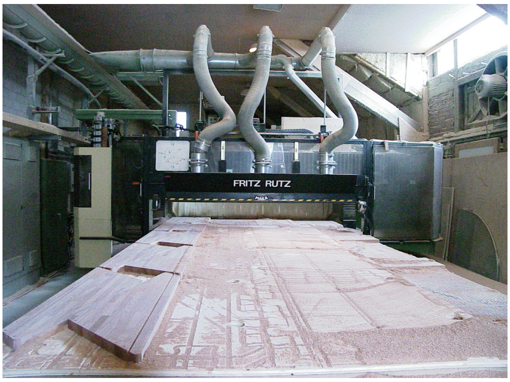


Fig. H.16: CNC-Unit

Fig. H.17: Board element with heating pipes

- The layers are then in the fourth step placed upon the sandwich panel using the frame profile. This step is not timely bound and is prepared by the installer. This way the machines are better operated in terms of capacity.
- The next step is the assembly of the covering layer consisting of solid parquet in the form of planks or similar elements, each layer glued together using the vacuum method. The completed sandwich panel is then placed upon the vacuum press and where it is pressed together into the finished ceiling element.
- Cavities are then milled into the upper surface of the panel to create room for the adjustment units. The robot automatically changes the sawing head from a round saw to an end mill. With the position already predetermined by CAD and cross referencing with reference-points, the cut is made with millimeter precision.
- Additionally the front faces of the panel are milled to accommodate the positioning of the rapid connectors and special brackets for the transportation of the panel.
- The soffit is then either plastered and ground or processed using the mill and vacuum unit if the soffit is to function as a traditional wooden surface.
- The element is following the painting of the panel sides covered with a protective foil and one last time turned over to have the parquet layer ground, oiled and sealed.

4.6 “Plug & Play” Wall Elements

“Plug & Play” wall elements are wall units or wall components prefabricated and completed to a high degree. They can be joined or connected on-site within a minimum of time by the use of special connection systems. (Fig. H.18)

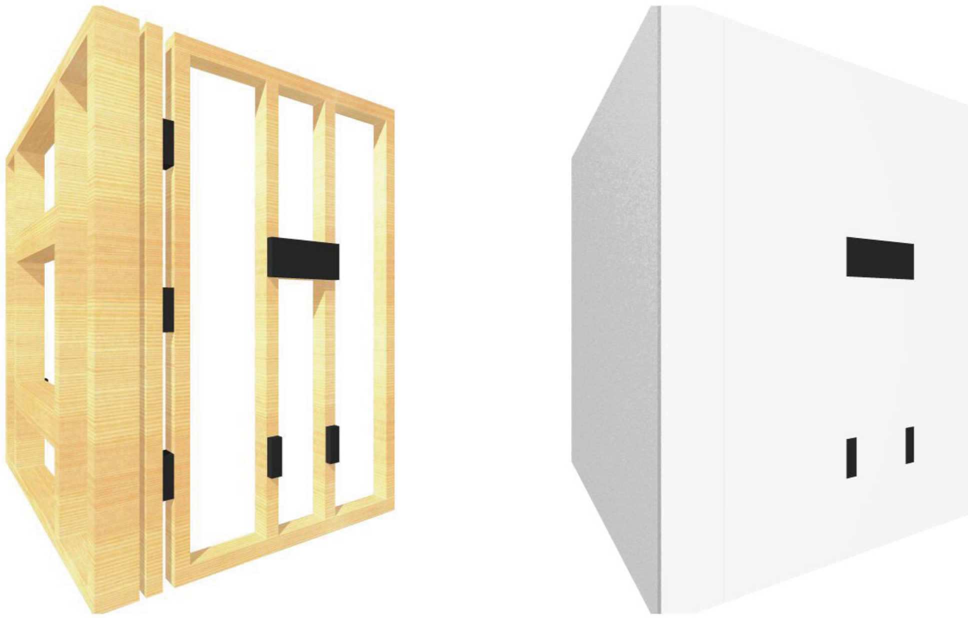


Fig. H.18: Simulation of exhibition walls with Weber Company– Standardised "Plug & Play" connectors

4.7 Automated Off-site Cabling

The electric wiring in wooden prefabricated construction is still primarily completed on-site. Merely taut wires and ductwork is integrated. In order to change this several prerequisites are still not being fulfilled. The disadvantages of the conventional installation:

- The installation of taut wire into fabricated walls requires great diligence in order not to damage the neighbouring cables and moisture barrier foil, since this damage could lead to condensation and a deficiency in wind proofing.
- The cable channelling is due to the taut wire channelling not always orthogonal thus not in compliance with for example DIN 18015 in Germany, which could result in problems/damages during the installation since the user is not aware of the positioning of the cables

Due to these preconditions an installation principle should be developed which allows the orthogonal cable channelling and in no place damages the moisture barrier foil whilst leaving enough space for the installation of plugs, cables or rapid connectors. This method also allows the commonly used installation of bus systems, and other cables. The actuators can be integrated into the wall components thus making a short cable channel feasible.

5 Conclusions

Similar to the standardised body frame of a car which is -after the decoupling point- customised to individual requirements by one-piece-flow and just in sequence delivery of ready-made subsystems, the future prefabrication of timber elements or units will be designed as system frames that could be customised on demand for any layout. Advanced and continuous IT and production infrastructures integrate all processes and applications to a decentralised and flexible production network. Above that advanced 3D CNC pre-cut technology is on the way to support multiple kinds of joints, structure or shape to be made in the factory. Plug and Play components and elements will fasten all process on site and off site and moreover allow enhanced flexibility during the building products' life cycle. The product structure of future timber construction products should be designed in respect of those developments and provide a modular coordination system based on industrial standards and installation slots for the placement of subsystems and sub-components throughout a subsequent factory and process due to individual needs.

6 References

Fig: Fig. 1, copyright Hundegger Company, K1, Germany;
Fig. 2-11, copyright Weinmann Company;
Fig. 12, copyright T. Bock & T. Linner;
Fig. 13, copyright Blansol Company;
Fig. 14, copyright Rövekamp Company;
Fig. 15, copyright Geberit Company;
Fig. 16, copyright Fritz Company;
Fig. 17, copyright Fritz Company;
Fig. 18, copyright Weber Company /BMBF Projekt BEO

BALDWIN, C. & CLARK, K. (200) *Design Rules – The Power of Modularity,* The MIT Press, Massachusetts ISBN 0-262-02466-7

BOCK, T. & LINNER, T. (2009) *Structural Changes and Technology Utilization in German Construction,* in JCMA, Japan Construction Mechanization Association, Japan

BOCK, T. (1988) *Robot Oriented Design*, Shokokusha, Tokio

BOCK, T. (2008) Digital *Design and Robotic Production of three dimensionally shaped precast concrete elements*, Keynote 25th ISARC, 27th., Vilnius, Lithuania

JOHNSON, R.E. & CLAYTON M.J. (1998) *The impact of information technology in design and construction: the owner's perspective*, Automation in Construction, Vol.8, Nr. 1, Elsevier.

MATSUMURA, S. (1990) *Precut Koho no gensai to sono tokucho*, Tokio

PELTZEDER, A. (2006) *Lifecycle costs of immovable property*, Immobilien Informationsverlag Rudolf Müller, Köln, 2006, ISBN 3-89984-156-5

PILLER, F.T. (2006) *Mass Customization,* Deutscher Universitätsverlag, Wiesbaden, 2006 , ISBN-10 3-8350-0

VAN GASSEL, F. (2008) *mechanizing, robotizing and automating construction processes,* i- tech education and publishing KG Vienna, Austria

I) Automation and Robotics of On-site Production and Urban Mining

THOMAS BOCK[1] & THOMAS LINNER[2]

1 Introduction

A high degree of automation and integration of different production levels has already been achieved in industrial manufacturing by the application of microelectronics and intelligent control systems. In the construction industry, however, this development is limited so far to computer-aided planning (e.g. designing by CAAD, 3D modeling, calculation of costs and quantities, preparation of project specifications for contract award, static calculations, etc.). Industrial automated processes are only implemented in the production of components in stationary prefabrication plants (e.g. masonry and concrete elements) in order to obtain high quality results.

However, there is a high demand for on-site solutions since on site construction has a strong culture in Europe and many construction processes could not be transferred to the factory. The conventional building construction on site represents the largest potential for cost and time reductions as well as potential in the development of new technologies in the area of automation. Prefabrication only is a first step and a part of the solution transforming specific and costly adding processes. Irregular demand, great variety and high capital costs in construction require similar strategies as already applied in the manufacturing industry. The shorter the time span between contract signing and utilisation of the building the cheaper the financing of the project. Therefore robot oriented manufacturing requires standardised planning, production and assembly systems.

Systems for these applications have been developed for several years, but they hardly become accepted on the market. The fact that attempts for on-site robotics frequently suffer from technical or systematic shortcomings is no secret: They are often too ponderous and can hardly be transported within the construction site. The navigation of these systems in the chaos called *construction site* is still full of problems and the adherence to relevant safety standards is not yet ensured to its full extent. Nevertheless these problems do not represent insurmountable obstacles. Larger and still hardly

[1] Prof. Dr.-Ing./ Univ. Tokio, Chair for Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.bock@bri.arch.tu-muenchen.de

[2] Dipl.-Ing., Scientific Assistant, Building Building Realization and Building Robotics, Faculty of Architecture, Technische Universität München, Arcisstrasse 21, 80333 München/Germany, Phone +49(0)89 289-22100, www.bri.ar.tum.de, thomas.linner@bri.ar.tum.de

investigated obstacles for a considerable on-site automation are planning issues, subcontracting structures and site organisation.

However the need for more efficiency in the construction sector is not the only reason for considerable automation. There is still a multitude of uncomfortable, hard, partial unreasonable and dangerous jobs on the construction site. The statistics of construction associations and social security institutions regarding accidents at work, occupational illness and long-term disability of building workers clearly characterise the situation. Here automation can make a substantial contribution to humanisation and ergonomic improvement of working processes, if this aspect is considered in the design of the machines and devices. Not least the need for quality improvement in the building industry is to be mentioned, where the application of robots and the associated propagation of efficient procedures will contribute to a higher quality of end products.

2 Robot Oriented On-site Project Planning

An efficient use of robots on-site could be only guaranteed, if specific rules and requirements are considered and integrated already during early stages of project development, modular architectural design, and project planning. In the following chapters planning principles and requirements for automated construction will be shown:

2.1 Awareness of the Robots' Requirements

In general planners are not aware of the requirements of robots and machines. The application of a robot on the building site makes accurate demands on planning and execution of the project. For example the dimensions of the device (width, length, height and weight) are to be considered and the availability of a freight elevator has to be taken into consideration. The knowledge of these prerequisites in the planning stages of the project, however, cannot be taken for granted, rather a system of information and training has to be developed and offered.

2.2 Obstacles at the Location of Robotic Assembly

A highly mobile and flexible human worker can get along with installations on the floor, huddles of building material and stored tools without significant problems. Such obstacles in large quantities are common practice on today's building site. For a robot however they represent an enormous handicap, if not even a prevention from its operational performance.

2.3 Working Sections for the Robot

Working sections for robots are not considered in early stages of planning and construction. Used at a late point of time in building process, no larger and connected working sections remain for the robots. For example when using the machine only for the assembly of the attachment of suspended ceilings, the robot has to deal with many light construction walls, which are rigged up before hand. Taking the common case of an office building including many single offices on both sides of a long corridor, the robot will find working areas not larger than approx. 10-15 square meters. Here an effective application of the unit is completely impossible.

2.4 Reorganisation of Construction Site and Processes

Today the flow of the assembly processes in a space with different assembly troops is being planned only in small measure. There are only few processes, which require an exclusive allocation. The machine in contrast is able to operate within a certain area alone and therefore requires a higher degree of organisation in building site planning. A systemic reorganisation of the building site structure is necessary to deploy automated on-site construction processes. Each automated assembly sequence contains special demands to the building site flow and the building site organisation and requires an individually adapted methodology of the management in each case. Due to the high capital investments, caused by a robot, attention has to be paid to a preferable nonstop utilisation of the device.

2.5 Creation of New Planner- and Trade Structures

The conventional component- and product-oriented separation of planners (architect, engineer for building services, electrical engineer, etc.) and trades (sanitary, heating, electrical installation, interior works for suspended ceilings and walls, etc.) suffices no longer. The process orientation of the robots requires a process orientated organisation of planning and realisation. Regarding the planning as a new engineering profession (like an engineer for physics in construction or other special engineers) could care for the automation know-how and the needed coordination between the other planners in the project team.

Automation engineers would perform the following tasks:

- Specification of task criteria for the planners
- Expert advice during the design process
- Examination of all plans concerning its special criteria
- Generating specific data such as project specifications of pure machine trades.

These partial tasks are taken away from the classical task profiles of different other engineers. Here the problem has to be solved how to organise the fee structure. This task also could be taken over by the coordinating architect or another planning engineer, both educated and qualified in the field of automation. In this case they deliver a "special service", which requires supplemental fees. Concerning executing companies, like the planners, a rearrangement of tasks from existing trades to new trades has to take place.

2.6 Automation and Building Information Model (BIM)

For the robot trade the planning specification of different engineers has to be unified. This determines the creation of a common digital building model. Apart from the fact that this should be required for each planning by the reason of increasing effectiveness, in automation additional rationalisation potentials arise as a result of this measure. The use of computer controlled assembly devices offers for the first time the possibility of a constant data flow from planning to the execution on construction sites.

2.7 Industrialised Components and Processes Integrated by CAD

In order to ensure a strict data flow from planning to realisation this method applies pre-defined building elements, which have to be used by all programs and have to be to all planners' disposal on demand. The building elements could be offered by individual producers of CAD-system according to general standards. It is also imaginable that component producers or realizing companies offer CAD-building elements in form of product catalogues. In both cases these elements make it possible to create defined interfaces with regard to data transfer into other planning areas (e.g. mass determination, room equipment catalogue, submission, calculation, calculations of building physics, etc..). In this case a defined interface to the realizing company is of special relevance: the data model of the planning enables the contractor of the robot craft now, to attach his data for preparatory work (materials allocation, personnel planning, logistics, etc.) and even working data for the robots (drilling positions, driving data determination and optimisation, material supply, collision calculations, etc.). Just as in manufacturing, robots and automated plant only become advantageous when properly integrated into a continuous IT infrastructure which links design to manufacture.

2.8 Virtual Assembly Simulation and On-site VR Deployment

In other industries as for example car industry and ship building industry this request is considered a matter of course and products are not assembled until the virtual assembly could be conducted frictionless. However in conventional building industry this method has never been considered. Yet with the gradual integration of CAD, BIM and in combination with continuous IT infrastructures and robotic on-site applications virtual assembly simulations of on-site construction becomes interesting. Virtual simulations of the construction organisation and joining processes could help to detect difficulties and collisions before the construction starts and could later also serve as basis for VR supporting on-site tasks.

2.9 Integrated, Continuous and Automated Measurement Process

The demand for a continuous measurement of the shell on the part of the principal to a correct quality control as well as to a status statement of all subsequent work seems to be evident for any kind of construction - however it is not always applied in the building industry. This method is essential to the efficient use of robots. The adjustment of the theoretical building model of planning to the built reality is necessary for the generation of the correct driving and working data. Additionally thereby an early and coordinated reaction on realizing errors is possible for all subsequent systems. There is big potential in linking those data to advanced organisation and on-site automation and thus making a step towards real-time awareness of what is happening on the construction site.

The items mentioned show that extensive research work has to be done in the field of planning and building management to assist the evolution of robots on the building site. Therefore the following chapters give an overview concerning state of the art in on-site industrialisation and automation and show arising tendencies in different application fields.

3 Stand-alone On-site Robotic Devices

Big Japanese construction companies for example have been researching and developing robotised construction processes since the beginning of the 1980s. Initially, individual robots and remote-controlled manipulators were developed for specific processes on building sites. This included robots for delivering concrete, handling concrete, applying fireproofing to steel constructions, handling and positioning large components and, as a final example, facade robots for plastering and painting. Over 400 different prototypes were developed and tested on building sites. They all had in common that they were intended for use on specifically defined tasks under building site conditions and were not supposed to have an adverse affect on the work carried out by the construction workers. It became clear that only a few robots were economic to use under these conditions. The restrictions on the workers, the safety regulations and the unforeseeable and unplannable events that affect building sites strictly limited the use of individual robots in parallel with normal work. There are only a few currently in economical use or offered for sale on the market. Examples are the concrete smoothing robots from Kajima and Tokimec. This development revealed that it is difficult and, in particular, not economic to transfer production conditions from the factory floor to the building site. This might seem to be a mundane and predictable result, but it must be acknowledged that these developments were only seen as a first step on the way to automating construction processes and that economy was not the primary objective. There are two other crucial results of significance to the future of the Japanese construction industry. The first is the knowledge and skills acquired in the area of automation and robotics, and the preparation of workers for innovation in the construction industry. The second is the groundwork for the real objective - to automate the final assembly of a building on a building site under factory-like conditions and in bringing to bear the laws familiar from serial production.

3.1 Modular Robot Systems

Alternative process units for different assembly operations can be mounted on a flexible transportation unit. The components *transportation unit* and *process unit for ceiling attachment* were selected for further development and production of a prototype. Because of the multitude of obstacles on the floor, it was decided to use a track vehicle as transportation module. Navigation is realised by an image processing system mounted on the transportation module detecting the chalk line which had been applied manually on the floor. So the machine is able to follow the line and to detect the marked points of operation. The travel on site and the change from one chalk line to the other are controlled by the user with a joystick. At the point of operation the process module drills the borehole into the concrete ceiling, fixes subsequently a pin or a dowel, and assembles the suspension rod for a suspended ceiling system.

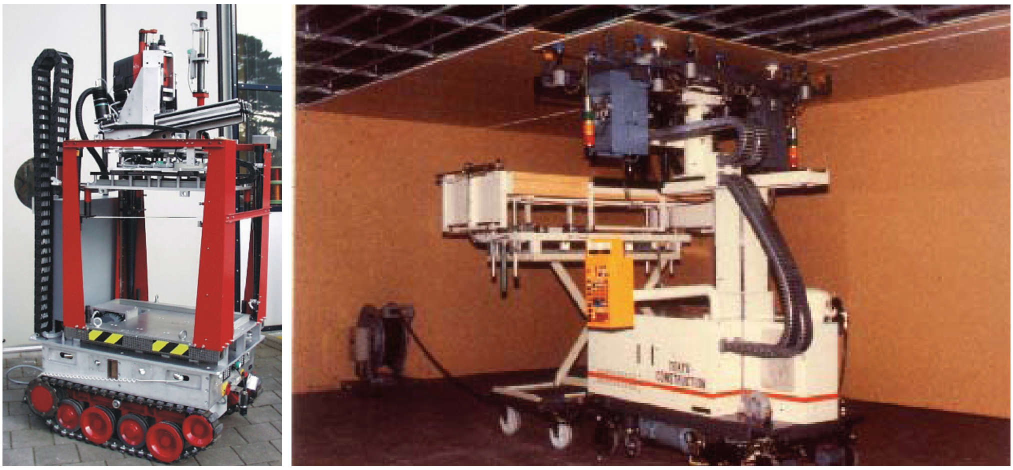


Fig. I.1: Prototypes of a modular robot system for interior finishing

In order to perform these tasks the prototype comprises several lifting mechanisms, a conventional hammer drill, and a conventional device for fixing bolts. Sensor technology and computer control ensure the fine positioning and the perpendicular transfer of the point of operation from the soil to the ceiling. This device was developed as a prototype in the context of a research project. While testing it on several building sites it was recognised that many prerequisites in the aspects of planning, subcontracting structure and site organisation are opposed to an economic application of the new technology. A further development and optimisation of techniques is was sufficient: new planning methods and adapted methods of site organisation are to be found in order to enable automation on the building site at all! Additionally it was realised that the application of the new machinery will be impossible without special knowledge of planners and contractors. Therefore tools and aids have to be created, which enable all involved parties to apply such new construction techniques.

3.2 Robots for On-site Construction Assistance

In Japan the first facade and roof robots were developed and put into operation at the beginning of the 1980s. It should be noted that these devices were almost without exception developed by the technical departments of large building companies or by their construction machinery suppliers and not by service providers or cleaning equipment manufacturers. This was due to the narrowly defined area of application of the equipment which, as a rule, was used only on one large building erected by the company in question.

Fig. I.2: Construction material distribution robot

Fig. I.3: façade diagnostics robot;

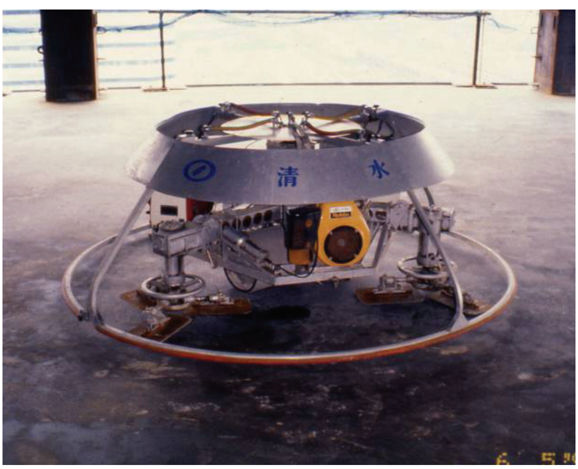


Fig. I.4: Finishing robot Shimizu

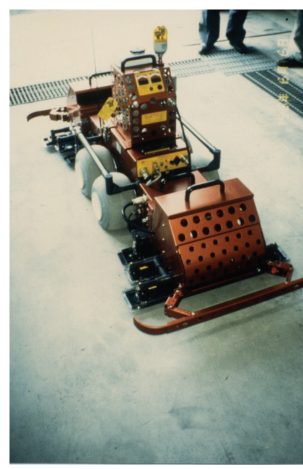


Fig. I.5: Modular mobile light weight concrete finishing robot

There are many varied applications. Initially there were bulky, rail-guided robots such as the exterior wall painting robot from TAISEI, which was developed to apply paint to the 100,000 m^2 facade on the 220 meter high Shinjuku Center Building in Tokyo.

3.3 Robots for Building Structure Assembly

ROCCO is a Robot Construction System for Computer integrated Construction (CIC). During a research project a system had been developed which enables fully automated masonry construction off-site or on-site. Goal of the project was the development of a computer integrated robot system, which also contains a continuous solution in the ICT for all steps from the architectural design to the automated assembly of the components on the construction site. The mobile robot system executes the generated programs on the construction site by a hydraulic controlled manipulator on a mobile platform. (The system is described in detail in Chapter III, Brickwork)

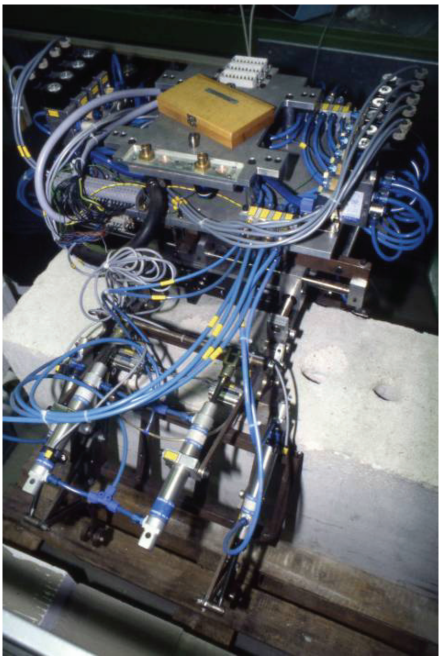


Fig. I.6: gripper for solid structure components

Fig. I.7: manipulator on mobile platform

4 On-site Mechanisation by NCC Komplett production System

The combined and strictly organised off-site/on-site factory concept of the Swedish construction group NCC marks a step between the development of stand-alone robotic solutions for specific construction tasks and their interconnection to more complex and IT integrated networks of robotic systems on-site. In the NCC factories 60 operators work on job rotation time schedule. The yearly capacity amounts to 1000 apartments, each worker producing 17 apartments yearly. Automation and mechanisation are ergonomically designed to reduce labour fatigue. NNC also implemented advanced logistics and every 15 Minutes a truck leaves the factory to related and mechanised on-site factories. The on-site factory concept is connected to a high rate of prefabrication: apartments are 90% prefabricated. The investment was about 30 million euro. The on-site assembly factory is all weather proofed enabling ergonomic working conditions all year around. According to the company construction time is reduced by 75% and total labour by 50 %. Replacing craft labour with mechanical skills all processes are relying on computer technology.

Fig. I.8: assembly of prefabricated wall components in on-site assembly hall

Fig. I.9: On-site factory of NCC Complete

5 Hybrid Construction Systems and Automation

About 200 different robotic devices had been developed, tested on site and improved. The highest degree of automation had been reached in tunnelling from the prefabrication of tunnel sections, its transportation and assembly. Since sites and its conditions greatly vary at each project, the processes have to be well defined in order to be robotised. Furthermore the planning and design has to facilitate robotic construction by robot oriented design methodology. The full potential of robotics will unfold as soon as robots do not just copy human work but rather be enhanced by robot oriented planning, engineering, management, labour training and qualification. The financing of expensive robotic equipment must be supported by financial institutions. Investors should appreciate the immediate availability of their real estate by forwarding their higher and earlier return of investment in the form of higher construction project costs.

Several hybrid construction systems were running between early nineties till year 2004. Some companies developed systems that pushed the building up to ten floors, others had climbing systems with one to three gantry cranes or about 20 trolleys simultaneously transporting and assembling columns, beams, floor, interior wall and exterior wall panels and sanitary or installation units. Working conditions on site became similar to factories and there were no accidents or quality problems. The first step to fully automated construction sites were hybrid construction systems where conventional construction and advanced It controlled machinery and automated construction methods had been combined. Additionally in hybrid construction sites often parts of the building (e.g. solid core units) are erected by more or less automated systems meanwhile other parts are constructed simultaneously by conventional processes.

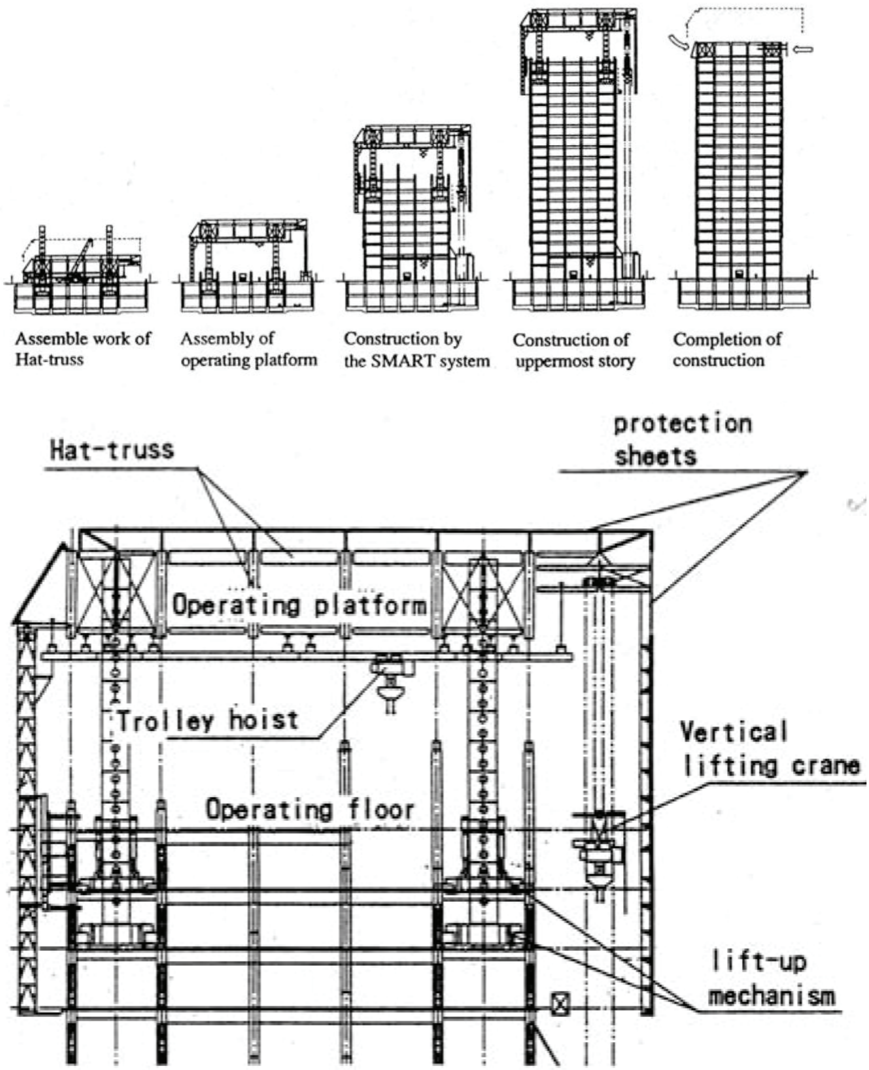


Fig. I.10: Section of a hybrid integrated automated building construction unit with about 20 robotic trolley hoists for logistics and positioning

Similar as the JIT (just in time) of the Toyota production system factories supplied building components in a ten minute cycle to the site in some central city areas in Tokyo. Since there were no storage areas for construction materials on site, construction materials were directly grasped by the robotic trolley hoists from the truck. Some systems could also adjust to non rectangular floor plan layout proving that flexibility in design can be achieved by constantly improving robotic technologies.

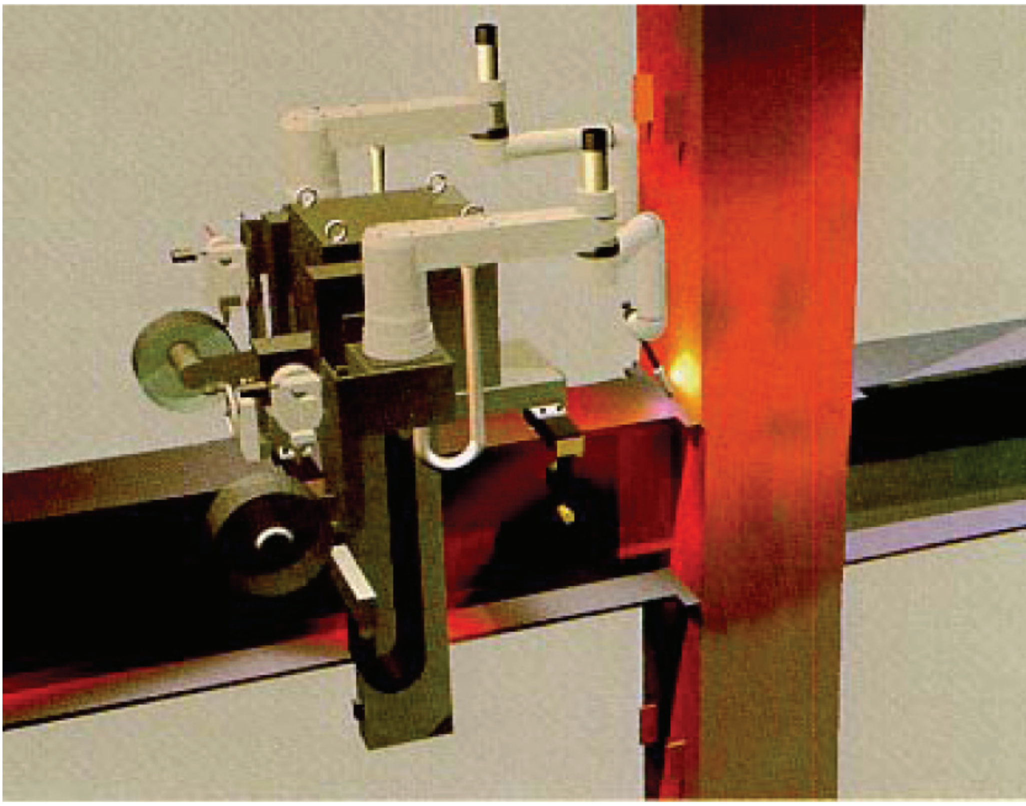


Fig. I.11: Transportable welding robot in a hybrid building construction site

6 Automated High-Rise Construction Sites

The first prototypes for mainly automated high-rise construction sites were put into operation in 1990 and 1991 by Shimizu after five years in development and a financial outlay of almost 16 million Euros. Since then, 20 automated high-rise sites have been operated by different companies (Taisei, Takenaka, Kajima, Maeda, Kumagai). The finishing ratio of those systems also relying on co-adapted prefabrication could reach up to 90%.

An automated high-rise construction site is understood as the semi- and fully automated storage, transport and assembly equipment and/or robots used to erect a building almost completely automatically. It is the attempt to improve the sequencing of construction processes and construction site management by using real-time computerised control systems. This includes an unbroken flow of information from planning and designing the building through programming the robots with this data to using computers to control and monitor building operations on site.

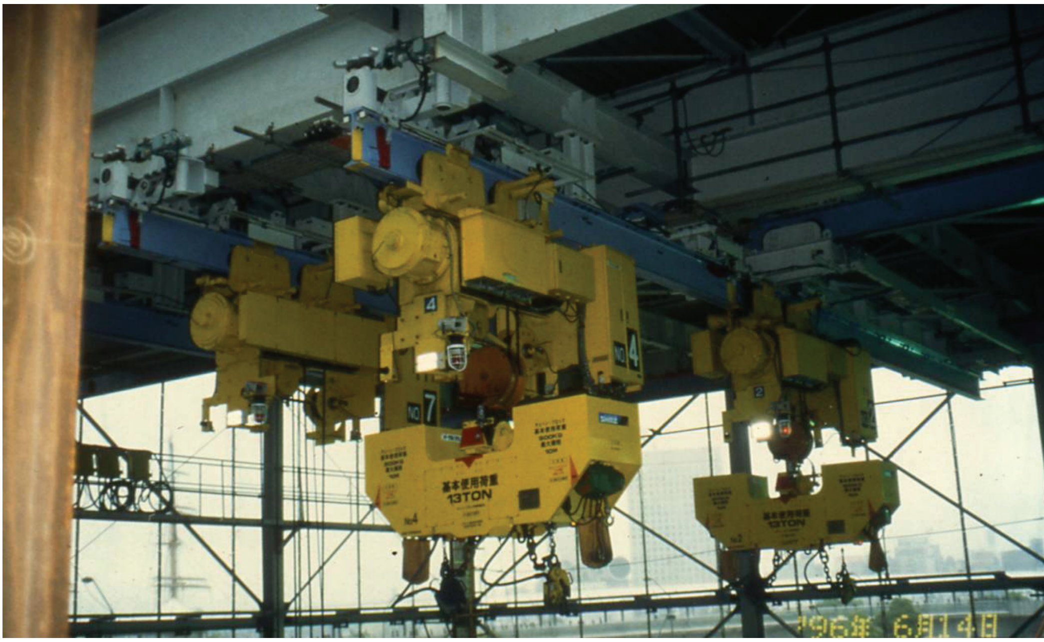


Fig. I.12: robotic trolleys for transporting and positioning of beams, columns, floor panels, building services units and facades

After the foundations have been laid, the production equipment, on which the steel construction has been installed with assembly and transport robots, is covered completely with a roof of plastic film. Depending on the system, this takes from three to six weeks. Then the robots go into action. Two steel and ten concrete plants supply parts in ten-minute cycles on a just-in-time basis. This approach to supplying is not necessarily part of the system, but is due more to the lack of space around building sites in large Japanese cities.

Fig. I.13: column placing system

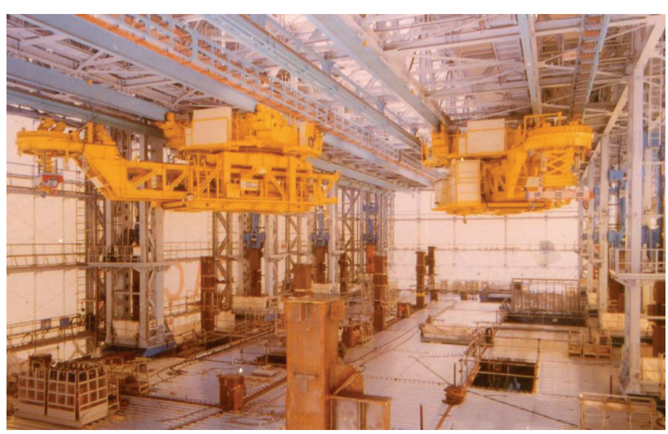


Fig. I.14: interior of on-site construction area

The prefabricated parts are checked and then placed in specific depots at the foot of the building or in the building itself to be available to the robots. This is where the automated construction process actually starts. Up to 22 robots equipped with automatic crane winches deliver the pillars, supports, floor, ceiling, wall and other elements to the floor of the steel skeleton under construction. They are also mainly positioned and fixed into place automatically. The steel pillars and supports are joined together by welding robots after they have been positioned. The position and quality of the welding seams are monitored with lasers.

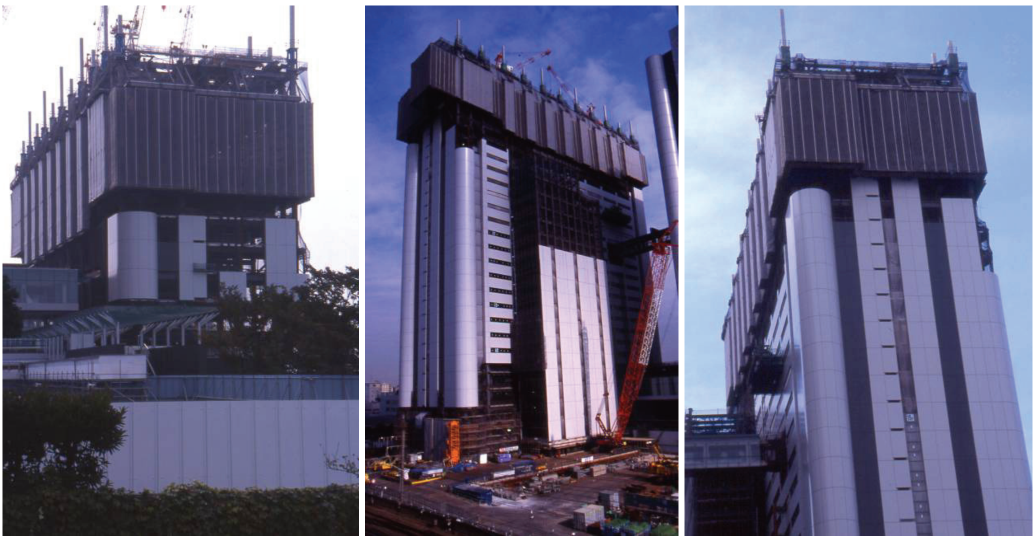


Fig. I.15: ABCS: Automated Building Construction System

Once a story has been finished, the whole support structure which rests on four columns is pushed upwards by 12 hydraulic presses to the next story. Three 132 ton presses in each pillar are required to achieve this in 1.5 hours. Fully extended, the support structure is 25 meters high; retracted it measures 4.5 meters. Once everything has been moved up, work starts on the next story. By fitting out the topmost story of the high-rise as the roof at the beginning of the building process, the site is closed off in all directions, considerably reducing the effect of the weather and any damage it might cause.

7 On-site Customisation

Today's advanced automated building construction sites can not only erect buildings based on standardised components and orthogonal grids but also individually designed and customised buildings. The example shows a building constructed by a semi-automated construction system.

Fig. I.16: Automated construction of a individually designed building

IT-integrated on-site processes and customised prefabrication have been combined with automation suitable building construction organisation and rigorous JIT/JIS on-site logistics. Additionally interconnected and co-adapted on-site robotic systems have been used for the finishing works. Once the foundations have been laid, the remaining construction procedure can be described as a matter of configuring transport and geometry. Nearly all elements are prefabricated and prepared for the on-site processes; only some of the fitting, joint insulation and other minor works need to be carried out by hand. Problems with the construction arise less from the timing of deliveries of materials or from the choice of processes and/or machines but more from the need for accurate planning, from programming the robots or from the just-in-time supply of parts.

