Mobile On-site Factories – scalable and distributed manufacturing systems for the construction industry

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***Abstract*—The concept of the "On-site Factory" consists in the temporary use of fully functioning mobile mini-factories or production cells at the site of consumption. This concept of a Mobile Factory is well suitable for situations in the construction industry with long distances and therefore high logistics costs. The advantage of this concept is not only the proximity to customers, but also the economic efficiency combined with a maximum of flexibility. By a high degree of reconfigurability and scalability of the On-site Factory, it can also be adapted to its individual mission and the quantity demand at the construction site. This paper presents the current state of research in the area of distributed manufacturing as well as on-site and off-site manufacturing. It discusses the need for new and innovative JIT solutions for construction industry and addresses the specific requirements for scalable and reconfigurable on-site manufacturing factories. The main content of this research paper consists in the definition of generally applicable Design Parameters for On-site Factories using Axiomatic Design as a methodology for the analysis of functional requirements and the related design solutions. Through practical examples and illustrations, the application of the deduced Design Parameters will be explained.**

Keywords— Distributed manufacturing systems (DMS); axiomatic design; mobile factory; lean construction; scalability

I. Introduction

In order to satisfy the growing demands from ecological, economic-functional, and organizational points of view, enterprises, future-compliant concepts and solutions for sustainable buildings are needed. The goal is to provide better cost efficiency and shorter construction times, while enhancing the construction quality. Consequently, processes and technologies to carry out the construction of sustainable buildings in an efficient and economical way must also be developed [1].

Today many Construction and Engineer-to-Order (ETO) companies are under pressure to reduce their costs while minimizing the completion time on site. Companies have worked in recent years to industrialize their manufacturing processes and to introduce prefabrication by standardization and modularization of their products. Manufacturing should be driven according to the demand needed on the building site. In construction supply chains the installation on-site stands for the consuming process (customer). Finished parts should be delivered to the construction site Just in Time (JIT) with short lead times and low stocks on-site. This requires a synchronous production for both, the construction site and the supplier fabrication shop. Supplier lead times are very often longer than the possible accurate foresight regarding on-site installation. Thus, JIT deliveries of components are usually only possible through high buffer stocks at the supplier fabrication shop or at the construction site [2].

Prefabrication should be “pulled” according to the construction progress. In usual construction supply chains, manufacturing and prefabrication processes are disconnected from the installation on-site and scale effects of large batch production and economics of transportation charges determine the assembly sequence on site. [3]. Construction is a different type of production than manufacturing and has greater uncertainty and flow variation. Furthermore, construction is schedule driven. Given a well-structured schedule, if everyone stays on their part of the schedule, the work flows smoothly and maximum performance is achieved. Business conditions change, deliveries slip, a design requires correction, etc., and therefore it is rare that projects perform precisely to their original schedule. The JIT ideal is elimination of buffers (materials or time) and the achievement of one piece flow [4].

Increasing market dynamics require manufacturing systems to become even more flexible [5]. In the future, long-established paradigms of production will continue to change in order to meet the demand for even more individuality, customer-specific product variants and shortest delivery times within the meaning of the term "production on demand" [6]. Particularly due to the increasingly loud request for JIT deliveries as well as sustainable and ecologically delivery processes, decentralized and mobile manufacturing systems are an ideal approach, because the production takes place at the point of consumption. It needs modern organizational models for small, flexible and scalable production units in decentralized production networks, which produce as possible locally in mini and micro production systems. The main advantages of such decentralized production structures are a higher flexibility to react at individual requirements as well as lower logistics costs and shorter delivery times due to their proximity to the successor or consumer.

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II. Literature Review

A. On-site and off-site fabrication

The construction industry is struggling with problems, such as low quality and increasing costs in comparison to the consumer price index. In comparison to the manufacturing industry both the productivity development and the technical development are lower [2, 7]. Crisis, spin up in 2008–2009, had differently affected the construction industry markets of the European Union countries. The general part of countries had faced a decrease of outputs, real estate transactions, and predictable reduction in employment and quantity of construction companies [8].

Construction is originally an on-site production: Construction corresponds to site position manufacturing and assembly as opposed to factory position manufacturing in which the product has to be moved to the construction site [9, 10]. Nowadays in construction, we can differentiate generally between manufacturing and assembly operations executed on-site or off-site. The work on-site requires different kind of resources. These resources have also to flow to and within the construction site. Very often there is a discontinuous work-flow on-site and this results in low productivity on-site. Construction workers are not always provided with the required conditions needed to keep the work going and are often forced to, if possible, switch to another task or have to get the prerequisites in place. Construction workers can not be productive when required to switch between activities or execute multiple activities at the same time, working under suboptimal work space conditions etc. [7].

