Mass Customisation and Personalisation in Architecture and Construction

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ROBOT ORIENTED CONSTRUCTION MANAGEMENT

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Abstract

Construction industry has a low productivity rate concerning the raw material input and about 40% - 50% of global raw materials are used for the construction of our environment. Construction waste states the largest waste fraction even in highly industrialized countries and buildings are among the most expensive goods that we produce. Although we have achieved that complex high-tech products as cars and computers are produced with high efficiency, we have not brought the production of simple low-tech products as buildings to a comparable level. An alternative method to conventional construction is the large scale deployment of industrialization, enabled by applying automation and robotics based processes and technologies throughout all phases of the life cycle of built environments. The present chapter first analyzes best-practice industrialization/automation and building production projects, which have been tested or applied successfully in

larger scales during the last decades. Furthermore, the chapter derives from that analysis, a framework for combined on/off-site building production as an approach for managing sustainable and resource efficient construction processes. Strategies from the presented framework are currently applied by the authors of this chapter to various projects around the world.

1. INTRODUCTION

The paradigm of sustainability gradually pervades all industrial sectors, all levels of value creation and all aspects of daily life, leading to a new 21st century industrial revolution (Hawken et al., 1999) where the importance of environmental and social factors finally becomes equipollent to pure economic efficiency. Legal frameworks, financial incentives and market/price developments urge more and more industries to change their processes and to shift from economic growth to sustainable development. This change affects the value system as well as multiple enterprise levels and reaches from organization, new product structures, new processes and technologies, microelectronic devices, ICT structures, flexible automation, robotics and knowledge based logistics to life cycle performance, reuse and remanufacturing. Industrialized structures are deployed in nearly all industrial sectors and form a solid basis for steady advance and gradual development towards a more sustainable economy. However, in construction industry industrialized structures are merely developed and advanced devices, which are state-of-the-art technology in other producing industries, are still rejected. Construction industry has the lowest productivity rate of raw material input and about 40% - 50% of global raw materials are used for the construction of our environment. Construction waste states the largest waste fraction even in highly industrialized countries and the capability of that waste to be recycled with low environmental impact is rather low (OECD, 2008). Moreover, the working conditions for construction workers in highly industrialized countries as well as in the emerging construction industries of India and China are challenging. Furthermore, buildings are among the most expensive goods that we produce, and although we have achieved complex high-tech products such as cars and computers being relatively affordable for everybody, we have not brought simple low-tech products as buildings to a comparable level. Finally, this becomes even worse when we look at the life cycle performance of our built environment and the fact that in a time of dynamic societies and fast changing needs, built environment can hardly be adapted, rearranged, deconstructed or remanufactured (Bock, 2007).

State of the Art in Automation and Robotics

An alternative method to conventional construction, which is labor intensive, consumes tremendous amounts of energy and material, causes large amounts of waste, provides unsatisfactory working conditions and moreover, is not able to supply more affordable buildings, is the large scale deployment of industrialization: prefabrication, automation, advanced logistics, Enterprise Resource Planning (ERP), flexible automation, robotics and other smart assistance devices. Toyota Home prefabricates customized and highly modular housing units “to order” while it relies on adapted principles of Toyota`s lean and demand oriented production system. Flexible machinery, “Kanban”, “Kaizen” and “Just-in-time Just-in-sequence” minimize the input of workforce, resources and energy meanwhile only products are fabricated, that are demanded (Linner and Bock, 2009). Other Prefab companies in Japan operate their business in a similar manner. The total output of Japan’s prefabrication industry is about 150,000 buildings per annum . In Europe, at this point, Radio-frequency Identification (RFID) (Finkelzeller, 2003), enabled construction logistic systems are developed and tested in order to upgrade conventional construction logistics (Helmus et al., 2009). Those RFID logistics are currently developed further for integration with ERP systems. The automation of high-rise construction and on-site factories have been realized in Japan by several of the leading construction companies (Shimizu, Obayasi, Kajima, Takenaka) since the eighties. There, the construction process has not only been automated partly, but logistics are organized strictly and the construction progress is displayed and controlled in real-time (Ikeda and Harada, 2006). Today those systems are also able to erect not-rectangular and individually designed buildings with reduced workforce and optimized resource performance (Bock, 2009). Autonomous mobile and modular site robots for finishing and refurbishing tasks, have been developed and used since the nineties in Japan and Germany (Bock and Linner, 2009). Recent R&D in Korea, supported by the authors of this chapter, is now focusing on human-machine-cooperative systems (Lee et al., 2007), power-assistance devices, wearable robots and new types of automated construction sites (Bock et al., 2009). The goal of Korean researches is to integrate the workers` skills and intelligence and the power of the machines and robots. Furthermore, the digital data gathered throughout planning and construction can be used for the operation of mobile servicing robots, such as examples from Japan (Kajima, Taisei) and France (Louvre Glass Cleaning Robot) demonstrated by (Bock and Linner, 2009). Finally, systemized and partlially automated systems (Kajima) for controlled deconstruction allow a recycling rate of up to 93% (Bock, 2009) and Japans Prefab makers try to build up reverse logistics and remanufacturing systems (Sekisui Heim, 2012).