8 Urban Mining by Systemic and Robot Supported Deconstruction

Fig. I.17: Automated, IT-coordinated and robot supported deconstruction

Within 11 month three high-rise buildings in the center of Tokyo recently have been deconstructed by a semi-automated deconstruction system. The process of deconstruction was reengineered and it started with the dismantling of the ground floor. The upper part of the building was meanwhile jacked by IT-coordinated robotic hydraulics. With this method floor by floor was dropped down subsequently and disassembled at the ground floor level. As the deconstruction thus was highly coordinated and could additionally be conducted on ground floor level, 93 % of the building components could be recycled (recycling rate of conventional demolition: 55 %). This example also shows that the consequent deployment of advanced on-site technologies could be crucial for sustainability in construction/ de-construction in the future.

9 Service Robotics

Today robotic systems are not only developed for the construction of buildings but also for the economically important life span of buildings and other construction products. The first service robots for buildings and construction products had been developed end of seventies beginning of eighties of the last century in Japan. These early service robots were used in the construction sector for inspection of nuclear power plants, exterior walls of high rise buildings and cleaning of high rise facades or glass roofs. In the nineties service robots were applied to civil engineering projects such as inspection of tunnels, railroad tracks and bridges. Advances in the autonomous robotics research resulted in service robots for office logistics of files and security against intruders, gas leaks or fire hazards.

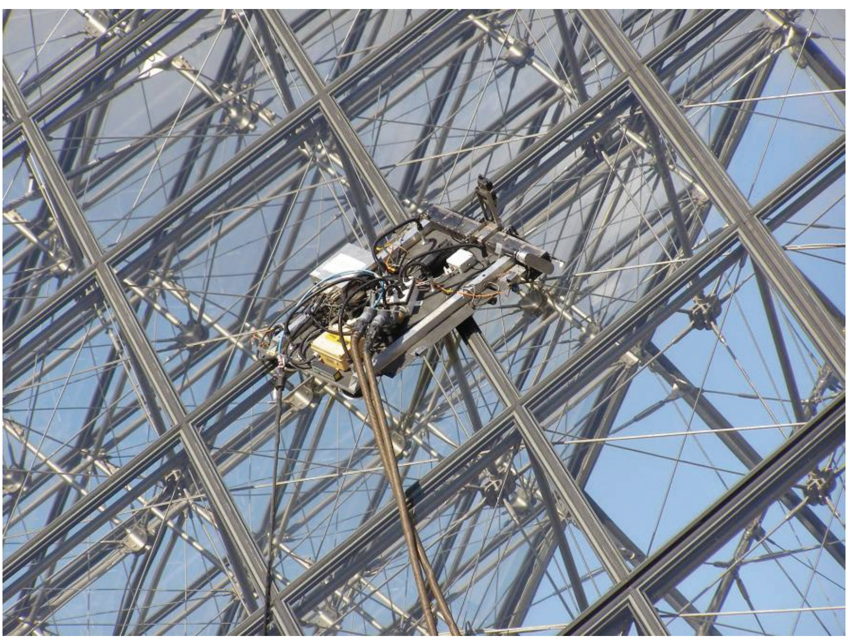


Fig. I.18: Comatec robosoft glass cleaning robot

10 Virtual Reality and Real-Time On-site Control

Construction work needs in many cases human sense and decision, and consist in combination of every task and machine. VR and the related vision of a “wearable cockpit” aim at total control of a construction project. This means extension of the concept to a cockpit for project control from that for only operating a machine. In other words VR in on-site use includes not only a tele-operation system but also assistance for decision making, enhancement of recognizing ability in time and space, optimised task ordering and integration of machines and on-site robotics.

10.1 Enhancement of Sensing

Most of monitoring at construction site relies on human senses. Therefore a direct assistance in human sensing could be effective. These could be for example functions of clear visibility in the dark, visualisation of dead angle sections or backward sight.

10.2 Enhancement of Identification

Decision making needs an object to indicate clearly the situation in progress. A visual instruction of work (e.g. virtual indication of excavating section in the operator's real sight) and a process management by visual comparison could serve as examples. VR system can also indicate the visual situations such as position, appearance or movement. Therefore a manager could take also invisible objects into account and on operator's demand; the system could relate an object to more detailed data instantly.

10.3 Mobile Project Control Systems

Wearable and mobile project control systems could especially support semi- automated construction processes in situation where for example automatic transportation and manual adjusting and final positioning is combined.

10.4 Communication Assistance

Communication, coordination and continuous information flow among workers and between workers and machines or robots is crucial for high quality construction products.

10.5 Wearable Cockpit

Up to now embedded chips or systems, wearable computers, and "Exoskeleton" systems for construction o-site have been developed and tested on site. The next step could be their integration and combination with on-site automation and robotics.

11 Humanoid Construction Assistants

Fig. I.19: Humanoid robot riding an excavator

When carrying a component with a human, they use an adaptive and flexible arm system. An image processing system with a mobile portable control system has been developed to allow location detection. When it moves over uneven surfaces, a force sensor in the sole of the foot and a balance sensor in the body register the difference and the gradient allowing the robotic control system to adapt the sole of the foot to the surface. Since approximately six years humanoid construction robots were developed to drive forklifts, excavators or carry building parts jointly with a construction worker. This humanoid robot technology transfer to construction is based on nearly two decades of humanoid robot subsystem technology development. Humanoid construction robots vary from tele-operated devices through autonomous ones that can walk on 5 degrees inclined slopes, compensate 2cm high obstacles and are able to get up by themselves once they fell down. Positioning is achieved by vision systems, forces sensors in the feet recognise inclined slopes, balancing sensors detect the body's inclination versus the surface slope and an autopilot controls its attitude.

12 Conclusions

The performance of robotic technology is increasing rapidly and we can support its advancement by designing, engineering, managing the construction processes and products in a robot oriented way. On the engineer level we need robotic and mechatronic construction engineers, managers and architects education. The workers need mechatronic and robotic training and qualifications. For real estate to be build by robots and integrated automated construction systems we need additional investment in order to cover the higher construction costs caused by greater capital investment in construction equipment.

One way could be borrowing financing methods from the leasing sector, aircraft or car industry, which often offer 0% interest loans to attract new customers. Towards the investor we have to communicate the advantages of constant construction quality and faster availability of rental space resulting in higher return on investment.

13 References

Fig: Fig.1-25, copyright T. Bock;
Fig. 26, copyright;
Fig. 27, copyright T. Bock

ANDRES, J. & BOCK, T. (1994) *First results of the development of the masonry robot system ROCCO: a fault tolerant assembly tool*, Proceedings of the eleventh International Symposium on Automation and Robotics in Construction, Elsevier, Amsterdam

BOCK, T. & ASHIDA, S. (2003) *Wearable Cockpit for Construction Work,* ISARC Conference

BOCK, T. & LINNER, T. (2009) *Service Oriented Design,* in: 2. Deutscher AAL-Kongress 2009, Berlin; Ed.: VDE Verlag, Berlin: Tagungsband, CDVerlag

BOCK, T. & LINNER, T. (2009) *Structural Changes and Technology Utilization in German Construction,* in JCMA, Japan Construction Mechanization Association, Japan

BOCK, T. (1988) *Robot Oriented Design*, Shokokusha, Tokio

BOCK, T. (2004) *Humanoide Bauroboter statt Billiglöhner*, in BFT 10/2004 , Betonfertigteiltechnik , Bertelsmann, Germany

BOCK, T. (2009) *Turning Points in Construction*, TH Award Keynote, in: 26th ISARC International Symposium on Automation and Robotics in Construction, Austin/Texas, USA. Ed.: International Association for Automation and Robotics in Construction, I.A.A.R.C. DVD, www.iaarc.org

FELDMANN, K. & KOCH, M. (2000) *Development of an open and modular control system for autonomous mobile building robots with flexible manipulators*, published at the 17th International Symposium on Automation and Robotics in Construction

JOHNSON, R.E. & CLAYTON M.J. (1998) *The impact of information technology in design and construction: the owner's perspective*, Automation in Construction, Vol.8, Nr. 1, Elsevier.

MATSUMURA, S. (1985) *Mokuzo chikugumi buzai no precutka to kanri taisei*, Dai ikai kenchiku seizanto kanri gijitsu symposium, Tokio

MATSUMURA, S. (1990) *Precut Koho no gensai to sono tokucho*, Tokio,

MIAGAWA, K.K. & HIRAJI, N.(1994) *Precut Kojo no shinsetsujini hitsuyona shochoken no kendo*, Tokio

PILLER, F.T. (2006) *Mass Customization,* Deutscher Universitätsverlag, Wiesbaden, 2006 , ISBN-10 3-8350-0

SCHRAFT, R.D. & VOLZ, H. (1995) *Service Roboter,* Springer-Verlag Berlin Heidelberg

SEWARD, D. & QUAYLE, S. (1999) *Global integration of construction automation and robotics*, Proceedings of the J6th International Symposium on Automation and Robotics in Construction, Madrid.

VAN GASSEL, F. (2008) *mechanizing, robotizing and automating construction processes*, i- tech education and publishing KG Vienna, Austria

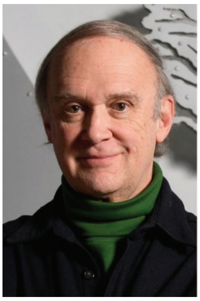
CHAPTER IV:
PRODUCTS – NEW INDIVIDUALISED INDUSTRIAL BUILDING CONCEPTS

There are many good examples of contractors with a vision and even some with experience with full industrialised construction systems. But the strongest developments in respect of industrialisation are reported from the component industries. For this last chapter we collected a number of papers demonstrating eye catching examples of industrialised construction based on the use of industrial components. Both integral load bearing structural systems and infill components are introduced.

Several papers were presented to the editors on structural systems. Lawson e.a. present an overview of light steel systems. Girmscheid gives an insight in what is available in Precast concrete today. Elzbieta Rynka from Poland informs us about the Eastern European approach to deal with a tremendous stock of precast panel construction. Finally we included a paper on Italian structural systems for light weight temporary buildings.

From the many components we selected some advanced components such as the Infra Plus flooring system (Cox e.a.) a system of concrete sandwich facades (Dr. Erik Vastert, Eindhoven University of Technology) and an overview of systems for light weight building envelops (Ingrid Paoletti, Politechnico di Milano)

A) Generic Classification of Industrialised Building Systems



ROGER-BRUNO RICHARD[1]

1 Introduction

The idea of producing buildings along an assembly line has fascinated architects and engineers ever since the beginning of the last Century. Yet, construction is still a service-oriented approach where a different process is applied each time a building is projected. A fully industrialised building industry will be product-oriented and the products would normally be Building Systems: sets of coordinated parts and rules where the same details are applicable to many different and individualised buildings. Nine generic types of building systems can be identified based on the relationship between the factory and the site as well as on the geometry of the structural sub-system.

2 Industrialisation

Industrialisation is a generic organisation based on quantity and offering an individualised finished product (RICHARD 2005):

- "Generic organisation" means bringing together all the participants (manufacturers, assemblers, designers, managers, distributors, installers, etc.) either as employees, sub-contractors or partners.
- "Based on quantity" means aggregating a large market to justify a continuous interaction between all the participants.
- "Offering a finished product" is quite different from the service approach offered by the building professional nowadays, although the finished product can actually be individualised through "mass-customisation".

A generic Organisation does not mean that all the participants are working for the same large corporation or company. More and more contemporary organisations are completely "horizontal", concentrating on the management and relying on consultants and sub-contractors for the design, the manufacturing of components and sub-systems, the assembly, the marketing, the distribution, etc. The lead capital investment for a horizontal organisation can then be as low as 10 % to 20% of the total involved in setting up a production. The horizontal approach is an appropriate strategy for the many operations involved in the production of buildings.

[1] Prof., M.Arch. (Berkeley), Architect (OAQ), Head of the graduate Design & Systems for Construction (DSC) profile, School of Architecture, Université de Montréal, P.O. Box 6128 Centre- ville, Montreal (Quebec) H3C 3J7 CANADA, Phone +1 514 343 7968, Fax +1 514 343 2455, roger.richard@umontreal.ca

3 Building Systems

The situation with buildings is quite different from most other types of industrialised products: the buildings are never totally completed at the factory and the products are not finished buildings but mainly Building Systems.

A Building System is a set of coordinated parts and rules where the same details are applicable to many different buildings. The same parts and their details are aimed at a large number of buildings for the very purpose of reaching a large quantity market while allowing for diversity and even for individualisation. Therefore, construction details are not re-invented each time a building is planned, as is often the case with the traditional "professional service" approach still present nowadays.

A Building System is a set of coordinated parts and rules where the same details are applicable to many different buildings. The same parts and their details are aiming at a large number of buildings for the very purpose of reaching a large quantity while allowing for diversity and even individualisation. Therefore, construction details are not re-invented each time a building is planned, as it is often the case with the traditional "professional service" approach still present nowadays.

The main parts of the building system are its sub-systems, which correspond to the main functions of the building. A building system is usually composed of five major sub-systems: STRUCTURE, ENVELOPE, PARTITIONS, SERVICES and EQUIPMENT.

Building systems can be either "Open" or "Closed". Open systems mean that the system can exchange parts, components and even sub-systems outside its original production environment. The parts, components and sub-systems are then considered as "interchangeable". By definition, an Open System can offer more choices to the user and a larger market to any manufacturer that abides by the rules in terms of quality (performance criteria), dimensions (modular coordination) and interfaces (compatibility).

In the European Community, there is a large movement towards the exchange of components in a kind of Open Systems framework, a movement called ManuBuild: "*The ManuBuild vision is of a future where customers will be able to purchase high quality, manufactured buildings having a high degree of design flexibility and at low cost compared to today. For the first time, inspirational unconstrained building design will be combined with highly efficient industrialised production….. ManuBuild targets a radical breakthrough from the current 'craft and resource-based construction' to 'Open Building Manufacturing', combining ultra-efficient (ambient) manufacturing in factories and on sites with an open system for products and components offering diversity of supply in the market*" (MANUBUILD 2006).

4 Three Categories of Building Systems

With reference to the fact that building is a site-related process and technology factory-related, three basic building systems categories can be outlined, as schematised in Fig. A.1:

I - The Site-Intensive Kit-of-Parts;

II - The Factory-Made 3D Module;

III - The Hybrid.

The first two categories represent the two extremes.

- Since the building is tied to its site, the final assembly of components delivered from different manufacturers is done at the site: I- The Site-Intensive Kit-of-Parts.
- Since maximizing factory production is the normal path to industrialisation, the building is divided into volumetric modules fully assembled at the plant and just connected to the infrastructure and between themselves once at the site: II- The Factory-Made 3D Module.

The third category is reaching for the best of both worlds, manufacturing the complex parts at the plant and leaving the heavy or simple tasks to the site: III- The Hybrid.

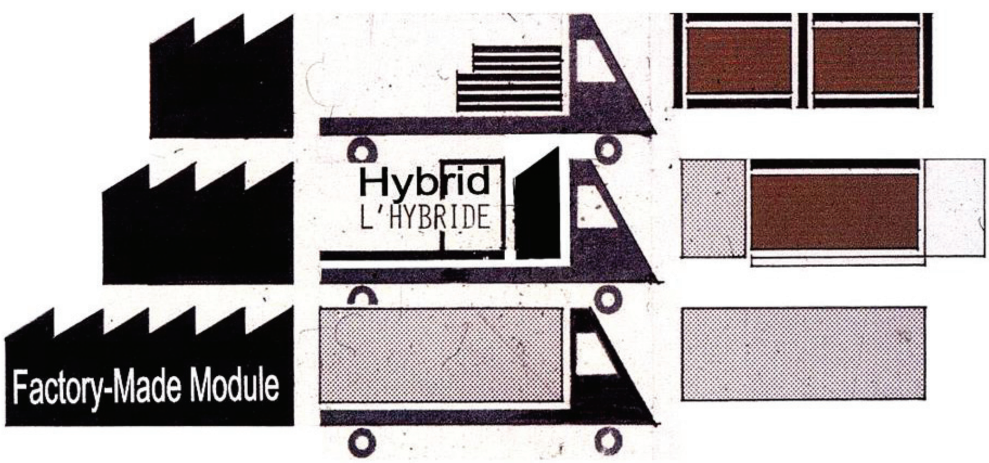


Fig. A.1: Relationship between the factory and the site © Roger-Bruno Richard 2000

5 The Site intensive Kit of Parts ("Meccano")

The Site-Intensive KIT OF PARTS ("Meccano") involves a few simple components produced in large quantity at specialised plants and transported to the site as separate parts, which implies a series of jointing operations at the site.

The four types of systems within the Site-Intensive KIT OF PARTS category are distinguished by the geometry of the structural sub-system: the Post & Beam ("A"), the Slab & Column ("B"), the Panels ("C") and the Integrated Joint ("D"). Their specificities are summarised on Fig. A.2.

Strategically, the initial capital investment can be reduced significantly when the components are simple and when the production is sub-contracted to a large number of specialised manufacturers who in turn amortise their own investments over many other clients.

Functionally, when all the components/sub-systems are easily and rapidly assembled at the site, they can be as easily and rapidly demounted and relocated if dry (mechanical) joints are used; thereby allowing for adaptability through space and time.

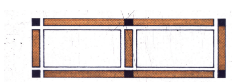
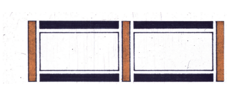
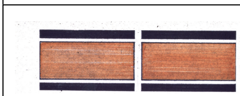
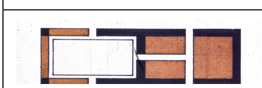
I - Site-intensive KIT OF PARTS	All sub-systems, including the structure, are made at specialised plants and transported separately, which implies a series of jointing operations at the site.	Sub-Divisions
 A- POST & BEAM	Skeleton open to horizontal and vertical infill	• Segments • Continuous Column • Continuous Beam
 B- SLAB & COLUMN	Continuous horizontal elements open to vertical infill	• Solid Slab • Ribbed Slab • Slab Incorporating a Perimeter Beam
 C- PANELS	Load-bearing flat components providing a linear distribution of the loads	• Lightweight • Reinforced Concrete • Pre-stressed Concrete • Mixed
 D- INTEGRATED JOINT	Monolithic component simplifying the connections by locating the joints outside the geometrical meeting point	• Point to point • Framed • Planar

Fig. A.2: The Site-Intensive KIT OF PARTS © Roger-Bruno Richard 2004

As one moves from "A" to "D", the work on the site is simplified: a Post & Beam system needs more connections and infill than a Slab & Column one, whereas Panels adopt a linear distribution of loads and the Integrated Joint locates all the joints outside the geometrical meeting point.

A) POST & BEAM: Skeleton open to horizontal and vertical infill at the site

Advantages:

- Loads concentrated on points, offering maximal planning freedom.
- Appropriate for "Open" sub-systems, since the skeleton can serve as connector to horizontal slabs and vertical panels.
- Adaptability in three directions.
- Possibility of offering continuous columns to reduce the number of joints and cantilevered beams to provide additional spans and/or reduce the number of columns.

Limitations:

- Higher structural costs due to the concentration of loads on the beams and the columns.
- Large amount of site connections and infill.

The components themselves can be designed to incorporate multiple options, like the many modular holes present on a piece of the Meccano set. In the GenterStrasse townhouses project in Munich, designed by Otto Steidle (KOSSAK, 1994), multiple-corbel columns allow for a variety of configurations (split-levels, 1½ storey rooms, etc.). The twin post & beam system developed by Vittorio Gregotti for the Scientific University of Palermo (RYKWERT, 1996), notably for the purpose of integrating all the conduits, is an eloquent testimony of the rich architectural vocabulary possible with imaginative component designs.

B) SLAB & COLUMN: Continuous horizontal elements open to vertical infill

Advantages:

- Horizontal integration of the structure to provide a continuous area with a single element.
- Adaptability in two directions.

Limitations:

- Conflict between the uniform distribution of loads expected in a slab and the concentration required to interface with a column.

Therefore, the "Ribbed Slab" and the "Slab Incorporating a Perimeter Beam" are the prevailing Sub-Divisions. Although the IMS system, developed in Belgrade, has been using horizontal post-tensioning for the joint between straight flat slabs and columns.

C) PANELS: Load-bearing flat horizontal and vertical components providing a linear distribution of the loads

Advantages:

- Direct economical distribution of the loads from the vertical to the horizontal axis without any transfer.

- Facilitating the soundproofing and fireproofing performances.

Limitations:

- The vertical axis generates a continuous wall which governs the planning, an acceptable situation in housing due to the large number of partitions required.
- Adaptability limited to the structural bay.

The Descon system (HUD, 1968), only non-US winner of Operation Breakthrough, clearly shows the potential of "off-the-shelf" precast concrete panels and is a good example of a totally horizontal organisation as it had no manufacturing facility of its own, as all the components were sub-contracted. Descon was inviting local and regional manufacturers to bid on the basis of three documents: performance criteria, modular coordination rules and interfacing details. Its bolted structural connections were using oval holes punched through standard steel angles and tees.

D) INTEGRATED JOINT: Monolithic component simplifying the connections by locating the joint outside the geometrical meeting point

Advantages:

- Simplification of the jointing operations through a series of single (one to one) connections rather than dealing with 4 to 6 components (sometimes heavy) converging at the same geometrical meeting point.
- Accelerated site assembly.
- Reduction of the structural requirements by meeting both positive and negative moments.

Limitations:

- Some components can be quite bulky.
- Adaptability conditioned by the geometry of the structural sub-system.

The best example of an Integrated Joint system is Componoform (COMPONOFORM, 2003): it is literally a joint-to-joint system, generating an open skeleton identical to the configuration of a Post & Beam system as far as the other sub-systems are concerned.

6 The Factory-Made 3D Module

The Factory-Made 3D Module category implies that all spaces and all components of the building are entirely made, assembled and finished at the plant as structural 3D modules, requiring only simple connections to the infrastructure (foundations + main service conduits) and between themselves once at the site.

Strategically, an important capital investment is required to initiate and operate a 3D Module plant. Functionally, the dimensions are limited by the highway regulations. Of course, carrying the 3D module from the factory to the site means paying to transport “air”, since most of the volume is occupied by empty space and since transportation is usually calculated in terms of volume.

The two types of systems within the Factory-Made 3D Module category are distinguished by the ratio of factory-made content in the completed building: partial for the Sectional Module (“E”) and total for the Box (“F”). Their specificities are summarised on Fig. A.3.

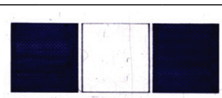
II - Factory-Made **3D MODULE**	All spaces and all components of the building are entirely made, assembled and finished at the plant as 3D modules requiring only simple connections to the foundations + main service conduits once at the site.	Sub-Divisions
 E- SECTIONAL MODULE	Small and easy to transport modules but incomplete, as they need a complementary component or process once they reach the site	• By Addition • Checker Board • By Compaction (Fold Out)
 F- BOX	Autonomous unit entirely completed at the plant	• Framed at the Edges • Panellised • Monolithic

Fig. A.3: The Factory-Made 3D Module © Roger-Bruno Richard 2004

E) SECTIONAL MODULE: Small and easy to transport module but incomplete, as it needs a complementary component or process once they reach the site

Advantage:

- Compact transportation as a limited percentage of the space is factory made, the rest being generated at the site.

Limitations:

- Necessity of an important site team to complete and finish the building, which can easily cost more than the transportation savings.

The classical example of the “By Addition” module is the Nakagin building in Tokyo by Kisho Kurokawa (KUROKAWA, 1992): the circulation tower is cast in situ incorporating a steel structure to which factory-made “capsules” are suspended through mechanical joints, thereby allowing for disassembly.

The Shelley Operation Breakthrough project in Jersey City (HUD, 1968) claimed saving one box out of two by jointing the units at 45° following a “Checker Board” pattern. However, they went into bankruptcy mainly due to the amount of site work to finish and equip the spaces generated in situ.

The task of folding out large size “By Compaction” modules is most of the time more expensive than the transportation of fully completed ones, although the situation can be different with small size modules.

F) BOX: Autonomous unit entirely completed at the plant

Advantages:

- Maximal factory production features freedom from the weather; semi-skilled labour; sophisticated tooling; precision & quality control; rationalisation (notably transversal dispatching of components along the main assembly line) and bulk purchasing of components.
- Minimal work at the site.
- Variable grouping geometries.
- Particularly affordable in a low-rise situation (3 or 4 stories), since a box meeting the transportation stresses can usually support two or three other boxes once at the site.

Limitations:

- High initial capital investment and continuity of the demand to amortise it.
- Strict planning discipline.
- Important (but not prohibitive) transportation costs, as they are related first to volume and second to weight; therefore, empty boxes (living areas, bedrooms, etc.) cost as much as the ones filled with value added content (kitchen, bathroom, services, etc.).

The North-American wood-framed boxes are large size structural shells (width between 3.6 to 4.8 m and length between 12 to 16 m): 2 to 4 boxes are required to generate a single-family house. Due to the very restricted road gauge, the Japanese 3D “units” (Sekisui Chemical, Misawa and Toyota), are small (± 2.4m in width and ± 5.5 in length) framed-at-the-edges steel structures, creating a series of skeletons which can be grouped to form a large room: 12 to 16 “units” are required to generate a single-family house, which means as many delivery trucks and a lot of jointing at the site.

Concrete boxes would normally have to be lightweight to be considered as a feasible solution.

7 The Hybrid

The Hybrid is aiming at getting the advantages of the Site-Assembled Kit of Parts while avoiding the inconvenient of the Factory-Made 3D Module: manufacturing at the plant the complex parts of the building and entrusting the site with the heavy or simple ones. Altogether, the Hybrid systems are borrowing features, and eventually components or even sub-systems from the other two categories.

The three types of systems within the Hybrid category are distinguished by the nature of the technology allocated to the site: the Load-Bearing Service Core ("G"), the Mega-structure ("H") and the Site Mechanisation ("I"). Their specificities are summarised on Fig. A.4.

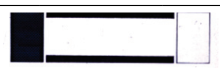
III - HYBRID	Manufacturing at the plant the complex parts of the building and entrusting the site with the heavy operations.	Sub-Divisions
 G- LOAD-BEARING SERVICE CORE	The "service area" is built at the plant within a module with structural capacity	• Linear • Point to Point • Half Load-bearing
 H- MEGASTRUCTURE	Framework to stack lightweight boxes in order to reach a high-rise status without piling them up.	• One Storey • Two Storeys • Three Storeys • Four Storeys
 I- SITE MECHANISATION	Transforming the site into a factory producing a monolithic structure.	• Mobile Factory • In Situ Factory • Mechanised Formwork • Permanent Formwork

Fig. A.4: The Hybrid © Roger-Bruno Richard 2004

G) LOAD-BEARING SERVICE CORE: The "service" area is built at the plant within a 3D module with structural capacity.

The "service" area (kitchen / W.C. / laundry / mechanical-electrical shaft / stairs / etc. in the case of housing) is concentrated in factory-made 3D linear Cores (small "boxes"). Once at the site, those Cores are set perpendicular to the facades and large flexible "served" areas (living room, dining room, bedrooms, etc. in the case of housing) are generated by spanning slabs and envelope panels between them (RICHARD 2005).

Advantages:

- Factory production justified by the concentration of complex high-tech services and equipment.
- Easy transportation as the Core is a self contained container-size module.
- Simple site work since the Core acts as a connector to the other sub-systems.

- The "served" area between the Cores offers a completely flexible transversal space.
- The Core itself is a closed sub-system but the served areas are offered to open sub-systems; therefore, various floor/roof slab options and various exterior envelope panel options can be supplied at the local level when the Cores are exported abroad.

Limitations:

- Imposition of a planning discipline.
- Additional facade width due to the presence of the perpendicular core, whereas the services are usually positioned longitudinally in the middle of a building.

Being full of value-added services and equipments, the cores are not "transporting air", which is generally the case for boxes accommodating a living-room or bedrooms.

H) MEGASTRUCTURE: Framework to stack lightweight boxes in order to reach a high-rise status without piling them up.

Advantage:

- Allowing light-frame factory-made modules or panels to reach higher densities.

Limitations:

- Expensive structural redundancies as the boxes or panels become live loads to the framework;
- The jointing between the framework and the boxes could be complex, mainly due to dilatation and capillarity factors.

The Megastructure may appear as a way to stack boxes for many stories without overloading the ones underneath, but there is a high price to pay: the redundancy, brought by supporting another structure as a live load can double the cost of the overall structural sub-system. No past tentative applications of the Megastructure have ever reached the feasibility status.

I) SITE MECHANISATION: Transforming the site into a factory producing a monolithic structure.

The basic idea is to transport the precast concrete production facilities directly into the building right at the site, rather than transporting precast components from the plant and having to join them one by one at the site. Whereas the non structural sub-systems, being both complex and compact, are better served by factory-made "plug-in" or clip-on" components transported to the site in bundles or containers.

Advantage:

- The logic of producing heavy components at a site-plant.

<u>Limitations:</u>

- The structure cannot be dismantled.
- Same as for the Site-Assembled Kits-of-Parts as far as the sub-systems other than the structure are concerned.

Different technologies are offered:

- Mobile Factory, literally setting the prefabrication tools on a "flatbed";
- In-Situ Factory, using site-friendly processes like Sprayed Concrete, etc.;
- Mechanical Formwork, casting within the building with a Tunnel Formwork to generate an egg-crate structure or a Sliding Formwork which is operating like a vertical extrusion machine;
- Permanent Formwork, using another sub-system as formwork.

8 The "Palette" of Options

By analogy, the three building systems categories can be considered as the basic three colours (i.e. blue/red/yellow) from which the "Palette" of 9 types of building systems is generated: from "A" to "I" with the addition of an eleventh option, the "Open" Sub-Systems, as illustrated on Fig. A.5.

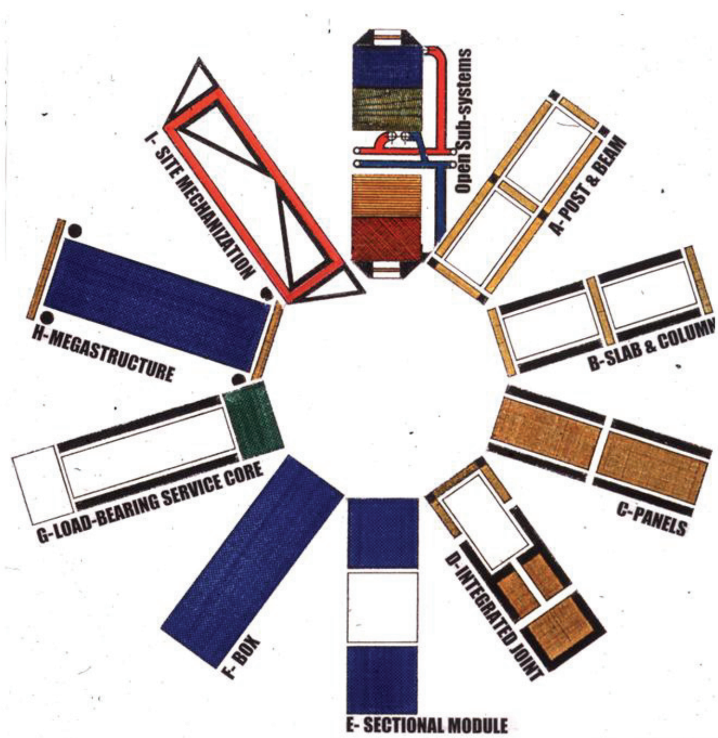


Fig. A.5: The "Palette" of Industrialised Building Systems © Roger-Bruno Richard 2000

“Open Sub-Systems” are interchangeable and complementary sub-systems; they can stand alone, be produced by an independent specialised plant, or be part of another system.

“Open Sub-Systems” are a necessity as many systems do not include all the sub-systems; either because a sub-system is outside their technological scope or in order to accommodate local options.

Many systems are integrating two (sometimes three) sub-systems within the same component, in order to further simplify the process while reducing the operations as well as the costs. For instance, a load-bearing sandwich panel can meet both the structural and envelope criteria, a load-bearing pre-cast concrete wall panel normally acts as a support to the floor slabs and performs as a party wall assuring fireproofing and soundproofing between two different apartments, a modular closet kit can provide a partition between two rooms of the same apartment, etc.

9 Selecting a Building System

Altogether, there is no “best system in the world” but a wide variety of options to choose from. The context should then lead to the generation, the development or the selection of an appropriate Building System: matching the users needs with the resources (the four “Ms”: Materials, Machinery, Manpower and Money).

For the purpose of selecting a strategy, the “Palette” of options can be articulated to include the distribution of the work between the factory and the site, as shown on Fig. A.6.

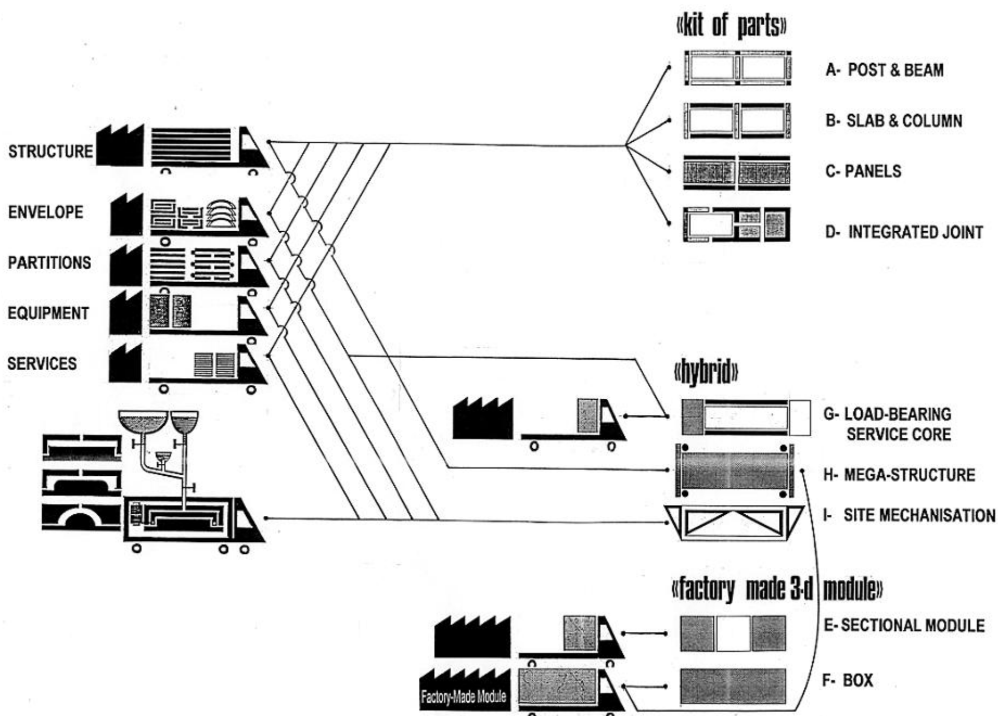


Fig. A.6: Distribution of the work between the factory and the site © Roger-Bruno Richard 2004

Decisions are taken mainly at the Sub-Systems level because the Sub-systems represent specific expertise areas which can be distributed to different participants of the “Generic Organisation” behind any industrialisation activity.

Selecting the appropriate building system is a strategic operation taking into account three major factors:

- The performance criteria set forward to meet the objectives and the architectural features of the project.
- The actual or prospective technologies available inside the organisation or outside through various sub-contractors.
- The benefits of including all the sub-systems in a closed framework or of leaving one or more as “Open Sub-System(s)”.

10 Conclusions

Industrialised Building Systems are introducing a new architectural language that the architects and the builders need to study and understand in order to really benefit from their specific advantages. But the language has to be applied at the outset of a project, as a non-systematic design would be repulsive to most types of systems. Building Systems do not pretend to meet all the architectural programs: they merely want to provide solutions to the large majority of needs and people, looking forward to becoming the “ready-to-wear” offerings of architecture.

Society and technology are in perpetual evolution, just as individuals are different from their neighbours and different from themselves over time. Very often the building program becomes obsolete even before the building is completed. Since most factory-made components or sub-systems are designed to facilitate and accelerate site installation, they could then be easily dismantled and generate change without any partial or total demolition when “dry” (mechanical) joints are used, thereby addressing the sustainability agenda and contributing to the formation of “Industrialised, Flexible and Demountable” (IFD) systems (QUAH et al., 2004):

Industrialised: Factory production generates precise jointing features.

Flexible: Dry-jointing methods allow for change without the usual destruction of partitions associated with renovation.

Demountable: Whenever the changes go beyond the scope of flexibility, dry-jointing methods allow for a major reconfiguration and/or relocation of the building without any demolition waste.

An IFD approach would then provide solutions to the large majority of needs and people trough both space and time, thereby addressing the life cycle of buildings and the sustainability agenda.

11 References

COMPONOFORM (2003) *Componoform: The Universal Building System,* www.componoform.com/.

HUD (1968) *Design and Development of Housing Systems for Operation Breakthrough*, Washington, U.S. Department of Housing and Urban Development.

KOSSAK, F. (1994) *Otto Steidle: Structures for Living*, Artemis, Zurich, pp. 50-72.

KUROKAWA, K. (1992) *From Metabolism to Symbiosis*, Academy Edition.

MANUBUILD (2006) *Open Building Manufacturing* (Summary), www.manubuild.org/summary.

QUAH, L.K., et al. (2004) *Process Innovation for Design and Delivery of IFD*, www.bwk.tue.nl/ade/includes/download.php?fileId=328.

RICHARD, R.B. (2005). Looking for an Optimal Urban Residential System? *International Journal of Construction Management*, Vol. 5, No 2, pp. 93-104.

RYKWERT, J. (1996). *Vittorio Gregotti & Associates*; Rizzoli, New York, pp. 66-69.

B) Projecting with Precast Concrete Components

MATTHIAS BRÄM[1]

1 Introduction

The planning of buildings takes different paths and leads to different results depending on whether one chooses to build with precast or in-situ construction. This paper will describe the specific character, which exemplifies a project conceived in bearing precast concrete components, as well as its specific potentials. Such systems were by far not completely exploited by the European precast slab methods of the 1960s (in German called "Plattenbau"). An insight-provoking work using directional structural framework will be shown (A. Mangiarotti).

A selection of types of directional components is shown by the construction-based configuration of floor and wall components. These configurations permit the derivation of an idiosyncratic series of building types. Following this examination, the paper will consider another form of a modular system, which assembles concepts for load-carrying exterior walls, building on flat components and offering structural apertures.

General requirements and idiosyncrasies of planning with precast components are presented. The potential of structuring a building as a carcass with a long lifespan and interior work with a shorter one, and the accompanying possibility of "carcass-aesthetics" is shown, concluding with the activation of a dialectic collaboration between civil engineer and architect.

2 The Specific Character of Designing with Concrete Elements

The structural design of contemporary buildings takes extremely different trajectories depending on whether it is based upon in situ or prefabricated element construction. There are several shared characteristics of design deploying current element-based building practice in steel, wood and concrete (Fig. B.1 and Fig. B.2):

[1] Dipl. Architect ETH-Z, Managing director BWA bausysteme GmbH, CH-1006 Lausanne, Phone +41 (0)21 312 81 06, Professor at HEPIA, haute école du paysage, d'ingénierie et d'architecture de Genève, CH-1202 Genève, matthias.braem@sunrise.ch

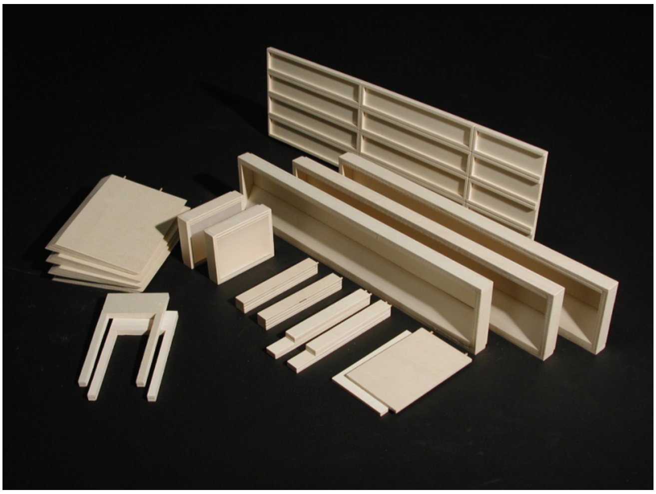


Fig. B.1: School of Architecture Nancy (France, 1995), Architect Livio Vacchini with François & Henrion; Model of the modular system (Zürcher Hochschule Winterthur (ZHW))

Fig. B.2: School of Architecture Nancy; Cutaway of Model (Zürcher Hochschule Winterthur (ZHW))

- The repertoire of possible building elements is laid out in an "intellectual" kit of parts in order to conjoin or configure it as a new building in an opportune manner.
- The form of these building elements and their diverse configurations demands a congruity between the "engineering form" and the "architectural form."
- Bearing structure, construction and material are extremely closely linked and generate the central impulse for the final character of architectural space and form.
- Element-based construction tends to support the expression of the building's primary and bearing structure

Concrete element construction, in contrast to steel and wood, also demonstrates a series of inherent, specific qualities, which are particularly interesting for the design process.