The incorporation of off-site manufacturing in the construction process consists usually in a pre-assembly or prefabrication of components installed at the construction site. In recent years, especially the principles of industrialization in construction through prefabrication of factory-finished elements have gained more and more acceptance in the construction sector [11]. Prefabrication of modular elements increased and led to a higher impact of work in the manufacturing hall of Engineer-to-Order companies [12]. The benefits attributed to off-site fabrication are numerous and well documented [13, 14, 15]:

- Less time on site – speed in construction through more efficiency in installation
- Less time spent on commissioning and material preparation
- Higher quality through industrial work conditions and machinery in the off-site fabrication shop
- Improved working conditions in manufacturing of prefabricated parts (e.g. weather conditions on-site and safety risk on-site)
- More reproducibility of components off site
- Less on-site damage
- Less site disruptions and therefore higher productivity
- Fewer people and fewer machinery/tools on site.

However, there are some limitations and disadvantages of an off-site prefabrication [2, 15, 16]:

- Prefabricated items will have a lead in time and this must be built into the construction process from the beginning
- Thought must also be given to the arrival of the pre-assembled item on site
- Parts may need to be adjusted on site (for complex parts and uncertain tolerances on-site)
- Break in the supply chain through the transport from fabrication shop to the installation site
- Thereby increasing organizational and planning effort for material logistics
- JIT delivery could not always be guaranteed or only through buffer stocks at the fabrication shop or on-site.

B. JIT supply at the construction site

Just in Time (JIT) is a method well known from Lean Management developed by Taichi Ohno, producing small lot sizes at the point of demand [17]. JIT is a technique of pulling work forward from one process to the next "just-in-time"; i.e. when the successor process needs it, ultimately producing throughput [4]. Just in Time in construction is also known for the delivery of materials to a construction site, suggests that materials will be brought to their location for final installation and be installed immediately upon arrival without incurring any delay due to storage in a laydown or staging area. The ultimate objective of JIT production is to supply the right materials at the right time and in the right amount at every step in the process [18]. Benefits of JIT are reduced work-in-process inventory, reduced working capital and shorter production cycle times, since materials spend less time sitting in queues waiting to be processed [4]. Studies of logistics show that a substantial increase in productivity can be obtained by delivering building materials on conditions laid down by the construction site, i.e. 'just in time' and 'packed for the work process [19].

At the construction site JIT for supplier deliveries is not always easy [2]. Large schedule buffers between suppliers and construction may shield the contractor from the impact of late deliveries, but shielding is expensive [16]. The realization of JIT in construction through improving the synchronization of off-site manufacturing and on-site installation is actually highly discussed in research [2, 3, 13, 18, 20].

Nevertheless, it is also important to extend research activities for other innovative solutions where the benefits of off-site fabrication can be combined with those of on-site fabrication. Mobile and scalable mini-factories play a major role to reach this goal. Through these type of “mobile On-site Factories” components can be produced Just in Time in an industrial environment and process at the point of consumption. Therefore, the following section shows an overview of existing types of Distributed Manufacturing Systems (DMS) factories and goes into detail on mobile On-site Factories.

C. *Distributed Manufacturing Systems (DMS)*

Regarding the study "Manufacturing work of the Future", executed by the Fraunhofer IAO we recognize a shift away from mass production to individual production and micro production [21]. We need modern organizational models for small, flexible and scalable manufacturing units to fulfill actual requirements such as just in time delivery and individual customer needs or a sustainable supply chain [6]. This trend towards a so-called "glocal" production thus combines the goals of global market development and the fulfillment of local customer requirements [22]. Geographically independent or distributed production facilities composed of reconfigurable and mobile production systems allow these quick adjustments of production capacity and functionality with respect to local customer needs [23].

The following are the key trends and reasons for the development towards Distributed Manufacturing Systems [6]:

1. Megatrend Sustainability – reduction of transport and therefore CO2 emissions
2. Rising logistics costs – reduce physical transports
3. Individuality and mass customization – individual products
4. Democratization of Design and Open Innovation – Involvement of the customer in product development
5. Proximity to the market and point of consumption – JIT delivery and shorter delivery times
6. Production at the place of critical resources – e.g. raw materials or highly qualified human resources
7. (Regionalism and authenticity – in special cases like "Authentic Food").

Manufacturing systems are changing dramatically by the increased use of information and communications technology. Companies will be able to control their production decentralized and are thereby now able to coordinate distributed manufacturing networks [24].