2. BEST-PRACTICE INDUSTRIALIZATION PROJECTS

Industrialization projects are organized and presented in accordance with the value-added steps in order to show that all projects, processes and technologies in combination would represent the whole value chain (Section 2). This book chapter derives from that analysis a framework for integrated on/off-site industrialization technologies as an approach for managing sustainable construction processes through closing the value chain (Section 3). Finally, the findings are summarized in the conclusion (Section 4).

Conveyor Belt Based Off-Site Fabrication in Japan

Customized fabrication has a long history in Japan. After the second world war, Toyota Motor Corporation searched for a way to improve its productivity by a factor of ten (Ohno, 1988). Already at that time, the Japanese market was changing fast and demanding for extremely small series of cars. Toyota Researchers at that time also visited the factories of Ford and GM and concluded that a fabrication strategy based on mass production strategies and “economies of scale” would not be efficient and successful in the Japanese socio-economic system. This strongly demand oriented thinking in industrial fabrication made it easy for Japanese companies to later deploy industrialized structures also in the fabrication of houses. Nowadays, the production systems of Toyota Home (85% factory completion), Sekisui Heim (80% factory production) and Sekisui House, are highly advanced and automated. Toyota Home

(Skeleton and Infill) and Sekisui Heim (Unit Method) have based their systems on cubical metal frames specially designed for customized and demand oriented factory production of buildings (Bock and Linner, 2009) on the conveyor belt.

Advanced Logistics and ERP Solutions

Complex projects are characterized by a high number of operators, activities and logical links. Therefore, in all advanced industries with a high diffusion rate of automation and robotics technology (i.e. automotive industry, aircraft industry, and ship industry), real-time ERP communication systems are used to coordinate highly modularized organizational structures. Modularization offers the possibility to react to changes fast and dynamically. Nowadays, modularity is not only limited to the product itself, but cuts cross all enterprise levels: management, design & product engineering, logistics, supply, and production (Moum, 2006). Sekisui Heim, famous for its legendary "Unit-Method" introduced its HAPPS (Heim Automated Parts Pickup System) in the 70s (Furuse and Katano, 2006), and started to deliver industrialized houses with individual floor plans. HAPPS was one of the first ERP solutions enabling continuous workflow management for industrialized production of individual buildings.

On-site/Off-site combined Fabrication

From 2002 to 2005 NCC (Nordic Construction Company) Sweden had worked on developing an industrialized concept for multi-storey residential buildings and according to that from 2005 to 2007 it had been running a test project called "NCC Komplett" (Thuesen and Johnsson, 2009). This was a manufacturing system combining factory prefabrication with a mobile on-site assembly hall. In the off-site factory, concrete walls were customized according to customer demands and architect plans. Most of the fit-out work, i.e installation of electrical cables and appliances, sub-components, windows, doors, radiators and fixed furniture modules for bath and kitchen, was performed in the factory. Only four assembly workers and one assembly foreman were needed per average building, since the flow of materials, components and resources was highly controlled through advanced logistics systems and the combination of controlled off-site and on-site processes.