- The casting process facilitates more complex, three-dimensionally formed elements, which allow for a multiplicity of optimised bearing elements, connection geometries and aesthetic forms.
- In fact, a whole series of "hybrid" building elements is possible: hybrids amongst beams, struts, angles, frames, folded elements and plates or shells which can range to hyperbolic rotational forms. Many of these are hardly realizable in steel or wood.
- Concrete elements are heavy, have a high bearing capacity, can retain heat, are non-combustible, have high resistance to weathering and can be finished on site. All these factors tend towards a construction process with fewer additional functional layers.

Given this potential for efficiency, variety and possibilities for deployment, the European style of prefabricated concrete construction dating from the 1960s seems to have subjected itself to a rigid and senseless self-limitation. Walls and floor plates were, at that time, built up from entirely planar bearing concrete plates, with apertures created by making holes in a plate. The limited spanning capacities restricted its use to housing. It was in housing that the uninhibited dynamism of the 50s and 60s produced enormous quantities of such economical buildings which were nonetheless hardly of long-lived qualitative value. In contrast, however, such architects of the 1960s as Angelo Mangiarotti in Northern Italy (Herzog and Mangiarotti, 1998) demonstrated that concrete element construction systems can also be surprisingly intelligent and cultivated.

In the following, Mangiarotti's (Herzog and Mangiarotti, 1998) pioneering work will be introduced. Thereafter, a comprehensive description of directional concrete elements for contemporary design will be offered in order to clarify in brief another principle, known as "Domino," for configuring planar elements for exterior walls.

3 Isocell U70 - A Key Project Using Oriented Concrete Elements

Angelo Mangiarotti developed and realised a full palette of building systems for industrial and commercial buildings in the post-war period in Northern Italy. All share an exemplary, tightly-integrated form, which locates itself between fabricational and bearing capacity optimisation, and the modest aesthetic of Italian industrial high-design in the 1960s. The rough construction was developed in itself as an harmonious kit-of-parts system which could guarantee a pronounced flexibility by virtue of its wide column grid and additive character, clearly advantageous for a successful business venture and its future. The vertical interior and exterior culmination of the system comprised a finely scaled structure in steel, wood, concrete and glass, largely realised through prefabrication and in formal terms, by virtue of their scalar differentiation, used as elegant "architectural elements" which can be relatively freely combined with the powerful-seeming rough construction system.

The Isocell U70 building system was, in this case, used for Unifor, a furniture factory in Turate (Como) in 1982 (Fig. B.3). The engineers responsible for the project were G. Ballio, G. Colombo and A. Vintani. The column grid within the basic roofed unit measures 9 x 20.5 meters, for a nearly 200 m^2 area **(**Fig. B.6**)**. "The columns, measuring 55 cm along their edge, are H-shaped in section. The trapezoidal volume of the column cap resolves in two brackets that serve as support. The trough-shaped Primary beams each rest upon one of the column cap's brackets (Fig. B.4, Fig. B.5 and Fig. B.7); the u-shaped steel elements provide adjustability and are later integrated into cast concrete. The actual height of the beams remains constant (75 cm) regardless of span. Section and reinforcement are relative to the structural diagram. Six floor plates span each field longitudinally (Fig. B.6). Its section, also trough-shaped, and lateral ribs stiffen the plate, which is only 3 cm deep. The conical form at the support allows for the production of a strong bearing connection immediately at the time of installation, to stiffen the system against racking. To provide natural light, domed skylights can be positioned in the beams and floor plates. In the free areas of the floor plates between the bearing elements is room for building systems installation; moreover, the fine net of lines deriving from the fabricational and constructional grids remain visible on the underside of the floor plate. The U70 building system provides for simple and quick installation of the bearing system. By virtue of the consistent heights of beams and floor plates, facades and interior walls can be aligned. And, by virtue of this characteristic of the system, it is thus possible to make changes in fit-out and in the expanse of the building as needed." (Herzog and Mangiarotti, 1998)

Fig. B.3: Isocell U70, application in industrial building in Turate (Como, I, 1982), architect Angelo Mangiarotti (Matthias Bräm)

Fig. B.4: Underside view of floor with Isocell U70, Turate (Matthias Bräm)

Fig. B.5: Indoor with Isocell U70, Turate (Frank Mayer)

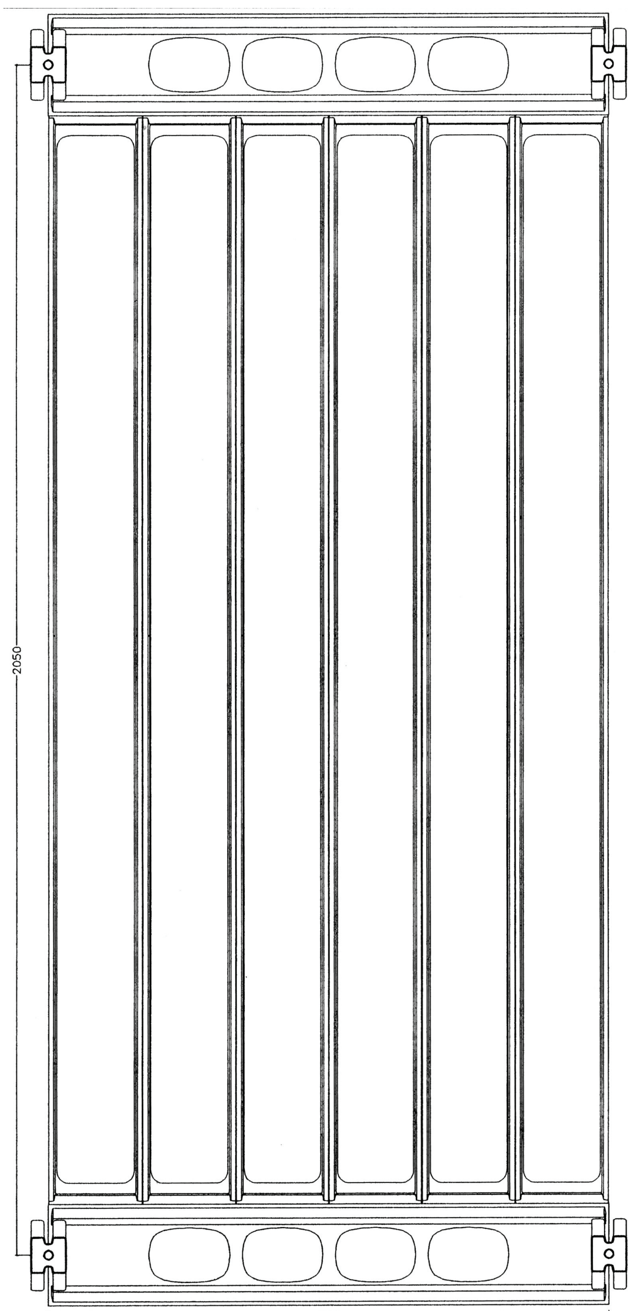


Fig. B.6: Underside view of basic unit of floor with Isocell U70, Turate (Nardi, 1997)

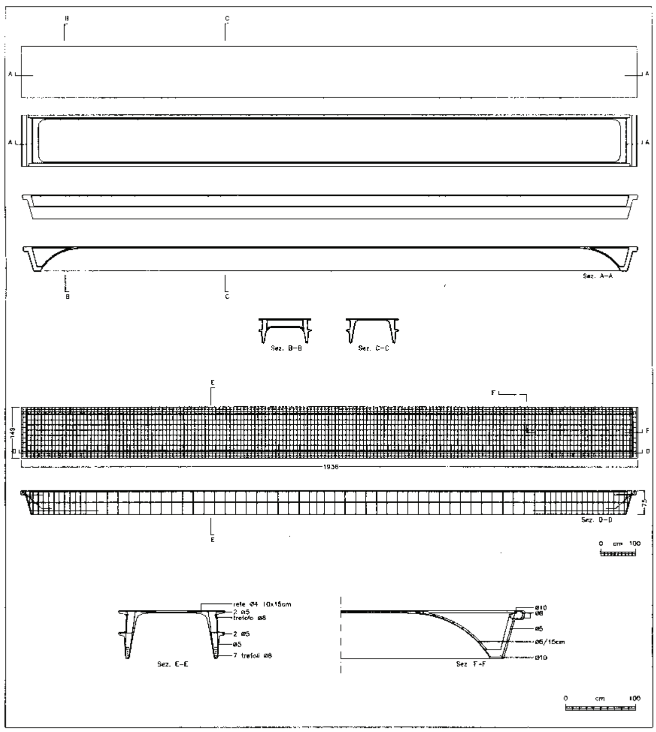


Fig. B.7: Floor component with Isocell U70, Turate (Nardi, 1997)

4 A New Repertoire of Directional Concrete Elements: from the Construction-based Configuration of Building Elements to Building Typological Areas

Directional slab and column systems comprising concrete elements have been used in Europe for decades in the context of European industrial and commercial buildings. On the other hand, they were only rarely used in such other sectors as housing and office building. The much greater spanning distance offered by these elements in comparison to in situ concrete flat slabs - achieved by means of easily-realised pretensioning - permits a higher degree of programmatic variation in plan and, over the long-term, creates a greater degree of amenability for later, larger renovations and adaptive reuses. The voids in the slab elements can be efficiently used for building systems. These characteristics seem to imply the logicalness of considering directional bearing systems systematically for housing and office buildings (Zürcher Hochschule Winterthur, Bräm, 2002).

The contours shown in Fig. B.8 are those of the slab element sections. Considered from bottom to top, these contours have the following characteristics:

- Wood-concrete composite element: Wood absorbs tension and concrete, compression. The elements' joints can be "camouflaged."
- Open U-shaped element: slightly conically-shaped web, simple production.
- Louver-effect: expansion of the surface creates better heat exchange and a better energy household.

- TT-plank: Economical, if ribs are on the interior (lower third of overall height) with pronounced ribbing.
- Basin-like element: Economical, with planar underside. Used as a floor slab, they can be leveled by casting a concrete screed on top.

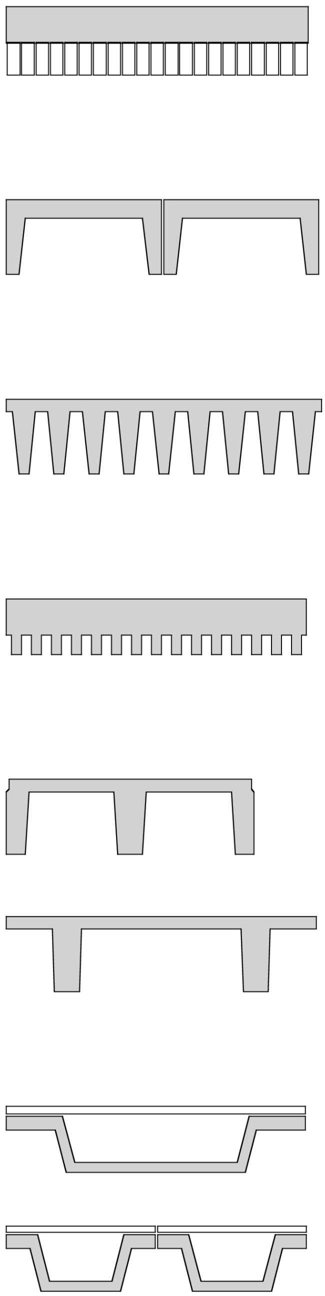


Fig. B.8: Sections of floor components, overview (Zürcher Hochschule Winterthur and Bräm, 2002)

A small selection of such elements as bearing walls is shown in Fig. B.9. A combination incorporating apertures for doors and windows is apparent. Fig. B.10 shows spatially three different degrees of openness in the lateral wall.

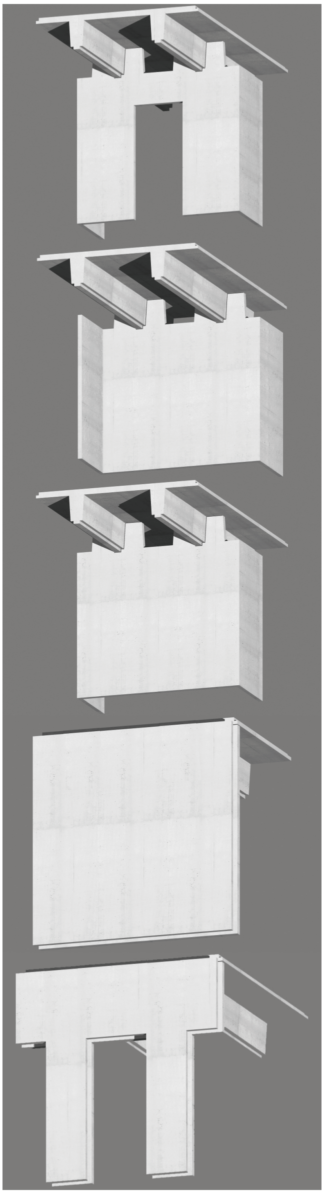


Fig. B.9: Wall components with transition to floor, overview (Zürcher Hochschule Winterthur and Bräm, 2002)

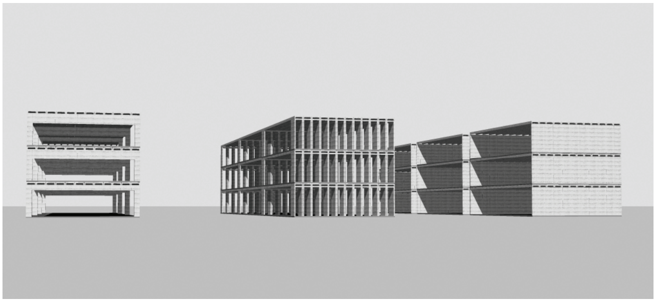
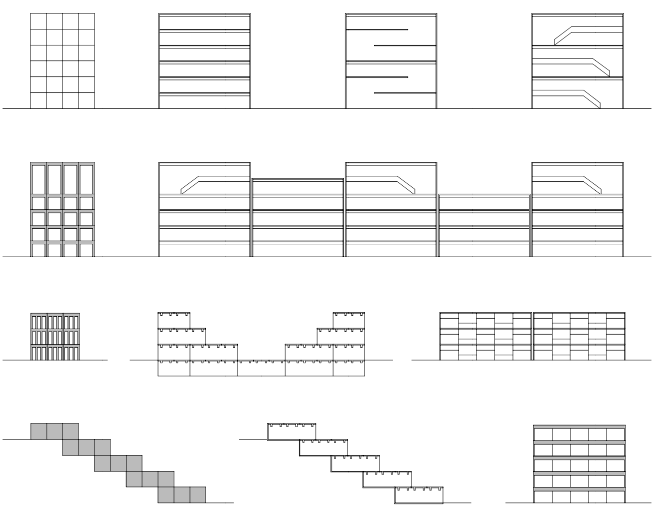


Fig. B.10: Statical structure directional frameworks, different grades of opening of front wall (Zürcher Hochschule Winterthur and Bräm, 2002)

The choice of directional bearing systems implies self-limitation relative to the form and orientation of a building based upon those of the bearing system. Looked at more carefully, this in fact reveals itself as the kernel of an enormous variety of spatial configurations. These may be represented in a building typology matrix (Fig. B.11 and Fig. B.12). It is decisive here that the urban situation, the building and space typological solution and the construction-based form for floor slab and wall be developed in the design process through iteration and simultaneously, in close collaboration between architect and engineer



.

Fig. B.11: Overview of building types with directional frameworks, section (Zürcher Hochschule Winterthur and Bräm, 2002)

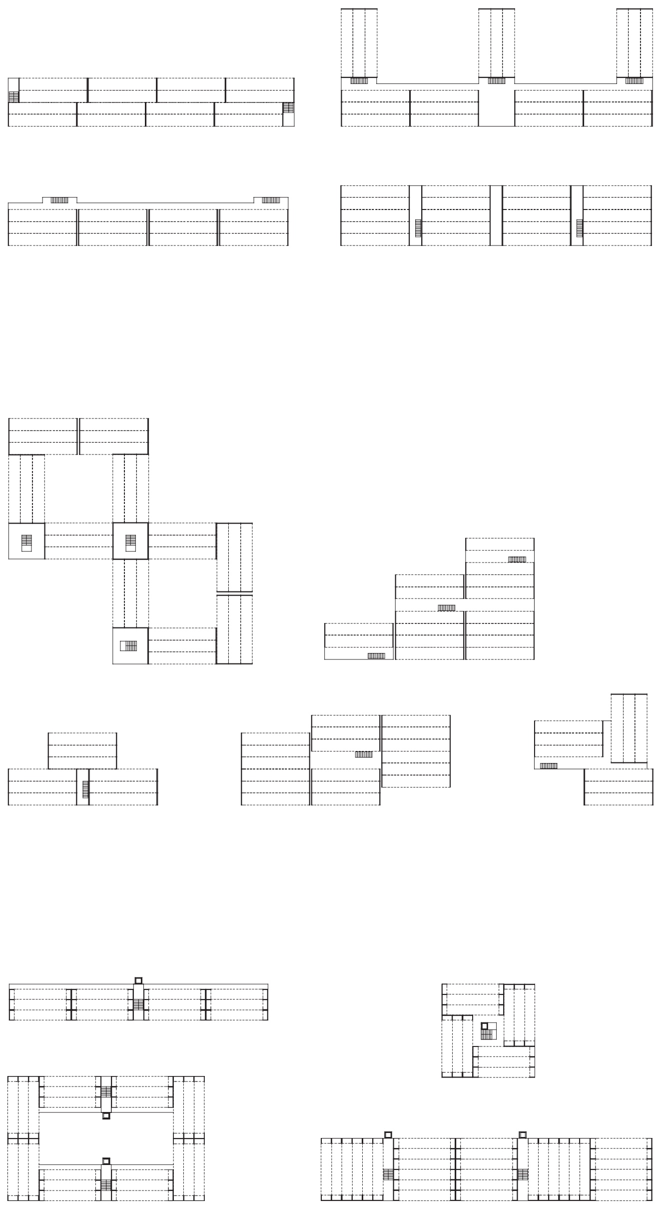


Fig. B.12: Overview of building types with directional frameworks, plan view (Zürcher Hochschule Winterthur and Bräm, 2002)

Of particular interest for the construction execution is, at present, the increasing integration of rough construction - in this case, pretensioned floor slab elements - and building systems, as in Fig. B.13. Overall, it seems clear that directional column-slab bearing systems tend to offer a higher degree of use flexibility in plan. They are easy to maintain and to renovate because of the system’s inherent and clear separation between bearing (i.e. long-lived) and demising (i.e. build-out, short lived) elements. In terms of space and façade, they facilitate a strong, structural-tectonic expression.

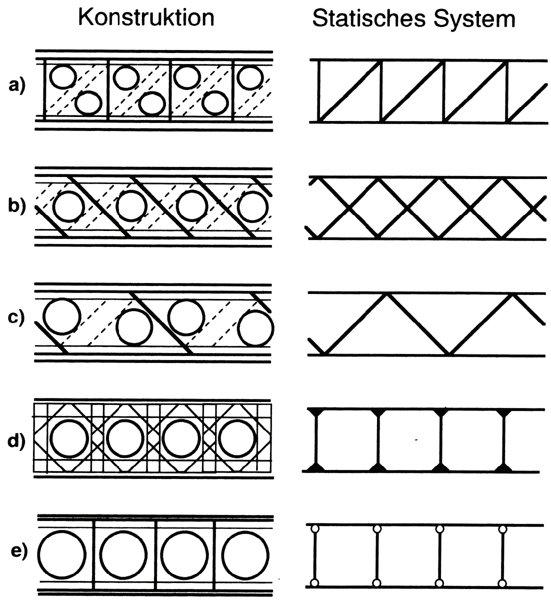


Fig. B.13: Breakthroughs in ribs of floor components: a) – c) skeleton framing systems; d) structural frame; e) flexible connection, transfer of forces only by booms (Zürcher Hochschule Winterthur and Bräm, 2002)

5 Concepts for Exterior walls as "Domino"

The concepts described by the term "Domino" are all based upon concrete element systems with which bearing vertical planes can be built up on the building perimeter and, in part, on the building's interior. Within this configuration, the insulating perimeter can be position either on the exterior, in the same plane as the elements (using multilayered sandwich elements) or within the element. Fig. B.14 shows the "Domino T concept"; it is based upon a T-shaped concrete element which integrates column and perimeter beam for the slab.

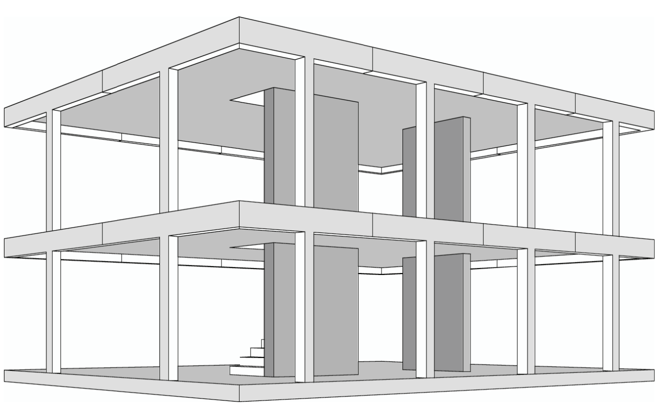


Fig. B.14: Concept for construction of a wall „Domino T" (Zürcher Hochschule Winterthur and Bräm, 2002)

The concept described in Fig. B.15 uses - like a house of cards - wall elements which function in terms of statics like spur walls, stacked on one another floor by floor with minimal area of overlaps. The interior or exterior wall are, in the process, configured in a kind of solid construction matrix with large structural openings which are closely allied to the logic of the subdivision into elements.

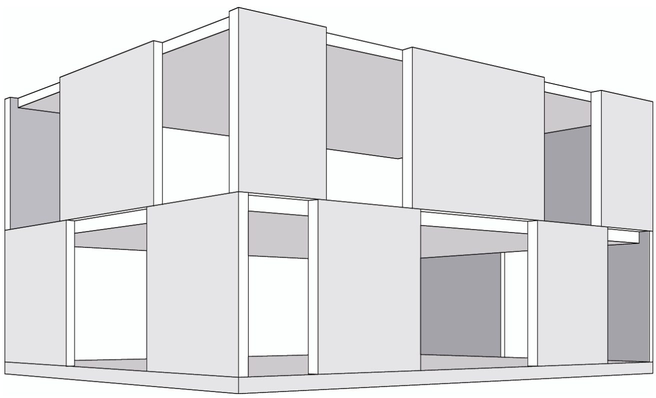


Fig. B.15: Concept „wall house of cards“ (Zürcher Hochschule Winterthur and Bräm, 2002)

The concept in Fig. B.16 works with walls that also appear to be spur walls, and with perimeter beams which function like large-format lintels above apertures. In this way, the loads can be carried over large distances horizontally along the façade. This allows for a high degree of freedom in the organisation and dimensioning full storey-high apertures.

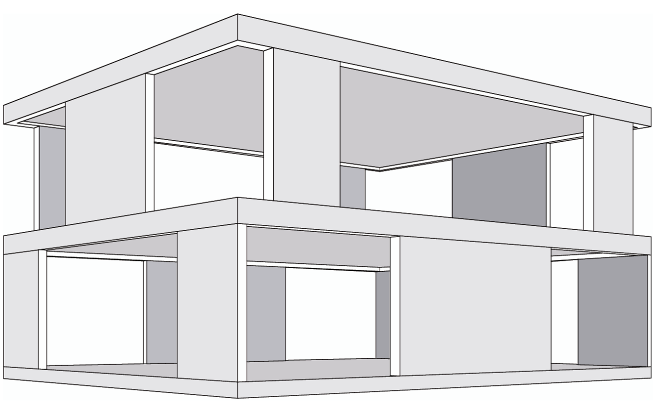


Fig. B.16: Concept „Domino wall movable“ (Zürcher Hochschule Winterthur and Bräm, 2002)

6 Concluding Observations on the Potential of Load-bearing Concrete Element Construction

The text above, a précis of the longer publication “Construction-based Design with Concrete Elements” (Zürcher Hochschule Winterthur, Bräm, 2002), relating to new fields in concrete element construction, is based on a critical evaluation of the failures of prefabricated panel construction. It also integrates an analysis of contemporary conditions and the demands arising from construction planning as well as a reconsideration of the architectural design potentials of innovative concrete element construction in the form of pilot projects.

The prefabricated slab construction of the 1960s failed at least in part because it created inexorably an inflexible relationship among panel, aperture and the space behind it, which often resulted in a monotony by virtue of the additive growth pattern of the "spatial cell". If concrete element construction is used today once again as a rough construction component, then there are several strict planning rules to observe in addition to the specific material characteristics in order to circumvent problems. Concrete element construction requires a precise level of know-how on the part of those involved in planning - both engineers and architects. The decision to work with this kind of construction has to be made early, in the schematic design or competition phase. In situ construction methods are more amenable to later adjustments in planning. A certain quantity of the same or similar elements is necessary to complete construction economically. The precondition is also open-mindedness on the part of those planning relative to the eccentric and ineluctable systematicism of this kind of construction.

In order to develop more extensive individual functional, spatial and aesthetic freedoms, concrete element construction should be conceived as an "open" building system, as demonstrated under the heading of the "directional bearing system," with its rich building typological possibilities. As open systems, hybrid systems, which use concrete elements with other means of rough construction, are also interesting.

The decision to develop a building using concrete element construction privileges the expression of the primary bearing building structure next to secondary, demising and shorter-lived fit-out elements. This can often be developed in formal terms as a dialectic between the aesthetic of rough construction and the elegance of interior fit-out. The economic competitiveness of concrete element construction compared to an in situ concrete skeleton can be achieved by considering the flexible plan configuration and by integrating ancillary functions such as surface treatment, building systems or integral acoustical treatments. In the case of façade elements, it is possible to incorporate window sills, sun shade compartments, lintel and surface treatments, all of which can be cast into a single component in the fabrication process.

The structural design of contemporary buildings is often marginalised or "neutralised" to the benefit of other priorities. Conceived as a stack of in situ floor slabs, neutral in formal and directional terms, carried on point columns or spur walls, allowing for arbitrary subdivisions in plan, the structural skeleton serves here as the neutral and silent servant to the free formal development of function and architecture. All that remains for the engineer, particularly in the case of residential and office building is the optimisation of reinforcing bars in the slab section.

Concrete element construction is - like other elemental systems - developed in the reverse direction: the bearing element is a constituent, recognizable cell on the basis of which the building's spatial and aesthetic form is generated as an organic matrix. It is this fact, finally, that promotes a dialogical collaboration between engineer and architect.

7 References

Herzog, T., Mangiarotti, A. (1998): Bausysteme von Angelo Mangiarotti, Technische Universität München, München, 1998.

Nardi, G., Mangiarotti, A. (1997): Angelo Mangiarotti, Maggioli Editore, Rimini, 1997.

Zürcher Hochschule Winterthur, Bräm, M. (2002): Konstruktives Entwerfen mit Betonelementen, Zürcher Hochschule Winterthur, Winterthur, with Reto Bonome (Bauingenieur), SwissBeton, cemsuisse, Riss-Mobatec, KTI (Kommission für Technologie und Innovation des Schweizerischen Bundesamtes für Berufsbildung und Technologie), 2002.

C) Temporary Building Intended as Adaptable and Reversible Building: a Sustainable Strategy for Housing – The Recent Situation in Italy

VALERIA GIURDANELLA[1] & ALESSANDRA ZANELLI[2]

1 Introduction

Aim of this paper is to investigate significant aspects of the relationship between temporary and sustainable constructions, identifying some of the current trends which seem to suggest potentialities to eco-friendly strategies in construction industry.

This paper starts to consider that industrially manufactured systems expected to be reversible by designers or architects can encourage industry to extend its responsibility to whole life cycle of building products, taking care also of their end of life and "recovery" potentials (TOFFEL, 2002).

After a brief overview on the diffusion of lightweight prefabricated construction systems in Europe, which mainly consist of off-site pre-assembled products, the paper will dwell on current Italian situation (as for production and use of these systems) focusing on the (mainly cultural) reasons why their diffusion is resisted within the Italian context. Finally, the paper will introduce three research products from the authors' research team dealed with a wider application of lightweight prefabricated systems in Italy and the evaluation of their attitude to the natural and built environment, and one more built product, designed by our Department research group, as sample of recent temporary construction in Italy. These products also suggest recent and gradual increase in use of lightweight prefabricated systems and reversible construction techniques in Italy.

1.1 The social context

Some key paradigms are emerging in the contemporary building landscape of today's society, which is characterised by intangible work, weightless capital and the instantaneous exchange of information at the speed of light. A new type of nomadism seems to characterise contemporary society, in which everything appears to be transitory and modifiable (BAUMAN, 2002). People move for work, study or pleasure, by either need or choice. Travelling and relocating are now worldwide trends, which

[1] Dr.-Arch. Ph.D. in Technology and Design for Environmental Quality, Building Environment Sciences and Technology Department, Faculty of Architecture & Society, Politecnico di Milano, IT-20133 Milano, Phone/Fax +39.02 23995105, valeria.giurdanella@polimi.it

[2] Dr.-Arch. Ph.D., Assistant Professor in Technology of Architecture, TensiNet Associate Member and Regional Representative, Building Environment Sciences and Technology Department,Faculty of Architecture & Society, Politecnico di Milano, IT-20133 Milano, Phone/Fax +39.02 23995135, alessandra.zanelli@polimi.it

generate consistent migratory flows of people of different duration and size, almost all over the world, Fig. C.1.

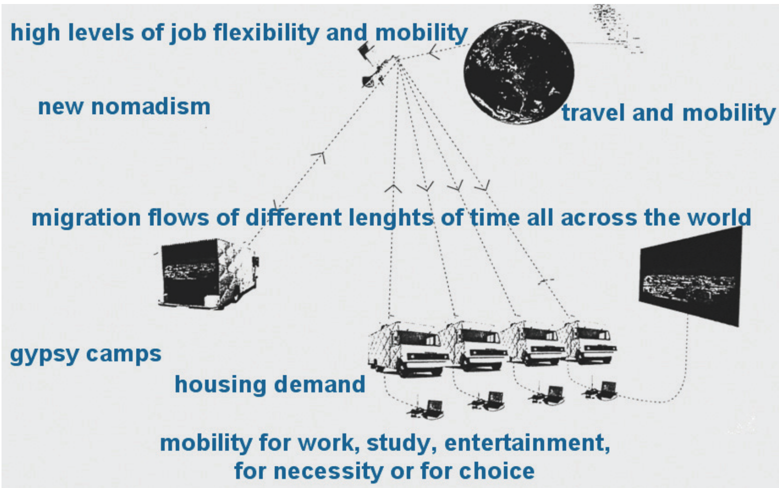


Fig. C.1: Contemporary social issue: Flexibility and mobility in contemporary society (AUTHOR'S REDESIGN, 2006)

Metropolises, which are the working centres of industrialised societies, are more and more exposed to the pressure of migration flows. This increasingly translates into precarious and deeply discomforting housing conditions at the outskirts of cities. In many European countries, the housing demand has become a huge problem; in Italy, research carried out by Cresme (AA.VV., 2005) has pointed out that housing has become more critical than in the '80s and '90s. In 2005, the demand for primary housing approximately amounted to 400,000 dwellings (in 1991, the housing demand was 173,000 dwellings) Fig. C.2. Moreover, the increasing housing demand does not only come from the weaker social groups, but also from the elderly people, students, singles and regular immigrants with their families (between 2001 and 2004, residence permits increased from 1.5 to 2.5 million in Italy) (AA.VV., 2006).

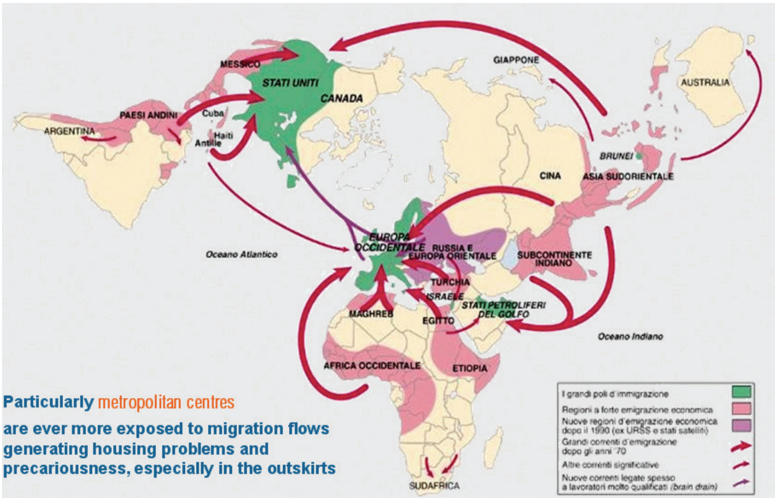


Fig. C.2: Global migration flows: Current migration flows in relationship to housing demand (WORLD WIDE WEB, 2006)

The conditions of nomadic camps are also creating a lot of problems at the outskirts of Milan. So it seems possible to identify new and old communities of nomadic people, who are expressing different housing needs but also are sharing their quest for lightweight, adaptable and reversible rather than unalterable, eternal, heavy and unchangeable architecture. Today, temporary use of space can be increasingly considered as a "normal" dimension to live, which suits contemporary needs and is chosen by people who prefer temporary construction rather than traditional rigid and inflexible ones. In houses built with heavy construction techniques, dwellers are forced to adjust them as much as possible or abandon, dismantle and reconstruct them making sure they meet their new needs. In houses built with lightweight materials and easy to disassemble construction techniques, as a temporary construction, the inhabitant can conform the house to itself and to his changeable demands, and gets open to on-going modification thanks to use of lightweight materials, flexible design, adaptable and multi-functional technologies. In designing new architecture and also in rebuilding our cities, adaptability, flexibility and reversibility paradigms become a priority. Now the building sector causes the widest environmental impacts because of the exploitation of non-renewable raw materials, in addition to the soil and energy consumption in whole life cycle.

Lightweight, adaptability and reversibility paradigms are becoming increasingly popular in architecture, introducing or reintroducing weight and matter reduction strategies and the ability to adapt or change over time according to needs and easy-to-assemble and disassemble products which can easily be reinserted into their production cycle (recycling) or used for new purposes (reuse). Design should be able to meet needs of these new social dynamics, as well as take an open approach, be "error friendly" (MANZINI, 2004) and draw changeable and adaptable spaces for future requirements. Open design is then followed by construction techniques, which allow the highest level of reversibility (reversing construction process, dismantling built parts) to provide opportunities to modify a building according to their new needs and/or also discard it by recovering all its individual components.

1.2 The industrial context

The construction industry is one of economy driving forces which is responsible for most of the environmental impacts. On the one hand, building has an impact on the environment not only during the construction process, but also throughout procurement, production and transport of raw materials, also throughout discarding of the building and disposal of debris. On the other hand, a building has impacts to guarantee comfortable conditions of use and indoor well being, interacting with dwellers' needs and providing them with a liveable environment suitable for activities carried out within the buildings. The construction sector is therefore one of the main responsible players for environmental impacts as a result of the exploitation of non-renewable natural resources, use of land, energy consumption relating to the whole life cycle of a building product and production of demolition waste. Hence, the implementation of concrete strategies that improve economic and environmental effectiveness and efficiency of the sector can no longer be procrastinated. Even though the architectural production cannot be assimilated through and through to the industrial one, a building is increasingly the result of assembly and commissioning of industrial manufactured materials and components. With industry and architecture getting closer to each other, the architect can seize the opportunity to exploit innovative elements which allow more conscious designing at all the different levels of social, environmental and economic issues. When considering lightweight prefabricated construction which could provide effective answers to current needs for temporary and flexible spaces, originating from contemporary societies, it is important to demonstrate that this area of the building industry is not only economically but also environmentally sustainable. The use of prefabricated systems and components which are also diversified in terms of form and quantity at a large scale, is today an attained and viable goal thanks to products' "mass customisation", made possible by state-of-the-art electronic technologies integrated with industrial production.

The use of lightweight prefabrication can offer great potentialities and can be addressed to be sustainable from the environmental point of view: if we examine prefabricated building elements, their potentials and also their impacts throughout the whole life cycle of the building, ranging from the extraction of raw material, to the manufacturing of the product, to its assembly on site and to the use of its functionalities during the useful life of building, and last but not least, to its residual potentials after being discarded (when directly reused or recycled). Building with lightweight components is not only a good answer to dwellers' demand for flexible use, but it is a potential reversible way to build, which allows the individual parts of a building to last longer and be reused in future constructions, increasingly meeting the needs of future users/inhabitants. Conceiving, designing and constructing buildings being aware of their social and environmental impacts means planning them to be "temporary" and to last as long as required by their expected use. It also means largely relying on lightweight prefabricated components modern construction methods, which are highly adjustable over time with reversible assembly techniques, so as to allow buildings to be easily dismantled and their individual components to be reused.

2 Reversible Building in Europe and in Italy

The off-site construction and modern construction methods offer great capacity in support of lightweight, adaptable and reversible buildings, in achieving social, economic and environmental issues for a sustainable development (AA.VV., 2003; Ross, 2005). Off-site construction is a term used to describe the spectrum of applications where buildings, structures or parts are manufactured and assembled in a different location from the building site prior to installation in their final position, Fig. C.3. Recently off-site construction and Modern Methods of Construction (MMC), are providing interesting outcomes and benefits to sustainability issues: energy conservation; waste reduction; pollution control and Kyoto Protocol due to materials being easier to control in a factory environment.

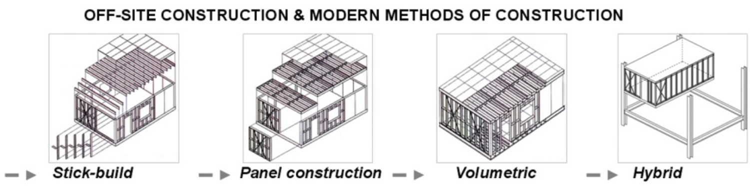


Fig. C.3: Off-site construction: methods' alternatives, author's redesign from (AUTHOR'S REDESIGN FROM LAWSON, 2006)

Some of the most important benefits of factory manufacturing are: superior quality and less defects; more Health & Safety benefits; a faster construction result in savings on on-site management and on-site activities. Off-site construction is based on manufacturing of lightweight components which are then assembled through dry construction methods. The reduction of elements' weight allows low carbon emission construction. Factory manufacturing allows greater predictability of completion and greater predictability of cost than traditional on-site construction methods, and above all it allows reduction of waste material from 11.8% for on-site construction to 1.8% for off-site construction (Blandshard in AA.VV, 2006). In addition, factory manufacturing enables product "design for assembly and disassembly". An emerging theory suggests that the interface between technical systems should allow the replacement of one system with another performing the same function. Interface with other elements and simple construction processes allow open, flexible and adaptable space and deconstruction rather than demolition at the end of buildings' useful life so allowing reuse and recycling for a sustainable life cycle thinking approach. Alternatives to traditional construction methods will not always be appropriate, but they could be used cost-effectively for different residential use, far more than it is currently done. In effect all off-site construction is a mix of off-site manufacturing and on-site installation and completion. Just as most traditional construction today may incorporate significant elements of off-site manufacture, the difference is a matter of degree (ROSS, 2005). Modern construction methods claims great benefits in high density housing, such as meeting affordable housing targets, immediate availability of buildings, high level of buildings customisation (not standardisation), high level of flexibility, adaptability and assembly/disassembly capacity. The most important problem with MMC is the cost issue. People think it is more expensive because simplistic cost analyses show it to be more expensive and because many of the savings are hidden. Time and quality savings may not actually bring benefits anyway. So the thing is: "Are we prepared to pay for quality and future environmental benefits?" (Gibb in AA.VV, 2006).