The concept of Distributed Manufacturing includes many possible forms for their design. Figure 1 [6] summarizes existing forms of decentralizing production. A distinction is made between the decentralized model factories with their individual stages of evolution and possible special forms of Distributed Manufacturing. One of the mentioned special forms of Distributed Manufacturing Systems fits to realize Just in Time also in construction:

Type 6: Mobile and non-location-bound On-site Factories.

III. MOBILE AND NON-LOCATION BOUND MINI-FACTORIES FOR ON-SITE JIT SUPPLY

A. *Concept of mobile On-site Factories*

Several authors [6, 25, 26, 27, 28, 29, 30] recommend On-site Factories, as combination of advanced manufacturing in micro-factories and industrial construction on site. The "factory on-site" consists in the temporary use of fully functioning mobile mini-factories or mobile production cells at the site of need or consumption. Through a highly flexible as well as scalable design they can be very well suitable for different temporary manufacturing requirements reducing transport costs and delivery time. Particularly, this concept of a mobile factory is well suitable for situations with long distances and therefore high logistics costs like fabrication of components on the construction site.

Evolution stages of distributed model factories			Special forms of decentralized production		
Type	**Classification**	**Description and characteristics**	**Type**	**Classification**	**Description and characteristics**
1	**Standardized and replicable model factory**	Replicable and standardized model factories for geographically distributed production of defined products with a defined number of units.	**5**	**Service model of industrial contract manufacturing**	Production service providers and intermediaries ("Production Provider") for distributed industrial contract manufacturing of different products with similar manufacturing steps and varying quantities on behalf of diverse clients.
2	**Modular and scalable model factory**	Modular model factories for geographically distributed production of defined products with flexibility in relation to item quantity and thus scalability of the manufacturing system.	**6**	**Mobile and non-location-bound model factories**	Mobile non-location-bound and highly flexible as well as scalable model factories for temporary production requirements reducing procurement and/or distribution transports.
3	**Flexible und reconfigurable model factory**	Flexible and rapidly reconfigurable model factories for geographically distributed manufacturing of products in different variants (product flexibility) and various quantities (quantity flexibility).	**7**	**Production-Franchise**	Model factories, operated independently by franchisees, with more or less flexible and adaptable production units for geographically distributed production of products in a franchise network.
4	**Changeable and „smart" model factory**	Intelligent and self-optimizing model factories with a high degree of adaptability to geographically distributed production of different products with similar manufacturing steps and varying quantities.	**8**	**Additive manufacturing in production laboratories (Cloud Production)**	Highly flexible and geographically capillary distributed laboratories for the production of various products with generative manufacturing processes (3D printing) by means of digital transmitted CAD data from the "Cloud".

Fig. 1. Forms of Distributed Manufacturing Systems (DMS) [6]

On-site Factories or Field Factories bring efficient manufacturing and pre-assembly operations to building sites, providing safe and clean working environments, and drastically reducing the number of transport kilometers between the factory and the building site [30]. The basic activities in on-site-factories are preparation of material, machining, assembly and finishing [30].

Figure 2 shows the basic concept of mobile On-site Factories compared to off-site manufacturing and a traditional on-site fabrication.

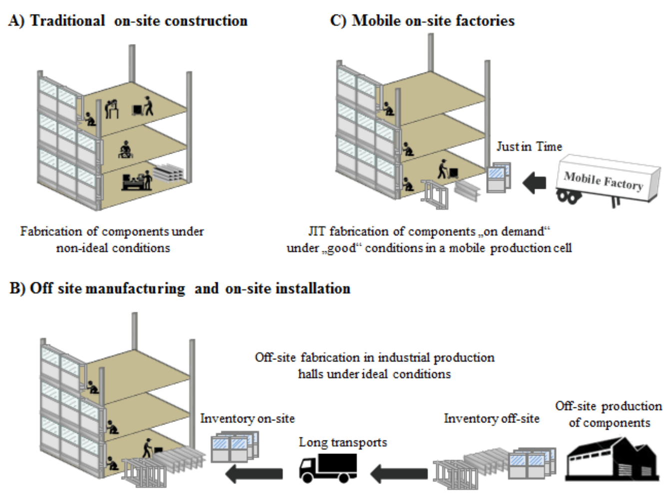

Fig. 2. Concept of mobile On-site Factories

B. *Practical reasons for the application of On-site Factories*

In the construction industry On-site Factories have already been used very early. They were used particularly on large construction sites, which allowed it to make investments realizing own manufacturing systems and On-site Factories for extensive construction sites. An example shows the realization of the Tokyo Sky Tree using the Automated Building Construction System (ABCS) developed in the 1980s. It was designed to automate on-site assembly operations to a high degree by installing an On-site Factory, with automated logistics, automated column and beam positioning, automated welding and real-time process control [31].