Modular and Flexible On-site Automation

Since 1990, about 25 automated high-rise sites (Bock, 2007) have been operated by various Japanese companies (Taisei, Takenaka, Kajima, Shimizu, Maeda, Kumagai, Ohbayashi). An automated high-rise construction site can be defined as a vertically moving factory **(Fig. 1)** combining semi- and fully automated storage systems with transport and assembly equipment and/or robots to erect a building almost completely automatically. A further goal of those systems is to improve the organization of construction processes and construction management by using real-time ICT and advanced control systems enabling a continuous flow of information from planning and designing to control the automated on-site systems. Fully automated and semi-automated on-site factories reduce labor requirements by around 30%, and in the future they are expected to achieve a labor saving of more than 50 %. Nowadays, semi-automated high-rise construction systems are even capable of creating individual and not-rectangular buildings. The high rate of defined processes reduces material and resource consumption, and construction waste is nearly completely avoided. Moreover, on-site factories provide an appropriate and safe working environment. Automated

Building Construction Systems can be designed highly modular and flexible. European construction firms have also adopted today flexible site-automation systems (e.g. Skanskas, **Fig. 2)**.

Flexible On-Site Robots

Early on-site construction robots were introduced in the civil engineering sector, due to repetitive working tasks such as road construction tower and bridge building, dam construction, nuclear power plant construction and tunneling. Major Japanese construction companies were researching and developing robotized construction processes since the beginnings of the eighties. Initially, individual robots and remote controlled manipulators were developed for specific processes on building sites. This included robots for delivering and handling concrete, applying fireproofing to steel constructions, handling and positioning large components and façade inspection or painting robots (**Fig. 3**). In Japan over 400 different robots were developed in total which were used on building sites. In Germany since the nineties various robots have been implemented for supporting interior finishing and refurbishing work in order to increase productivity of building stock modernization.

On-Site Servicing Robot Systems

Robotic systems are not only developed today for the construction process, but also for the buildings, economically important, life span. The first service robots for buildings in Japan were developed at the end of the seventies beginning of the eighties. 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 inaccessible glass roofs. In the nineties service robots were applied to civil engineering projects such as inspection of tunnels and railroad tracks and bridge monitoring. Later on, advances in robotics research and its integration with computational engineering resulted in service robots for office logistics, security and detection of gas leaks or fire hazard.

Systemized Deconstruction

Within 11 months, three high-rise buildings in the center of Tokyo were recently deconstructed by a semi-automated deconstruction system (Kajima). The process of deconstruction was reversed and re-engineered. It starts with the dismantling of the ground floor. Meanwhile dismantling the ground floor, the upper part of the building was held by IT-coordinated hydraulics. With this method, floor by floor was dropped down subsequently and disassembled at the ground floor level. As the deconstruction was highly coordinated and could conveniently be conducted on the ground floor level, 93 % of the building components could be recycled (recycling rate of conventional demolition: 55 %). This example shows that the consequent deployment of advanced on-site technologies could be crucial for sustainability in construction/de-construction in the future. Kajima has developed several robotic systems for supporting automated con- and deconstruction tasks **(Fig. 4)**.

Off-Site Building Re-Customization

All obsolete building modules of Sekisui Heim can be accepted as trade-in values for a new Sekisui Heim building. Therefore, the deconstruction process is a reversed and modified version of the construction process which is based on subsequent unit factory completion of modular units on the conveyor belt as described before. For deconstruction joints between steel frame units are initially eased, and then the house is transported to a special dismantling factory unit by unit. There, the outdated finishes are dismantled and fed into advanced reuse cycles established around factories. The bare steel frame units are further inspected and renovated, which are finally equipped with new finishes, desired by a customer who has chosen to buy a remanufactured house. On a Web-Platform for "Reuse System Houses", Sekisui organizes a gathering of people who want to sell their modular house for reuse, and people willing to buy a remanufactured home. The newly outfitted units are then assembled on a new foundation in the new site.

3. INTEGRATION ALONG THE VALUE CHAIN BY ROBOT ORIENTED MANAGEMENT

Information can be seen as common element of development, planning, production and (building) product. Based on the knowledge about a prospective customer, information is embedded in a product through design and production. T. Fujimoto, famous for his research on the Toyota Production Systems, goes even one step further and claims that consumers consume not goods or services but information: "(…) what he or she consumes is essentially a bundle of information delivered through the car rather than the car as physical entity". Similarly, Piller is describing production as a process where physical materials are transformed through machinery, organization and information into products. From this information point of view, it is necessary to see all steps of the value creation process as a set of complementary subsystems which is jointly embedding information and transforming physical materials through information in order to create value. For the integration of processes along the value chain in construction advanced production technology, advanced product structure, advanced management and organisation, and advanced philosophies have to be synchronized and applied as complete and co-adapted set of strategies **(Fig. 5)**.