There is a diffusion of lightweight construction methods in residential house building, especially in USA and Japan, and recently in some European countries, particularly in northern Europe (Sweden, Germany and UK). But in European Mediterranean countries and especially in Italy there is a greater resistance to them and a scarce diffusion of lightweight, adaptability and reversibility in buildings. Especially in Italy MMC are not so diffused as they are considered lightweight construction methods unsuitable for housing buildings, also Italy is traditionally anchored to heavy construction methods, with brick and block masonry built in. An interesting diffusion of lightweight construction methods is being achieved in Spain with an important development of stick build systems in Cold Formed Steel (CFS) single family housing, and this kind of construction is acquiring a large share of residential market. In Spain the relevant push to modern construction methods has arrived from manufacturing firms and this allowed to overcome the initial distrust from the building sector operators. The great distrust in Italy has many reasons: the strong bond with traditional methods construction; the diffidence to innovations, especially in residential house building, and the general refusal of prefabricated construction systems, but also due to the lacking knowledge of technological and environmental performances of this construction methods. Certainly lightweight construction methods and off-site construction cannot be indiscriminately adopted for every kind of construction and in every situation but it is claimed that they can meet many housing targets in relation to the advantages and benefits of these construction methods in achieving a balance between different levels of sustainability. Lightweight construction methods may also give a more qualitative alternative to low quality buildings and constructions, particularly buildings built before 1977 (marked by fixed and unchangeable typological solution, scarce flexibility, and ineffectiveness of construction techniques employed), projections for Italy foresee investments in the range of 70% of the total value of the construction market (AA.VV., 2004).

Despite the low and sporadic use of modern construction methods in Italy, the present production system seems to have the potentials for the rapid conversion of some of the existing production segments, such as those concerned with the manufacturing of semi-finished products, steel boxes and containers and timber prefabricated structures, which are already largely used for building sites, exhibition facilities and in post-earthquake emergency situations.

The Istituto Nazionale di Statistica (ISTAT) figures of the last three years indicate that building companies in Italy have nearly doubled between 1981 and 2001. From the information regarding the last decade and, in particular, the activities which largely rely on use of lightweight steel prefabricated products, it can be inferred that it was the service sector (hiring and real estate businesses) which made the largest step forward as a result of the constant increase in the number of metal production and building companies. This also highlights the receptivity of the market towards ready-to-use systems, including temporary ones (for hiring purposes), provided that they are designed to offer required functions. According to investigated data analysis, quantity and importance of the actual productive market, it appears that the sector could be qualified and oriented towards products that could allow the application of modern methods of construction. Moreover Italy has some considerable precedents, for example in steel production, and especially CFS which date back to the 70's. CFS, together with semi-manufactured products in timber and concrete, are some of the most used elements. Today a substantial part of the Italian iron and steel production is represented by CFS categories, which however are used only as secondary elements (for example roof framing and internal partitions), while the structural use is limited and applied only to commercial and industrial buildings. Only 10% of single-storey construction in Italy incorporates CFS (72% in France, 83% in UK). In buildings over two storeys high, the Italian structural standard requires to use CFS profiles only for secondary elements of steel structure, or as support for cladding systems. That is due to the huge seismicity of great part of the Italian region, but also to cultural reasons. Nevertheless, interesting signals are forthcoming from collaboration between research and manufacturing factories (an example is the experimental prototype of Modular Light-weight Cold-Formed Beams, MLC, at the Università Federico II di Napoli) which can suggest developing of manufacturing sector and potentialities to diffusion of lightweight construction methods in Italy as well. According to the report on Italian industries drawn up by Confindustria (the Italian Manufacturers' Association) in 2004 (CONFINDUSTRIA, 2004), the production of raw steel of the same year came close to 28.5 million tons, hitting a 6% increase over 2003. The utilisation rate of the steel production capacity improved by 4 points, increasing from 72.4% in 2003 to 76.4 in 2004. The production concerning rolled products is interesting as well: over the whole year, flat products increased by 16% and long products by 6%. However, the 7% increase of cold-rolled products is particularly interesting.

3 Research and Experimental Projects about Reversible Construction in Italy

Four theoretical and applied researches are presented here, concerning architectural projects about temporary construction intended as adaptable and reversible construction. The four research works examine temporary construction at different degrees that seems emblematic of a gradual acceptation of lightweight and open prefabricated components based technologies in the current Italian context:

- a minimum degree of acceptability, when a temporary construction gives immediate answer to emergency situations (product 1);
- an intermediate degree, when temporary construction systems are appreciated because of their ease of disassembly which can take the building back to its original status as to its historical and architectonical values (actions taken on existing buildings), or can be easily adapted to users' rapidly changing needs (use in the tourist sector) (product 2,4);
- an high degree, when temporariness in construction is intended as a designing strategy to think and realise eco-friendly buildings' end of life scenarios, in particular in housing field. This temporariness could be intended as a way to make reversible all the construction processes and to allow disassembly/deconstruction of building or part of its. To easy take apart and to salvage buildings' components and materials in relationship to the buildings' planned lifespan can offer potentialities of eco-friendly use of materials in case of maintenance, rehabilitations, adaptations and disposal, allowing diverting C&D waste from landfills, reusing salvageable components and recycling materials (product 3).

3.1 Product 1: Research Work about Temporary Construction for Emergency

In the research work entitled "Over the emergency", co-financed by the Italian Ministry of Education, University and Research on 2000-2002 (national coordinator prof. Franco Donato, title of the national search "Technologies of intervention for the innovation in the installations for the emergency" - operational Unity in Milan, Responsible prof. Andrea Campioli) the attention was focused on flexibility and adaptability issues also in emergency dwelling, Fig. C.4 and Fig. C.5.

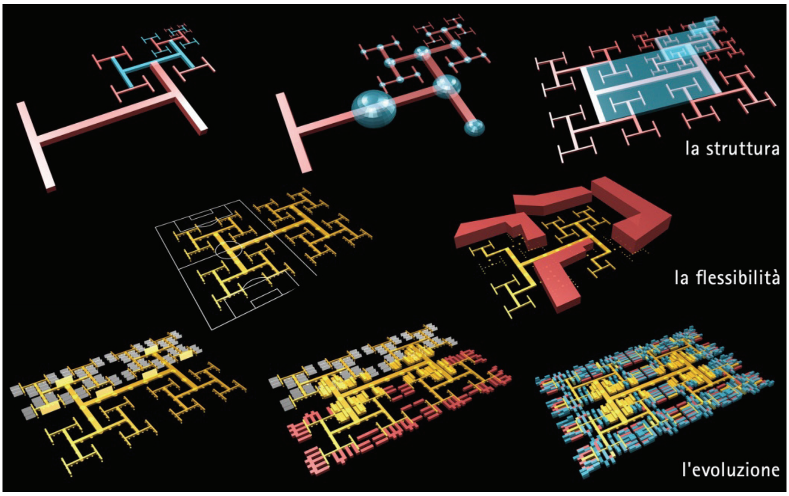


Fig. C.4: Research work "Over the emergency": planning schemes (AUTHOR'S RESEARCH WORK, 2003)

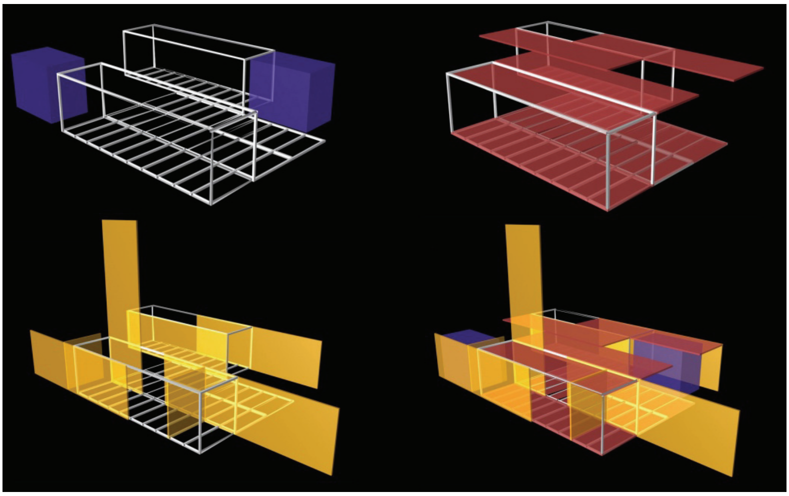


Fig. C.5: Research work "Over the emergency": modules schemes (AUTHOR'S RESEARCH WORK, 2003)

The research results make evidence that today there are more and more occasions for renewing the field of temporary constructions, making them more adaptable, and this trend has also spread to Italy. In fact they are not designed to replace massive constructions, but instead they are presented as alternative solutions for new temporary functions, not only for emergency situations but especially for new typologies of temporariness. From a "temporary use for necessity" - an emergency use - a new use of space now exists which can be called "temporary use by choice" - for leisure time, sport, tourism and also for new work and housing practices. Temporary solutions for necessity are simple kits of components, easy to build and to dismantle, but with low adaptability. Temporary solutions by choice are more sophisticated, often more difficult to build and therefore less mobile.

In the container-based temporary construction system, adaptability is often sacrificed to the transport and installation facilities.

Emergency container is portable but adaptable to a minimum degree, Fig. C.6, and, in Italy, it has represented, for many years, the favourite solution in situations of emergency following natural disasters.

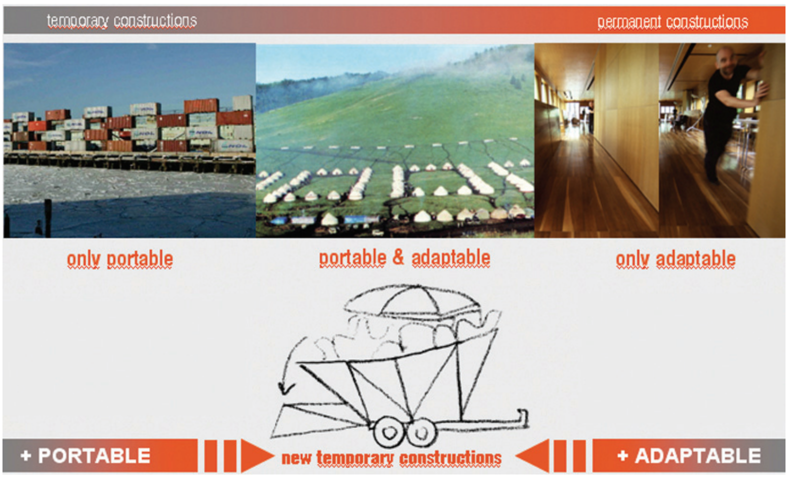


Fig. C.6: Temporary construction requirements: more adaptability is needed for contemporary spaces (AUTHOR'S REDESIGN, 2006)

First emergency housing containers is generally characterised by low quality and is sufficient to provide living space only for short periods of use (2-3 months), whereas it is totally inadequate for longer periods of time (1-2 years). This is what has emerged from the analysis of indoor conditions inside the containers used after the earthquake in Umbria and Marche in 1997. The analysis highlighted the most critical aspects relating to the use of emergency housing containers essentially focused on three types of problems: the discomfort resulting from indoor micro-climatic conditions, due to thermal discomfort in relation to the poor thermal insulation of the container panels and the presence of thermal bridges favouring condensation; the difficulty of airing the rooms, as well as problems due to design or installation errors, such as water infiltration from the roof or poor sound insulation. A third type of problem which cannot be overlooked was pointed out by studies carried out in the field of anthropology and environmental psychology (FLADE, 2002; RAMMLER, 2002). These studies demonstrate that the criticism made by individuals also concerns the psychological difficulty of accepting and adapting to the new situation. The living conditions inside the containers hardly manage to reproduce the social organisation of the urban settlements existing prior to the catastrophe. The main reason for discomfort is indicated in the limited space available and the lack of privacy and freedom. As a result, in order to meet these needs connected with indoor life, some maintenance or repair actions are taken by the users themselves, such as the repair of the roof, wiring and plumbing and the construction of shelters or verandas to extend the available space. Analyses of conditions of comfort in the temporary containers for the 1997 earthquake victims in Umbria and Marche have shown that even in emergency shelters the concept of adaptability and personalisation is important and must be considered. Observations above show that, even in those situations in which the sheltering and housing needs seem to prevail, adaptability and quality of built environment become unavoidable prerequisites. Even if emergency containers are designed to be highly mobile and economical, it is hoped that more lightweight and flexible materials will be integrated into this structures, such as membrane tensile structures, pneumatic cushions and retractable elements. These new integrated elements can favour not only a transformation of the external appearance of the container, but also lend themselves to personalisation by the inhabitant. In emergency situations, the basic container can be integrated with other components, for increasing thermal and acoustic insulation performances, indoor comfort. Also designing integration of base construction modules with additional lightweight components as textile membranes or flexible panels allows a greater expressive dynamism and adaptability to different and customised uses. Lightweight and flexible materials as membranes and thin shells, easy to move and remove by inhabitants of temporary containers can offer great opportunities to realise more qualified emergency buildings (CAMPIOLI, ZANELLI, 2006). In this way, it will be possible to use the potential of the new textiles more completely, not only for emergency situations but also for more and more qualified building applications. The employ of membranes and thin shells together with other flexible or rigid materials also can shape new typologies of building envelopes and create new adaptable environments for ever changing life style (BÖGNER-BALZ, ZANELLI, 2007).

3.2 Product 2: Reversible Construction and Existing Building. The Case Study of Renovation Project in Liguria, Italy

From that first research further ideas were developed about temporary housing, extending beyond the emergency and suggesting new potentialities and perspectives for construction methods lightweight, adaptable and reversible-oriented. From emergency housing these construction methods can take new housing spaces, more in conformity with durability and maintenance, starting from the most provisional houses to more durable ones, for example from temporary housing for universities' students (pod constructions) to retraining of existing historical building, expressing technical and formal potentialities in new building and in buildings' rehabilitation.

In particular, in the recovery project of an oil mill located in a small village of Ligurian hinterland called Marmoreo (GIURDANELA, MARTINA, MORENO, 2004), the existing building was integrated with a new modular construction featuring volumetric elements, based on panel construction method. The new building is located inside the old stone wall perimeter and along the terracing, Fig. C.7. The three-dimensional modular elements are mechanically assembled and are made of a cold-formed steel structure, with timber or aluminium exterior cladding, Fig. C.8. The construction elements, walls, floors and roofs are produced off-site in the form of panels, which are preassembled in the factory and then assembled on site to form box-shaped three-dimensional elements. These modules can be disassembled, packaged and moved as soon as they cease to satisfy their function and can be deconstructed and reassembled somewhere else or dismantled and selectively disposed at the end of their life cycle. In this way, the historical building and its natural context are designed and preserved without jeopardizing possibilities of use by future generations. The choice of lightweight components and materials and reversible connection techniques for ease of assembly and disassembly process offers great opportunities to design and build in accordance with eco-friendly design and requirements of sustainable development as to build flexible and adaptable spaces which can be easily customised and meet changeable housing needs.

Fig. C.7: The case study of renovation project in Liguria: The new construction is located inside the old stone wall perimeter and along the terracing (GIURDANELA, MARTINA, MORENO, 2004)

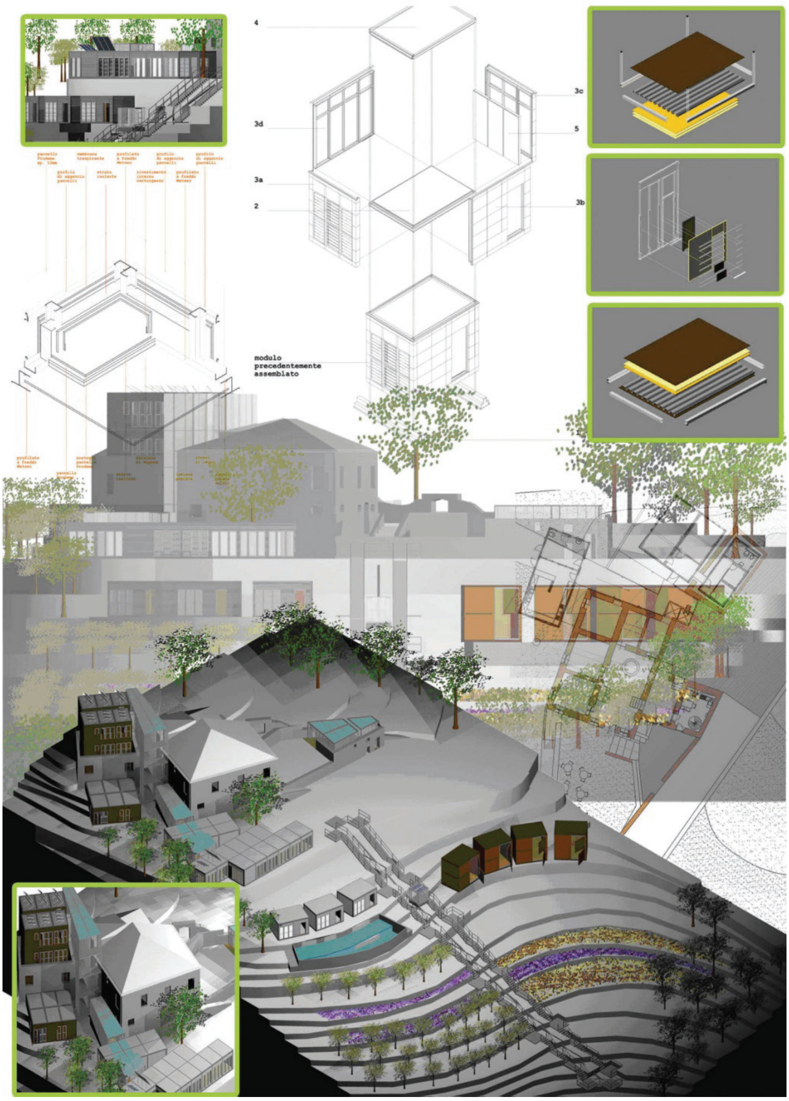


Fig. C.8: The case study of renovation project in Liguria: the existing building was integrated with a new modular construction featuring volumetric elements, based on panel construction method author's redesign (AUTHOR'S REDESIGN FROM GIURDANELA, MARTINA, MORENO, 2004)

3.3 Product 3: Reversible Design for Housing

Starting point of the research is the critical relationship between temporary and sustainable buildings in the construction field. Short term use of space with a reduction of useful life of residential buildings or parts of buildings make shorter life cycle of components and materials and environmental impacts at the end of buildings life, Fig. C.9.

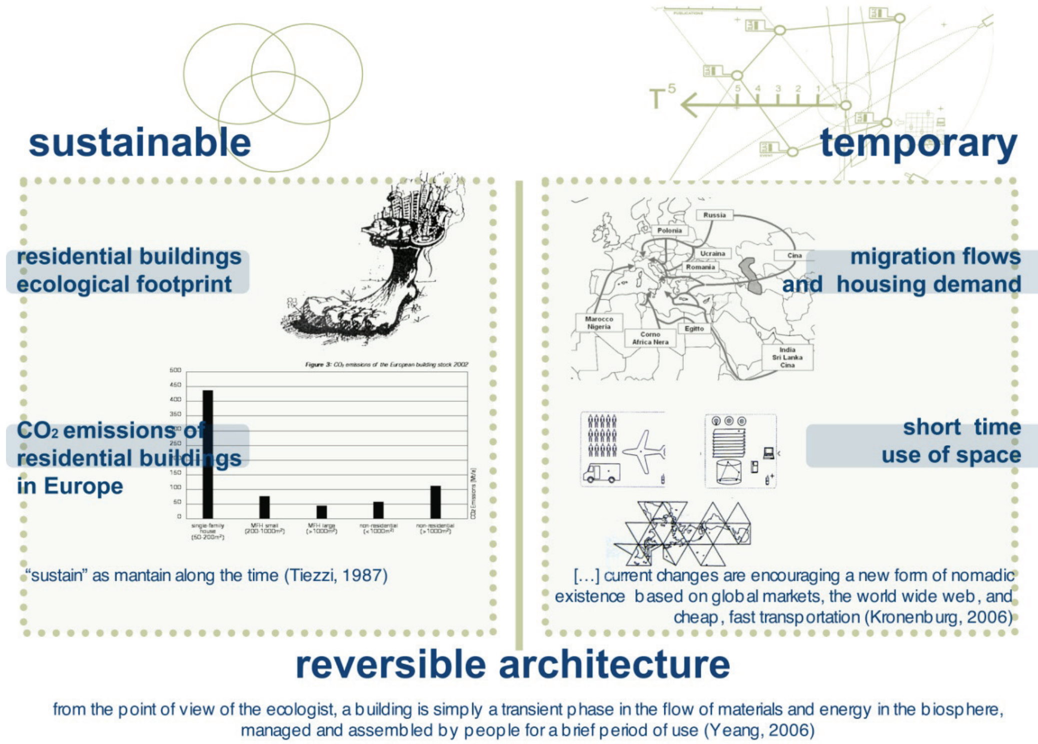


Fig. C.9: Reversible design for housing: Starting point of the research is the critical relationship between temporary and sustainable buildings in the construction field. Short term use of space with a reduction of useful life of residential buildings or parts of buildings make shorter life cycle of components and materials and environmental impacts at the end of buildings life (GIURDANELA, 2008)

Temporary use of space and continuous needs of adaptation lead to fast production of construction and demolition waste and are also current needs and spread social dynamics of living life styles. In this context strategies to close the loop extraction-waste in buildings are needed to make feasible a reverse construction process and reclaim resources, finding a relationship between temporary and sustainable construction by planning the lifespan of the building and consequently using of resources (components and materials) and potentialities to reuse/recycle them, Fig. C.10. The designer is ethically responsible for the designed system, over its entire life cycle up to its after life, so he must be concerned with how the designed system and all its component parts can be taken apart or disassembled in ways that will allow maximum levels of reuse and recycling (YEANG, 2006). According with the scientific literature it is possible to make useful decisions during the design phase about building's form and technical solutions that will allow to reverse the construction process and recover material resources for a second useful life (BOLOGNA, 2002; GANGEMI, 2004).

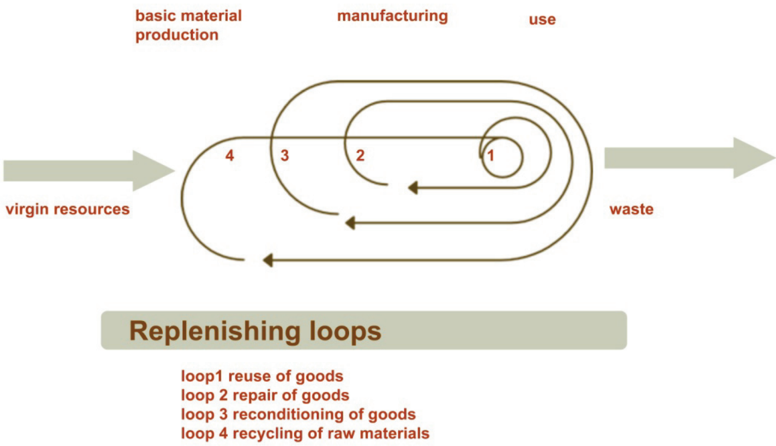


Fig. C.10: Reversible design for housing: Strategies to close the loop extraction-waste in buildings are needed to make feasible a reverse construction process and reclaim resources replenishing loops (GIURDANELA, 2008)

The state of the current social residential needs with changing, flexible and short-term use of space due to flexible life styles is investigated focusing on the demand of new residential buildings and at the same time on continuous needs of adaptation of the existent residential buildings Fig. C.11.

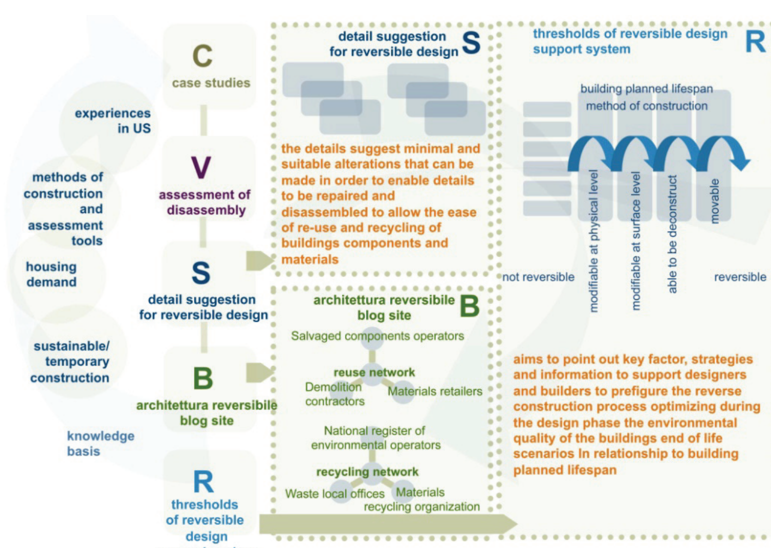


Fig. C.11: Reversible design for housing: research's steps, (GIURDANELA, 2008)

The environmental impact of this pressure requires urgent measures to designers and builders for an ecological response to the current residential needs. In the residential sector notable researches and actions were carried out during the last years to improve the environmental quality particularly related to saving energy during houses' service life, for example improving level of thermal insulation and using renewable energy systems. The ecological approach for an intelligent and eco-friendly use of resources and material along the whole building life cycle (from extraction to dismantling) needs actually more investigations and more concrete and spread application. Reversible design allow disassembly/deconstruction of buildings or part of buildings to easy taking apart and salvaging buildings components and materials in relationship to buildings planned lifespan and it can offer potentialities of eco-friendly use of materials in case of maintenance, rehabilitations, adaptations and disposal allowing diverting C&D waste from landfills, reusing salvageable components and recycling materials. The legitimating of those strategies is justified by minimizing the extraction of new virgin resources and the energy required to manufacture new materials and components, replenishing the loops and preserving embodied energy (KIBERT, CHINI, 2000; GUY, 2003).

Finally the goal of the research aims to suggest ecological strategies and easy to use tools to designers and builders, prefiguring potentialities and concrete actions in the current Italian context to promote eco-design in a life cycle thinking view considering and planning the lifespan of the designed system for an eco-friendly and intelligent use of resources along their lifetime. The second part of the research makes a critical investigation of methods of construction and the existent tools to evaluate buildings' end of life scenarios and it drives the innovative phase of the research with the selection of case studies, Fig. C.12.

Fig. C.12: Reversible design for housing: The investigation point out methods of construction as a key factor to allow buildings deconstruction and components and materials reclaiming with a selection of residential buildings case studies built with different methods and materials (GIURDANELA, 2008)

The investigation point out methods of construction as a key factor to allow buildings deconstruction and components and materials reclaiming with a selection of residential buildings case studies built with different methods and materials. Existent tools to evaluate buildings end of life scenarios are investigated, pointing out their specific goals and indicators to delve and implement parameters to assess potentialities for reversible design. Current researches in European and extra-European context are explored to learn the know-how (operational knowledge base) and useful tools (for management and assessment) to develop the research. Assessment of the technological solutions of the selected case studies with existent tool are carried out for a critical evaluation of methods of construction in relationship with potentialities to reverse the construction process, also pointing out barriers and opportunity for deconstruction of the case studies. By these assessments it is possible to outline barriers and opportunities to realise eco-friendly strategies for the buildings end of life scenarios in relationship to components and materials, assembly techniques, accessibility to the parts. In particular technical solutions of the case studies are assessed with Deco tool (AA.VV., 2000) to evaluate disassembly level in relationship to the potentialities to recover salvageable materials during the dismantling. Deco tool analyzes the technical solutions to evaluate potentialities of buildings components and materials to preserve on one hand original physical, geometrical, dimensional qualities on the other one original chemical composition so allowing potential salvage process. Starting from the analysis of layers of the selected technical solutions and the type of connection of two adjacent layers (gravity connection mechanical connection, welding, bonding) it is possible with the tool to assess the intrinsic level of reversibility of the solution. The critical aspects emerged by the assessment of the selected technical solutions of the case studies are the starting point to elaborate suggestions for eco-design detailing. The innovative part of the research aims to suggest strategies and information to support designers and builders to prefigure the concrete feasibility of deconstruction at the end buildings useful life allowing reclaiming of components and materials in relationship to methods of construction and thresholds of reversible design.

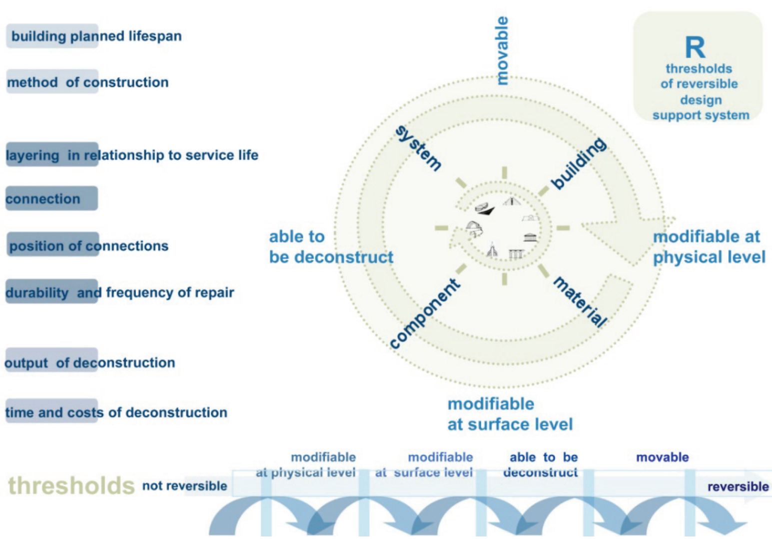


Fig. C.13: Reversible design for housing: key factors to prefigure the reverse construction process to optimise during the design phase the environmental quality of buildings' end of life scenarios, allowing deconstruction and reuse/recycle of components and materials (GIURDANELA, 2008)

In particular three proposal are carried out. *Detail suggestions for reversible design*: starting from assessment of the selected technical solutions carried out in the fourth chapter, the critical connections between layers are investigated and suggestions to improve them to allow disassembly and salvage are elaborated in specifications. The details suggest minimal and suitable alterations that can be made in order to enable details to be repaired and disassembled to allow the ease of re-use and recycling of buildings components and materials; *Architettura reversibile* blog site is the web access point to collect the existent nodes of the market of salvaged materials, with names and addresses of reclaim operators where finding or conferring salvaged components and materials. The concrete possibility to reclaim salvaged materials is the real benefit of deconstruction, so the research investigated and point out the network of operators found out in the current context. The Architettura reversibile blog site is the access point to recycling and reuse existent market network to localise the existent flows of salvaged materials, in Italy and in Lombardy. *Thresholds of reversible design support system* in relationship to the planned lifespan for buildings aims to point out key factors, strategies and information to support designers and builders to prefigure the reverse construction process optimizing during the design phase the environmental quality of the buildings end of life scenarios, Fig. C.13. Goal of the system is to identify the key factors and related needed information to suggest eco-design strategies and qualitative inputs to make concrete reversible design, linking methods of construction and planned lifespan with feasibility of deconstruction and reclaiming of buildings components and materials for eco-friendly buildings end of life scenarios.

3.4 Product 4: Reversible Construction and Existing Building. The Case Study of Research Campus Point in Lecco, Italy

In the current Italian context one of the most recent construction based on modern methods of construction was realised in Lecco, near Milano, as new temporary research office space of Politecnico di Milano's university campus, Fig. C.14.

Fig. C.14: Research Campus Point in Lecco: The temporary office is a three storey construction built in front of the old hospital existing structure of Politecnico di Milano campus, in Lecco (NORLIGHT, 2007)

The Research Campus Point was designed by Studio Ardea with professor Ettore Zambelli, BEST Department, for the client Univer Lecco, Politecnico di Milano. The construction is a three storey building built in front of the old hospital existing structure of Lecco's campus, made of 27 cold formed steel containers to accommodate researchers and laboratories during the four years' construction works of the new campus and renovating works of the existing structure, Fig. C.15.

Fig. C.15: Research Campus Point in Lecco: New temporary offices integrated to the existing building (NORLIGHT, 2007)

Need of quick and temporary spaces able to be easily assembled and disassembled at the end of the four years first useful life has oriented the choice of lightweight steel construction methods, Fig. C.16, Fig. C.17. The new steel modules have the container standard dimensions of 3,00 x 8,11 x 2,70m. They were built off site in Edilsider factory near Lecco and then transported and assembled in four days along the main front of the existing building, Fig. C.19, Fig. C.20.

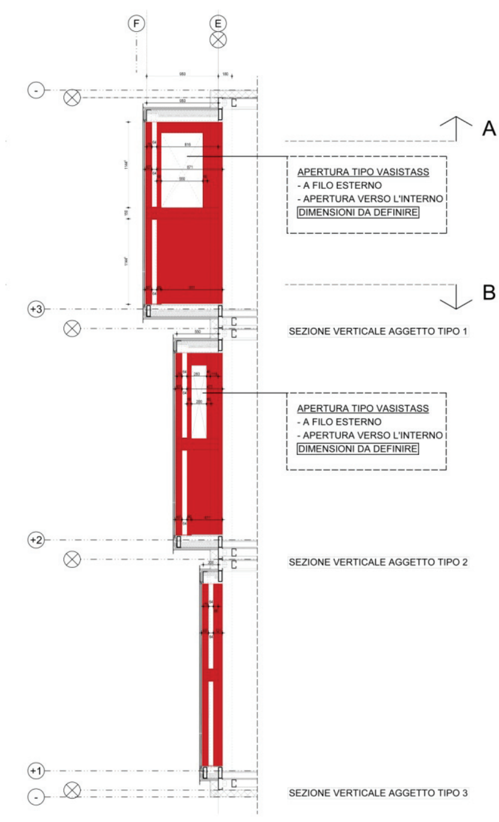


Fig. C.16: Research Campus Point in Lecco: interior view of the offices with interior finishes made of OSB panels (NORLIGHT, 2007)

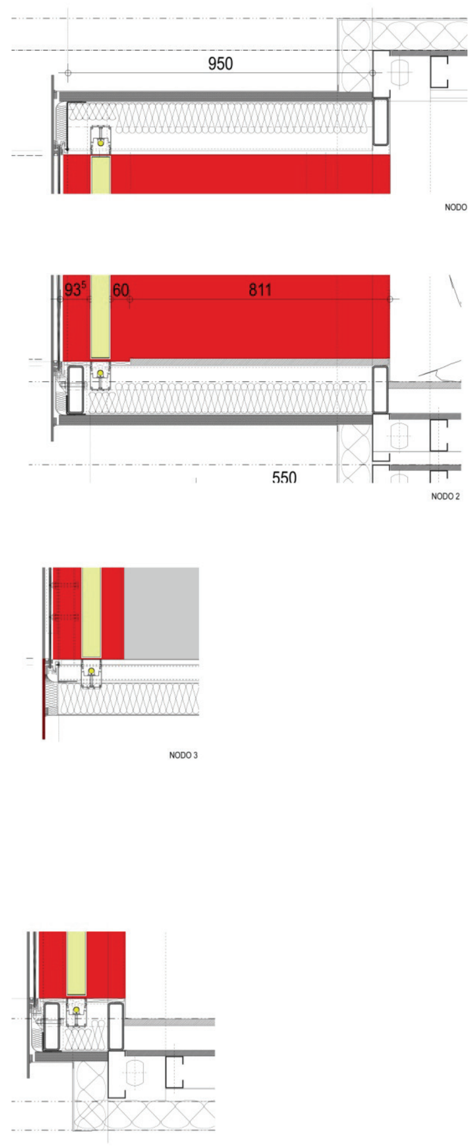


Fig. C.17: Research Campus Point in Lecco: Construction detail and lighting connection (STUDIO ARDEA, 2007)

Different dimensions' volumes were added to the container based structure which creates exterior variations to the modular shape with lug wrenches. The steel structure is made of cold-formed steel "C" sections, which are connected to the concrete footing by steel connections. The main front of the modules is entirely made of high ceiling windows without frames to maximise interior lighting; also metallic nets were used as sunscreen.

Fig. C.18: Research Campus Point in Lecco: Construction detail and lighting connection, (STUDIO ARDEA, 2007)

The building orientation covered by the existing building on west and south side aims to protect the new construction by summer climatic conditions. High level of insulation were provided in the building system to solve first of all winter comfort conditions and different types of insulation were used: 10 cm panels foam in exterior walls and roofs, 10 cm mineral wool panel in interior walls and floors, and 5 cm sandwich panels with polystyrene in added volumes to the container structure. Exterior finishes are made of polycarbonate sheets and interior finishes are made of OSB panels, Fig. C.18.

Fig. C.19: Research Campus Point in Lecco: Construction phase of the building (SANDRO BACCHI, STUDIO ARDEA, 2007)

Fig. C.20: Research Campus Point in Lecco: Construction phase of the building (SANDRO BACCHI, STUDIO ARDEA, 2007)

4 Conclusions

According with carried out researches reversibility emerges as design paradigm to meet temporariness and sustainable issues in architecture and construction industry in order to consider social and environmental needs in current housing context. Designers and builders can play an important role in triggering this change of views in relation to production of industrial components for new buildings and also for actions taken on existing ones. Design and build with reversibility paradigm in mind can offer great potentialities to eco-friendly address of construction industry and to guarantee, at the same time, high quality level of buildings in accordance with buildings' planned lifespan.

In particular the investigation about methods of construction, as key factor to allow a reverse construction process, drove the elaboration of the concept of "thresholds of reversible design", as levels that methods of construction straddle. The thresholds of reversible design are elaborated as potential improvement level to optimise technical solutions for ease of separating parts to obtain salvageable components and materials and are related to the key factors of methods of construction and building planned lifespan. With barriers and opportunity for deconstruction and its intrinsic features every method of construction straddle a threshold of reversible design, starting from this level it is possible making design decisions and technical choices improve the level of reversible design and allow a "threshold jump" to a better level. The different thresholds going from non reversible to reversible level in relationship to the salvageable resources and to the level on which disassembly can take place: physical level (modifiable at physical level), surface level (modifiable at surface level), component level (able to be deconstruct), building level (movable). The investigated tools suggested potentialities to develop the research theme and to implement different aspects related to the environmental quality for eco-design of buildings end of life scenarios, also emerges the consideration to implement qualitative and easy to use tools to support designers and builders in their daily work to promote eco-design in a life cycle thinking view considering and planning the lifespan of the designed system for an intelligent use of resources along their lifetime.

At that point, also by introducing in buildings' end of life cycle concrete actions to those currently in progress to make energy-efficient buildings during their useful life, great potentialities for more rapidly dissolving cultural resistances to lightweight construction methods in Italy might be found.

5 References

AA. VV. (2005), *Il mercato delle costruzioni 2006.* XIII Rapporto Congiunturale Cresme, CRESME Ricerche, Roma,

AA.VV. (2006), *Gli scenari della domanda residenziale nella provincia di Milano 2006-2015. Rapporto di ricerca*, Quaderni del piano territoriale n. 25 Provincia di Milano, Alinea Editrice, Firenze.

AA.VV. (2006), *Futurebuild 2006 – Innovation in construction methods and material*, 22-23 February 2006. Earl Court, London. Proceedings of the conference, supported by BRE, English Partnership, Housing Corporation, London.

AA. VV. (2003), "Modern methods of house building", *Postnote*, n. 209, The Parliamentary Office of Science and Technology, London.

AA.VV, F.IN.CO. (2004), (Federazione industrie prodotti impianti e servizi per le costruzioni), ENEA (Ente per le nuove tecnologie l'energia e l'ambiente); Ministero dell'ambiente e della tutela del territorio, *Libro bianco energia, ambiente, edificio: dati, criticità e strategie per l'efficienza energetica del sistema edificio*, Il sole-24 ore, Milano.