The application of On-site Factories is particularly useful in the following cases:

- Long distances between construction site and off-site manufacturing
- Logistically rational shortening of the supply chain (reduction of transports to distant suppliers)
- High uncertainty in material and component deliveries
- Difficult or impossible transport of large or heavy components or building modules
- Complexity of parts due to the need to adapt them
- No space for material inventory on the construction site and therefore "production on demand"
- High necessity of punctual JIT delivery of parts to avoid delays in the construction process
- Unpredictable building progress (caused by changing weather conditions or else) and therefore difficult planning of JIT-deliveries.

As part of the research, several interviews were conducted with companies in the construction sector. A case recorded shows a practical example of a useful application of on-site production cells to shorten the supply chain: The interviewed company is a middle sized Italian Engineer-to-order company producing steel facades for design buildings. The company applied the concept of on-site production cells in a project in UK. The architectural design for certain façade elements demanded a special bending process. This work was outsourced to a specialized company in Scotland. To avoid long transports due to bending in Scotland, machining and pre-assembly in Italy and finally installation in UK a small production cell was developed and installed at the construction site. Through this production on-site the company reduced the supply chain avoiding the transport from UK to the company headquarter in Italy.

IV. Design of Mobile, Scalable and Reconfigurable On-site Factories

A. *Axiomatic Design as methodology for manufacturing systems design*

In this section will be explained an Axiomatic Design (AD) based approach to identify the Functional Requirements and Design Parameters for mobile, scalable as well as reconfigurable On-site Factories. The Axiomatic Design methodology was developed by Nam P. Suh in the mid-1970s with the aim to create a scientific, generalized, codified, and systematic procedure for design. In order to systematize the thought process and to create demarcation lines between various design activities, four domains represent the foundation of Axiomatic Design procedure: the customer domain, the functional domain, the physical domain and the process domain [32]. The Customer Domain contains the so called customer-benefit attributes (CAs; Customer Attributes), the Function Domain contains the deduced Functional Requirements (FRs), the Design Domain provides Design Parameters (DPs) for the consequent implementation of the FRs, whose transformation into processes shall be regulated by the Process Variables (PVs) in the Process Domain [33]. The AD approach was firstly introduced in product development. Later the AD methodology was applied also in other fields and shows today an established instrument for the design of manufacturing systems [34, 35, 36].

The designer is guided by two fundamental axioms moving between the domains. The axioms helps for evaluating and selecting designs in order to produce a robust design [33, 35]:

Axiom 1: The Independence Axiom. Maintain the independence of Functional Requirements. The Independence Axiom states that when there are two or more FRs, the design solution must be such that each one of the FRs can be satisfied without affecting the other FRs.

Axiom 2: The Information Axiom. Minimize the information content of the design. The Information Axiom is defined in terms of the probability of successfully achieving FRs or DPs. It states that the design with the least amount of information is the best to achieve the functional requirements of the design.

The FRs and DPs are described in AD mathematically as a vector. The Design Matrix [DM] describes the relationship between FRs and DPs in a mathematical equation [33]:

$$\{FR\} = [DM]\{DP\} \tag{1}$$

An ideal and robust design solution is given by a diagonal and uncoupled Design Matrix (see (2)) when the number of FRs and DPs is equal (Axiom 1) and the information content is zero (Axiom 2) [33].

$$\begin{Bmatrix} FR1 \\ FR2 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ 0 & x \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \end{Bmatrix} \tag{2}$$

When the matrix is triangular, the independence of FRs can be achieved only if the DPs are determined by a certain sequence. In this case the Design Matrix is called decoupled. Any other form of the design matrix is called a full matrix and results in a coupled design [32, 33].

B. First level Customer Attributes (CA), Functional Requirements (FR) and Design Parameters (DP)

The definition of the first level Functional Requirements requires a careful analysis of the related customer needs (also Customer Attributes CAs). The translation of the CAs into FRs is very important and difficult at the same time, as the quality of the further design level directly depends on the correctness of the chosen CAs.

