

Changeable, Agile, Reconfigurable & Virtual Production

## Analyzing Interdependencies between Factory Change Enablers applying Fuzzy Cognitive Maps

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### Abstract

Enablers of change play an important role for competitive manufacturing systems in a turbulent corporate environment. In the process of designing factories, companies face the decision of which enablers to choose for dealing with market-induced uncertainties and fuzzy planning data. Current research, however, does not provide information on how the enablers influence each other when implemented in real production systems. This paper first provides an overview of relevant change enablers and categorizes them with regard to their degree of abstraction, based on an intensive literature review and expert interviews. With the aim of creating a method for the selection of feasible enabler-combinations, a fuzzy cognitive map to analyze fuzzy interdependencies between the different change enablers is developed. To validate the relations modelled in the fuzzy cognitive map in industrial practice, a survey-tool is presented and applied in enterprises from the field of factory planning. The developed method for modelling change enablers' interdependencies empowers the factory planner to actively select a combination of enablers that influence each other positively and thus allow for a cost-efficient design of changeable factory layouts in early planning stages.

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### 1. Introduction

An increasingly turbulent environment, more volatile and dynamic markets and growing competition makes the ability to change, i.e. changeability (see chapter 2.1), a major success factor for producing enterprises [1].

To design factories under the premise of changeability, so-called change enablers (in short: enablers) are of rising importance [2]. Over the last 15 years, several authors have developed planning methods for changeable factories in which they identified change enablers of varying degrees of abstraction and top-down. However, interdependencies between these enablers are not taken into account, although highly important for deciding on which enablers to choose from the vast field. In addition, about 90% of all planning scenarios in reality are brownfield [3], meaning that a certain combination of enablers is already implemented and others

are not applicable. In order to identify a combination of enablers that fit together, meaning that enablers do not weaken each other's functionality or effectiveness, it is vital to know about how the enablers affect each other and their impact on invest. This information is neglected in existing planning approaches for changeable factory structures. According to [4] it is more important to be aware of a system's elements' interdependencies than possessing exact knowledge about the elements themselves.

A further deficit in many contributions is the enablers' high level of abstraction, making it difficult for practitioners to realize change enablers like "Universality" in factory planning projects.

This paper is structured as follows: In Chapter 2 we review the state of the art regarding changeability and its enablers as well as methods for modelling interdependencies. In Chapter

3 the research methodology applied is described in more detail.

Chapter 4 is based on chapter 2 and 3 and comprises the elemental part of this paper. The goal of chapter 4 is threefold: Firstly, we identify and categorize change enablers applying a bottom-up approach. Hereby, a catalogue of concrete, practical enablers like “machine on wheels” is constructed which is then structured into more abstract categories (chapter 4.1), making the link to already existing research. Secondly, we determine the interdependencies between these concrete change enablers using a survey tool developed for this purpose (chapter 4.2). Thirdly, the overall network of change enablers’ interdependencies based on the survey is modeled in a fuzzy cognitive map (chapter 4.3). Chapter 5 gives further research directions and a conclusion.

## 2. State of the Art

### 2.1. The Concept of Changeability

Until recently “the ongoing industrial and academic interest in flexibility, robustness, adaptability, and many other properties closely related to changeability has not yet converged in a precise domain-neutral definition of terms” [5]. Acknowledging this deficit, Plehn et al. determine definitions for the above-mentioned notions, which they summarize under the umbrella term *Changeability*. In our contribution, we follow this idea of changeability comprising the concepts of *Robustness*, *Resilience*, *Flexibility*, *Adaptability* and *Transformability* which are defined in [5]. Thus, changeability can be defined as “umbrella term comprising more specific properties describing a system’s ability to change its structure (incl. interfaces), form, and function at an acceptable level of valued resources (i.e., time and money)” [5]. In conformity with [6], we define the term “Change Enabler” as *an action, measure or construct with different possible degrees of abstraction which enhances a factory object’s callable and individual ability to change.*”

### 2.2. Enablers for Changeable Factories

In this chapter, we discuss the change enablers identified in current research. The number and terminology of these enablers vary and a common understanding has not yet been established.