AA.VV. (2001), *Tecnologie di intervento per l'innovazione negli insediamenti per l'emergenza ipotesi progettuali e tecniche costruttive per la realizzazione e l'adeguamento prestazionale di residenze provvisorie*, Ricerca cofinanziamento Murst 2000, Unità operativa di Milano, Responsabile Guido Nardi.

AA.VV. (2000), "Strumenti operativi per valorizzazione degli scarti finalizzati alla definizione di criteri di scelta per possibili strategie di riduzione/recupero", report della Ricerca finanziata con fondi MURST 2000PRIN, *Strategie per la formazione della pratica del riciclo in Architettura*, coordinatore nazionale Virginia Gangemi, Unità operativa Istituto Universitario di Architettura di Venezia, responsabile scientifico Nicola Sinopoli.

ANTONINI ERNESTO, edited by, (2001), *Residui da costruzione e demolizione : una risorsa ambientalmente sostenibile : il progetto VAMP e altre esperienze di valorizzazione dei residui*, Franco Angeli, Milano.

BAUMAN ZYGMUNT (2002), *Liquid Modernity*, Polity Press, Cambridge, 2000(It. tr. of Sergio Minucci, *Modernità liquida*, Laterza, Roma - Bari.

BÖGNER-BALZ HEIDRUN, ZANELLI ALESSANDRA, edited by (2007), *Ephemeral Architecture. Time and Textiles,* Proceedings of TensiNet Symposium 2007, 16-18 April 2007, Politecnico di Milano, Libreria Clup Milan.BOLOGNA ROBERTO, edited by, (2002), *La reversibilità del costruire. L'abitazione transitoria in una prospettiva di sostenibilità,* Maggioli, Rimini.

BRIAN EDWARDS, edited by, (2003), *Green Buildings pay*, Spon Press, New York.

FLADE ANTJE (2002), *Psychological Considerations of Dwelling*, in SCHWARTZ-CLAUSS MATHIAS (edited by), *Living in Motion. Design and Architecture for Flexible Dwelling*, Vitra Design Stiftung gGmbH, Weil am Rhein, pp. 220-237.

CAMPIOLI ANDREA, ZANELLI ALESSANDRA (2006), *Membrane and Shells: adaptable structures for the building sector*, Proceedings of the joint CIB, Tensinet, IASS International Conference on Adaptability in Design and Construction, Eindhoven University of Technology, Department of Architecture Building and planning, Adaptables 2006. International Conference on Adaptable Building Structures. 3-5 July 2006, Eindhoven (vol. 2, pp. 6-58-6-62).

CAMPIOLI ANDREA, MANGIAROTTI ANNA, ZANELLI ALESSANDRA (2008), Textile Architecture in the Italian Context. In *International Journal of Space Structures*. vol. 23, n. 4, pp. 201-206

CONFINDUSTRIA (2004), *Rapporto sull'industria italiana*, Camera di Commercio Industria e Artigianato, Roma.

GANGEMI VIRGINIA, edited by, (2004), *Riciclare in architettura. Scenari innovativi della cultura del progetto*, Clean Edizioni, Napoli, 2004.

GIURDANELLA VALERIA (2008), *Reversible design. Strategies to allow buildings' deconstruction and second life for salvaged materials and components*, Ph.D's thesis, Politecnico di Milano, tutor prof. Alessandra Zanelli.

GIURDANELLA VALERIA, MARTINA SOFIA FRANCESCA, MORENO MANUELA (2004), *Marmoreo oil mill retraining and high reversibility construction*, degree's thesis, academic year 2002-2003, Politecnico di Milano, tutor prof. Alessandra Zanelli, co-tutor arch. Monica Lavagna.

GIURDANELLA VALERIA (2008), www.architetturareversibile.blogspot.com, blog site about reversible design, elaborated in connection with the Ph.D. thesis *Reversible design. Strategies to allow buildings' deconstruction and second life for salvaged materials and components*, Politecnico di Milano, Milano.

GUY BRAD, WILLIAMS T. (2003), "Design for Deconstruction and Reuse", *Final report on behalf of the US EPA Office of Solid Waste and Emergency Response*, Powell Center for Construction and Environment, University of Florida, Gainesville.

IMPERADORI MARCO (2007), "La ricerca trasparente", in *Il Sole24Ore Arketipo*, n. 14, , Milano, pp. 80-89.

KIBERT CHARLES J., CHINI ABDOL R. (2000), *Overview of Deconstruction in Selected Countries*, CIB Report, Publication 252, Task Group 39: Deconstruction, Univesity of Florida, Center for Construction and Environment, M.E. Rinker Sr., School of Building Construction, College of Design, Construction and Planning, http://s14.cfaa.ufl.edu/centers/sustainable/.

KRONENBURG ROBERT (2008), *Flexible. Architecture that responds to Change*, Laurence King Publishing, London.

MANZINI EZIO (2004), *Processi sociali di apprendimento*, in Bertoldini Marisa, a cura di, *La cultura politecnica*, Paravia Bruno Mondadori Editori, Milano, pp. 161-167.

MONTANELLI ARTURO (2008), www.arturomontanelli.com, the Studio Ardea Office website, Lecco

PIETRABISSA RICCARDO, edited by, (2008), *Campus point: un prototipo di centro di ricerca aperto,* Polipress, Politecnico di Milano, Milano

RAMMLER STEPHAN (2002), *"A mighty fortress…"?! On the Sociology of Flexible Dwelling*, in SCHWARTZ-CLAUSS MATHIAS (edited by), *Living in Motion. Design and Architecture for Flexible Dwelling*, Vitra Design Stiftung gGmbH, Weil am Rhein, pp. 196-219.

REESER AMANDA (2004), *"Complexity and customization"*, in *Praxis* n. 6, pp. 46-53.

ROSS KEITH (2005), *Modern Methods of house construction. A surveyor's guide,* BRE Trust, Garston, Watford.

RUSSO ERMOLLI SERGIO (2006), *Green buildings. Architetture sostenibili nel Regno Unito*, Clean Edizioni, Napoli.

TOFFEL MICHAEL W. (2003), "The Growing Strategic Importance of End-of-Life Product Management", in *California Management Review* 45, no. 3.

TOFFEL MICHAEL W. (2003), "Closing the Loop: Product Take-back Requirements and their Strategic Implications", in *Corporate Environmental Strategy* 10, no. 9.

TOFFEL MICHAEL W. (2002), "Strategies for end-of-life product recovery: Drivers, prior research, and future directions", in Conference on European Electronics Take-back Legislation: Impacts on Business Strategy and Global Trade, INSEAD Fontainebleau, France

YEANG KEN (2006), *Ecodesign: a manual for ecological design*, Wiley-Academy, Londra.

ZAMBELLI ETTORE, VANONCINI P.A., IMPERADORI MARCO (1998), *La costruzione stratificata a secco*, Maggioli, Rimini.

ZANELLI ALESSANDRA (2003), *Trasportabile / Trasformabile. Idee e tecniche per architetture in movimento*, Clup, Milano.

ZANELLI ALESSANDRA (2008), www.architetturatessile.polimi.it, the Italian website about membranes and shells usable for nautical and building applications, Politecnico di Milano, Milano.

D) Industrialisation for Complex Building Envelopes: State of the Art and Future Developments

INGRID PAOLETTI[1]

1 Introduction to Industrialised Curtain Wall Systems

Throughout history, building envelopes has attempted to embody a constant research on protection (from rain, cold heat, solar radiation and intrusion), prestige and identity (dimension, materials and decoration) and comfort (light ventilation, insulation, perception).

Initially, building envelopes provided shelter and protection, but with time and with the dawn of the industrial revolution, architecture of building envelopes developed to incorporate advances in industrial technology: new forms of industrial production and capital organisation necessitated new forms of spatial organisation.

Buildings became a system of components with minimal integration, and in order to facilitate the pace of building construction, building envelopes no longer had any overall structural function and simply became the “skin” of the building. The building envelope developed into a prefabricated factory assembled-site installed component: the curtain wall.

Moreover a great attention has been undertaken on transparency, either as a desiderable dream of architects such as Frank Lloyd Wright and Mies van der Rohe (Fig. D.1) either in order to plan wider spaces without compromising energy performance and indoor comfort.

The skyscraper was made possible by a combination of two technologies: steel framing and the passenger elevator. The potential was first explored in Chicago and realised by Burnham and Root in their design of the Reliance building (Fig. D.2).

The liberation of the coincidence between structure and cladding, started by the historical avanguardes, is nowadays widely confirmed. Envelopes have so far evolved very rapidly in design and technologies expressing most of the time the edge cut technologies and innovation of industrial products, that is why it’s a system of great interest from the industrialisation in construction perspective.

[1] MSc Arch., Phd, Assistant Professor in Technology for Architecture, Coodinator of Innovative Technologies and Construction Industry Cluster, BEST - Building Environement Science Technology Dept., Politecnico di Milano, Via Bonardi, 9 - 20133 Milano, Phone +39.02.23995117, Fax +39.02.23995151, ingrid.paoletti@polimi.it

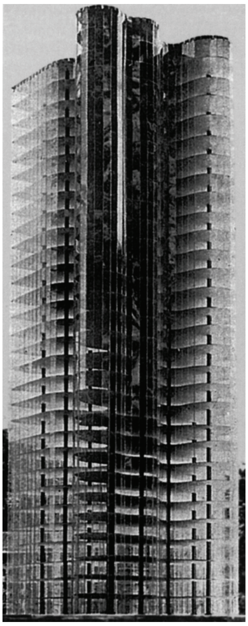


Fig. D.1: Mies Van Der Rohe, glass skyscraper idea, 1920.

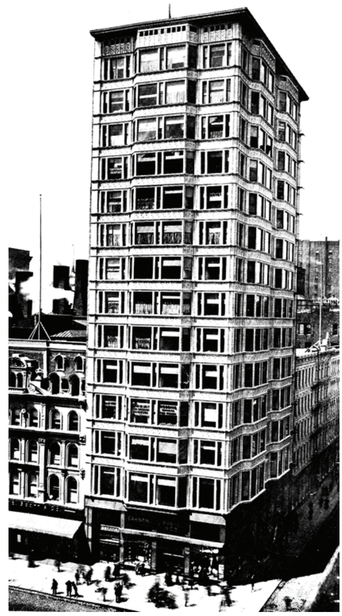


Fig. D.2: Burnham and Root, Reliance building, Chicago, 1950.

In this context, construction industry seems to proceed towards product development on two sides: for the material part (the system), as for the immaterial part (the necessary knowledge for its use), far from the dimensions of handicraft traditions as well as from the pure industrial reproduction.

This is connected to the change in digital technologies, that unable a more direct production from design drawings thanks to parametric software, and production modalities, nowadays realised by flexible CNC machines. In particular, during the last years, construction industry is proceeding towards a production made of custom products but on a large scale, with simplified processings and systems of light pre-fabrication, introducing mass-customisation production systems. This term indicates a personalisation of products which, recognizing the importance of the requirements for each single project, does not renounce to the conception of efficient technologies at a contained costs. Thus, products are realised to measure for each project and not as standard production for market forecasts.

Mass-customisation assumes, in the context of building envelopes, a double meaning: on the one hand it is the expression of a mature construction industry applying for a qualitative development, on the other hand it approaches constructive choices at the early stage of design, before site operations. «In other words, the formal complexity of many contemporary projects is offering the opportunity to reconsider the sequence idea-project-site based on engineering, to propose instead the central explorative character of the design activity and technological solutions» (Campioli, in Pignataro, 2005, p. 47).

2 Innovation for Facade Technologies

Façade is nowadays a completely designable system which has a high level of industrialisation.

In the recent past, placed at the end of the operative chain, strangled by contracts with general contractor and impeached by a traditional company culture, construction industry seemed to have few possibilities for development. Today, the construction process becomes more and more global with a high international competition and the industrial production is necessarily obliged to reply to the requirements of architects in terms of flexibility and innovation.

For what concern flexibility, it is possible thanks to lightweight technologies and dry assembly construction modalities which seem to catalyze a big interest in façade construction.

On the one hand, there is an exponential diffusion of industrialised components, due to opening markets competitivity, the improvement of performances and quality control, but also due to their capability of suiting technological complexity and construction flexibility of many architectural projects. A tendency near to the "technological push", i.e. to the pressing of new products and systems towards design, pushed by an industry which searches for new markets investing in technology.

On the other hand, the exchange between these technological potentialities expressed by the industry and the capacity by many representatives of the contemporary architecture to interpret it in an innovative way is increasing. This tendency can be seen as "need pull", a research of satisfaction which can generate profitable interferences with the technological push. In reality, in fact, it is difficult to find models exclusively referred to one or the other, but more often a wide range of hybrid solutions: the genesis of a technology can be found in an intermediate position between the necessity to satisfy a need and the availability of solutions for this need (Verganti, Calderini, 2005).

For what concern innovation, it is introduced in envelope technologies due to different processes.

The first mechanism refers to the research by the designer of new materials and configurations, where nowadays this cannot occur in the conventional way, by only examinating the offers from market, but has to be studied and faced in relation to the numerous interdependent variable factors of building envelopes. For example structural complexity, together with morphological language, together with specific performances also because of new requirements in sustainability (Claudi de Saint Mihiel, 2005).

The second mechanism refers to technology transfer, where, specific products or technologies penetrates in construction, aiming to implement specific requirements. The sectors involved are usually chemistry, molecular biology, computer systems, material science and far away sectors such as aeronautic and naval.

In front of innovation possibilities proposed by know-how from other fields, the problem is not only to individualise the appropriated technology for the project, but mostly to study the usage conditions able to progress the knowledge and the research towards advanced and at the same time improved technical solutions. Examples of this mechanism can be found in different fields: from materials (shells, polymers, fibres), to semi-processed products (profiles, accessories for the construction, gluing systems), to components (metallic nets, adhesive tapes), and not least to technologies (led, optical systems). All these elements can be called "pervasive" i.e. they are created in sectors of high technology, but are diffused transversally in all sectors, also the traditional ones, introducing in these important changes (Utterback, 2005).

A further mechanism for innovation is created by the development of the digital platforms, which permit the passage from an arbitrary representation of complex forms to an almost objective one. These computer systems support the increase of technical and computable performances by series of functions linked to the planning and the modelling of the architectural project, which have repercussions on the technical possibilities, accelerating the phase of feasibility. "In a certain manner, nowadays, there is a change from the mental imagine of the project to its instrumental imagine and it is completely different, i.e. the creation is modified by the instrument, by the software, independently of the quality and the performances of the instrument." (Virilio in Burkhardt, 2005, p.8)

Livio Sacchi (2005) asserts "(...) numerous software are now available aiming at the management of the modelling of the architectural space, in an evident creative meaning, and there are more and more architects who declare expressively that their projects or buildings would not have been possible to imagine or to realise without the assistance of these computer programs. Thanks to the digital systems, the interaction is still stronger between the preliminary phases of the project process, the following executive operations and at last the construction and the management." (p. 29). Placing side by side digital tridimensional instruments, such as the parametrical software, to the usual bidimensional techniques, not only increases the possibility of representation of the project, but adds useful information for the realisation of the project, introducing often innovative processes.

This innovation is more and more placed upstream the used technology, it is the result of synergies supported by digital technologies, which depart from the division between product and process towards a transversal research, in which both slopes are linked in a delicate balance between the possibilities offered by industry and research and the potential applications.

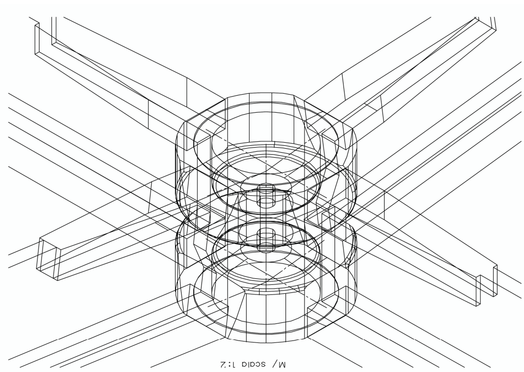


Fig. D.3: The integration between technical and software innovations has allowed the conception and construction of the sail of the new fair by Massimiliano Fuksas, studied by Schilich.

3 Complex Shapes Construction: Case Studies of Building Envelopes

Traditional forms of vertical buildings are radically changing in the last decades. This is due to a renovated cultural context, new technological boundaries, innovative digital tools and industrial building components. Those factors give a new freedom to designer, who is spured to experiment more complex shapes, using materials and construction systems according to completely unusual methods.

Therefore contemporary architectural envolopes appear more complex not only in their morphology but also in their constructive configurations, raising new technological requirements. In order to meet those requirements construction industry is very soon involved in the design process, in order to dialogue with complex configuration and discretisation of shapes at the very early stage. On another side construction industry evolves very fast in knowledge, thus trying to reach new markets in architecture.

Some projects finished in recent years have underlined an industrialised approach to façade that goes beyond a traditional process and have arisen innovation.

Four examples will be analyzed with different technologies. The first one is Post Tower in Bonn by Murphy and Jahn, with a steel extruded façade structure, the second one is Coophimmelb(l)au BMW welt in Munich, with a steel file to factory production, the third one is Gehry New York office building, with a cold curved unit system façade, and the last one is Zaha Hadid Innsbruck station with double curved glass envelope.

The first example is **Post Tower by Murphy and Jahn**, a 160 meter high building that stands at the edge of the city adjacent to the Rhein River. park. The split, shifted oval tower is oriented to the Rhine and the city, facilitating views from the city and minimizing negative wind effects through its aerodynamic shape. In plan the split oval wedges are separated by a 7.40 m wide space. The connecting glass floors at 9-story intervals form skygardens, which serve as communication floors and elevator crossovers. (Fig. D.4)

The tower has a twin-shell facade, enabling natural ventilation, especially in the spring and fall. The glass outer shell protects from rain, wind and noise and allows for placement of the sunshades. Glass from floor to ceiling optimises daylight.

The peculiarity of this project from industrialisation in construction perspective is the steel structure of the façade that has been designed and engineered in order to face high speed wind pressure but at the meantime to have a light section of brackets.

It has been studied by Thyssen Krupp and Hoesch Bausysteme, two big steel companies in Germany, a special geometry that could allow the external fixing of the glass façade, the possibility to open it for ventilation and a reduced section of steel brackets.

This has been achieved by extruding steel bars in two pieces, one with a T shape and the other one with a parenthesis shapes and fixing them together in a unique profile for glass positioning.

Extrusion of steel has not been so easy at it needs stronger machines, higher forces, and matrix gets used very fast due to hot temperatures. However this technique applied to steel really allowed a 60 mm section profile for a floor high of 160 metres with strong structural performances.

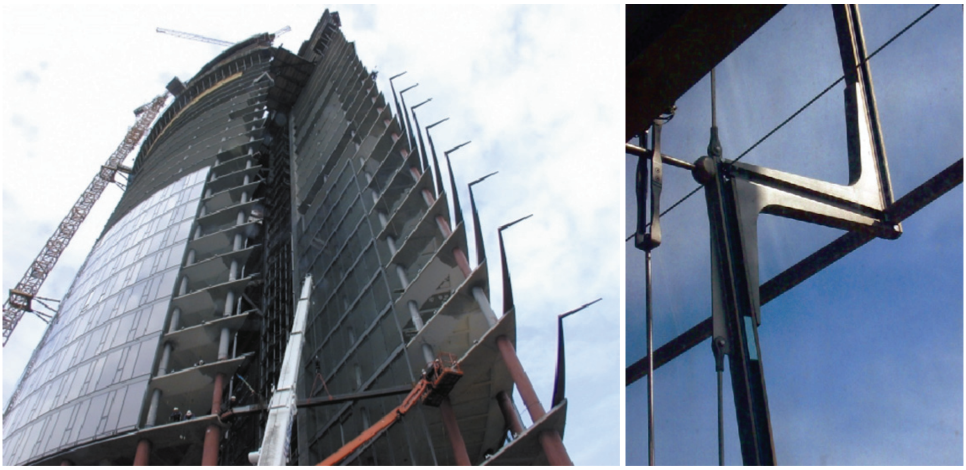


Fig. D.4: Murphy and Jahn, Post Tower Bonn, 2002. View of the cladding process and of the extruded steel brackets.

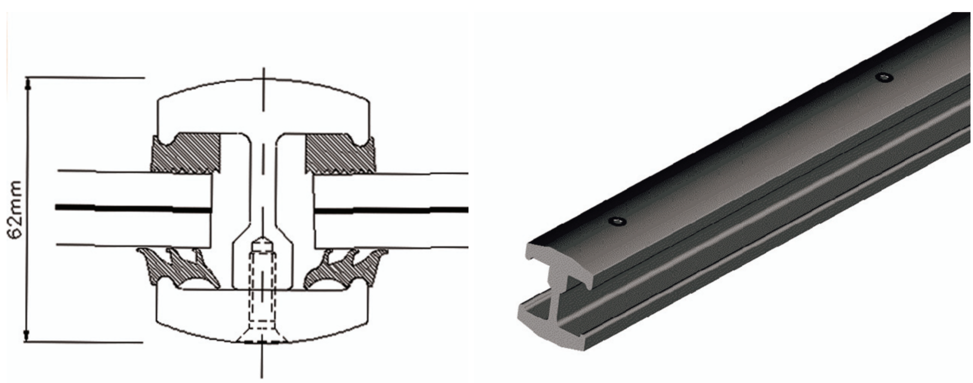


Fig. D.5: Murphy and Jahn, Post Tower Bonn, 2002. View of the steed extruded profile that has allowed a very thin section whilst guaranteeing high structural performances.

The second example of industrialisation for building envelopes is the ***Coophimmelb(l)au BMW welt*** for Monaco where the steel structure has been studied by consultants, cladding specialists and designers in order to optimise the steel layout.

The sight of the building is especially distinguished by what is called the “tornado”: a central cone composed by two cones connected at the top which create a sculptural and moved roofing system, catalyzing the attention of visitors. The roof shape suggests the idea of a cloud dominating the environment, which creates a feeling of continuous compression and decompression of spaces, due to the different internal heights. In addition, the roof is important for the lighting and the internal-external relation: it can indeed be considered a real source of light, emphasised also by the extreme construction lightness.

This lightness is expressed by using curtain walls, also for the great entrance hall, which are continuous, transparent and covering the complete height following the course of the overhanging roof . Coophimmelb(l)au explains that the shape of the tornado, symbol of this architecture, was conceived with an initial intuition and transformed in a concrete form through the fusion of two aspects: first a model to obtain a vision of the sculptural volume and then the study of the flexion moment and structural verification of the two cones. Both phases have been supported by software, the model thanks to the software SpaceArm, a layer scanner 3D which is able to convert the physical model into curves and surfaces Nurbs (Non-Uniform Rational B-spline), the second one by means of the software 3D Rhino which consents to verify the course of the solicitations on the structure (Fig. D.6).

The following step was to find the best surface solutions for the effective realisation of those shapes. The engineering of the complex form was made by means of the software Catia, which enabled to reduce the quantity of used iron, passing from a structure with primary and secondary beams to a structure with a single lay-out, improving in this way the structure frames. The quantity of iron used is in any case about 2.000 tons. The idea to connect the bearing carpentry to the structure for the curtain walls, giving the structural task to the support beams, was conceived during the engineering of the form, made by Gartner-Permasteelisa, constructor of the work. The special details used in these cases foresee the use of rectangular and square iron sections, to improve the structure and the materials, to be added to the L and C profiles for the support of the glazing. In this project, instead, the glazed part interfaces directly to steel by using supports in rubber which consent also to settle the glazing with corners and tolerances out of standards (Fig. D.7).

The main part of the structure is pre-assembled in workshop, in transportable pieces, and despatched to the site located about 100 km from the workshop. The bold challenge consists in the fact that the same metallic structures have also to contain, in the hollow parts, the tubes for the heating and cooling water, the sprinklers and all cables for the illumination, openings and automation systems: a factor of further complexity for a metallic carpentry.

In particular the steel structure has been completely produced by architectural drawings with CNC machines, thanks to curtain wall supplier. This technology is in any case mature for customisation as it already employs industrial production systems. This procedure has allowed a reduction of tolerance both in workshop and on site. This innovative way of construction has been possible also thanks to the final customer, BMW, that had the desire to express technological edge through architecture, without budget constraints.

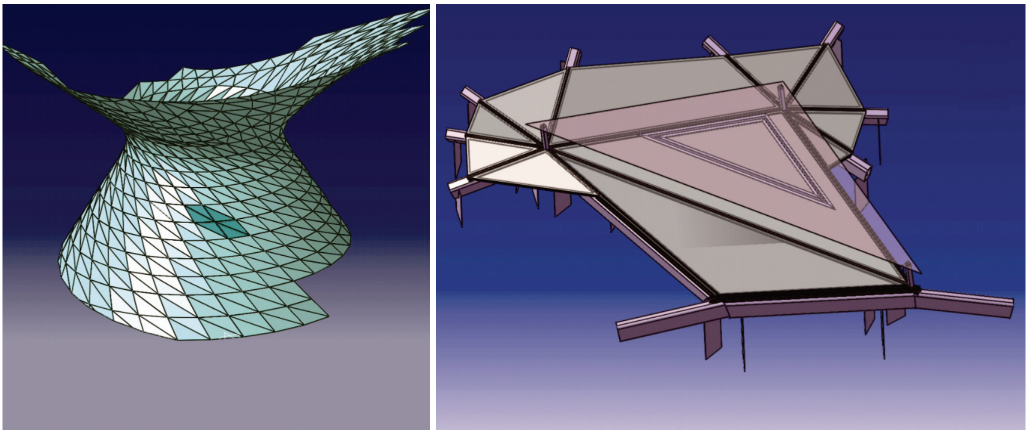


Fig. D.6: Coophimmelb(l)au Tornado, view of the parametric and structural model of the 'tornado' in prefabricated steel structure.

Fig. D.7: Coophimmelb(l)au Tornado, view of the prefabricated steel structure on site

The **IAC building of Gehry Associates** is a glass office located on two side streets in New York City, giving the building's main facade a smooth, uniform appearance. Horizontal, fritted white bands line the windows, a decorative element meant to control the flow of light inside.

The interest of this project consist on the unitised systems façade studied in order to maintain always a flat geometry, while at the same time having the possibility to 'twist' in a position that allows reaching a curved shape of the hole building.

Based on a parametric unit principle all the unit are similar but different in order to utilise cell geometry database and similar system design to configure the building shape. (Fig. D.8)

Directly extracted from a file design in parametric software called Catia, quite complex but very complete, curtain wall cells have their own dimension and an exact location in the building envelope structure.

In order to build this envelope with a ‘curved’ surface while keeping flat unit system façade, each cell has the possibility to ‘twist’ inside a certain range in order to keep into the correct position. This operation has been first modelled in software and then tested on site in order to verify the tolerances and the materials flexibility.

On site a manual pressure has been put on the transom in order to fit in its final position and glass at the end of the site operations has the possibility to be shaped for more than two centimeters. (Fig. D.9)

This is undoubtedly a strong evolution in building envelopes technology, because this technology starts from a unitised technology and tries to push the boundary of materials limits.

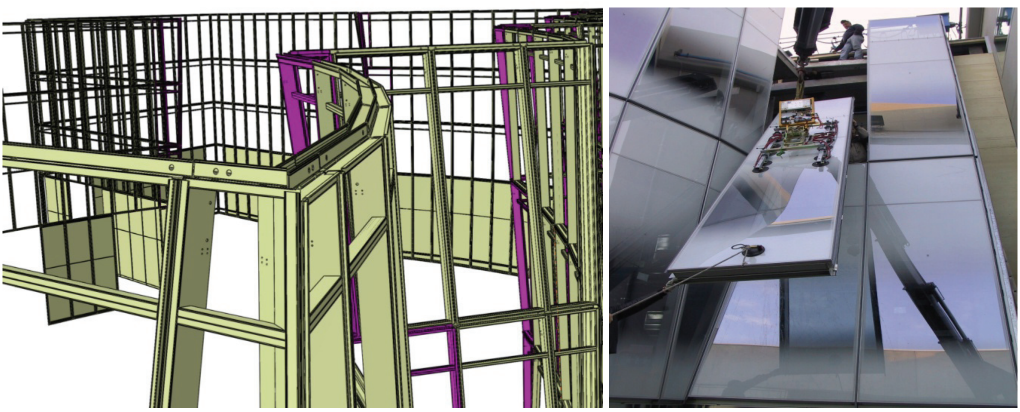


Fig. D.8: IAC building in New York by Gehry Associates, 2007. View of the parametric cell design and the mock up test.

Fig. D.9: IAC building in New York by Gehry Associates, 2007. Structure installation and envelope installation.

Zaha Hadid Innsbruck stations is the last project presented in this paper and probably the most complex, from different points of view. Those stations have been completely designed by the architect in Rhino and then produced thank to a file to factory production systems.

The envelope is a double curved surface, with glass panes, joined to the structure thank to a simple steel and epdm joints.

The moulded, double-curved shapes may suggest that they are made of fibreglass, but the material used for these canopies is far more brittle and unforgiving: it is pure glass. This gives the canopies a polished, lustrous finish, just like ice. Toughened glass also has the practical benefit of being durable and resistant to knocks from falling rocks or trees.

Not surprisingly, the design pushed advanced glass technology to its limits. In construction method, the canopies really do resemble aircraft wings, as the skin has been wrapped all around parallel steel ribs spaced at 1.25m intervals. The big difference is that glass could not simply be riveted to the steel ribs to assume its double-curved shape.

Instead, it had to be made up of a series of rigid panels, all fabricated to the same 1.25m dimensions as the spacing of the ribs. Far more tricky than that, each glass panel had to be moulded precisely to its final double-curved shape, while softened by heat at the glassworks. A total of 850 glass panels were used to cover all four stations, and each panel was unique in its sculptural form. Some of the panels even come with a continuous recess or trough, with a radius as tight as 60mm, to serve as a rainwater gutter sunk into the canopy's top surface and leading to a conventional downpipe concealed inside.

The glass technology was developed by structural engineer Bollinger & Grohmann, of Frankfurt and Vienna, and manufacturer Pagitz Metalltechnik, of Klagenfurt, although the panels were actually made in China using computer-numerical-controlled (CNC) machines linked directly to the design team's CAD system in Europe (Fig. D.10)

The basic material of the manufacturing process was a series of flat panes of 12mm thick glass. Moulds were made out of steel rods contoured to the precise double-curved shape of each panel. Then an 8mm thick glass pane was made pliable with heat and laid over the countoured bed as an underlayer to mooth out bumps and imperfections.

After that the final pane was laid over the underlayer. Next, a 1.5mm thick layer of white polyurethane resin was laminated to the underside of the panel to hold the glass together in case it shattered and give it a strong white appearance. All the panels were prefabricated to a tolerance of ±3mm and after manufacture, their precise shape and dimensions were checked by a 3D digital scanner

The assembly method on site was at least as ingenious and even more complicated. Hadid wanted the curved outer surface of the canopies to be streamlined across all the panels, uninterrupted by gaps, steps or bolt-heads. A secret fixing system was devised in which stainless-steel cleats were bonded with adhesive to each panel so that they that would project slightly from the edges. (Fig. D.11)

At the same time, a 93mm-thick strip of polyethylene that had been pre-formed by CNC to the precise curvature of each panel, was bolted around the outer edge of each steel rib. When each panel was offered up to its final position on-site, its projecting steel cleats were screwed into polymer buffer. Finally, the 25mm gaps between the panels were filled with black silicone that neatly concealed the cleats and screwheads.

A final consideration has be made on the final results that somewhere shows the criticism of experimental technologies. In this case the thin joins sometime become wide silicon joints not always as previewed in the design phase. (Fig. D.11)

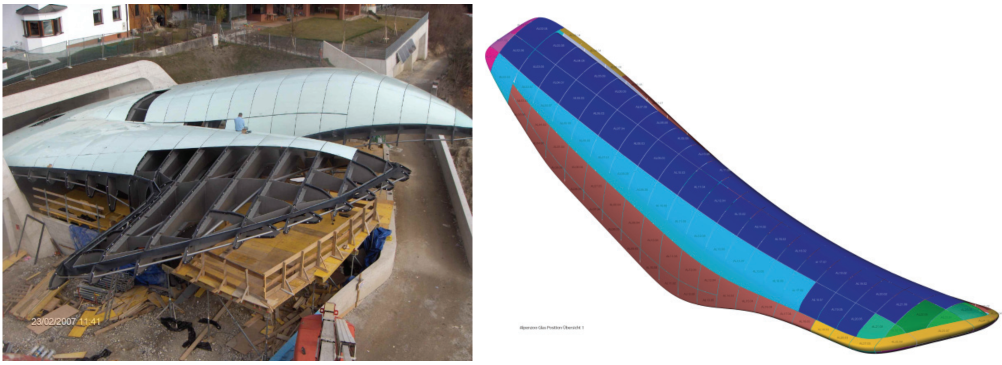


Fig. D.10: Zaha Hadid Innsbruck stations. View of one of the station on site and of the modelling of the complex envelope.

Fig. D.11: Zaha Hadid Innsbruck stations. View of one of the station on site and of the modelling of the complex envelope.

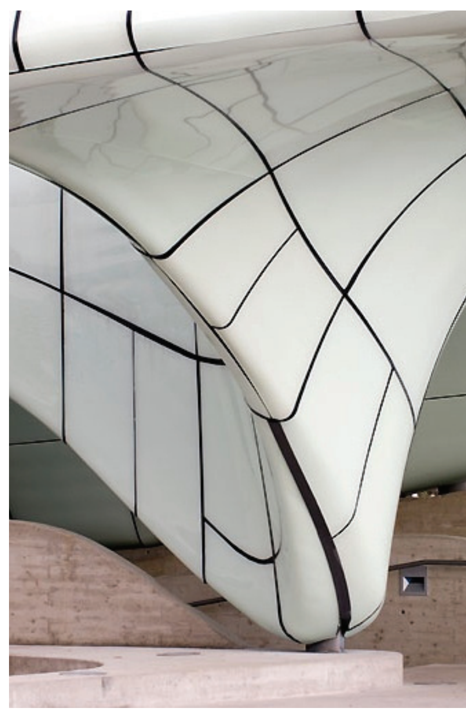


Fig. D.12: Experimental technologies still shows some criticism on site: in this case some joints became very large to close with silicone due to increasing tolerances.

4 Future Developments

Some opportunities and weaknesses of the employment of industrial technologies and advanced processes for complex building envelopes can be underlined.

The first opportunity refers to the innovation produced by new materials and technologies. They can be tailored to meet specific needs: not only their appearance but also their functionality can be modified by creating new configurations or a combination of the already existing ones.

A second opportunity refers to the increasing mathematical definition of surfaces, which can facilitate the accuracy of calibration between conceptual phase and detailed design phase for construction. This relation is guaranteed by the increasing use of parametric software, which can work with a 3d model and manage cam and cnc applications.

Another aspect to refer to is the reduction of construction timing, which can improve construction modalities. This is possible thanks to a planning and a coordination of the site operations by means of new procedures and equipments. For example, the topographic erection system Surveying 3D (through total stations and theodolites), usually employed in the mechanics or aerospace fields, allows to draw a cloud of points from a 3D drawing which corresponds to precise coordinates in the space.

A firs weakness consists in the very different processes of specialist aggregation involved in each project, that doesn't allow a specific record of experiences and methods. Each complex shapes is different and someway unique, that means that an implementation of knowledge at a wider level is quite difficult.

Another weakness is the special destination of those buildings that have unusual rules and high representative value, thus been far from diffused industrialisation knowledge.

In conclusion, all the case studies of complex envelopes examined revealed a strong cooperation with construction industry, encouraging a different profile of designer which has to combine specific knowledge with a cultural vision of architecture. The designer needs therefore to be constantly updated, to acquire new competences and knowledge of new instruments and technologies, to liaise with the industry and with those specialists able to introduce innovation through technology.

Moreover construction industry is more and more aware of the strategic importance of technology in the economic competition: acquiring outdoor products and services, adapting technologies, choosing partners able to manage at their best their knowhow and using mass customisation processes seems the way to improve quality while maintaining an edge cut knowledge. This means that innovative technologies developed in a specific context will be easily implemented in different projects, as they have been incorporated in the production processes.

5 References

Cagan Jonathan, Vogel Craig M., 2002, *Creating breakthrough pr*oducts, Prentice Hall, New York.

Campioli Andrea, 2005, *Idea, Progetto, Cantiere*, in Pignataro Maria (a cura di), Innovazione di prodotto e architetture di forma complessa, Clup, Milano.

Claudi de saint mihiel Claudio, 2005, *L'innovazione dei processi costruttivi*, in Losasso Mario a cura di, Progetto e innovazione. Nuovi scenari per la costruzione e la sostenibilità del progetto architettonico, Clean, Napoli, pp. 97-104.

Galli Riccardo, 2005, *Innovazione. Le parole della tecnologia*, Ediesse, Roma.

Lavodou Armelle, 2005, "Architectes, entreprises e industriel: une complicitè a rèinventer", in d'A, n. 151, dic, pp. 23-29.

Morin Edgar, 1985, *Le vie della complessità*, in Bocchi Gianluca, Ceruti

Mauro a cura di, 1985, La sfida della complessità, Feltrinelli, Milano.

Pignataro Maria (a cura di) 2005, *Innovazione di prodotto e architetture di forma complessa*, Clup, Milano.

Sacchi Livio, 2005, "Le reti e l'architettura della città", *Rassegna* n. 81, dic., pp. 29-35.

Sala Nicoletta, Cappellato Gabriele, 2004, *Architetture della complessità: la geometria frattale tra arte, architettura e territorio*, Franco Angeli, Milano.

Shodek Daniel, Betchold martin (et alii), 2005, *Digital design and manufacturing*, John Wiley & Sono, New jersey

Utterback James, 2006, *Design inspired innovation*, World Scientific Publishing Company.

Verganti Roberto, Calderini Mario, Garrone Paola, Palmieri Stefania, 2005, *L'impresa dell'innovazione*, Il sole24ore, Milano.

E) Pre-fabricated Systems in Light Steel and Modular Construction

R. MARK LAWSON[1] & RAY OGDEN[2]

1 Introduction

It is recognised that pre-fabrication by off-site manufacture leads to faster construction, improved quality, and reduced resources and waste. Although pre-fabrication is not in itself new, off-site manufacture (OSM) describes a supply and construction process in which the major parts of a building are mass-produced in factory conditions rather than on-site. In recent years, the term 'Modern Methods of Construction' (MMC) has been introduced by UK Government to describe both off-site manufacture and innovative construction techniques that are promoted as a way of improving quality, speed and reliability.

Steel construction is, by its nature, pre-fabricated to some degree, but the innovative use of this technology has arisen in response to market demand for higher levels of pre-fabrication. In the context of this paper, the uses of highly pre-fabricated construction systems will be reviewed, showing how steel technology has developed over the last 5 years and how research has supported these new developments.

The main sector for which MMC is being promoted is in housing and residential buildings, which also includes single person accommodation and affordable housing, particularly in inner cities. Steel construction has established a 'track record' in commercial buildings, where the benefits of speed of construction and long spans with service integration are well understood, and this is transposable to other sectors.

Volumetric or 'modular' construction is an example of a high level off-site manufacture, but there are also opportunities for 'hybrid' planar (2D) and volumetric (3D) technologies, which optimise the value-cost balance in housing. 'Open building' systems are relatively advanced as they allow for interchange of components to create more flexible building forms than is achievable in fully modular construction. This is the area in which the greatest advances are possible, and a CIB Working Commission is currently exploring open building systems at an international level.