Advanced Production Technology

Automation and Robotics: Fully automated and semi-automated on-site factories reduce labor requirements by around 30%, and in the future they are expected to achieve a labor saving of more than 50 %. Today semi-automated high-rise construction systems are even capable of creating individual and not explicitly rectangular buildings. The high rate of defined processes reduces material and resource consumption and construction waste is nearly completely avoided. Moreover, on-site factories provide an appropriate and safe working environment. Automated Building Construction Systems can be designed highly modular and flexible.

RFID based Logistics: Through tagging goods and product with RFID, logistics within a network or within a company can be traced and controlled in real-time. Thus the physical location of products and the state of the network can be displayed in a digital and alphanumerical way supporting advanced use of this data. RFID logistics can be integrated with ERP and experts systems allowing thus for optimized coordination and just-in-time just-in-sequence production flows. Thus, RFID used in logistics allows representing the physical condition of a logistics/production flow in an informative way – again information, its transmission and transformation are the key to efficiency. Even in construction RFID supported Site Logistics are tested and advanced in recent research projects in order to improve organization and material flow on construction sites.

Advanced Product Structure

Robot Oriented Design: In integrated industrialized construction, the product structure is the most crucial and most complex item of the whole process chain. Yet construction products are still inflexible, showing a highly interdependent component structure in contrast to what e.g. (Baldwin and Clark 2000) consider as industry and innovation supporting modularity. Systemized and modularized building structures have to be developed in close cooperation with the needs of fabrication, logistics, customization and robotic and cooperative applications (Bock, 1988). Furthermore, greater agreements and standards on those systemized building structures should be deployed in the industry's legal framework, to foster the exchange and substitution of materials, sub-components and components among the industry's players.

Advanced Management & Organisation

Supply Chain Design: For integration along the value chain, Supply Chain Design is an important tool setting up the flow of information and physical goods within a value creation network of firms. Fastening innovation cycles and an increasingly dynamic economic environments demand that those networks are flexible, can rearrange and adjust quickly and on demand the amounts of goods and information transferred between them. Thus, new concepts as information sharing in supply chains and IT tools for collaborative planning and managing of supply chains evolve in the field of Supply

Chain Design, in order to improve the integration along the value chain and thus the ability to respond as a total system to market changes quickly.

Mass Customization: Conventional construction today is heavily relying on human power. It delivers individual products, yet at high costs and nearly without relying on high-tech solution. Robotics and advanced equipment are not in the focus of architecture and construction. Industrialization in architecture and construction for a long time has not been considered as being able to deliver individual buildings adjusted to locations and people’s need (Bock and Linner, 2010). With Mass Customization (Piller, 2006), construction industry gets a strong new tool: based on integrating organizational structures over the whole value chain corresponding with information flows between enterprise, product, machinery, robots, customers and all complementary sub-processes.

Production Networks: Prefabrication of components, modules or completed units, logistics, ERP, automated on-site construction, construction robotics, robotic-co workers, systemized deconstruction and other new technologies and processes could be seen as complementary elements, forming an ecology of factories, devices, equipment, processes, resources and human beings.

Advanced Paradigm & Philosophy

Hyper Flexible Robotic Systems: The next generation of robots will work in the direct operating range of human workers in order to achieve optimum flexibility, which is a basic requirement for customization and flexible individual product fabrication by industrialized methods. Robotic systems of the next generation will rather be "assistants" (EUROP, 2009), helping human workers to perform complex tasks, than fully autonomous systems. New interaction concepts, interfaces, concepts for lightweight robots, integrated force-torque sensors and teaching systems, are therefore now developed by researchers around the world. The strategy of "Human-Robot-Cooperative-Manipulation" (Bock et al., 2009) integrates the advantages of both robots and human beings, and creates highly flexible cooperative systems that are predestinated for complex tasks in factories or on construction sites.

Reverse Logistics and Re-Customization: Eco-factories are factories that produce at high efficiency and in accordance with environmental needs: carbon neutral, powered by renewable energy, zero-waste (Business and Economy Trends in Japan, 2011). An essential economic and ecologic factor in most industries today is the implementation of factories with low or even no environmental impact. Factories are increasingly able to manage the closed-loop circulation of all resources and materials efficiently. Additionally, disassembled components can be reused or recycled with high efficiency through the dismantling process taking place in a controlled factory environment, feeding them again into new industrial transformation circles.