One of the first to use the term *enabler* (in German “Befähiger”) in the context of factory planning was Hernández Morales [6]. He differentiates between the following 6 enablers which are defined in table 1: *Mobility*, *Expandability and Reducibility* (named *Scalability* in later contributions), *Modularity*, *Neutrality regarding function and use* (named *Universality* in later contributions), *Networkability* and *Integration and Disintegration capability*. Several later contributions refer to these enablers and build on the work of Hernández Morales [6]: [2,7–15]. The majority of these authors use only 5 enablers, after [7] reduced the number from 6 to 5 by combining *Networking capability* and

*Integration and Disintegration capability* in the term *Compatibility*. Further changes in terminology lead to the frequent use of the term *Scalability* instead of *Expandability and Reducibility* and *Universality* replacing *Neutrality regarding function and use* [2,7–12]. In this contribution, we utilize the shorter terms *Compatibility*, *Scalability* and *Universality*.

Table 1. Overview and Description of Change Enabler Terminology

Enablers Name	Alternative Name	Description of Enabler according to [6]
Mobility		Factory objects can be placed and replaced with low effort and their functionality is location-independent.
Expandability and Reducibility	Scalability [2, 7-12]	Factory objects are “breathable” which means they can easily grow or shrink with regard to equipment, space, organization and personnel.
Modularity		Division of the factory structure into standardized, functional, pre-tested and autonomous elements.
Neutrality regarding function and use	Universality [2, 7-12]	Capability of factory objects for being employed for varying requirements and tasks.
Networking capability	Compatibility [2, 7-12]	Enables diverse and efficient material, information and personnel flow within and outside the factory.
Integration and Disintegration capability	Compatibility [2, 7-12]	Products, components and processes can be included or excluded with low effort into the factory structure due to uniform interfaces.

The resulting 5 enablers *Universality*, *Modularity*, *Mobility*, *Scalability* and *Compatibility* are named primary enablers in conformity with literature.

There are several authors who attribute change enablers to factory objects or design fields (e.g. factory layout, logistics equipment, manufacturing equipment, etc.; [6,9,10,13]) and thus achieve a lower level of abstraction (so called secondary change enablers). Others differentiate between enablers for each factory level (e.g. site, segment, system, station, etc.; [9,10,16]).

Heger [10] names a total of 232 enablers which are either quantitative (i.e. measurable on a discrete or continuous scale) or qualitative (i.e. measurable on a nominal or ordinal scale). For this purpose he uses a top-down approach, deriving the more concrete enablers from 7 abstract ones (to the 6 enablers by [6] he added *Standardization*). The methodology behind this procedure is not explained in detail, however. Nyhuis et al. [9], building on the enablers identified by Heger [10], argues that not every enabler is applicable to each factory design field. The design field *Space* for instance cannot be mobile and therefore has no secondary enabler in the field of *Mobility*.

Pachow-Fraunhofer [13] identifies secondary enablers through expert interviews which are, however, still on an

abstract level (e.g. Tolerance, Communication or Robust Dimensioning). Janorschke et al. [11], in contrast, list a number of very concrete change enablers for the building structure of factories, however, does not consider other factory design fields.

While the authors mentioned so far analyze and identify enablers from the technical point of view, Koch [12] introduces 6 socio-technical primary enablers and thus considers the social component of a factory system.

Sudhoff [17] focuses on *Mobility* in production networks and its monetary evaluation, being the first to mention the relations between primary change enablers, however not analyzing these in detail. He states that one enabler can either support or require another if a bilateral relationship between the two exists. Other authors analyzing interdependencies are De Weck et al. [15], focusing on abilities of a system which they name “ilities”. These *ilities*, however, are more abstract and apply to systems in general, thus adding up to a total number of 15. Examples for these *ilities* are adaptability, robustness, flexibility, modifiability and versatility. Based on an internet and literature research, [15] develop a network of *ility*-relations applying the following logic: If two *ilities* are mentioned together in an internet article or web page, a relation is assumed. The number of hits is used to derive the importance of each relation. Thus, a hierarchical network is developed, showing the most inter-connected *ilities* in the middle and the supporting *ilities* on the periphery. This method gives an overview of co-occurrences in literature, it does not analyze cause and effect relations between change enablers, though.