1 Prof Dr MICE, MIStuctE, MASCE, SCI Professor of Construction Systems, University of Surrey, GU2 7XH, UK, Phone +44 1483 686617, Fax 44 1483 682135, m.lawson@surrey.ac.uk

2 Prof Dr, SCI Professor of Architecture, Oxford Brookes University, OX3 OPB, UK, rgogden@brookes.ac.uk

1.1 Case Examples

Recent projects in the UK have demonstrated the benefits of pre-fabricated construction technologies, such as the award-winning Murray Grove project in Hackney, London, which used volumetric construction based on the Yorkon system. A project in Fulham, west London used light steel framing, modular bathrooms and a slim floor primary frame at first floor to optimise both the construction process and provision of space in this residential building. In both projects, the client was The Peabody Trust, a social housing provider, which took a strong interest in realising the value-benefits of these relatively new technologies. The projects are illustrated in Fig. E.1 and Fig. E.2 and are described by Lawson (2007)

Fig. E.1: Installation of modular units at Murray Grove, Hackney, London (Yorkon)

Fig. E.2: Completed mixed panel and modular project at Lillie Road, Fulham, London

The world's largest modular buildings (in terms of number of modules) are located in Manchester and use a similar technology based on the *Ayrframe* system, an innovative form of 'stressed skin' construction. The Royal Northern College of Music student residence consists of 900 modules in a 6 to 9 storey configuration (Fig. E.3), and a mixed commercial-retail development consists of 1400 modules is supported on a podium structure. (Fig. E.4).

Unite Modular Solutions, a major 'design build finance operate' provider in the student residence and key worker sector in the UK, has completed many projects using fully modular construction, and its factory produces bedroom modules at a rate of up to 20 per day.

Fig. E.3: Royal Northern College of Music, Manchester consisting of 900 modules

Fig. E.4: Mixed commercial-residential development in Manchester using 1400 modules on a steel-composite podium structure for the ground floor and basement

1.2 High-rise buildings

Modular construction is conventionally used for cellular buildings up to 8 storeys high where the walls are load-bearing and resist shear forces due to wind. However, there is demand to extend this technology up to 15 storeys or more by using additional concrete cores or structural frames to provide stability and robustness.

One technique is to cluster modules around a core to create high-rise buildings without a separate structure, in which the modules are designed to resist compression and the core provides overall stability. This concept has been used on one major project called Paragon in west London, shown in Fig. E.5, in which the modules were constructed with load-bearing corner posts and were placed around concrete core that was constructed in advance (Cartz and Crosby, 2007).

The building form may be elongated laterally provided that wind loads can be transferred to the core. This can be achieved by using in-plane trusses placed within the corridors, or by consideration of the structural interaction between the modules and their attachment to the core. The layout of modules in a high-rise building form in which modules are clustered around a core is illustrated in Fig. E.6. Apartments comprise two or three 3 or 3.6m wide x 7.2m long modules, some with an integral balcony.

An adaptation of this technology is to design a ‘podium’ or platform structure on which the modules are placed. In this way, more open space can be provided for retail or commercial use or below ground car parking as shown in Fig. E.4. Support beams should align with the walls of the modules and columns are typically arranged on a 6 to 8 m grid (7.2 m is optimum for car parking).

Fig. E.5: High –rise modular building in west London using a concrete core for stability (Caledonian Building Systems)

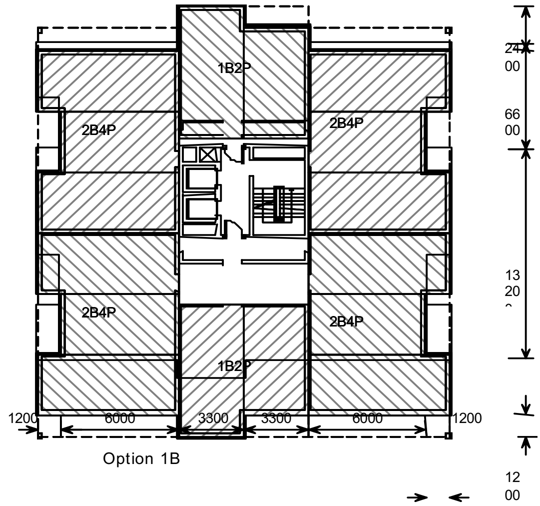


Fig. E.6: Plan form of high-rise modular building, showing apartment layouts (2B4P means 2 bedroom 4 person)

2 Generic Forms of Construction

Historically, steel has been used in housing for 70 years, and there are many good examples of its use worldwide. The modern forms of steel and mixed construction systems that are widely used in the housing and residential sector are described (Lawson, Ogden et al. 2005) in simple terms as follows:

2.1 Light steel framing

Light steel framing consists of galvanised steel C-sections of typically 65 to 200 mm depth and in steel thicknesses of 1.2 to 2.4 mm. Walls are generally pre-fabricated as 2D-panels, as in Fig. E.7, whereas floors can be installed in elemental form as joists or in 2D-cassette form. For 2 storey buildings, platform construction may be used (i.e. floors sit directly on walls as shown in Fig. E.8) but for medium-rise design, it is necessary to achieve continuity in load paths through the walls, for example by use of a Z trimmer attached to the top of a wall panel and which supports the floor on the inside face of the wall.

Fig. E.7: Assembly of light steel panels in production

Fig. E.8: Light steel framing using wall panels for housing

2.2 Forms of modular construction

Volumetric or modular construction systems are manufactured from 2D wall panels and floor cassettes in light steel framing, but are assembled into load-bearing 'boxes'. The primary limitations are those of production and transport as factory manufacture requires multiple similar units, and transport necessitates a unit width of less than 4.1 m.

Two generic forms of modular construction exist:

- Continuously supported or 4-sided modules where vertical loads are transmitted through the walls (Fig. E.9).
- Open-sided or point-supported modules where vertical loads are transmitted through corner and intermediate posts (Fig. E.10).

Fig. E.9: Continuously supported module in light steel framing (Terrapin)

Fig. E.10: Corner-supported module (Kingspan Off-site)

Corner-supported systems require deeper edge beams than continuously supported modules. In both systems, resistance to horizontal loads can be provided by bracing or diaphragm action in the walls, but for buildings more than 6 storeys high, a separate bracing system is required. Forces are transferred by the module-module connections in the form of plates and bolts, assisted by horizontal bracing in the corridors.

2.3 'Hybrid' modular and panel systems

'Hybrid' or mixed modular and panel systems optimise the use of the 3D and 2D components in terms of space provision and manufacturing costs. Modular units are used for the higher value more highly serviced areas, such as bathrooms, and wall panels and floor cassettes for the more flexible open space. Two generic forms of 'hybrid' steel construction may be considered:

- Load-bearing modules with floors supported by the modules.
- Non-load bearing modules (or pods) supported by floors.

The first system was used in a demonstration building for Corus (Lawson, Ogden et al. 2004), shown in Fig. E.11 and Fig. E.12, in which the central service core and stairs were manufactured as modules and the open plan space was provided by pre-fabricated panels and floor cassettes spanned up to 5.7 m. In this way, the internal space could be partitioned to suit the user's requirements. The construction of the Lillie Road project in Fig. E.2 comprises X-braced wall panels, floor cassettes and stacked bathroom modules, as shown in Fig. E.13.

Fig. E.11: Demonstration building using mixed panel and modular construction

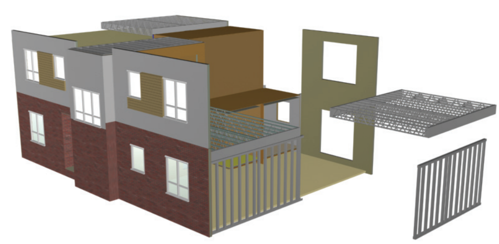


Fig. E.12: Hybrid panel and modular construction (by courtesy of Corus)

In modular construction, greater flexibility in building height and internal planning can be achieved by the mixed use with a primary steel structure. Various generic forms of construction may be employed by creating;

- A 'podium' or platform structure, in which the column spacings are located at multiples (two or three times) the module width
- A skeletal structure, which provides the open plan areas and the stacked modules provide the highly serviced areas or cores
- A skeletal structure, in which non load-bearing modules and wall panels are supported on the floor.

A podium structure is often used where retail outlets or communal space are provided at ground floor and car parking in the basement, as in the project shown in Fig. E.2. Composite construction may be used in which the podium level is designed to support the load from the modules above (typically 6 storeys).

A skeletal structure may be designed in the form of slim floor beams using HE or RHS sections in which the modular and floor cassettes are supported on the extended bottom flange of the beams, so that the beams occupy the same depth as the floor. In the MOHO residential project in Manchester, a steel 'exo-skeleton' was created, which provided stability to partially open sided modules that were placed inside the steel frame, as shown in Fig. E.14.

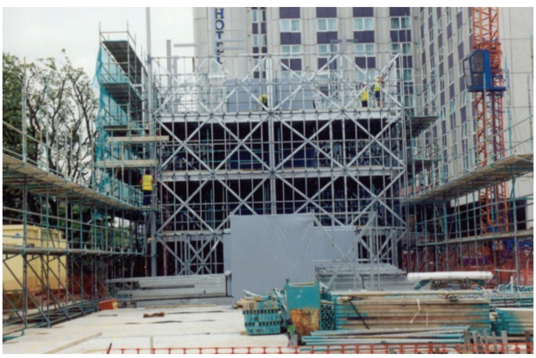


Fig. E.13: Load-bearing braced walls and stacked bathroom modules in the project shown in Fig. E.2

Fig. E.14: Steel framework supporting open sided modules- MOHO , Manchester (Yorkon)

2.4 Open-Building systems

'Open-building' is a general term used to describe systems, which provide flexibility in space planning and an inter-change of components. Many of the hybrid systems described above achieve some of the principles of 'open technology', but to be more widely applicable and to achieve economy in manufacture, geometrical standards and common interface standards are required for the cladding, services, lift and stairs and other key components. Geometric standards that may be used for concept design, which are based broadly on the following dimensions:

- wall width of 300 mm for internal separating walls and external walls.
- floor depth of 450 mm for the combined floor and ceiling depth in modular and 'hybrid' construction systems.
- floor depth of 600 mm for modules supported by a primary steel structure.
- internal planning dimensions based on 600 mm on plan (therefore 3 or 3.6 m are preferred internal modular widths
- floor-ceiling heights based on 2.4 m for residential buildings and 2.7 m for commercial, health or educational buildings.

Modular construction achieves the benefits of off-site manufacture, but it requires a new discipline in construction technology based on building 'blocks' rather than skeletal or planar components with which designers are familiar. An optimised modular system must allow for greater flexibility in internal planning, but must retain the primary benefits of speed of installation and improved quality. The inter-relationship between modules and efficient provision of space can be improved by strategically placed internal posts, which allow for both open-sided design and for re-orientation of modules. A typical plan of such a group of modules is illustrated in Fig. E.15. Openings of up to 3 m width can be created, and a cluster of posts form a column which can support loads of up to 8 storeys.

The Open building approach has been applied in two building systems. *OpenHouse AB* is a Swedish system (Lessing 2004) in which recessed modules are supported on a grid of 3.9 m by Square Hollow Section (SHS) columns, as illustrated in Fig. E.16. In this way, modules can be re-orientated. *Smart House* is an open building system used in the Netherlands using a tubular steel frame. A central non load-bearing service core is provided, and all light steel walls and floors are relocatable.

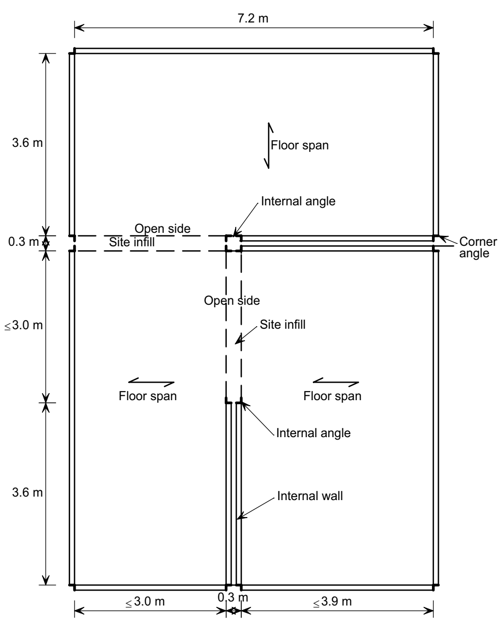


Fig. E.15: Creation of flexible space using modules

Fig. E.16: Installation of modules with recessed corners around SHS columns (OpenHouse AB)

3 Economics and Production

The underlying economics of off-site manufacturing (OSM), and modular construction in particular, are quite complex and require a significant production rate of repeatable components in order to be fully economic. OSM requires capital investment in the infrastructure of factory production, design development, product testing and certification, and overheads of a fixed facility and factory space. Cellular-type buildings, such as hotels and student residences consist of multiple similar units, and are the types of projects where OSM has proved to be successful. The breakthrough of OSM into the wider residential sector is still in its infancy.

Modern highly automated factories for modular production cost of the order of €15 million to set up. Although much less than the €1,000 million required to set up a new automotive production line, these costs are distributed over a yearly output of 1,000 to 2,000 units in a changeable building market, in comparison to a typical annual production of 50,000 of a successful car model over a 7 year cycle. Balanced against these fixed capital costs are savings due to more efficient production technologies, reduced site construction costs, higher quality levels, and time-related savings due to speed of construction. Although it is recognised that time savings of 30-50% in total construction time can be realised by modern offsite manufacturing, the economic value of this early completion depends on the business operation or early sales revenue. This can be quantified for a hotel chain or a time-constrained operation, such as a University, but is less apparent for a house builder in a speculative market.

Essentially, the additional costs of a permanent factory have to be balanced against savings in inefficient and wasteful site operations. Most OSM projects involve a proportion of site work (20 to 40% being typical, depending on the system), which are reflected in the overall costs. Although OSM leads to efficiencies in materials use and reduced wastage, many pre-finished components are bought in, which increases their cost. Small OSM projects may not result in significant economies, unless the same form of construction is repeated in a number of similar projects. However, large OSM projects can lead to cost savings of 10 to 20% in addition to time savings by reducing site infrastructure costs and increasing productivity and reliability.

The rationale behind the expansion of OSM depends on investment in numerically controlled machinery and integrated CAD/CAM software. In Europe, parallel technology was first developed in the timber frame industry, whereas in Japan, companies such as Sekisui and Toyota Homes are advanced in implementation of steel–based technologies in modular construction. Light steel sections may now be produced by small-scale roll-forming machines, and panels are assembled accurately on tables and boards are fixed rapidly, for example using ballistic nailing. A typical factory assembly process is shown in Fig. E.7. Turning tables permit panels to be worked on from both sides, and services can be pre-installed. Up to 30 stages are required in a continuous modular production facility. Completed modules are sent directly to site for ‘just in time’ delivery.

4 Conclusions

This paper reviews modern methods of light steel and modular construction that are used mainly in the residential sector, and identifies mixed forms of skeletal, planar and volumetric construction that are economic in the medium-rise sector. The structural behaviour of light frames is such that buildings up to 8 storeys high can be designed.. Modular units often have additional steel corner posts, which add to their compression resistance. Modular buildings up to 17 storeys high have been designed using concrete cores for stability. Open building systems can use modular units when supported by a separate structure or where modules are open-sided.

5 Acknowledgements

The research was carried out by the Steel Construction Institute and Corus under various European funded research projects. Photographic material and additional information was provided by Feilden Clegg Bradley. Michael Barclay Partnership, Unite Modular Solutions, HTA Architects, Caledonian Building Systems, Kingspan Off-site, Corus Living Solutions, Terrapin, Yorkon, and the Swedish Institute of Steel Construction.

6 References

Cartz J.P. and Crosby M. (2007) Building High-rise Modular Homes, The Structural Engineer Vol 85 No. 19. January 2007

Lawson R.M. (2007) Building Design using Modules, The Steel Construction Institute publication 367

Lawson R.M., Ogden R.G. et al. (2004) Steel in Residential Buildings for Sustainable and Adaptable Construction. Final Report to ECSC Project 7215-PP-058, European Commission

Lawson R.M., Ogden R.G., Pedreschi, R., Popo-Ola S., and Grubb, J. (2005) Development in Pre-fabricated Systems in Light Steel and Modular Construction, The Structural Engineer Vol 83 No 6 15 March 2005 p.28-35

Lessing J. (2004) Industrial production of apartments with steel frames. A study of the Open House system. The Swedish Institute of Steel Construction Report 229-4

F) A Flexible Topfloor System with Integrated Heating and Cooling for the Infra+ Floorsystem

MARK COX[1], LEO VAN HAREN[2], TIM DE HAAS[3]

1 Introduction

Adaptability and flexibility are frequently used but not well defined terms in the building industry. Due to the complexity of the building process and the wide variety of people and interests, adaptability and flexibility carry a different meaning and value for the various participants with regard to comfort and financial aspects. Therefore, we have determined that the starting-point is that "flexibility should not be an option but should be a standard feature of a building component at no or little additional cost". This has been the main goal of designing a top floor for the Infra+ floor.

The Infra+ floor is a hollow (piping) floor that can hold installations as drainage, electricity and ventilation pipes in X and Y direction. Through the flexible top floor the installations are always accessible (see Fig. F.1).

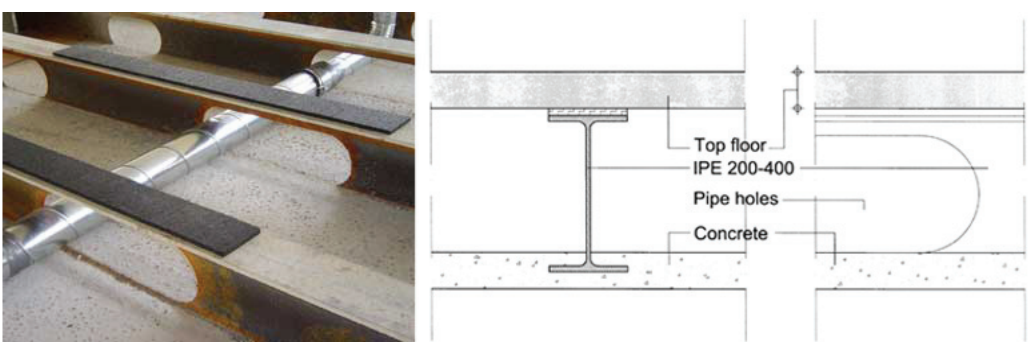


Fig. F.1: The Infra+ floor (picture) and sections of the Infra+ floor together with the top floor.

The design has been divided in several stages:

[1] Ir., Eindhoven University of Technolgy, Department of Achitecture, Building and Planning, Vertigo Building, floor 7, room 7.28, PO Box 513, 5600MB EINDHOVEN, The Netherlands, Phone +31-(0) 40-2474050, Fax +31 40 2475887, m.g.d.m.cox@bwk.tue.nl

[2] Ir., Chair of Product Development, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Phone +31 40 2474050, Fax +31 40 2475887, lcmvanharen@hotmail.com

[3] Ir., Chair of Product Development, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, Phone +31 40 2474050, Fax +31 40 2475887, t.c.a.d.haas@tue.nl

- The SlimBouwen® philosophy was used to define a design strategy for building products
- The Infra+ floor system is one of the existing products that is characteristic for the SlimBouwen® philosophy but does not completely fulfill all the criteria. This is mainly due to the fact that the existing top floors for Infra+ do not meet the expected adaptability and flexibility standards, especially when heating and cooling need to be integrated.
- The defined design strategy led to a completely new design of a top floor that integrates heating and cooling.

The new top floor is based on the SlimBouwen® philosophy of prof. dr. ir. J.J.N. Lichtenberg from the Eindhoven University of Technology. This philosophy states among others that the present building industry is characterised by a very conservative attitude, inefficient use of space and materials, producing lots of waste and by innovations that are mainly based on "Innovation by Addition". Designing a top floor system for the Infra+ floor according to this theory proves that a highly flexible and adaptable system is possible and, not necessarily an option but can be a standard feature of the product at competitive cost.

2 SlimBouwen®

Slimbouwen® is not a building system, but *"an integral view on building and possibly a system of agreements and guidelines at a strategic level"* (Lichtenberg, 2005). SlimBouwen® aims particularly at the following aspects:

- Flexibility and comfort (People);
- Reduction of waste, energy saving and emission of CO_2 (Planet);
- Efficiency (reduction of failure costs, weight saving, reduction of volume, gain of construction time by reorganisation of the construction process)(Profit)

Moreover, it is important that adaptability and flexibility are embedded into the design, so that when user requirements change, the building can anticipate, both on the level of 'support' and 'infill'.

Instead of Innovation by Addition, the following approach was used:

SlimBouwen® is a philosophy that can be used as a guideline to design building products that have standard features like flexibility and comfort and that are designed from an *integral* point of view. For example, not only the user or constructor are regarded as main users but also the building process and the end users' comfort and flexibility are taken into account.

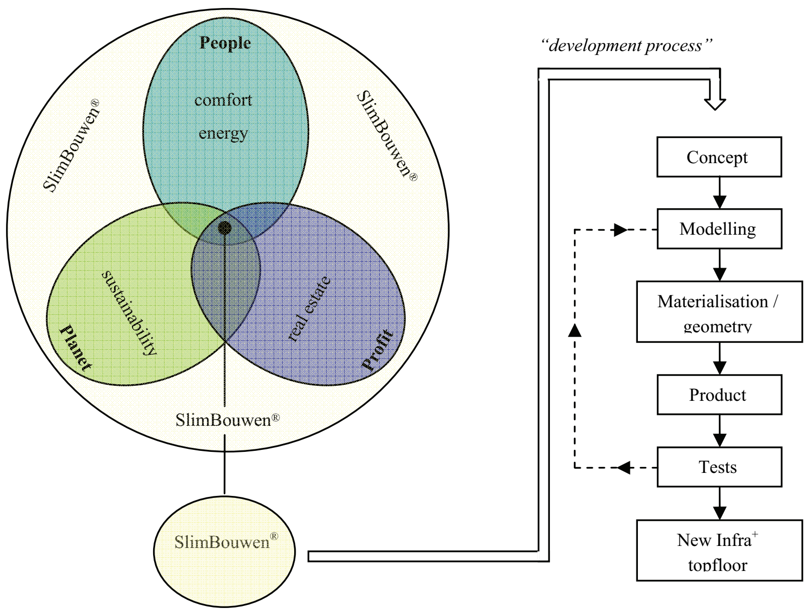


Fig. F.2: People Planet Profit and Slimbouwen ®, Ir. M.G.D.M. Cox

3 Background on the Design Method for Product Development in the Building Industry According to SlimBouwen Strategy

In the last decades the tendency has arisen in the Netherlands to deal more carefully with the available land/space. In this context the Dutch government has taken measures to use the land optimally by means of multiple and intensive space usage (MIR). Primarily MIR is intended as an instrument to build and invest in urban areas with an objective optimum use of the available ground.

This means explicitly that on the available ground, space destined for housing is created, which is not function-tied; i.e. the space is suitable for numerous applications and possibilities without costly investments when the function changes.

This requires not only creative solutions of architects and builders, but also of investors. One of the main objectives of investors is: a maximum return on their own capital. The output on a property investment is a combination of direct output arising from direct net turnovers and indirect output that is the change in value of the property investment. Both, direct and indirect output are influenced by the mechanism of supply and demand. Space, for which no tenant has interest, remains without rental incomes and therefore without positively direct output. The same applies to real estate that is not let or can be let. This has a lower value then real estate that is long-term let.

However, it must be taken into account that the location of the present real estate has a substantial influence on the value appraisal; a building due for demolition in the center of Amsterdam has a significant higher value than a similar object in a rural area. Therefore, investors have been interested in real estate that is readily marketable and is well located. The foundation is in fact laid for a number of investment risks such as vacancy and value development that have to be overcome.

Dutch society is continuously developing; the population increase continues to persevere, the need for living space per person increases steadily and the demographic composition of the population modifies, etc…This development will certainly have repercussions on the Dutch real estate market. Looking at the current Dutch commercial market, we can deduce that approximately 200,000 employees are necessary to fill the current vacancy in the offices. Several studies have demonstrated that the office market will not grow sufficiently to fill this gap, so office space needs to be used in another way.

Unfortunately a large number of office buildings have been built for a fixed function. This leads to restrictions with respect to function conversion, on account of applying land-use plans and the tight Dutch laws and legislation. Due to this obstacle, owners of office premises are faced with structural vacancy and a lot of insuperable problems.

Aforementioned developments demand for another approach and interpretation of the real estate market. From numerous sectors we know the phenomenon, in which production resources (supply market) are deployed as a company means and are also managed as such. Anticipating the market requires coordination of the production resources and the interpretation of this market's needs (demand market). Financial modifications and/or developments in the market are taken into account from the start.

In the past, the real estate market has used traditional building methods to interpret and meet the current market needs without anticipating future changes in the market needs. Housing constructions are still made from poured concrete structures or stacked constructions, offices are mainly realised by means of concrete elements - columns, beams and floors - and curtain walls. All these construction methods lead to buildings without considerable flexibility to provisions.

The choice for new innovative construction methods, that create flexibility and quality in buildings, combined with ingenious financing methods, offer investors in the future less risk and a more positive value development of their portfolio. Investors, however, have to be prepared to leave the conventional out-of-date process of building. Only in this way opportunities can develop for new construction concepts, that can anticipate simply to future market developments.

In times of high fluctuation in the use of spaces (housing/offices), it appears that function-tied buildings can anticipate the requirements and demands of the user/investor. The requirement for flexible construction systems originates from non function-tied building and the resulting requirements and demands. Flexible construction systems have the advantage that modifications in the design, implementation and use stage, modifications can be delayed until a late stage.

Within these flexible construction systems, floors have a distinguished role, due to the large number of services that are present in the floors. Choices that are made, in whatever stage of the construction process or use phase, generally have large consequences for existing services and therefore, for the floors.

A solution for the piping problems in the floor can be found in constructive flexible piping floors. These floors ensure a separation of the structural function and the piping installation. The constructive flexible floors have been designed in such a way that the piping at each stage of the process (design, implementation and use) can remain accessible. A good example of a constructive flexible control floor is the Infra+ floor (supplier: Prefab Limburg).

With the development of such structural flexible control floors one problem has been solved, but leads directly to a new problem. All constructive flexible control floors that are available on the market, are not the result of an integral approach. This has led to semi-finished products, which still must be provided with a top floor. The current generation of top floors do not meet all boundary conditions and requirements of the underlying semi finished product (constructive flexible floor). As a result, the advantages of the constructive flexible floors cannot be used.

The newly developed top floor is a result of the optimum flexibility in combination with low temperature floor heating/cooling. The flexibility of the top floor ensures a longer life span of the building. Changes regarding to the installation structure can be achieved easily. By detaching the accessibility of services from the building function, an important cost factor is controlled.

In other words, function free buildings with integrated heating and cooling are made possible by this top floor (in combination with constructive flexible floors). The presence of low temperature floor heating and high temperature cooling has big advantages, for example: healthier indoor climate. Furthermore, the advantage of the building users is the lower usage costs for such a system in terms of energy bill, in comparison with a traditional system (radiators). The substantial extra value for the investor and user by the application of the new developed top floor, is gained by combining low-energy heating/cooling with optimum flexibility. Because of this development shifts in the market that lead to function changes in buildings can be addressed by the flexibility of the top floor with conservation of low temperature heating/cooling. This can be realised without too much incremental costs for the investor or user.

4 The Structural Infra+ Floor System

The Infra+ floor system (see Fig. F.3) was one of the first products that resulted from SlimBouwen® philosophy.

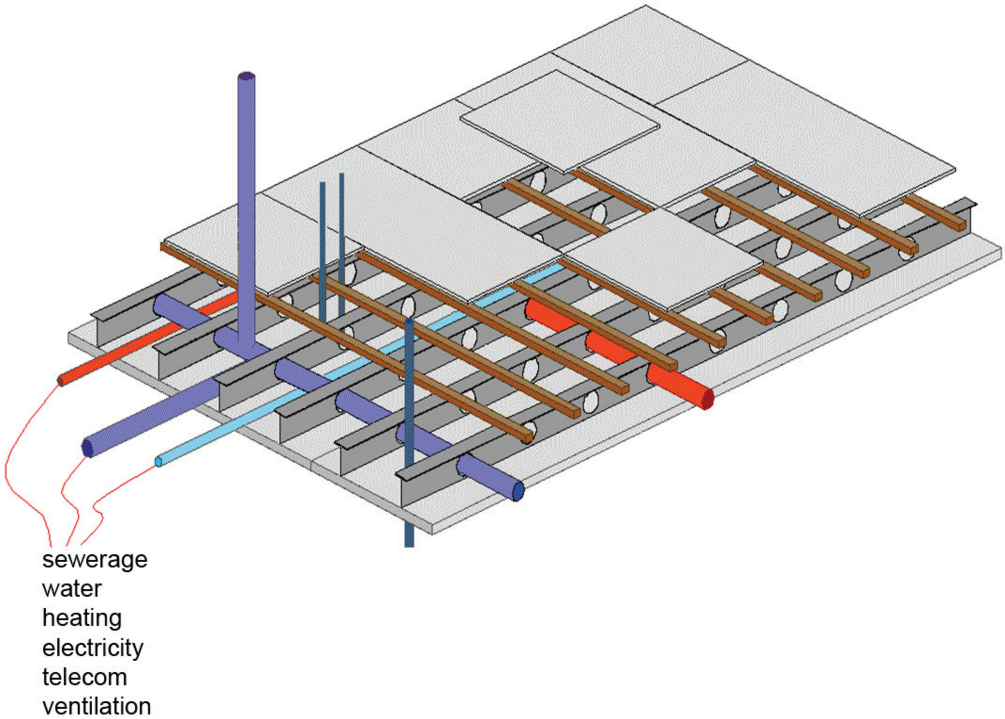


Fig. F.3: A schematic overview of the Infra+ floor system, which is standard to facilitate installations at a high flexibility and adaptability level, Lichtenberg, J.J.N. (2005)

4.1 Method

In the current Infra+ floor system, flexibility can be limited due to the currently used top floor systems. Especially if floor heating is desired, the top floor is mostly constructed as a self-levelling top floor, which is heavy and not flexible. A flexible top floor system with integrated heating and cooling was not available for the Infra+ floor until now. Therefore, de SlimBouwen® approach has been used to define a design strategy for building products and as result a new top floor was developed.

The development stages are:

- idea to concept
- from concept to laboratory product
- from laboratory product to industrial product.

The following topics were regarded while developing a concept and a product:

- flexibility (fully)
- low temperature heating (T_{water} 35 °C) and high temperature cooling (T_{water} 18 °C)
- thermal comfort aspects for the user (no radiation asymmetry)

- thermal comfort in relation to the heat demand of the building (less air movement)
- costs of production and installation (cost comparable with traditional equipment without flexibility)
- construction strength, weight and height (according to legalisation)
- fire resistance (depending on building function)
- labour legislation (< 20 kg per tile)
- installation requirements (accessibility)
- acoustics (according to legislation, extra: SlimBouwen® demand on low noise radiation)

5 Conclusions

The evaluation of these topics has led to a concept which could be materialised into a laboratory beta product by choosing appropriate materials. In the concept stage, no choice of material was made or required. By calculations and research, several appropriate materials have been chosen and adequate material dimensions have been calculated. This has led to the newly designed top floor which meets most of the requirements of the SlimBouwen® philosophy and the People/Planet/Profit requirements.

A detailed picture of the newly developed floor cannot be shown due to the patent procedure. Fig. F.1 is an impression of the existing infra+ floor with the newly developed top floor.

The use of the SlimBouwen® philosophy as a design method for product development in the building industry has proven to be highly effective and resulted in the newly developed top floor.

6 References

Cox, M.G.D.M.& Pepels, J.G.J. (2001), *1e fase onderzoek dakcollector, referentie MC/IS/M1_011*, Intern rapport K+ adviesgroep, Beek, Netherlands

Gijsbers, R. (2005), *IFD bouwen van een rundvee- en varkenshouderij, Eindhoven*, TU Eindhoven

Haren, L.C.M. van (2005), *HeCoFlex-topvloer "van concept naar product"*, TU Eindhoven

Haren, L.C.M. van (2006), *Nieuwe Infra+ topvloer "van product naar marktrealisatie"*, TU Eindhoven

Koschenz, M.& Lehmann, B. (2000), *"Thermoacktive Bauteilsysteme tabs*, Pomcany's Belaro AG, 8048 Zürich

Lichtenberg, J.J.N. (2002), *Ontwikkelen van projectongebonden bouwproducten*, Delft, TU Delft

Lichtenberg, J.J.N. (2005), *Slimbouwen®*, Boxtel; Æneas, uitgeverij van vakinformatie

Novem publicatie: *"Kwalitatieve aspecten van lage temperatuur warmte-afgifte-systemen"*, Novem Utrecht, Netherlands(1999)

G) Assembling Sandwich Facade Units

ERIC VASTERT[1]

1 Introduction

An important development in the area of industrial building is the construction with sandwich load bearing external facade units. These units are built-up with a concrete panel inside, an insulating layer, an external brick wall and are completely finished with windows and piping. In combination with prefabricated inner walls and floor systems the structure of a building with finished facade can be realised without requiring scaffold access in a short time. The high-rise (100 m) apartment building Porthos in Eindhoven has been constructed with this industrialised method in a 3–day building cycle for each floor. The working conditions, use of equipment and dimensional accuracy of the external facade have been analyzed. The dimensional quality of the finished façade is very good but the working conditions are difficult. The purpose of this research is to initiate further relevant development in this way of building.

[1] Dr. Ir., Assistant Professor, Chair Construction Engineering, Department of Architecture, Building and Planning, University of Technology Eindhoven, the Netherlands, Phone +31 40 2473281, e.w.vastert@tue.nl

Fig. G.1: Apartment building Porthos in Eindhoven

2 Project Description

The apartment building Porthos is one of three apartment buildings being developed by the Eindhoven urban district Woensel. The building is designed by Engelman architects from Roermond and Hurks Bouw and Vastgoed Eindhoven is responsible for the construction. The 33–storey building comprises three up to four apartments on each floor. In total the building incorporates 108 housing units with a total floor area of 17,500 square meters.

The building is composed of prefabricated parts. Each floor has been built with approximately 51 prefabricated wall and floor elements. Twelve sandwich external façade units are placed on each floor. These load bearing façade units consist of a concrete panel inside, an insulating layer, an air cavity, an external brick wall. Furthermore the units are completely finished with framing and glazing and sometimes with brise-soleil. Also the conduits and pipework for electricity, air treatment and sanitary has already been mounted in factory.

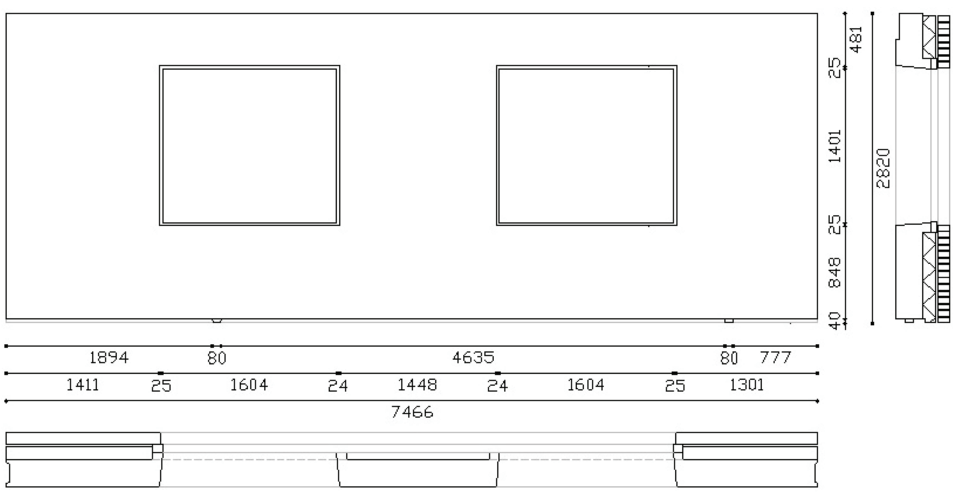


Fig. G.2: Elevation and section of a sandwich façade unit

3 Process Description

3.1 Prefabrication

The height of the facade units is 2820 mm, the height between two floor surfaces. The length varies between 7500 and 10000 mm; the thickness varies from 400 up to 500 mm. The elements are manufactured in a factory. First of all the bricks are laid in the steel formwork. These bricks are covered with mortar. Anchors are mounted in the external facade for the eventual connection between the walls inside and outside. Then insulating layer is attached, reinforcement fixed and the concrete panel inside is poured. When the concrete has matured sufficiently, the unit can be stripped and moved to the storage where casings, glazing and such are mounted. The units vary in weight from 11 to 20 tonnes. With a low loader two or three units at the same time are transported from the storage to the site.

Fig. G.3: Mounting of casings and glazing; storage of the units

3.2 Preparation

Before the façade units can be assembled on site, some preparations must be done. The dimensions are set out, the jobsite is cleaned-up, the props are put ready and the compression tape is fixed. For longitudinal and cross direction, 14 points are set out with a ‘Total Station’ according to the MOUS-system (VAN HOOF, 2003). With a folding ruler from these points it is indicated where the panel inside in longitudinal direction must be mounted. The ends of this panel are marked with a pencil.

A correction is made if the underlying façade unit deviates more than 3 mm. In the vertical direction filler plates are used that are positioned in height with a rotating laser. A fixed position is obtained on the underside near both ends of the façade unit.

3.3 Mounting

The facade units are mounted directly on the building from the low loader with a tower crane. On the floor the unit is manoeuvred by the construction workers into the correct position and is kept above the starter bars. When the guard-rail is removed the unit can be placed over the starter bars. At placing the units are aligned with the upper edge of the lower unit and the marks.

When the unit has been positioned over the starter bars it is manoeuvred on the underside with a iron bar on the marks. As soon as the shores have been mounted and tightened the upper edge of the unit can be positioned in the cross direction. With a long plumb level the unit is positioned vertically by adjusting the props. When it is positioned temporarily with the props it is disconnected from the crane. Afterwards wet mortar is injected in the seam under the unit with a compressor. In the same way also the vertical joints between the units are filled. When the wet mortar has hardened sufficiently the joints are poured with the compressor.

As soon as the sandwich units are fixed the earlier removed guard-rail is mounted. The guard-rail is slid over the starter bars on the top of the unit. As soon as the wet mortar in the joints has hardened sufficiently the shores are removed. The remaining holes are filled with mortar and finished with a filling knife. The bearing structure and the façade are assembled at the same time and without scaffold. A team of nine workers constructs every three workable days a windproof and impermeable storey. Activities occur simultaneously over two or three successive floors. The construction time of the apartment building lasts only 95 workable days. The construction time has been reduced by almost a half in comparison with building with separated inner and outer leaf.

Fig. G.4: Getting the façade unit in the right position. As soon as the unit is kept just above the starter bars, the guard-rail is removed

4 Dimensional Research

The success of this constructing method depends entirely on the precision of the production and positioning of the units. The joints between the facade units are comparable with the joints in the masonry of these units. The design measure is 10 millimetre with a tolerance of only a few millimetres. Great accuracy is demanded because a small deviation can disturb the façade. In the joint the following complete or partial dimensional deviations appear:

- Deviations of setting out in X-, Y- and Z-directions;
- Deviations of positioning the inside panel of the unit in relation to the marks in X-, Y- en Z-directions;
- Deviations of the thickness, height and length of the units;
- Twist and curvature of the units.

The dimensional accuracy of the facade has been examined (BROUWER, 2005). For that 160 joint widths and unflatness in 40 intersections of joints have been measured. Twenty-six of these intersections are located above each other, whereas fourteen intersections are located between the eleventh and fourteenth floor.

Fig. G.5 shows the measured joint dimensions. About 95% of the joint widths vary between 7 and 13 millimetres. The average joint width is 10.1 millimetres, with a minimum of 6 and a maximum of 14 mm. The unparallelness of the joints is similar. The unflatness of two adjoining units varies from –6 to 8 mm.