According to the introductive considerations in section III the following four basic CAs for the design of On-site Factories can be identified:

- CA1 Maximize operational capability and efficiency
- CA2 Minimize effort for assembling, disassembling and adaptation of On-site Factories
- CA3 Minimize rigidity of on-site manufacturing
- CA4 Minimize dependency from site-conditions

Inspired by this definition of customer needs the following generally applicable FRs for mobile, scalable and reconfigurable On-site Factories can be derived as follows:

- FR1 Industrialized and efficient manufacturing
- FR2 Reconfigurability and scalability of the On-site Factory
- FR3 Mobility of the On-site Factory
- FR4 Autonomy of the On-site Factory

The above defined FRs can be solved with the following set of Design Parameters (DPs):

- DP1 Industrial processes and environment
- DP2 Use of flexible production modules
- DP3 Mobile and easy transportable factory design
- DP4 Autonomous supply and operation

The design matrix provides a decoupled design (triangular design matrix) as shown in the following equation:

$$\begin{Bmatrix} FR1 \\ FR2 \\ FR3 \\ FR4 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 & 0 \\ x & x & 0 & 0 \\ 0 & x & x & 0 \\ 0 & 0 & 0 & x \end{bmatrix} \begin{Bmatrix} DP1 \\ DP2 \\ DP3 \\ DP4 \end{Bmatrix} \tag{3}$$

The above shown first level Design Parameters are still generally and not tangible enough to be helpful for the design of On-site Factories. Therefore, they need to be decomposed further. The decomposition of the first level of FRs and DPs is done in parallel by “zigzagging” between the single FRs and DPs [34].

C. FRs and DPs for the design of “industrialized and efficient” On-site Factories (FR/DP-1)

FR1 and DP1 (“Industrial processes and environment”) could be decomposed in the following FRs and DPs at a second level:

- FR11 Integration of usual manufacturing tasks
- FR12 Integration of Advanced Manufacturing processes
- FR13 Efficient as well as organized environment

The Design Parameters to satisfy the second level of above FRs are the following:

- DP11 Standard machining and assembly stations
- DP12 (Semi-)automated machining or assembling as well as use of robot cells
- DP13 Ergonomic and “lean” industrial workplace design

The design matrix of FR/DP-1 shows the dependencies between the deduced DPs and every FR. The matrix has a decoupled design (triangular design matrix), thus, the implementation of the Design Parameters have to follow a certain sequence:

$$\begin{Bmatrix} FR11 \\ FR12 \\ FR13 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 \\ x & x & 0 \\ x & x & x \end{bmatrix} \begin{Bmatrix} DP11 \\ DP12 \\ DP13 \end{Bmatrix} \tag{4}$$

Figure 3 illustrates the conceptual implementation and application of the above shown Design Parameters in On-site Factories at the construction site. DP11 and DP12 aim to integrate the most common and used machining and assembly processes like: cutting, drilling, bending, riveting, welding, manual assembly as well as automated or semi-automated machining and assembly processes (small machining centers, linear motion systems and robot cells). DP13 calls for ergonomically designed workstations and a lean and efficient material flow according to the “Lean”-principle.

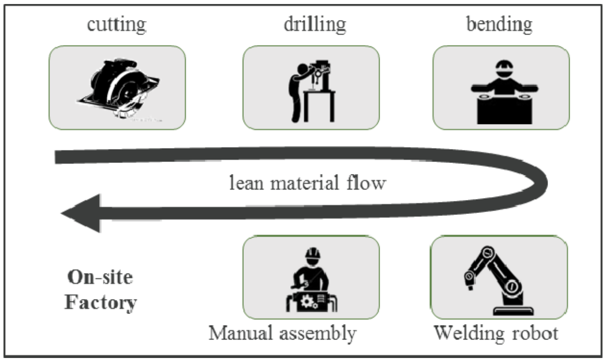

Fig. 3. FR/DP-1: Industrialized and efficient processes

D. *FRs and DPs for the design of “reconfigurable and scalable” On-site Factories (FR/DP-2)*

Considering FR2 and DP2 (“Reconfigurability and scalability”) we can decompose the following second level of FRs and DPs:

FR21 Reconfigurability of the On-site Factory

FR22 Scalability as a function of the amount of demand

The Design Parameters to satisfy the second level of above FRs are the following:

DP21 Universally and compatible standard production modules (e.g. standard module and standard interfaces)

DP22 Amount and performance of standard modules depending on quantity demand

The design matrix of FR/DP-2 shows the dependencies between the deduced DPs and every FR:

$$\begin{Bmatrix} FR11 \\ FR22 \end{Bmatrix} = \begin{bmatrix} x & 0 \\ x & x \end{bmatrix} \begin{Bmatrix} DP11 \\ DP22 \end{Bmatrix} \quad (5)$$

Figure 4 shows how scalability and reconfigurability of On-site Factories could be implemented. Scalability is requested to cover different quantity demand at the construction site. To adapt the manufacturing system to the actual demand of quantity different solutions are reasonable:

- Increase performance of standard modules or the size of machines
- Increase amount of modules or machines

In the case of so called “Container Factories” this could be achieved through flexible designed containers. In a first step one container could be sufficient. When demand of components increases a scalable extension of the On-site Factory is realized through more containers inclosing more machining or assembly modules. To be reconfigurable the single stations have to be compatible between each other and to their environment. Therefore standard interfaces for material transport, for energy supply and for information transport have to be defined.