### 2.3. Methods for modeling interdependencies

Current research provides a variety of methods for modeling interdependencies in systems. These can be subdivided into models with quantitative and qualitative relations between the elements of the system. Structural equation modelling, in which every relation is derived from correlating data representing the cause and the effect [18], is a typical representative of a quantitative method. Other quantitative methods are neural networks, as they need a data training set. Qualitative methods are Ishikawa diagram, Design Structure Matrix (DSM) and Fuzzy Cognitive Map (FCM).

The Ishikawa Diagram [19] is simple to develop but has limited functionality: Iterations cannot be modelled, there is only one effect influenced by a number of causes and the diagram is difficult to analyze systematically. The DSM is a tool from the field of structural complexity management which allows the user to model complex systems with a large number of elements as a matrix [20]. Manifold analysis (e.g. regarding criticality, activity and passivity of the elements) are possible. FCMs have initially been designed to model relationships which are hard to determine in a precise manner [21]. This is the case for interdependencies between change enablers: The relations are not measurable and experts’ judgments mostly underlie a certain fuzziness. Therefore, we

use an FCM to visualize and identify the cause and effect relations between the enablers and subsequently transform the FCM into a DSM for further analysis.

## 3. Research Methodology

With the aim of establishing a catalogue which contains a holistic overview of relevant change enablers for factory planning, at first an extensive literature review was conducted. Subsequently, we interviewed 18 industry experts from the field of factory planning in order to create an understanding of how changeable factories are designed in practice and which enablers play an important role here. Resulting from literature and expert interviews, a catalogue of 132 concrete change enablers with small degree of abstraction and a high degree of practical relevance was developed. These enablers then were categorized applying a bottom-up approach (ref. chapter 4.1).

To model the cause and effect relationships between these enablers, we developed a fuzzy cognitive map (ref. chapter 4.2). A survey tool was designed to validate the fuzzy relations proposed in the FCM within a second round of expert interviews (ref. chapter 4.3).

## 4. Identification, Categorization and Interdependencies of Change Enablers

### 4.1. Defining a Structured Catalogue of Change Enablers

One of the shortcomings of current literature is addressed in this section: We propose an approach to structuring change enablers according to their level of abstraction or generality (fig. 1). We call the highest level, which is most common in literature, primary enablers. This level comprises the 5 to 7 enablers defined in table 1. The second level contains so-called secondary enablers, which are created by assigning a primary enabler to a factory design field.

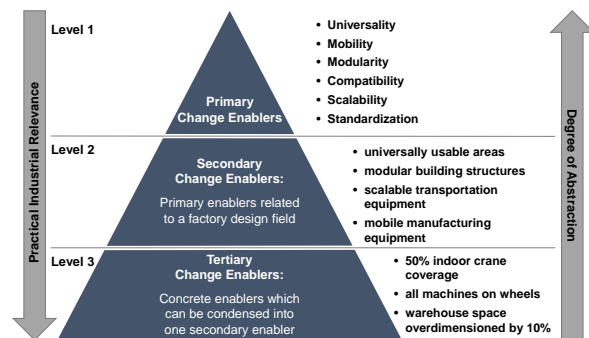


Fig. 1. Categorization of change enablers according to degree of abstraction

For instance combining the primary enabler *Mobility* with the factory design field *Manufacturing Equipment* results in the secondary enabler *Mobile Manufacturing Equipment*. This enabler can be further concretized as tertiary enablers within level 3. These enablers are often named in expert interviews

as practically realized measures occurring in industrial practice. 50% indoor crane coverage is an example which, together with other tertiary enablers like *machines on wheels* can be subsumed under the secondary change enabler *Mobile Manufacturing Equipment*.

The results from the literature review and the expert interviews concerning the identification of change enablers are shown in the schematic representation of the enabler catalogue in fig. 3. We structured the catalogue defining 5 factory design fields which include a number of secondary and tertiary enablers each (fig. 2).