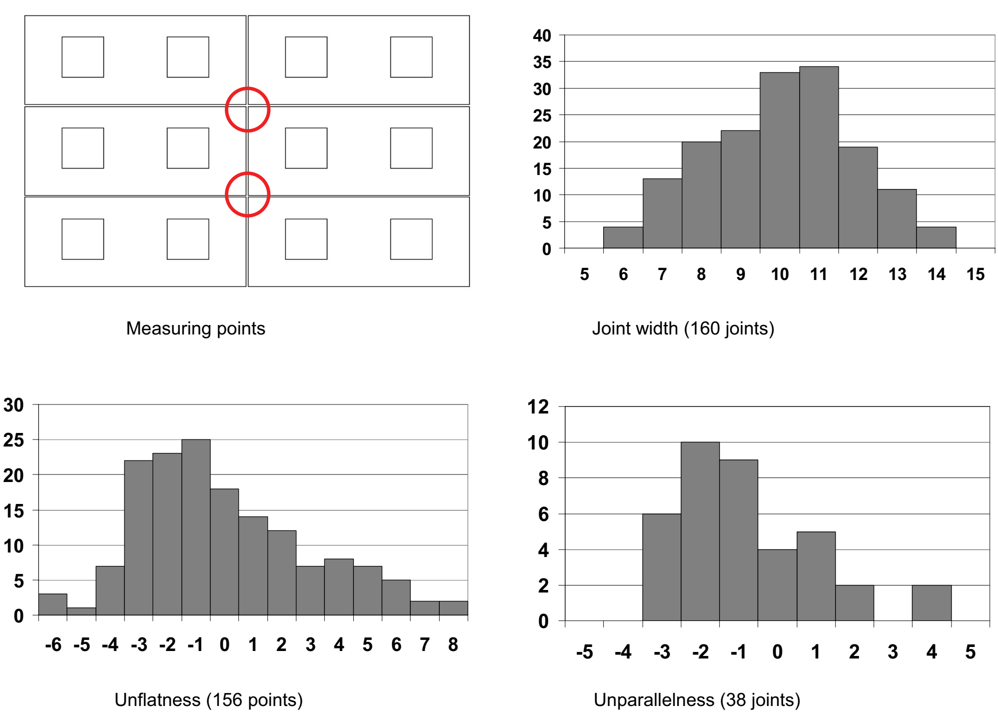


Fig. G.5: Measured joint dimensions in 40 intersections in millimetres.

The visibility of the dimensional deviations in the joints has been examined with the D–value, a standard for the visibility of dimensional deviations (VASTERT, 1995). The D–value 1 means that dimensional deviations are invisible, whereas D=5 means that the deviations are clearly visible. At D=3 the dimensional deviations are with effort indeed visible, but mostly accepted. Most of the carefully built facades with regular patterns have a D–value of approximately three.

The examined facades with dark grey joints (40% diffuse reflection) between panels with black bricks (45% diffuse reflection) have D–value D=2. This corresponds with the fact that from the ground floor no dimensional deviations are visible. All visual requirements are fulfilled.

5 Physical Stress

Apart from the dimensional research also the physical stress at the mounting of the sandwich units has been examined. The façade units are assembled by 7 construction workers. Two workers position the elements, four workers secure the elements and one person at ground level connects the unit to the crane. The total size of the team (9 persons) depends not only on the mounting of the sandwich façade units but also on the assembling of the floor units, walls and stairs. The physical stresses have been calculated on that day of the three-day cycle on which the biggest part of the assembling work of the façade units was done.

The posture and the kind of labour of the workers have been recorded on video during a whole workday for the calculation of the physical stresses. Combined with the duration of the activities the stresses are calculated. The calculation of the stresses is based on the total use of energy of the body (PEEREBOOM; 2000). During the whole working day the use of energy is measured that depends on the basic energy for the vital functions of the body, posture or movement of the body and on the load of the work.

The energetic load of a worker during one working day is the sum of used energy during all the activities of that person. The total used energy has been divided by the worked time to get the used energy per minute (Table G.1). With the traffic-light model has been defined if the performed labour is acceptable (green), needs attention (orange) or is not acceptable (red).

Table G.1: Used Energy of workers A – G at the mounting of the façade units; the hatched area indicates danger

	Whole working day		
Construction Worker	**Duration (minutes)**	**Used Energy (kJ)**	**Used Energy (kJ/min.)**
A	510	8285.8	**16.2**
B	510	7651.6	**15.0**
C	510	6765.5	**13.3**
D	510	6927.7	**13.6**
E	510	6282.3	12.3
F	510	6593.9	12.9
G	510	5632.9	11.0

Four of seven construction workers (A, B, C en D) end with their use of energy in the orange (grey) dangerous area. As an example the activities and the energetic load of worker A have been elaborated in Table G.2.

Table G.2: Used Energy of worker A during one day

Activities of Worker A	**Used Energy (kJ/min.)**	**Duration (minutes)**	**Used Energy (kJ)**
Moving materials and equipment	32.0	16.20	518.4
Putting ready shores	31.4	4.80	150.9
Removing concrete trash	13.5	6.60	89.1
Fixing compression tape	14.0	49.00	686.0
Manoeuvring façade units	37.5	7.40	277.5
Positioning units above bars	19.5	11.80	230.1
Removing guard-rail	29.1	8.40	244.8
Placing units over starter bars	19.0	6.60	125.4
Positioning units on floor	17.0	4.40	74.8
Adjusting underside unit	28.9	34.00	984.2
Positioning unit vertically	11.7	42.60	499.5
Fixing shores on unit	37.5	16.40	615.0
Disconnecting unit	17.0	5.00	85.0
Removing lifting eyes	17.0	6.40	108.8
Fixing guard-rail	21.8	45.20	986.3
Remaining activities	12.5	116.70	1458.8
Pause	6.0	70.00	420.0
Sum of activities façade units	**16.7**	**451.50**	**7554.5**
Placing floor unit (core)	12.5	58.50	731.3
Sum remaining activities	**12.5**	**58.50**	**731.3**
Sum activities of worker A	**16.2**	**510.00**	**8285.8**

Worker A uses no less than 8285 kJ this day. This means 16.2 kJ per minute. For placing floor units he uses 731.3 kJ. The remaining 7554.5 kJ he uses for the mounting of façade units. The use of energy per minute is 16.7 kJ. The used energy of the remaining workers is similar. The high use of energy per minute (18 kJ) of worker C is further caused by injecting the wet mortar in the joints between the façade units. Preparing (18.5 kJ) and moving (26.1 kJ) mortar cause the high use of energy of construction worker D.

The mounting of the façade units proves to be physically heavy work. The units from 11 up to 20 metric tons must be manoeuvred to the desired position using physical strength. Next the workers must place the heavy, cumbersome unit over the starter bars on their knees. With a pounding bar and physical strength the unit is positioned on the marks. At the same time the unit is attached to the floor with props of 24 kgs. Access to the props is via a ladder. The workers always gets down on his knees to inject the wet mortar in the joint under the unit.

The following activities cause the high use of energy of the workers in particular:

- Preparation, transport and processing of the mortar;
- Positioning of the facade units;
- Mounting of the shores and
- The attachment of the safety equipment.

Fig. G.6: Physical stresses at the mounting of the units

6 Conclusions

Industrial building means that products are fabricated in a factory under controlled circumstances by specialists and with specialised equipment. The dimensional accuracy of the units in the factory is also maintained in the joints between the units of this 100 meters high building. Dimensional deviations remain restricted on site to only a few millimetres. The product quality of the technically sophisticated units in the fabric and of the interlinked units on site proves to be similar.

The process quality on the other hand considerably differs in factory and on site. Although the labour on site is relatively restricted, the mounting of the industrial fabricated units remains according to traditional methods and the physical working conditions proved to be heavy. It is a challenge for the further development of prefabricated building products to ensure also a controlled and ergonomic installation of these products. This means for the façade units for example that not only, windows and piping need to be included but also ingenious facilities for the positioning and securing these units.

7 References

Brouwer. M., 2005, Montage van sandwich gevelelementen. (Eindhoven, University of Technology)

Hoof, P.A.J. van, 2003, Maatregelen; naar een betere maatbeheersing via een moderne aanpak van maatvoering en maatcontrole (Rotterdam: SBR)

Peereboom, K.J., 2000, Handboek fysieke belasting; Een complete methode voor het inventariseren en oplossen van knelpunten. Den Haag.

Vastert, E.W., 1998, Specification of Visual Requirements for Regularity of Joints. In Architectural Science Review volume 41 number 3, Department of Architectural and Design Science, University of Sydney, 99–104.

H) Prefabricated Systems in East Europe

ELŻBIETA D. RYŃSKA[1]

1 Introduction

Large prefabricated slab and panel structures were predominantly used in Poland during the 70-ties and 80-ties of the former century. Presently many negative issued are mentioned when describing this type of structures. This covers both the aesthetic as well as social, economic and health issues.

Often, it was said that large panel industry will "collapse" – literary – as many inhabitants of the residential complexes constructed in large panel technologies were sure that after some years of exploitation the steel connection joints will rust and buildings will be permanently damaged.

Yet, in reverse to those catastrophic visions not only individual buildings but large residential complexes fare very well. Nowadays, no one mentions the issue of a catastrophe – in reverse, many say that this type of structure is one of the most durable solutions. To sustain this thesis, scientists quote the case of Bucharest (Romania), where in 1977 during an earthquake, out of 35,000 destroyed edifices, 33,000 were old historic buildings, not prefabricated residential blocks.

A widely spoken of case, when one of the reinforced elevation panels fell off in a building in one the Polish cities, seems to be an individual case. Though, this case was, as earlier foreseen, due to faulty steel joints. Still, a complete inward collapse of a building is a very unlikely occurrence, and had not taken place anywhere.

In this period of world crisis, apartments located in low rise large slab buildings are also very much sought, as being cheaper to buy than newly built structures.

First buildings in large panel technologies were constructed after the First World War by the Dutch. Some years later – in 1923, this technology was used in Berlin-Lichtenberg at a Splanneman Residential Complex. Multilevel residential apartments were first constructed in the second half if the 30-ties in France, Sweden and Finland. Large panel construction systems were also quite widely used in former West Germany. Yet in none of the European Western countries did this type of structure become a dominant one, and already in the 70-ties, due to high costs of transport, this technology became dormant.

---

[1] Prof. PhD. MSc. Arch. working at the Faculty of Architecture Warsaw University of Technology from 1987. Stipends in USA and Japan. Main interests - sustainable architecture and urban planning, economy of design, dagny.rynska@arch.pw.edu.pl

In Poland and other Eastern countries, where most of the technical knowledge came from the West – this technology appeared rather late in the 20th Century. First large panel building was constructed in 1957 and first residential complex was constructed in 1961-1963 – both in Warsaw.

Fig. H.1: Slovakia - a residential complex in Bratislava, 1970

The development of large panel prefabricated technologies was similar in all of the east European countries. Most of the systems were designed during the 60-ties and 70-ties, based on the existing solutions. At that time prefabrication was not yet a predominant type of construction. For example in 1966, in Warsaw, only 24,6% of total residential building volume was actually constructed in a large panel technology. In fact, in Poland, a large block system (narrow heavy building units) was much more popular. Monolithic solutions were used widely – app. 35% (1966). In some cases, traditional brick and mortar solutions were also used.

Situation changed in Poland at the beginning of the 70-ties. This was after the specialists from the Department of Design in the Institute of Building Technologies and Techniques, designed a structural system based on the solutions used in the East Germany. This later became the base for the W-70 and OWT-75 systems. Newly developed system was an "open system" where only a few of the internal walls were load bearing, allowing for more flexibility and wider "free" span when designing apartments' interiors.

This new technology opened new possibilities quickly perceived by the new political authorities that came into power in Poland during the 70-ties - a way to solve, a difficult residential situation existing in Poland. Hence, this technology became a politically coordinated solution. In order to quicken the speed of construction, a 150 large panel plants were build in Poland.

The results of this political decision were and still are perceived in the Polish urban landscape. Even if the prefabricated large panel technology was not the only technology used in Poland during the 70-ties and 80-ties, it is the large panel that became the characteristic feature, and many people assume that all buildings were constructed in this technique.

Certainly, there are better and worse examples of complexes build in prefabricated technologies. The most negative solution was a typical block of flats, 10 storeys high and 10 staircases long – still to be found in many larger Polish towns.

Much better solutions were used in complexes which had mixed height buildings – starting from 3 and 5 storey 5-8 staircase long buildings to high rise towers. Hence, it cannot be said that every prefabricated solution was a nightmare. Yet the faults of the large panel solutions are evident – the basic colour of the settlements being grey and ugly, more than often the buildings were executed with the use of contaminated building materials (e.g. asbestos), apartments were small and not very functional, as well expensive in exploitation. Low quality insulation and a high heat loss factor are due to the fact that in many cases durability of the concrete was "quickened" through the use of high temperatures, which allowed maintaining the strength of the construction elements but often destroyed (melted) external walls' insulation layer. In some cases the heat loss was so intense that during winter time, furniture had to be moved to a distance of 15 cm away from the external walls, as otherwise moisture appeared on the walls later to become a layer of fungus.

What may be done with the exiting prefabricated residential building stock? A few years ago, it was generally said that large panel structures should be demolished and replaced by new buildings. Presently, the assumptions are not so radical. Many of the buildings are undergoing modernisation – exchange of door and window frames, heating systems; a new insulation layer is mounted on the external walls.

Those few cases of gas explosions in the residential buildings actually proved that prefabricated reinforced concrete panel system has high durability against dynamic forces due to the fact that most of the building elements are oversised (e.g. reinforcement as well as the steel suspension elements are thicker than required from the technology reasons). Additionally, analysis prepared with the data acquired in the buildings which underwent modernisation, showed that the modernisation costs are 25-60% of the total construction costs of a new building. The only technical issue is, not every large panel system is equally adaptable.

The main building elements of the large panel system are reinforced concrete wall and ceiling slabs. These, were prepared in industrial plants, and brought to the site ready for mounting. Polish large panel system evolved from "closed" systems used mainly in the 60-ties and first half of the 70-ties of the 20th Century, to more "open" systems.

In the "closed" systems, nearly every wall in the apartment was a load bearing one, and the whole layout was of a very rigid type. Each of the rooms was designed in accordance with a normative area (a law applicable in 1959-1974). In effect, the span of the ceiling slabs could not exceed 5,40m (in most cases it was 2,40 to 4,80m). Hence, in the block constructed in the "closed" systems, each of the apartments, analyzed in a vertical line, is identical and very small.

OWT-67 system appeared in 1967. Over 30% of all residential buildings were constructed in this system. These were usually 5 and 11 storey high. External slabs consisted of two layers of reinforced concrete (external surface finish and internal one) divided by an insulation layer. The edges were joined together with steel hangers. The largest area module was 540 x 480 cm. An apartment of approximately 50m2 consisted of two modules, and since the perimeter walls of the module were load bearing, hence it was impossible to connect rooms which were located in two different modules. Ceiling slabs were 14 cm thick, and were supported by three perimeter load bearing walls also 14 cm thick. Such structure limited the possibility of any changes. OWT-67 system can be recognised by characteristic external "columns" which were constructed after the assembly of the slabs between the windows. This vertical belt was usually covered with a different surface finish. OWT-67 slowly evolved into a more system. Such solutions as Domino, WUF-T, Dabrawa 70, Winogrady and Szczecin 1, also belong to the “closed” systems.

Fig. H.2: Lodz – example of OWT-67 system, 1970

All buildings constructed in those systems had many faults due to low quality of provided construction works.

Open systems W-70 and Wk-70 were used for the first time in 1972 (15% of all prefabricated residential buildings in Poland). W-70 system is characterised through four different spans (6; 4.80; 3.60 and 2.40 m), which allowed for variations in the apartments’ layouts. Internal load bearing walls were 15 cm thick and were constructed from reinforced concrete. External walls were manufactured as prefabricated „sandwich” elements. Also sanitary cabins were assembled as prefabricated units.

The second system – Wk-70, was simply a more updated version of the previous system. The main difference was a different solution of the ceiling slabs, which were manufactured on production lines purchased from West Germany. The 22 cm thick duct slabs, were exchanged with thinner, 16 cm thick solid slabs. This system was used for residential buildings from 3 to 16 storeys (approximately 20% of the existing prefabricated stock was constructed in this system). The span between load bearing walls varied from 2,40 to 6,00 m. External walls (both wall bearing and screen walls) were constructed as three layered, with an insulation insert.

Further development of the large panel systems was hindered by a new law demanding more strict values for the heat loss parameters. Existing external panel solutions were inadequate to fulfill new requirements.

Fig. H.3: Gdańsk – Rekina settlement, „wave” building, 1980

Fig. H.4: Poznan – Ruza settlement, 1980-85

2 Prefabricated Systems used for Residential Buildings and Support Facilities

2.1 System W-70 (Open System)

Has been accepted at the time of its production as a policy development system, to be used in all areas of Poland. Elements were manufactured in plants called housing factories. The main characteristics of the W-70 System are as follows:

- modular system, accepted dimensions of elements, characteristic forming of the elements' edges and typical internal structural solutions.
- sequence of assembly, forming of the joints and construction load bearing elements
- assembly of internal technical systems (water and sewage, HVAC, electricity, gas).

This system was mainly used for multifamily residential buildings. Basic modular structure, size of used elements and internal structure of the construction elements, and in consequence of the typical sequence of assembled elements and methods of construction, was based on the analysis of elementary elements and manufacturing methods and the "best" functional layouts of proposed flats and buildings. Additional research was provided concerning optimal areas of the apartments in view of the technology processes. The areas were based on Polish normative standards, as well as those used at the time in East Germany, Czechoslovakia and France. Following groups of elements were subjected to prefabrication:

- structural elements – slabs, external and internal walls (load bearing, self bearing and screening) in alternative solutions and different degree of integration, parapet and openwork walls used in the attic levels, balconies, loggias, roof slabs, lift shafts, reinforcement nets for construction joints.
- sanitary installation systems – sanitary modules and ventilation shafts, sanitary risers, basic kitchen equipment, heating risers and radiators, heating systems, boiler rooms and water pump units.
- electricity installations – transformer units, energy distribution rooms, main switch boards, power and telephone external connections, apartment switch boards, staircase lights, TV connections,
- construction and fit-out – windows and door, staircase balustrades.

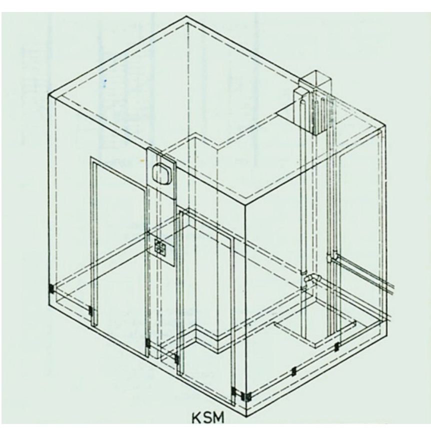


Fig. H.5: Standardised bathroom unit – W-70 system

National unification was used for the elements which were functionally ad architectonically neutral and were in use in every region of Poland. This centralised unification was implemented in every prefabricated manufacturing plant.

Local unification – external building elements or solutions used for a certain function or investment (a residential complex, a residential settlement). Furthermore, this meant repeated use of certain solutions used by the designers. It was assumed that those various levels of unification enabled architectonic unity of constructed complex.

After careful study and functional and technical analysis of the, system designers formulated general rules for the optimum dimensions of the prefabricated elements used within the W-70 system. These were as follows:

- in the plan layout
    - modular net 60 x 60 cm
    - designed net 60x120 cm
    - four basic spans: 600, 480, 360 and 240 cm.

Most buildings were constructed in a lateral load bearing walls (15 cm thick) wall. Thickness of external walls was the outcome of the calculated "U" value, and had no influence on the placement of internal areas. Offset of external walls was accepted at 60 cm and 120 cm.

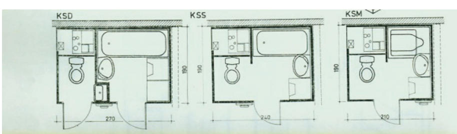


Fig. H.6: Typical layout of bathroom units – W-70 system

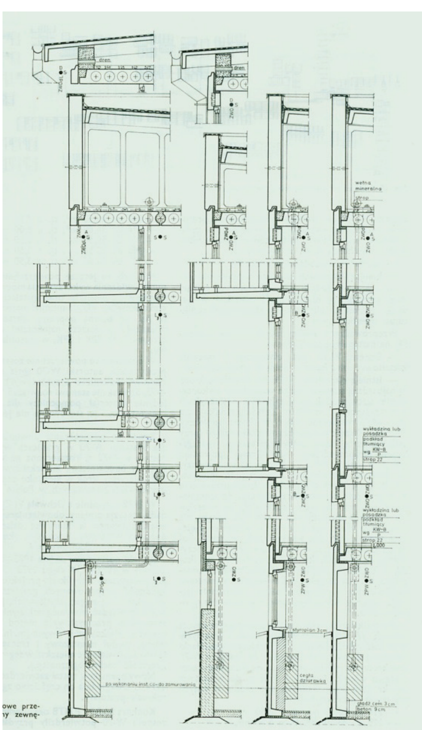


Fig. H.7: Cross sections – W-70 system

The height of a residential storey including the slabs was 280 cm, of the basement level – 250 cm. Two alternative attic solutions were possible: high attic – with some usable area, and low attic – used purely for the ventilation system purposes. Slab thickness was at 22 cm.

At that time, according to the Polish Building Code, buildings were divided into following categories:

- low height – 1-2 storey
- middle height – up to 5 storey
- high height – up to 11 storey
- high-rise – up to 16 storey

Technical risers were grouped in certain areas, and used as common access shafts.

Horizontal distribution of technical systems was provided either in the basement or attic levels.

2.2 Stettin (Szczecin) Residential Prefabricated System from large Panel Elements (SS)

This System was the outcome of a competition and was later used in various „residential building plants" equipped with manufacturing lines imported from Soviet Union. This political choice enabled a quick start-up of the plants and construction of the first buildings in 1971-72.

Basic functional elements in SS were designed according to following rules:

- unification of the building's solutions regardless of the building's height (5-11 levels)
- unification of the building's solutions regardless of the apartment's location in the segmented building (staircase, corridor and point types)
- creation of different type of apartments through merging of the basic areas: 4,80 x 4,80 m and 4.80 x 2,40m.

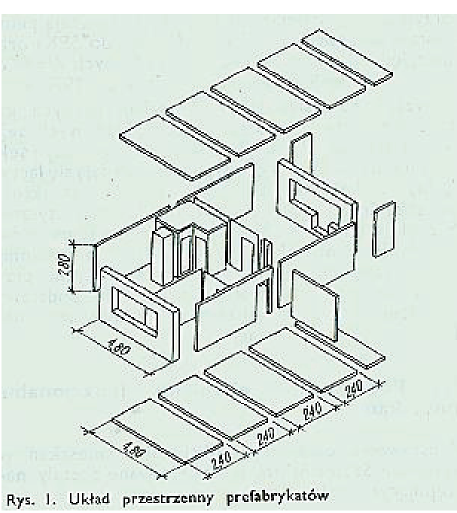


Fig. H.8: Stettin System – general layout

These solutions were based on repetition of used construction units, installation systems and equipment or on multiplication of typical catalogue elements – especially when used as the apartment's fit-out.

Following prefabricated elements were used in the "S" system:

- load bearing elements: slabs, staircase cores, roofs, loggias, external and internal walls, basement walls, elevator shafts, parapet walls, joint between elements, insulation layers in external walls;
- structural units – partition walls, ventilation blocks, balustrades in loggias and balconies, balustrades in stairs, decorative details in medium rise buildings, skirting
- sanitary installations – sanitary cabins with typical risers and connection solution to each of the apartments, equipment required in the basement level
- electricity installations – electricity unit was universal for all types of apartments, this included switch boards, apartments electricity boards, connection cables for unified systems.

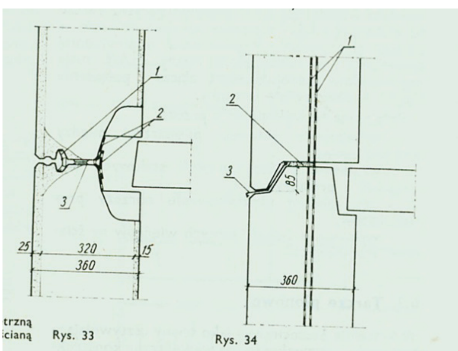


Fig. H.9: Stettin System – connection elements

Unification of apartment functional zones enabled the fit-pit of typified furniture, kitchens and wardrobes, used as standard furniture in most Polish apartments and homes during the '70-ties.

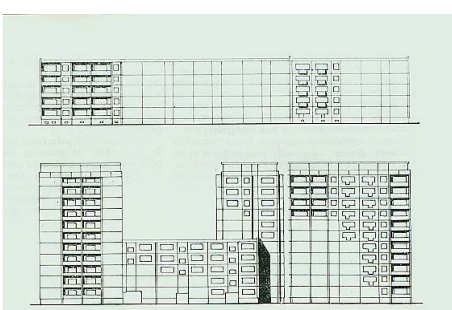


Fig. H.10: Stettin System – typical facades

Beside prefabricated elements, standard prefabricated elements were also used. These consisted of:

- window frames
- lifts

- sanitary equipment
- electrical equipment (RTV antennas, home phones)
- waste shoots

Based on the designed typical solutions, designers created 49 typical segments and sections for 5 and 11 storey high buildings - staircase, corridor and point type. It was accepted that all existing types of segments may be used in different configurations.

2.3 General Skeleton Building System

The scope of use of this system covers such buildings as – primary and secondary schools, high schools and universities; hospital buildings, hostels and hotels, student hotels and retail buildings; public administration buildings, some cultural and recreation buildings.

Due to economic and technical reasons, buildings were designed as not exceeding 33 m in height (11 levels).

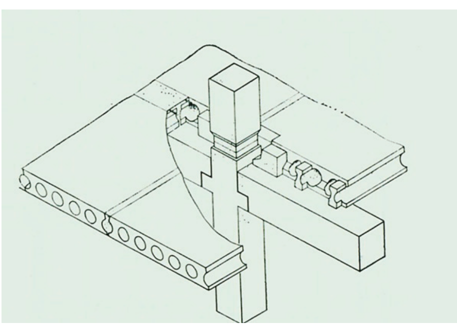


Fig. H.11: Typical structural solution - GSB

This system was designed on following general assumptions:

- an open system, based on a modular net of “n” x 60 cm
- basic parameters of the main construction elements - spandrel beam and slab spans were determined by the chosen functional layouts, allowing for their high flexibility;
- full prefabrication procedure was used for the load bearing elements, building elements and installation systems, all finishing works were also subjected to industrialisation procedures;
- prefabricated elements were formed according to accepted technology parameters as well as technical conditions in plants or “on site” prefabrication plants;
- prefabricated elements were manufactured to allow a maximum integration with the W-70 open system, within the technology procedures used during prefabrication.

Structural solutions were designed on a modular net n x 60cm. Main load bearing structural elements form a reinforced concrete perpendicular load bearing skeleton. The spans change every 60 cm (240 - 900 cm). Spans of 420 and 840 cm were eliminated and considered as not applicable in the layout solutions used). The height of levels was designed at: 280, 330, 360 and 450 cm. Various different staircase solutions were used.

Accepted beam and transom beam dimensions, allowed design of four types of skeleton structures. These were:

- light type - columns 30 x 30 cm
- medium type - columns 30 x 45 cm
- semi-heavy type - columns 30 x 45 cm and 30 x 60cm
- heavy type - columns 30 x 60 cm

Skeleton frame structure was formed from single or double level high columns, carrying cantilevered transom beams. All horizontal elements were perforated slabs. Their dimensions changed every 60cm, and the span varied from 240 to 600 cm (except for 420 and 540cm). Slabs cross sections were also analogous to those used in the W-70 system.

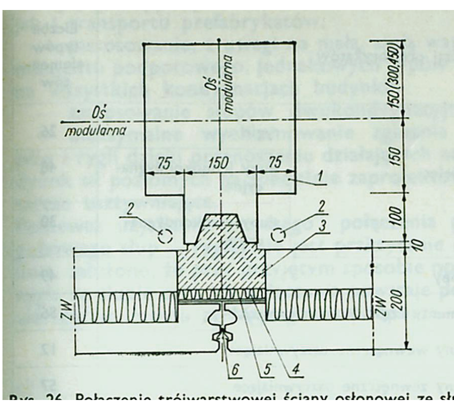


Fig. H.12: Connection between load bearing and external walls

2.4 SBM-75, Monolithic Residential Construction System

The main idea for his system was o use concrete and reinforced concrete load bearing elements manufactured “on-site”.

Manufacture process of each level was a continuous technology process. All works were executed with the application of steel shuttering elements.

Horizontal modular net was 60 x 60cm. Gross height of each level – 280, 330-360, 450 cm. Slab thickness – 16 cm for solid slabs, load bearing internal walls – 15cm. This monolithic solution as well as the fact that all elements were prepared on-site, allowed for more freedom in the choice of spans used. The 60 cm modular net allowed to execute slabs from 1,80 to 7,80 m wide (with the thickness of 16cm) in the residential sector. Whereas in the retail and public buildings a modular net of 6,0 x 9,0m was usually used.

Residential buildings did not exceed 30 levels.

The type of the layout chosen for each residential building depended on the solution of the staircase and corridor cores as well as the number of levels. Following types of buildings were constructed:

- a „point" and corridor building types, 5-11 levels high, or 30 storey high buildings
- staircase type buildings – due to economic reasons 5-11 levels high
- gallery type, up to 5 levels high (very rarely constructed in Poland due to negative cultural response to this solution).

Designers anticipated possible interaction and integration between each of the existing prefabricated systems.

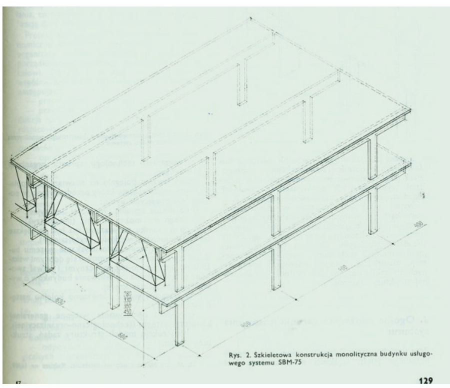


Fig. H.13: SBM-75 – model of a typical building

2.5 Prefabricated Modular Solutions in some other Post-Soviet East-European Countries

The **Czech Republic** – one of the countries of the once East European block, has approximately 10.250.000 inhabitants and a stock of app.5.00.000 apartments (2008). Like in other countries located in this part of Europe, the units are owned either by the co-operatives, municipalities or are private. The intensity of the construction versus time of the construction has high influence on the age and technical structure of existing residential stock.

Table H.1: Age structure of existing residential stock in Czech Republic

Level of residential construction	To the year 1899	is	8,4%	of the residential resources
	1900-1919		7,8%	
	1920-1945		20%	
	1946-1970		22,1%	
	1971-1990		31,2%	
	1991-2001		10,5%	
	2002-2008		`10,0 %	

Average size of an apartment has increased gradually from 23,5m2 in 1961, to 49,5m2 in 2001. In comparison average area of a house is approximately 96,6m2.

The quickest development of the residential construction sector took place from the ’60-ties to ’90-ties of the 20th Century. Most of the buildings were constructed in prefabricated technologies consisting of 15 basic typified systems. From those a series of local variations were derived. Elements were usually produced from:

- light concrete (i.e. expanded concrete, cinder concrete, “keramsit” concrete), walls were manufactured as a single layer structure
- ceramic units
- “sandwich” manufactured reinforced concrete elements with an insulation layer from foam glass or polystyrene.

National standardised construction process, but also for the fact that only typical repeatable residential units were produced. Technical faults were predominantly similar to those found in other East European countries – issues connected with the non tightness of the flat roofs and window frames, existence of thermal bridges, technical faults of the joints between prefabricated elements. Those buildings are still inhabited, and this causes further problems as Czech Republic has accepted European norms concerning effective use of energy and heat consumption in buildings. According to the new legal requirements, the construction and modification of completed buildings will be evaluated according to thermal, technical and energy performance.

One of the most important issues for the prefabricated buildings is how to extend building’s life, while reducing building’s energy demands and increasing the living comfort. Such regeneration can be provided through the use of peripheral thermal insulation layer, exchange of window and door systems, and modernizing of the interiors.

The thermal properties of buildings constructed in Czech Republic before year 2002 do not meet present requirements and the usable energy demand is too high. Contemporary requirements buildings in Czech, are shown in Table H.2.

Table H.2: Required and recommended values of heat penetration (Czech Norm 73 0540-2/Z1:2005)

Building description	**Heat penetration coefficient U_N [W.m^2.K^{-1}]**	
	Required values	**Recommended values**
Roof area, slope less than 45°	0,24	0,16
Exterior wall: light	0,30	0,20
heavy	0,38	0,25
Ceiling under unheated attic	0,30	0,20
Slab on the ground	0,60	0,40
Window, door: new	1,7	1,2
repaired	2,0	
Slanted roof windows	1,5	1,1

The “thermo-modernisation” façade method used to achieve better heating factors can be carried out by two methods: as a full contact system or as a ventilated system (with an air gap). The choice of thermal insulation depends on the quality requirements, as well as price.

To the support the renovation process of the prefabricated units constructed as standard prefabrication units, Czech Republic has created the PANEL Subsidy Program, which concerns the procedure for state fund financing and covering part of the credit interest provided by banks and issued for the modernisation and regeneration of prefabricated buildings. Specialised technical assistance consists of consultancy activities in advisory and information centers.

City of Bratislava, **Slovak Republic**, has approximately 452.000 inhabitants, out of which 77% resides in prefabricated housing estates. The function and structure of this culturally important city centre was highly influenced by demolition and modernisation. Starting from the ’70-ties, the construction of large housing estates began East, West and South of the city, in the areas adjacent to the former rural villages. Nearly 79% of the housing stock was constructed after 1945, and the majority – after 1960 when building 16 housing complexes started. Whereas the old city centre and pre-war housing areas, as well as older single family housing play a limited role in housing provisions, exiting large residential estates mostly in pre-cast concrete panel structures, are the main factor of the local housing system. The large estates were planned as individual districts including support services, they are well connected with surrounding areas and city centre.

Unfortunately, most of this residential stock has faults analogous to those found in other countries – defects in roof structures and window systems, insufficient insulation, high heat losses on the transfer of the heating media as well as inadequate funds for repair. There is also the question of unsolved land and flat ownership. From the functional point of view the outcome is – prevailing monotony of small apartments, anonymity and resulting vandalism, low safety of the residents in some areas.

Fig. H.14: Bratislava – typical residential settlement.

The typical **Bulgarian** residential building of ’70-ties and -80’ties was also constructed with prefabricated elements, floor slabs and flat roofs. The site in the western part of the Sofia City is a possible example - with large panel constructed apartment buildings 4-8 stories high with adjacent kindergartens, school and retail areas. A four story, twin section block surrounded by similar apartment buildings. The external load bearing are constructed of light concrete panels with 200mm thickness on the elevations and 260mm on the gable windowless walls. The internal load bearing walls are of 140 mm thick reinforced concrete panels, internal non-bearing walls are 60 mm thick and the prefabricated floor slabs – 140 mm thick with 30mm screed. The roof is constructed as a layer of two 100 mm thick concrete panels with a 1010mm void. The outer slab has a weatherproof covering. The average U value of the whole building is 2,16 W/m2K. Central heating is provided from district heating.

The problems are similar like in all other prefabricated systems:

- Inaccuracy of panel joints allowing for the penetration of rain water
- Low U value of external walls and windows allowing for high heat losses
- Low standard waterproofing

The heating system is not equipped with any possibility to regulate the heating level in individual apartments.

3 Contemporary Ideas. Political Transformation and its Influence on the Construction Solutions.

Transformation within the construction industry from large state owned co-operatives to private developer firms caused the fall of the large panel systems. This took place in the first half of the 90-ties. This change within the construction sector did not allow to maintain financially viable manufacture of prefabricated elements and ended in the mass bankruptcy of the housing industrial plants. Low quality of construction works, different social expectations and requirements were the other reasons for this radical change.

Nowadays new buildings and complexes, very often located in the city centers, are designed individually. Withdrawal from the typical design allows the designers more freedom in the provided solutions. New, energy saving solutions and additional cost analysis shows that it is far more economic to build in conventional or light weight technologies. Large panel is usually manufactured as a load bearing slab. E.g. perforated slabs similar to those used in W-70 system can still be found in construction elements used mainly for industrial purposes. Some of the slabs are pre-stressed and treated as a „lost” formwork. Slabs are only 5,0 cm thick. Part of the lower reinforcement is already imbedded into the slab, remaining part of the reinforcement is assembled in-situ and then covered with additional a concrete mixture allowing for the required calculated slab thickness. Some manufacturing plants also provide pre-stressed wall elements, also used for industrial buildings.

Utilisation of prefabricated concrete elements in industrial construction sector is accepted, beside on-site technologies, as a more advanced standard of construction methods.

Modernisation of existing prefabricated residential building stock started from removal of tar from the expansion joints in the external façade elements. Then, new thermal norms forced the exchange process of the door and window systems, as well as placement of additional insulation on the gable walls. This “thermomodernisation”, as it is called in Poland, not only allows for better heat coefficients, but also protects the construction joints between prefabricated elements. Lately, the heating systems are also undergoing mass modernisation. Those actions are required, but unfortunately they are also chaotic. A complex modernisation process should start with an expert opinion on the technical state of the structural elements, and if required – the state of the steel joints should be checked. One of the most important issues, is extension of the building with an additional level or exchange of flat roofs with sloped ones, where it is possible to provide additional “attic” apartments. Those new apartments can provide additional financial support for further modernisation of the buildings. Elevations are presently plastered, or covered with new type of external finishes. In some cases it is possible to add self load bearing loggias to each of the flats.

Development of surrounding areas is equally important – kids recreation areas, green areas as well as small landscape details become a must.

Unfortunately, the scope and type of modernisation processes depends on the original system in which the building was constructed. In “closed” systems, it is possible to connect small rooms on higher levels. W-70 and Wk-70 systems are more adaptable.

The most important factor within the modernisation process – is the time. Very little maintenance was provided to those buildings during 30 years of their existence, except for most basic repair (sometimes this consisted of repainting of the staircase areas only). In the 80-ties and 90-ties, the co-operatives started with the insulation process, but due to economic reasons, often low quality materials were chosen. More than half of the building stock has been constructed over 15 years ago. In Poland it is impossible – mainly due to economic reasons - to move inhabitants of existing prefabricated blocks into new higher standard buildings. Hence modernisation and upgrade are the only possible solutions.

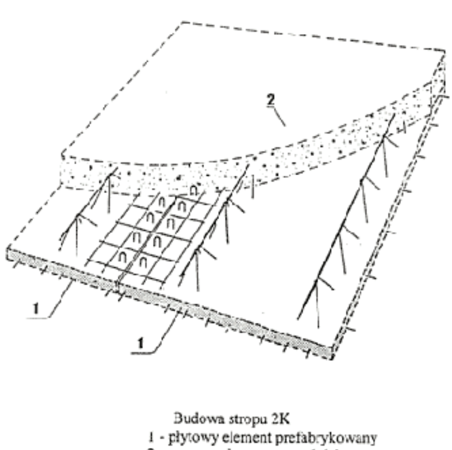


Fig. H.15: Slab – 2K.

On a large scale prefabricated construction has been forgotten on Poland, on a small scale certain building elements are still much in use. These are:

- rib-and-slab prefabricated ceilings (e.g. Filigran, 2K and 2K+; hollow slabs “Zeran type”)
- pre-stressed beams
- prefabricated flight of stairs
- prefabricated balcony and loggia slabs

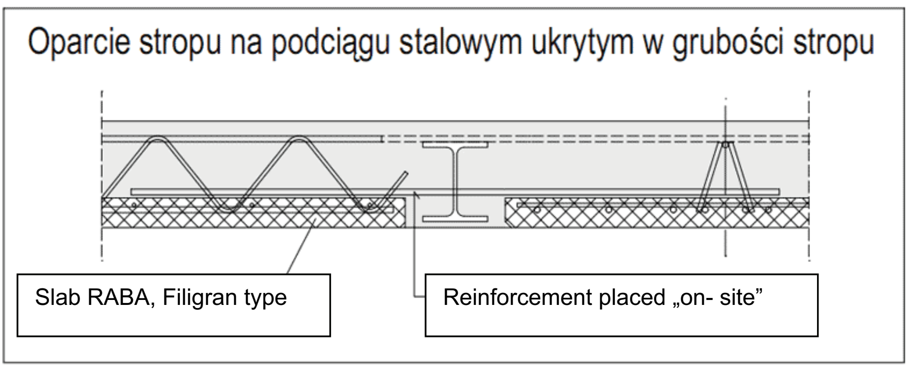


Fig. H.16: Slab supported by a steel beam placed within the slab’s thickness

Above elements are used mainly in multifamily residential buildings, together with the traditional masonry work and reinforced concrete main load bearing elements

There are also some systems, manufactured in accordance with the new norms, available on the market. These are: Oleszno 86, System Elsa, Exbud, M-04, Bau-Pol They are used mainly to construct small retail, industrial and parking buildings. Nevertheless, most investors in Poland prefer traditional type of construction or of reinforced concrete type perceived as more durable and easier to maintain.