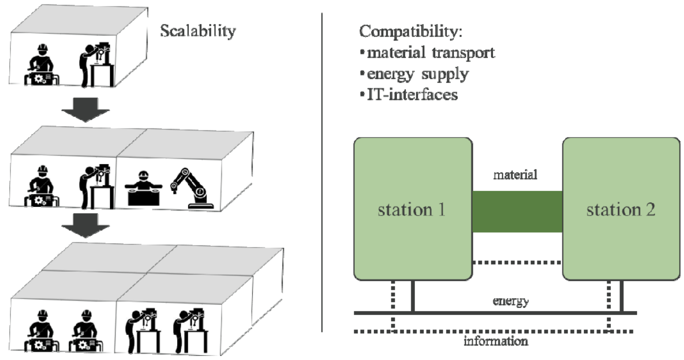

Fig. 4. FR/DP-2: Reconfigurability and scalability of On-site Factories

E. *FRs and DPs for the design of “mobile” On-site Factories (FR/DP-3)*

Looking at FR3 and DP3 (“Mobility”) we can deduce the following FRs and DPs at a second level:

FR31 Mobility of the single components/machines in the manufacturing system

FR32 Mobility of the entire manufacturing system (transport from site to site)

FR33 Mobility of the entire manufacturing system on the building project

The Design Parameters to satisfy the second level of above FRs are the following:

DP31 Mobile production equipment (e.g. drilling machine “on wheels”)

DP32 Mobile factory in a container (20ft/40ft ISO-container or construction containers)

DP33 On-site Factory, that moves together with the “growing” building. $\alpha + \beta = \chi$. (1) (1)

The design matrix of FR/DP-3 shows the dependencies between the deduced DPs and every FR:

$$\begin{Bmatrix} FR31 \\ FR32 \\ FR33 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 \\ 0 & x & 0 \\ x & x & x \end{bmatrix} \begin{Bmatrix} DP31 \\ DP32 \\ DP33 \end{Bmatrix} \quad (6)$$

Considering this Design Parameters, On-site Factories can be positioned in different ways or a combination of them at the construction site (Fig. 5):

- In temporarily rented production halls next to the construction site with mobile production equipment
- At the construction site itself through entirely mobile factory structures (e.g. container factory)
- On the “growing” building object (e.g. production cells on the top of a building)

In all of the shown evolution grades of On-site Factories in Fig. 3 the mobility of manufacturing equipment is an important argument for a flexible use of the On-site Factory. An example of a mobile On-site Factory that moves together with the building object is the SMAT system developed by Shimizu [31] – a full-robotic factory on the top of the building used for construction of more than 30 stories office building. The lift-up mechanism automatically raises the construction plant and at the same time raises the On-site Factory (called also "field factory").

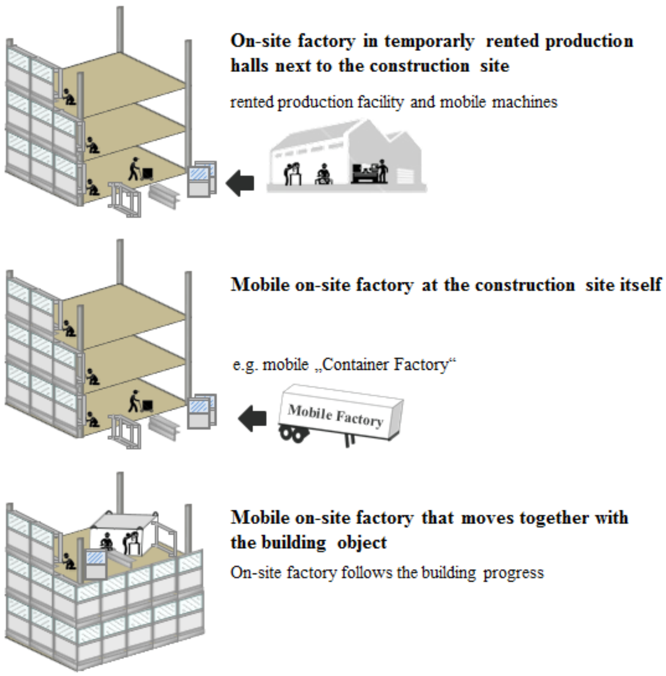

Fig. 5. FR/DP-3: Levels of mobility of On-site Factories

F. FRs and DPs for the design of "autonomous" On-site Factories (FR/DP-4)

Looking at FR4 and DP4 ("Autonomy") we can deduce the following FRs and DPs at a second level:

FR41 Autonomy from weather conditions

FR42 Autonomy of material handling (e.g. to be independent from the construction site crane)

FR43 Autonomy of energy supply (to be independent from

The Design Parameters to satisfy the second level of above FRs are the following:

DP41 Enclosure with its own temperature control (heating)

DP42 Standard modules for material handling

DP43 Standard modules for energy generation (e.g. power generator, compressed air, oil pressure)

The design matrix of FR/DP-4 shows the dependencies between the deduced DPs and every FR:

$$\begin{Bmatrix} FR41 \\ FR42 \\ FR43 \end{Bmatrix} = \begin{bmatrix} x & 0 & 0 \\ x & x & 0 \\ x & x & x \end{bmatrix} \begin{Bmatrix} DP41 \\ DP42 \\ DP'43 \end{Bmatrix} \tag{7}$$

In Figure 6 are shown different examples of suitable and autonomous material handling systems for On-site Factories. The material handling systems are necessary primarily for the handling of raw materials, for the movement of parts between stations as well as for the handling of the finished parts from the On-site Factory to the construction site. In the figure is illustrated an example of a mobile factory consisting of a mobile container on a truck trailer. Raw materials as well as finished goods are moved on the trailer by an overhead travelling crane with telescope system. Through flexible material trolleys the finished goods are positioned at the construction site. In this way material can be handled autonomously without waiting times for the construction site crane.

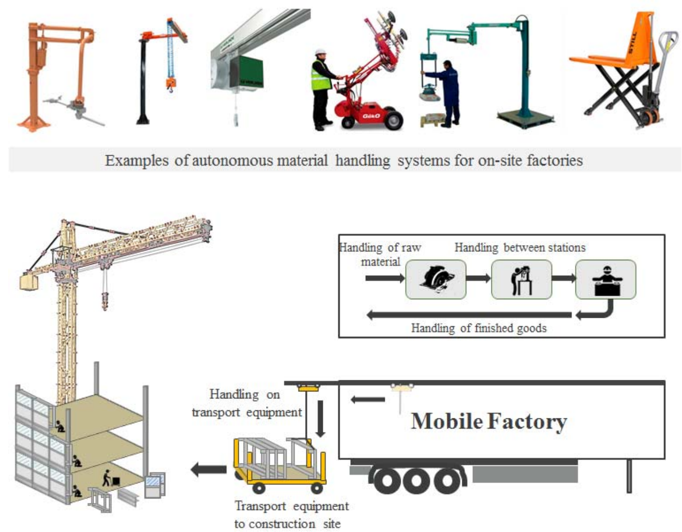

Fig. 6. FR/DP-4: Autonomy in supply and operation of On-site Factories

G. Design Matrix and FR/DP-tree

The shown application of the Axiomatic Design methodology helped to individuate the Design Parameters for an On-site Factory. In this research the AD approach was applied with the software Acclaro DFSS, which is a special instrument for robust design and risk mitigation during the requirements analysis phase. The single steps of the AD approach are summarized in Fig. 7. In a first step (a) the top-down mapping and decomposition process of Functional Requirements (FR) and the related Design Parameters (DP) has been done using the software Acclaro DFSS. In a second step (b) the software helped the manufacturing system designer to illustrate and define the Design Matrix for analyzing dependencies between single DPs and single FRs. The single level Design Matrices as well as the complete Design Matrix are decoupled. The software signalizes these dependencies through a blue color, while a full-coupled design is represented in red. If the design matrix shows a coupled design, the FRs and DPs must be revised until an uncoupled or at least a decoupled design is achieved. In this way, the manufacturing system design is revised until a suitable and less complex design could be identified. A decoupled design satisfies the Independence Axiom if the design sequence is correct. This means, that in the presence of a decoupled matrix, the correct path is necessarily, because DPs are affecting more than one FR. In the last step (c) the software supports a top-down visualization of Functional Requirements and Design Parameters of different levels in the FR-DP-tree. The sequence for implementing the Design Parameters is given in the FR-DP-tree reading the lowest level DPs from left to right. Interested readers are referred to [36] and [38] for more detailed information about the AD based template approach for manufacturing system design.