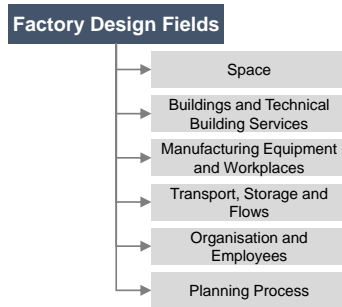


Fig. 2. Factory design fields defined to structure the catalogue of change enablers

Enabler Description	Level	Assigned Primary Enabler	Sources											
Space			I	J	HG	HE	W	NY	F	SW				
<b>universally usable areas</b>	2													
ground plate thick enough for all machines	3	Universality	x	x										
no pits, holes and special fundaments in the floor	3	Universality		x		x								
<b>scalable areas</b>	2													
machine areas are overdimensioned by 5%	3	Scalability	x											
machines are accessible from 3 sides for supply	3	Scalability												
<b>standardized areas</b>	2													
standardized	3	Standardization												
Manufacturing Equipment and Workplaces			I	J	HG	HE	W	NY	F	SW				
<b>mobility of machines</b>	2													
machines on wheels	3	Mobility	x											
ground anchor instead of special fundament	3	Mobility	x											
avoiding special fundaments	3	Mobility					x							
<b>compatible</b>	2													
Standardized clamping device for workpieces	3	Standardization									x			
using...	3	Modularity												

Sources:

I	Expert Interviews	W	Wiendahl 2009
J	Janorschke et al. 2009	NY	Nyhuis et al. 2008
HG	Heger 2007	F	Fink 2003
HE	Hernández Morales 2003	SW	Schenk et al. 2004

Fig. 3. Schematic excerpt from the change enabler catalogue

In fig. 3, an excerpt from the factory design fields *Space* and *Manufacturing Equipment and Workplaces* is shown as an example. In the first column, the enabler is described, while the second column shows the level of abstraction (ref. fig. 1). Each tertiary enabler can be assigned to at least one primary enabler which is named in column 3. All tertiary enabler assigned to the same primary enabler and the same factory design field can be consolidated to a secondary enabler. For example, all tertiary enablers enforcing the *Scalability* of the production layout and referring to the factory design field *Space* can be assigned to the secondary enabler *Scalable Areas* (ref. fig. 1). The source in which the enabler was identified is marked with an “x” in the column “Sources”, the key for the abbreviations can be found below fig. 3.

The catalogue developed provides a structured overview of change enablers for producing factories and is a vital prerequisite for further analyzing the interdependencies between tertiary enablers.

#### 4.2. Modelling the Enabler Interdependencies in a Fuzzy Cognitive Map

In order to model the interdependencies, first a DSM containing all 132 change enablers was created, resulting in a square matrix with 17,424 possible entries. Subsequently, we reviewed each of these entries with the aim of identifying directed relations between each tuple of enablers, applying fuzzy categories for weighting these relations as shown in fig. 4. Different forms of negative relations were defined: Two enablers are redundant if they have exactly the same effect and if realizing only one of them leads to the same result as implementing both in the factory. Construction effort is another cause for a negative relation. For example, a high *indoor crane coverage* is difficult to realize constructively if

Meaning			
	Redundance	Construction Effort	Limiting Effects
--	enablers are redundant	constructive realization of both enablers extremely difficult	effect of one enabler is eliminated by another
--	enablers are partly redundant	high constructive effort for realizing both enablers	effect of one enabler is strongly limited by another
-	enablers are partly redundant but influence each other positively	constructive effort for both enablers slightly higher than for only one enabler	effect of one enabler is weakened by another
+++	one enabler significantly enhances the effect of another (perfect synergy)		
++	one enabler enhances the effect of another		
+	one enabler potentially enhances the effect of another		

Fig. 4. Weighting scheme for fuzzy relations between change enablers

the distance between supporting pillars is greater than 30 meters. The weakening influence of one enabler on the effect of another is the third form of a negative relation. Realizing a pair of negatively related enablers always leads to a rising invest. Positive effects between enablers are not subdivided and cover perfect synergy, meaning that one enabler significantly enhances the effect of another, until potential enhancement.

Applying these fuzzy weights for evaluating the interdependencies between change enablers, an FCM can be drawn. An excerpt from this FCM is presented in fig. 5. This schematic representation does not include every identified relation in favor of better comprehensibility. Its aim is rather to illustrate the fundamental idea behind the developed model. An example for a strongly positive relation is the influence of removability of floor signalling on transformability of assembly into logistics space and vice versa. Realizing technical building services via roof support structure constructively collides with an indoor crane which is the reason for this negative relation between the two enablers. According to fig. 2, the enablers shown in this example are assigned to 4 factory design fields framed by dashed lines. Intracategorical edges relating enablers in the same design field can be distinguished from intercategory relations connecting enablers from different fields. There are three types of elements in this FCM: An element, which influences other elements only, without being influenced itself, is called initial node, while an element which is only influenced by others is called end node. If an element is linked to others by inbound and outbound edges, we call it embedded node (fig. 5).