On a small scale the prefabricated industry still exists. One of the main issues is provision of high quality workmanship as well as aesthetic values. One of such small scale plants is “Bogucin”, where an up-graded W-70 system is manufactured.

Fig. H.17: Bogucin Plant, Poland – basement walls

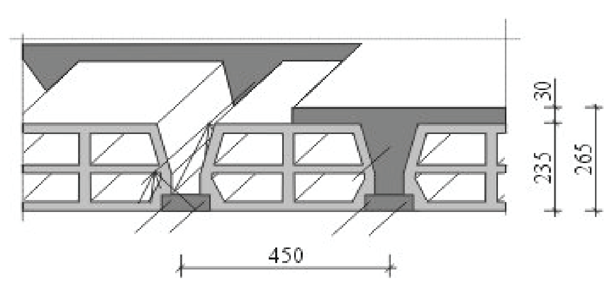


Fig. H.18: Bogucin Plant – cross section through the ceiling slab.

The owners try to attract potential customers with a wide scope of PR techniques, including information on the sustainable and environment friendly and economic aspects of his technology.

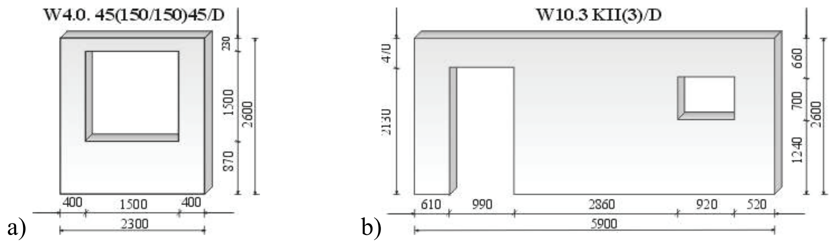


Fig. H.19: Bogucin Plant – external walls, examples

Prefabricated load bearing internal walls and perforated ceiling slabs are used as skeleton frames for residential buildings, and may be used as an alternative for the monolithic solutions. External walls are constructed from hollow ceramic blocks or other small scale light elements, and light insulation layer on the external side of the walls. This merge of large prefabricated panels and traditional brick and mortar technology gave birth to the so called "mixed technology".

Fig. H.20: "Bogucin" residential stock – typical building

Thickness of internal prefabricated walls is 15 cm only, allowing to for more usable area than in any other technologies. Additionally, this technology allows for quick assembly of elements, it does not require additional frame work or in-situ concreting. Also, assembly process does not require any specific climatic conditions and may in fact be one of acceptable solutions for the construction of average income apartments.

4 References

Case studies in Bulgaria (author's info – not published) Predictive modeling of a Building in Sofia, Bulgaria. Default site for Sofia, Bulgaria.

Case studies in Slovak Republic (author's info – not published) European Academy of the Urban Environment. Institute for Regional Development and Structural Planning. Large Housing Estates.

Galda Z., Kubenkova K. (2007) *Housing Stock in the Czech Republic – maintenance and modernization*. ENHR International Conference Sustainable Urban Areas, Rotterdam. W07 Housing Regeneration and Maintenance

I) Principle Precast Systems and their Application

GERHARD GIRMSCHEID[1]

1 Introduction

Principle precast systems and their application in building construction are one outcome of industrialisation efforts in construction. Efforts on standardisation, systematisation and rationalisation, but also flexibilisation led to the development of precast systems and off-site prefabrication in building construction. Element connections, supports and joints become important to connect these precasted elements, and deal with tolerances which still occur in the construction process.

2 Principles of Assembly Construction

A distinction is made between the principles of assembly construction as follows (Fig. I.1):

- Frame constructions
    - frame structure
    - hinge systems
    - trussed beam construction
- Ribbed construction
- Panel construction
- Cellular construction

[1] Prof. Dr.-Ing., M.ASCE, John O. Bickel Award 2004 and 2005, Chair of Construction Process and Enterprise Management, Director of Institute for Construction Engineering and Management, ETH Zurich, CH-8093 Zurich, Phone +41 44 633 3114, Fax +41 44 633 1088, girmscheid@ibb.baug.ethz.ch

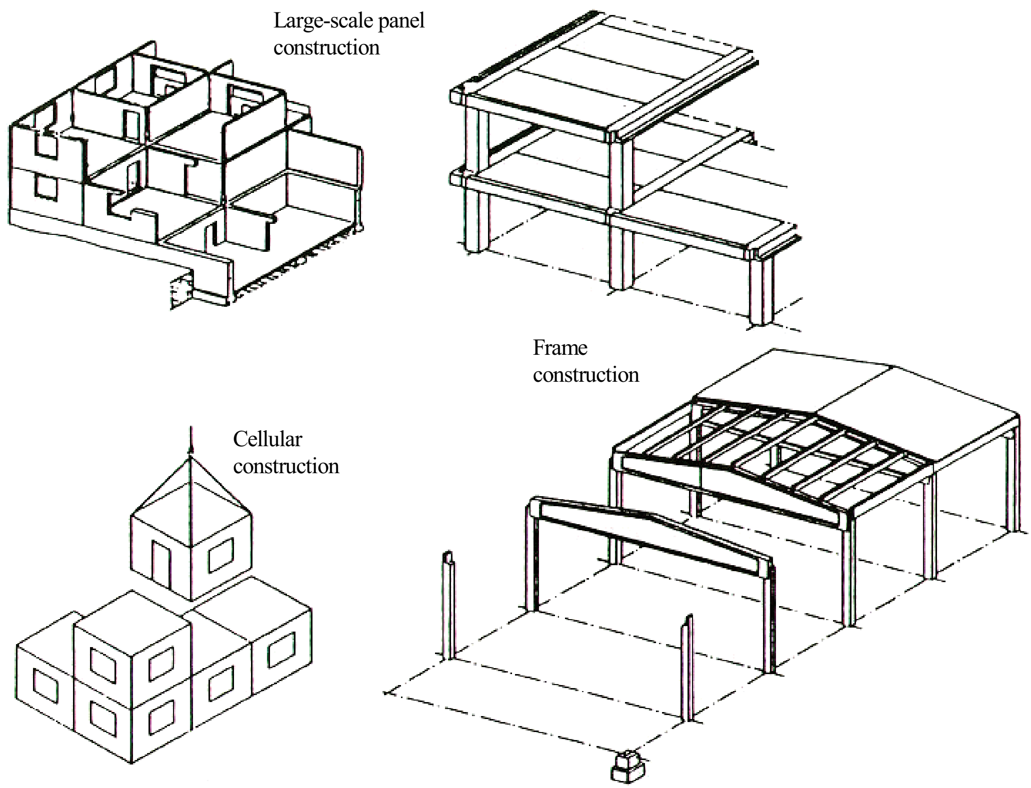
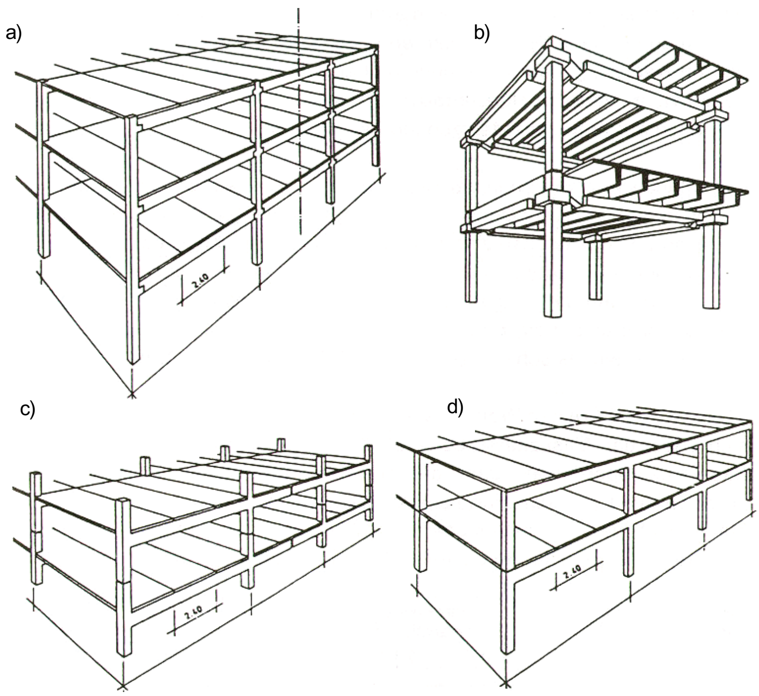


Fig. I.1: Prefabrication methods (Brandstetter)

2.1 Frame Construction

In the case of frame construction (Fig. I.2) a system of supports and beams forms the load-bearing structure. Various principles exist to brace the structural system. The overall structure - load-bearing and enclosing parts - is prefabricated and assembled. Structural roof elements and folded plates are special constructions in open frame systems.



a) Frame construction with continuous columns
b) Frame construction with single-story columns, open box sections, binding beams and ceiling panels
c) Single story frames jointed in the middle
d) Two-hinged frame

Fig. I.2: Examples of structural systems for prefabricated frame constructions (Frenzel, 1973)

Frame construction using an frame structure

Questions of overall stability arise when erecting a frame construction building, both during construction and in terms of the final state. In order to brace a frame construction, a distinction needs to be made between two fundamental applications as illustrated by the static principle of frame structures in Fig. I.3:

In the first case, the building is braced using cantilevers fixed to the foundations, the cross beams are jointed to the supports and act as single-span girders. Fixing to the foundations is, however, usually only possible for single-story halls.

In the second case, the building is braced using flexural resistant frame structures where the horizontal components (e.g. roof frame) are flexural resistant jointed to the columns. If the flexural resistant frame structure only runs in one direction, e.g. across the hall, the stability in the other direction needs to be ensured by other means (bracing diaphragms).

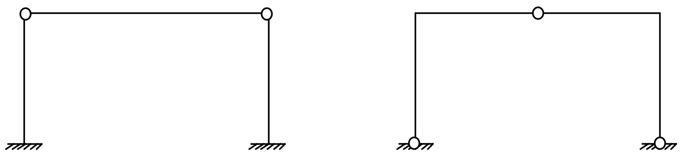


Fig. I.3: Frame structures

Frame structures are used as a construction method in concrete, steel and wood constructions.

Frame construction using hinge systems

As soon as a frame construction building is fitted with shear walls or cores the large differences in rigidity mean that other bracing structures only play a minor role in carrying horizontal forces. Since flexural resistant frame structures are comparatively more complicated in production technology terms, hinge systems with bracing cores or shear walls made from in-situ concrete (Fig. I.4 are widely used and offer static, production and assembly advantages.

The horizontal beams on hinge systems act as single-span girders. Columns carry vertical loads over one single floor, sometimes over two floors. Simply supported joints are generally used for the connections to foundations (block foundations). Sometimes these connections are flexural resistant fixed to a bucket foundation for assembly reasons. The building is braced by shear walls and/or cores.

Fig. I.4 shows a further frame construction where the columns carry vertical loads over one storey whereas the slab beams act as cantilever beams. The benefits of this system are the simple formwork for the columns and the construction height of the cantilever beams, which is up to 20 % lower than the aforementioned system.

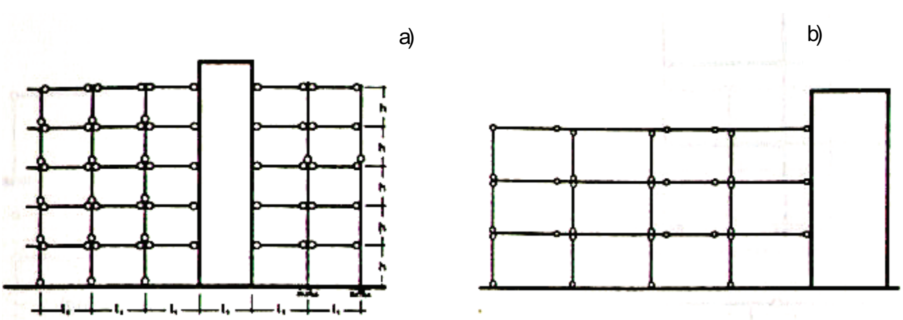


Fig. I.4: Hinge systems in prefabricated frame construction (Frenzel, 1974)

Frame construction using trussed beam construction

In addition to the frame structures and the option of using solid building cores to brace articulated systems, trussed beams are frequently used to brace wooden, steel and steel composite constructions.

In the case of trussed beams, bar-shaped components are jointed together thus ensuring that the components (in a pure trussed structure) only bear a load under tension or pressure, while at the same time the arrangement of the components creates a braced and stable support system. Fig. I.5 shows a trussed beam bracing system made of steel components for a high-rise building.

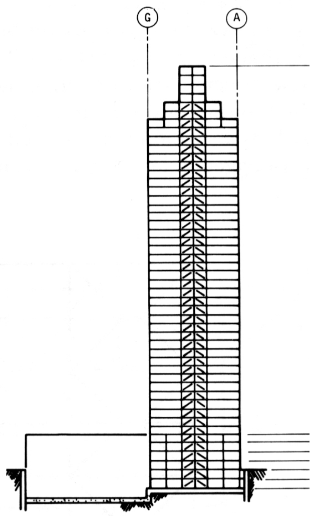


Fig. I.5: Principle of a trussed beam bracing system in a high-rise building (Beedle, 1998)

2.2 Ribbed Construction

Ribbed construction is half way between frame construction and wall construction. In ribbed constructions the ribs or verticals perform a load-bearing function, similar to frame construction, but are planked with statically required diaphragms, similar to wall construction. The verticals or ribs are planked during prefabrication but only on one side, not on both sides of the wall, as is the case in wall construction. Unlike pure wall or panel construction, the wall structure is therefore finished on the construction site.

Ribbed construction is relatively widespread in wooden buildings, where square timbers as the load-bearing elements are braced with enclosing and frictionally-locked wooden slabs.

Fig. I.6: Ribbed wall construction (Informationsdienst Holz, 2000)

2.3 Wall or Panel Construction

Wall or slab panels used in panel construction (Fig. I.7) perform both static load-bearing and enclosing functions. Floor-to-wall panels, so-called massive panels, are mainly used. Panel construction is predominantly found in residential housing.

The principle of **massive panel construction** consists of linking wall-to-slab plates to form a spatial system. The large-scale elements are linked together along the edges of the room.

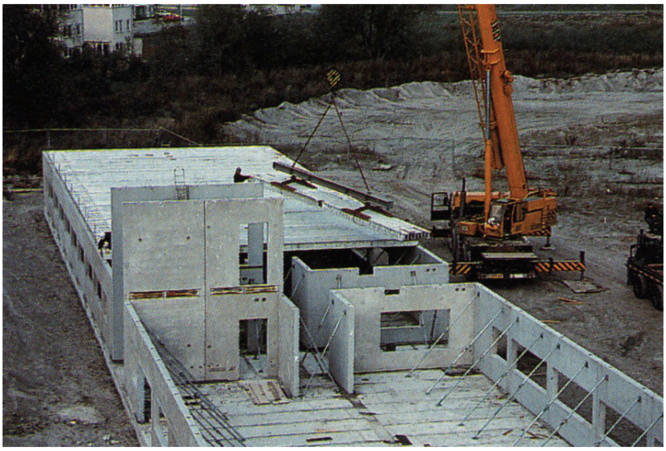


Fig. I.7: Panel construction with load-bearing plates and slabs (Swiss Beton, 2004)

The slab panels transfer the static support forces at the edges to the cross and lengthwise walls. Tension, pressure and shear-resistant connections are used to join them to form an overall load-bearing system.

Panel construction (Fig. I.8) is also widespread in **timber construction**, where prefabricated wall elements are used to act simultaneously as load-bearing and enclosing elements.

Fig. I.8: Panel construction of a (timber) building

The following construction systems are used for wall elements:

- prefabricated wall panels, planked on both sides and featuring appropriate electrical and installation fixtures
- wall panels planked on one side (ribbed construction)

The following construction features are used as wall or slab elements:

- timber strip elements
- massive wallboard and prefabricated hollow sections made from timber (Fig. I.9)

Fig. I.9: Timber wallboard and joined hollow sections (Informationsdienst Holz, 2000)

2.4 Cellular Construction

Cells are load-bearing, self-contained units that perform structural functions, either as single elements or in combination with other similar units.

In the case of cellular construction, the basic units of a structure are prefabricated and assembled in their entirety if possible. A cell is a construction component consisting of large-scale panel elements with or without the use of frame-style components. It is perfectly possible to design the load-bearing structure as an open frame and to use large-scale wall or ceiling elements to close the residual surfaces. Fig. I.10 shows basic cell alternatives in frame construction, Fig. I.11 shows examples using panel elements. A cellular (timber) building is shown in Fig. I.12.

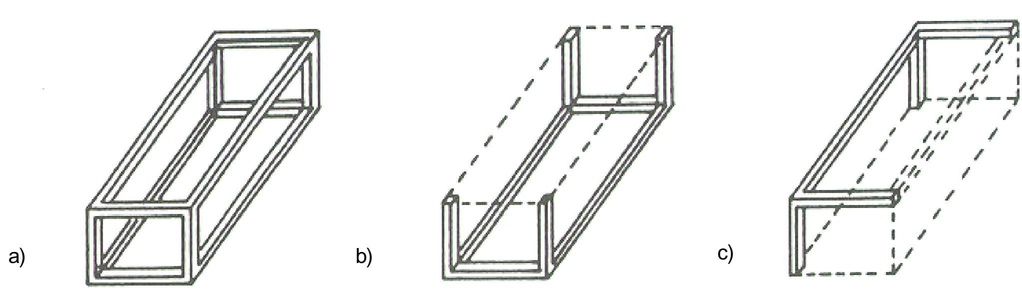


Fig. I.10: Basic cell alternatives in frame construction (Huth, 1975)

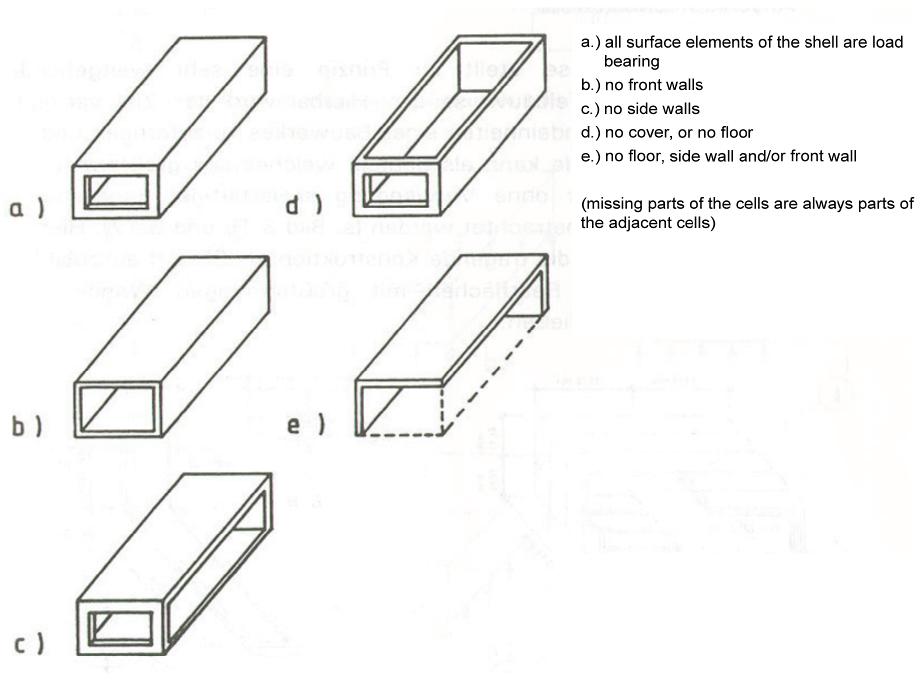


Fig. I.11: Basic cell alternatives using panel elements (Huth, 1975)

Fig. I.12: Cellular building (Informationsdienst Holz, 2000)

2.5 Element Connections, Supports and Joints

Forces, bending movements and torques have to be transferred in the connecting points in line with the planned static system. The joints and details therefore have to be designed and executed from a constructional and assembly perspective.

Assembly construction offers various options for connecting prefabricated parts to each other or to neighbouring structures. In order to reduce costs, the assembly processes of jointing, connecting and sealing should be performed solidly, simply, quickly and permanently offers a brief overview of the various methods of producing permanent and non-permanent connections.

Table I.1: Overview of permanent and non-permanent joining methods (acc. to Weller,1985)

Primary area of application	Non-permanent connection	Permanent connection
Reinforced concrete construction	Bolting cast steel connecting parts	Mortaring; Welding / mechanical connections of reinforcement (screwed / pressed connections)
Steel construction	Bolting; mechanical plug-in connections	Welding; Studding; Gluing
Timber construction	Bolting; mechanical plug-in connections	Nailing; Clamping; Press fitting steel connecting parts; Gluing

All joining methods using non-permanent connections can be adopted virtually irrespective of the weather conditions. Joining by mortaring or cementing does however require dry and frost-free weather where at all possible, respectively specific minimum temperatures to allow the cement and casting materials to harden. Non-permanent connections are, moreover, crucial if the structure is to be non-destructively dismantled at a later date for purposes of conversion, recycling or reutilisation.

Types of Joints

In the case of joints in diaphragms, structural engineering distinguishes between wall-wall joints and wall-slab joints, depending on the static function of the method of fabrication.

- **Vertical diaphragm joints** are primarily sheared power-grip connections of the vertical edges of adjacent wall panels. The shear transfer must be ensured using appropriate joint edge profiles and reinforcements vertically to the joint.
- **Horizontal diaphragm joints** are primarily subject to shear and thrust, whereby the shear can be transferred by friction given sufficient lateral thrust.

- **Horizontal joints connecting diaphragms and slab panels** are primarily subject to shear, bending and thrust.
- **Horizontal joints in slab panels** are primarily subject to shear and bending. Tensile components should generally be assigned to the reinforcement whereas the absorption of thrust components is assigned to the joint concrete.

The numerous methods for **sealing component joints** are virtually unaffected by the weather when prefabricated sealing strips are used. If sealing compounds are used, however, these must be applied at a specific minimum temperature to a dry and frost-free surface. Smooth, nonporous surfaces in the vicinity of the joints, which must be free of dust and dry during the sealing process, are absolutely crucial to ensure that the sealing strips or sealing compounds produce a flawless seal.

The simultaneous performance of numerous functions when sealing component joints is a huge challenge for the permanent elasticity and weather resistance of the sealing materials. Above all, they need to be able to address the significant variations in the width of the joint caused by frequently recurring compression and expansion as a result of traffic and wind loads and of changes in temperature and humidity. Fig. I.13 illustrates the changes to the width of a joint caused by seasonal differences in temperature and the ensuing impact on the change in shape of the joint sealing compound.

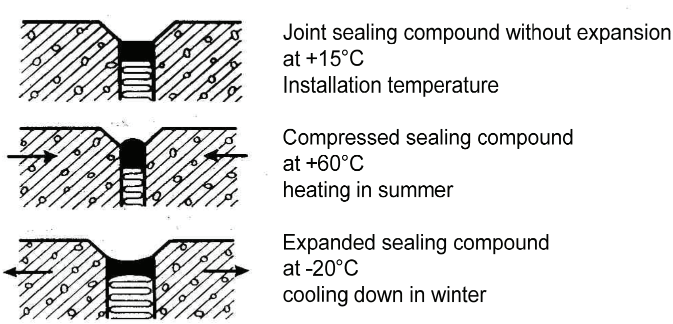


Fig. I.13: Changes in joint width (Weller, 1985)

In-situ Concrete Connections

The transmission of force in an in-situ concrete joint is largely dependent on the quality of the mortar or concrete used. The concrete or mortar used to cast the joint must be low-shrink where at all possible as otherwise the ensuing crevices have to be subsequently closed once more. Moreover, the joints must be sufficiently sealed and cured.

Tensile forces in the joint must be absorbed by connecting reinforcement bars. If the size of the joint does not allow for sufficient overlap, the reinforcement bars must be welded or bolted together.

Steel Construction Connections

To simplify the constructional design of connection points, connection methods used in steel construction are frequently adopted for concrete or wooden structures as well. For example, appropriate steel components are already built and anchored into the prefabricated components during the prefabrication process. Fig. I.14 shows anchor bolts that are used for the steel connection of reinforced concrete components. In addition to anchor bolts, steel front plates are also used for welded joints.

Fig. I.14: Anchor bolts for steel connection of reinforced concrete components (Peikko Deutschland GmbH, 2006)

Dimensional Tolerances

When planning and executing a connection detail, care must be taken to address the problem of permissible **component-specific dimensional tolerances**. According to Swiss standard SIA 414/10 resp. German standard DIN 18203-1 the length of a 15 m prestressed concrete girder can vary by ± 16 mm from its required length. Columns are used as supporting points for the roof truss; according to the standards, these can also vary by up to ± 30 mm. As such, the supporting points must be designed to cope with unfavourable overlaps in dimensional tolerances.

Attention must also be paid to the different tolerances of in-situ concrete structures and off-site prefabricated elements in practice. Often the site tolerances are much higher than the tolerances of precast elements. This frequently leads to considerable problems on site during the installation of precast elements.

In addition to the component-specific dimensional tolerances within one method of construction, the issue of **varying dimensional tolerances of a combination of different methods of construction (steel, concrete)** also needs to be addressed. The dimensional tolerances allowed by the prevailing standards for various construction elements and materials differ, in part, to the power of ten (steel construction: mm; concrete construction: cm tolerances). If these are not separately coordinated for each specific project, they will create insurmountable problems when it comes to assembling the components. One typical example of such connection problems between two methods of construction is the connection of steel-glass façade elements to the reinforced concrete structure of a high-rise building.

The use of special connecting elements for producing a power-grip connection of the relevant façade elements has become commonplace. These elements offer high levels of constructional flexibility and the ability to adapt to the dimensional tolerances, and ensure that the façade elements can be adjusted and fixed to the concrete components (e.g. Halfen elements Fig. I.15, Fig. I.16).

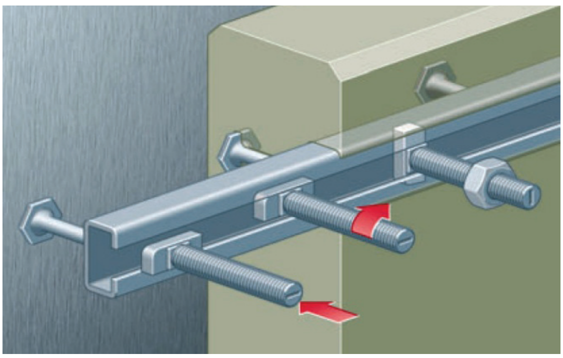


Fig. I.15: Basic diagram: cast-in Halfen bars with corresponding mounting bolts (Halfen-Deha Vertriebsgesellschaft mbH, 2006)

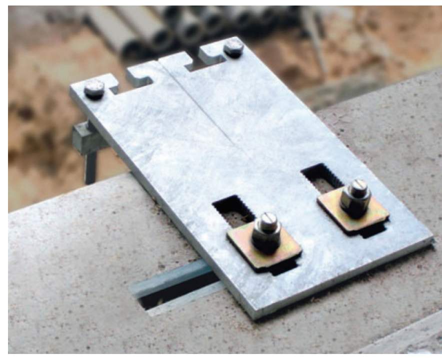


Fig. I.16: Adjustable Halfen connector for joining a façade to a concrete ceiling (Halfen-Deha Vertriebsgesellschaft mbH, 2006)

Element Seating Points

Fig. I.17 shows typical types of seating plates for prefabricated components for frame structures.

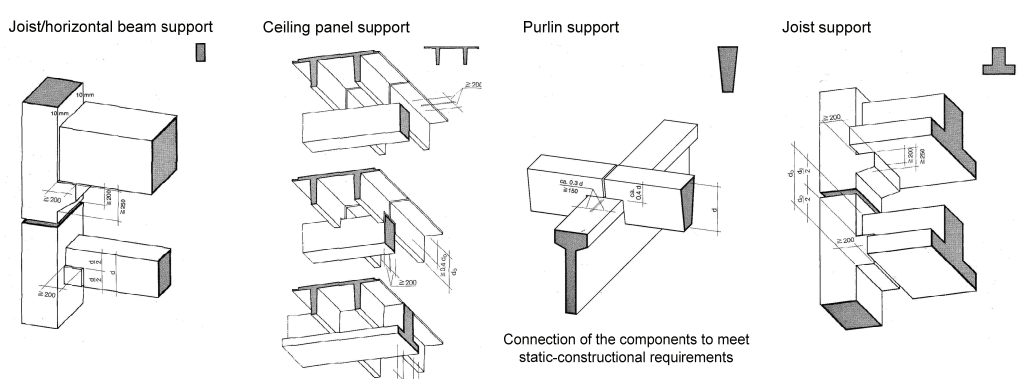


Fig. I.17: Typical seating plate structures (Steinle, 1998)

3 Conclusions

Principle precast systems are both; result and precondition of standardisation, systematisation, flexibilisation and rationalisation in industrialisation in construction. In conjunction with the classification of prefabricated components in chapter I precast systems enables the individual provision of client oriented solutions by mass-customisation on platform basis.

4 References

Beedle, L. S. (1998): Second Century of the Skyscraper. Council on Tall Buildings an Urban Habitat, Van Norstrand Reinhold Company, New York

Brandstetter, K. Haben wir die richtige Massordnung für das Bauen mit Fertigteilen? Vortragsveröffentlichungen aus dem Haus der Technik, Nr. 348, Vulkan-Verlag, Essen

Frenzel, D. (1973) Einige Kriterien für die Planung bei der Auswahl von Skelettsystemen aus Stahlbetonfertigteilen. Fertigteilbau und industrialisiertes Bauen, F+I-Bau 8 (1973)

Frenzel, G. (1974) Einige grundsätzliche Überlegungen für weitgespannte Konstruktionen aus Fertigteilen, Betonwerk und Fertigteiltechnik 40, Heft 9

Halfen-Deha Vertriebsgesellschaft bmH (2006): Produktinfo B-P 04 Halfenschienenen. http://www.halfen.de/d/22_696/de/media/catalogues/fixingsystems/b-p-d.pdf (02.05.2006)

Huth, S. (1975) Bauen mit Raumzellen, Bauverlag GmbH, Wiesbaden und Berlin

Informationsdienst Holz (2000) Holzbausysteme. Holzbau Handbuch Reihe 1 Teil 1 Folge 4, 12/2000

Peikko Deutschland GmbH (2006) http://www.peikko.de/software/pdf/P_PPM-HPM_Ankerbolzen_1005.pdf (30.03.2006)

Steinle, A. (1998) Bauen mit Betonfertigteilen im Hochbau. Ernst & Sohn, Berlin

Swiss Beton (2004) Handbuch für die Planung und Entwurf von Betonfertigteilbauten. Bauverlag BV GmbH, Gütersloh

Weller, K. (1985) Industrielles Bauen 1, Grundlagen und Entwicklung des industriellen, energie- und rohstoffsparenden Bauens. Kohlhammer, Stuttgart

International Council for Research and Innovation in Building and Construction

CIB's mission is to serve its members through encouraging and facilitating international cooperation and information exchange in building and construction research and innovation. CIB is engaged in the scientific, technical, economic and social domains related to building and construction, supporting improvements in the building process and the performance of the built environment.

CIB Membership offers:
- international networking between academia, R&D organisations and industry
- participation in local and international CIB conferences, symposia and seminars
- CIB special publications and conference proceedings
- R&D collaboration

Membership: CIB currently numbers over 400 members originating in some 70 countries, with very different backgrounds: major public or semi-public organisations, research institutes, universities and technical schools, documentation centres, firms, contractors, etc. CIB members include most of the major national laboratories and leading universities around the world in building and construction.

Working Commissions and Task Groups: CIB Members participate in over 50 Working Commissions and Task Groups, undertaking collaborative R&D activities organised around:
- construction materials and technologies
- indoor environment
- design of buildings and of the built environment
- organisation, management and economics
- legal and procurement practices

Networking: The CIB provides a platform for academia, R&D organisations and industry to network together, as well as a network to decision makers, government institution and other building and construction institutions and organisations. The CIB network is respected for its thought-leadership, information and knowledge.

The CIB has formal and informal relationships with, amongst others: the United Nations Environmental Programme (UNEP); the European Commission; the European Network of Building Research Institutes (ENBRI); the International Initiative for Sustainable Built Environment (iiSBE), the International Organization for Standardization (ISO); the International Labour Organization (ILO), International Energy Agency (IEA); International Associations of Civil Engineering, including ECCS, fib, IABSE, IASS and RILEM.

Conferences, Symposia and Seminars: CIB conferences and co-sponsored conferences cover a wide range of areas of interest to its Members, and attract more than 5000 participants worldwide per year.

Leading conference series include:
- International Symposium on Water Supply and Drainage for Buildings (W062)
- Organisation and Management of Construction (W065)
- Durability of Building Materials and Components (W080, RILEM & ISO)
- Quality and Safety on Construction Sites (W099)
- Construction in Developing Countries (W107)
- Sustainable Buildings regional and global triennial conference series (CIB, iiSBE & UNEP)
- Revaluing Construction
- International Construction Client's Forum

CIB Commissions (November 2009)

TG53	Postgraduate Research Training in Building and Construction
TG57	Industrialisation in Construction
TG58	Clients and Construction Innovation
TG59	People in Construction
TG62	Built Environment Complexity
TG63	Disasters and the Built Environment
TG64	Leadership in Construction
TG65	Small Firms in Construction
TG66	Energy and the Built Environment
TG67	Statutory Adjudication in Construction
TG68	Construction Mediation
TG69	Green Buildings and the Law
TG71	Research and Innovation Transfer
TG72	Public Private Partnership
TG73	R&D Programs in Construction
TG74	New Production and Business Models in Construction
TG75	Engineering Studies on Traditional Constructions
TG76	Recognising Innovation in Construction
TG77	Health and the Built Environment
TG78	Informality and Emergence in Construction
W014	Fire
W018	Timber Structures
W023	Wall Structures
W040	Heat and Moisture Transfer in Buildings
W051	Acoustics
W055	Building Economics
W056	Sandwich Panels
W062	Water Supply and Drainage
W065	Organisation and Management of Construction
W069	Housing Sociology
W070	Facilities Management and Maintenance
W077	Indoor Climate
W078	Information Technology for Construction
W080	Prediction of Service Life of Building Materials and Components
W083	Roofing Materials and Systems
W084	Building Comfortable Environments for All
W086	Building Pathology
W089	Building Research and Education
W092	Procurement Systems
W096	Architectural Management
W098	Intelligent & Responsive Buildings
W099	Safety and Health on Construction Sites
W101	Spatial Planning and infrastructure Development
W102	Information and Knowledge Management in Building
W104	Open Building Implementation
W107	Construction in Developing Countries
W108	Climate Change and the Built Environment
W110	Informal Settlements and Affordable Housing
W111	Usability of Workplaces
W112	Culture in Construction
W113	Law and Dispute Resolution
W114	Earthquake Engineering and Buildings
W115	Construction Materials Stewardship
W116	Smart and Sustainable Built Environments
W117	Performance Measurement in Construction

International Council for Research and Innovation in Building and Construction

Publications: The CIB produces a wide range of special publications, conference proceedings, etc., most of which are available to CIB Members via the CIB home pages. The CIB network also provides access to the publications of its more than 400 Members.

Recent CIB publications include:
- Guide and Bibliography to Service Life and Durability Research for Buildings and Components (CIB 295)
- Performance Based Methods for Service Life Prediction (CIB 294)
- Performance Criteria of Buildings for Health and Comfort (CIB 292)
- Performance Based Building 1st International State-of-the-Art Report (CIB 291)
- Proceedings of the CIB-CTBUH Conference on Tall Buildings: Strategies for Performance in the Aftermath of the World Trade Centre (CIB 290)
- Condition Assessment of Roofs (CIB 289)
- Proceedings from the 3rd International Postgraduate Research Conference in the Built and Human Environment
- Proceedings of the 5th International Conference on Performance-Based Codes and Fire Safety Design Methods
- Proceedings of the 29th International Symposium on Water Supply and Drainage for Buildings
- Agenda 21 for Sustainable Development in Developing Countries

R&D Collaboration: The CIB provides an active platform for international collaborative R&D between academia, R&D organisations and industry.

Publications arising from recent collaborative R&D activities include:
- Agenda 21 for Sustainable Construction
- Agenda 21 for Sustainable Construction in Developing Countries
- The Construction Sector System Approach: An International Framework (CIB 293)
- Red Man, Green Man: A Review of the Use of Performance Indicators for Urban Sustainability (CIB 286a)
- Benchmarking of Labour-Intensive Construction Activities: Lean Construction and Fundamental Principles of Working Management (CIB 276)
- Guide and Bibliography to Service Life and Durability Research for Buildings and Components (CIB 295)
- Performance-Based Building Regulatory Systems (CIB 299)
- Design for Deconstruction and Materials Reuse (CIB 272)
- Value Through Design (CIB 280)

An example of a recent major CIB collaborative activity is the Thematic Network PeBBu Performance Based Building: a four-year programme that included 50 member organisations, that was co-ordinated by CIB and that was funded through the European Commission Fifth Framework Programme.

Themes: The main thrust of CIB activities takes place through a network of around 50 Working Commissions and Task Groups, organised around four CIB Priority Themes:
- Sustainable Construction
- Clients and Users
- Revaluing Construction
- Integrated Design and Delivery Solutions

CIB Annual Membership Fee 2007 – 2010

Fee Category		2007	2008	2009	2010
FM1	Fee level	10526	11052	11605	11837
FM2	Fee level	7018	7369	7738	7892
FM3	Fee level	2413	2534	2661	2715
AM1	Fee level	1213	1274	1338	1364
AM2	Fee level	851	936	1030	1133
IM	Fee level	241	253	266	271

All amounts in EURO

The lowest Fee Category an organisation can be in depends on the organisation's profile:

FM1 Full Member Fee Category **1** | Multi disciplinary building research institutes of national standing having a broad field of research

FM2 Full Member Fee Category **2** | Medium size research Institutes; Public agencies with major research interest; Companies with major research interest

FM3 Full Member Fee Category **3** | Information centres of national standing; Organisations normally in Category 4 or 5 which prefer to be a Full Member

AM1 Associate Member Fee Category **4** | Sectoral research & documentation institutes; Institutes for standardisation; Companies, consultants, contractors etc.; Professional associations

AM2 Associate Member Fee Category **5** | Departments, faculties, schools or colleges of universities or technical Institutes of higher education (Universities only)

IM Individual Member Fee Category **6** | Individuals having an interest in the activities of CIB (not representing an organisation)

Fee Reduction:
A reduction is offered to all fee levels in the magnitude of 50% for Members in countries with a GNIpc less than USD 1000 and a reduction to all fee levels in the magnitude of 25% for Members in countries with a GNIpc between USD 1000 – 7000, as defined by the Worldbank. (see http://siteresources.worldbank.org/DATASTATISTICS/Resources/GNIPC.pdf)

Reward for Prompt Payment:
All above indicated fee amounts will be increased by 10%. Members will subsequently be rewarded a 10% reduction in case of actual payment received within 3 months after the invoice date.

For more information contact
CIB General Secretariat:
e-mail: secretariat@cibworld.nl

PO Box 1837, 3000 BV Rotterdam,
The Netherlands
Phone +31-10-4110240;
Fax +31-10-4334372
Http://www.cibworld.nl

CIB General Secretariat
post box 1837
3000 BV Rotterdam
The Netherlands
E-mail: secretariat@cibworld.nl
www.cibworld.nl

CIB Publication 329