4. CONCLUSION

New organizational structures, new processes and technologies, microelectronic systems, ICT, flexible automation, robotics, human-machine-cooperative systems, tagged equipment, modular building components and knowledge based logistics are enablers of a shift towards sustainable economic construction, when they are designed as complementary parts of a total system. Industrialized structures provide the basic foundation for a gradual development towards a more sustainable construction industry. Therefore, in this book chapter, examples have been given which outline best-practices in sustainable industrialized construction. Moreover, a framework for future industrialization and robot oriented management has been presented, which suggests the combination and integration of processes and technologies over the whole value chain to an advanced ecology of factories, devices, equipment, resources and human beings. Prefabrication, advanced logistic structures, automated construction, modular high-tech (robotic) equipment and systemic reverse logistics are various proven stand-alone industrialization solutions. Those advanced industrialization methods could now be integrated and further developed to large scale sustainable building fabrication networks, producing sustainable buildings with determined economic, environmental and social impact.

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Figure 1: Shimizu's horizontally moving "Smart" factory in operation

Figure 2: Skanska's prototype of an automated building construction system

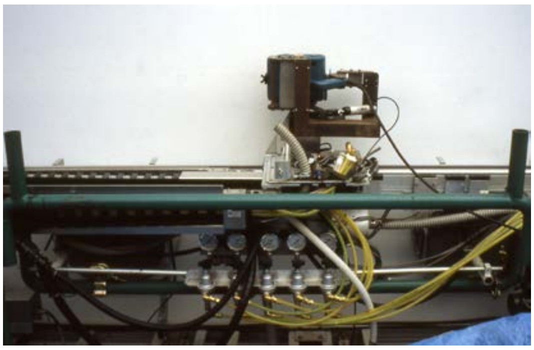

Figure 3: Wall and façade painting robot capable of multilayered painting, *Tokyu*

Figure 4: Kajima has developed several robotic systems for supporting automated con- and deconstruction tasks.

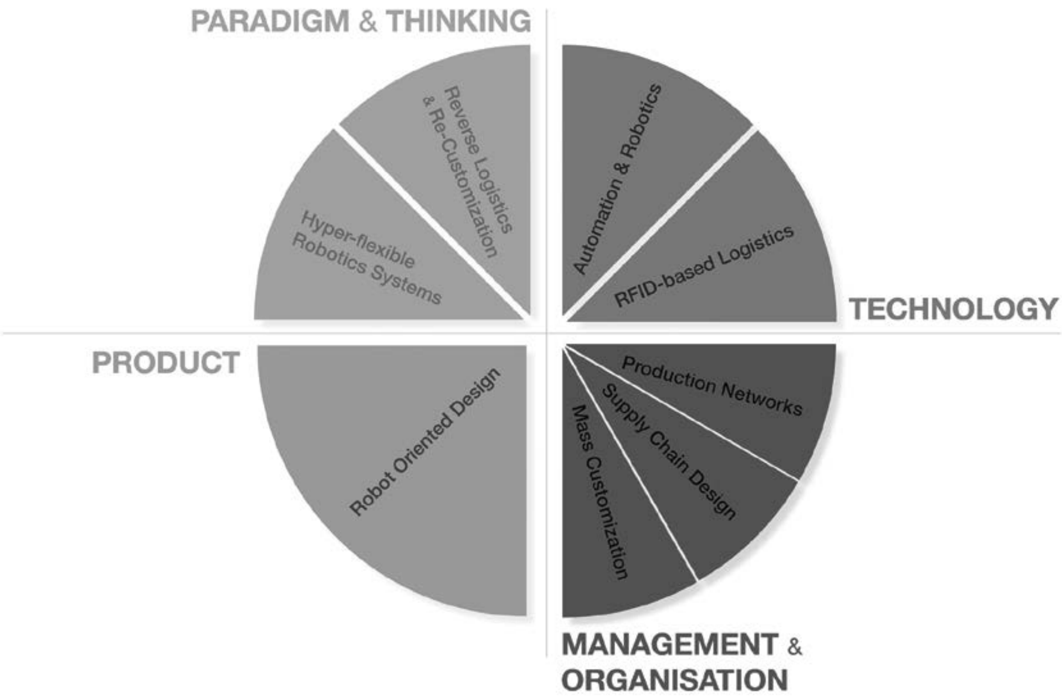

Figure 5: For the integration of processes along the value chain in construction advanced production technology, advanced product structure, advanced management and organisation, and advanced philosophies have to be synchronized and applied as complete and co-adapted set of strategies.