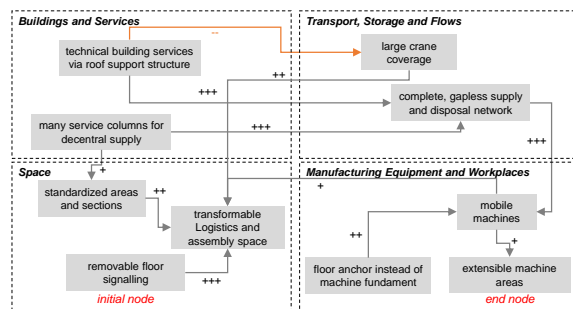


Fig. 5. Schematic excerpt from the FCM of change enabler interdependencies

4.3. Validating Fuzzy Relations between Change Enablers

Whereas the example presented in fig. 5 is rather simple, the entire FCM containing all 132 enablers with a total of 318 identified edges is far more complex. Hence, the challenge was to validate the assumed relations methodically. Validating all 318 relations in one expert interview or even extended workshop is extremely time consuming. This is why the subdivision of the whole network into factory design fields is of importance: Different expert groups were chosen and each group was assigned to one factory design field with the included relations according to the expert group’s specific

area of competence. For instance, general planners and architects were grouped together and with their help the enabler relations within the factory design field buildings and technical building services were validated. To conduct the expert interviews, we developed a survey-tool (fig. 6). The experts were asked to evaluate the effect of the first enabler (column 1) onto the second (column 3) applying the weighting scheme provided in fig. 4. The experts were also asked to critically assess the existence of the proposed relation and add further missing ones if necessary.

The tool provides a further column (4) to state if an expert’s judgement was uncertain and to evaluate the effect of an enabler on initial investment (column 5). Some of the identified enablers were thereby identified as theoretically realizable but precaution has to be paid to the negative effect on the planned investment.

Survey-Tool for Validating Enabler Relations				
Causal Enabler (influences)	effect weight	Effected Enabler (is influenced)	Further Notes	
			Uncertainty	Effect on Invest
large crane coverage	++	transformable logistics and assembly space		-
technical building services via roof support structure	--	large crane coverage		
technical building services via roof support structure	+++	complete, gapless supply and disposal network		
complete, gapless supply and disposal network	+++	mobile machines		
many service columns for decentral supply	+++	complete, gapless supply and disposal network		-
many service columns for decentral supply	+	standardized areas and sections	-	
		extensible		

Fig. 6. Survey-tool for the validation of fuzzy relations between change enablers

Applying the survey-tool designed for this purpose, we validated the FCM of change enablers and their interdependencies. With this result, factory planners are now able to estimate, how well an interplay of certain enabler combinations will counteract the negative effects of fuzzy planning premises. In addition, the existing change enablers of a brownfield factory can be modeled with this method and suitable additional enablers can be systematically chosen to meaningfully complement the already existing factory system.

5. Research Directions and Conclusion

In this paper, the existing research on change enablers and their interdependencies was reviewed and a comprehensive catalogue of change enablers developed. The catalogue is

structured according to a scheme focusing on the level of abstraction. With the aim of providing practitioners in the field of factory planning with a tool for estimating useful enabler combinations, we designed an FCM modeling enabler interdependencies. The enablers in this FCM are tertiary enablers with a low degree of abstraction and high concreteness. Subsequently, the cause and effect network of change enablers was validated by applying a survey-tool in expert interviews.

Further research should aim at fully exploiting the potential of the developed FCM by integrating it into a software tool. The tool with the aim of simulating different scenarios of enabler combinations could enhance industrial applicability by providing a function that automatically creates a DSM from the FCM and vice versa as well as a graphical user interface. This FCM-based simulation model will empower the factory planner to proactively select a set of enablers that influence each other positively and thus allow for a cost-efficient design of changeable factory layouts in early planning stages.

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