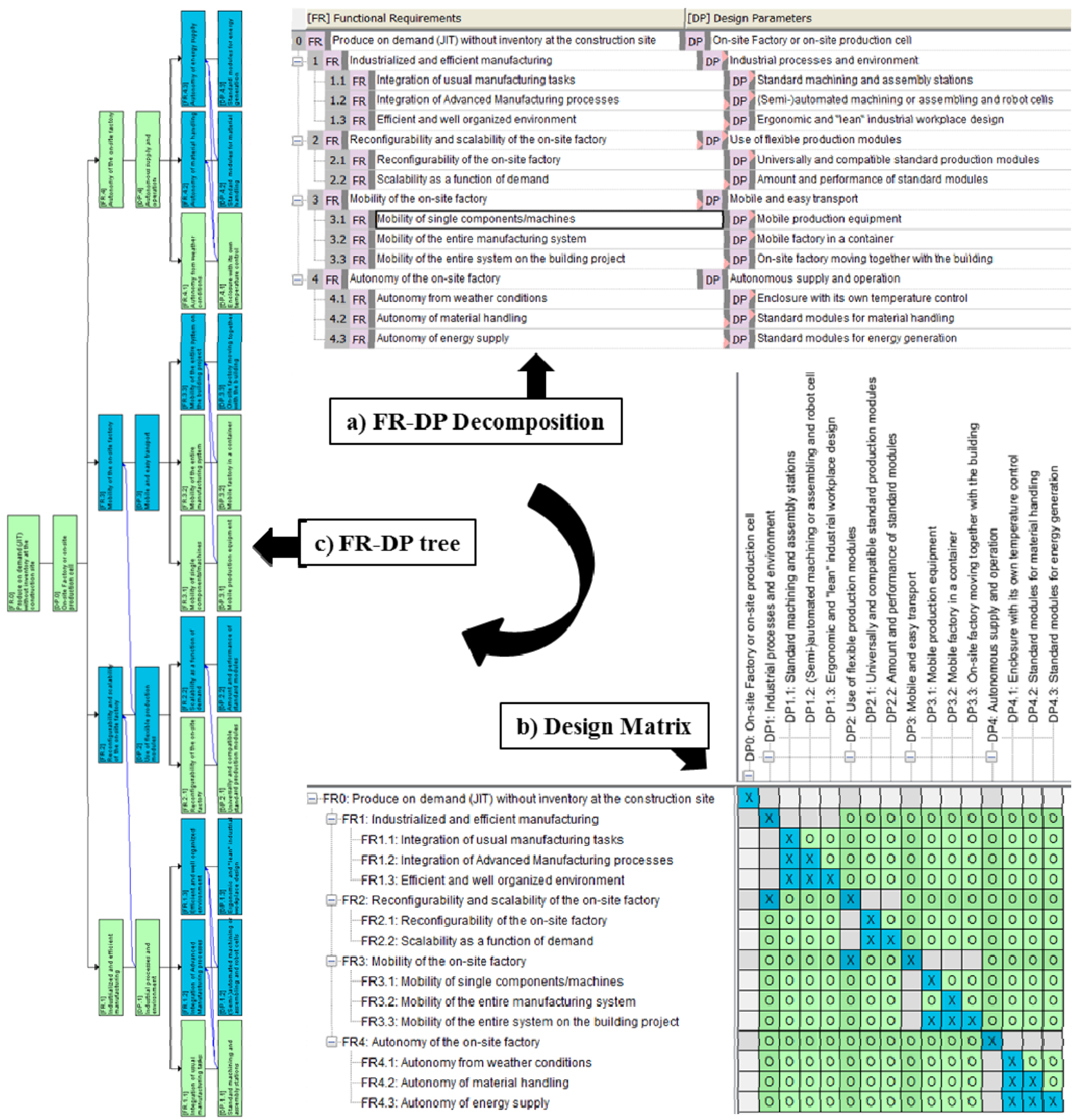

Fig. 7. Axiomatic Design Process for the derivation of Design Parameters in the design of On-site Factories: a) FR/DP Decomposition, b) Design Matrix for the analysis of dependencies between DPs and single FRs, c) Top-down visualization of Design Parameters in the FR-DP-tree (used software: Acclaro DFSS)

V. CONCLUSION AND OUTLOOK

The literature review has demonstrated that just in time delivery of the material on the construction site is becoming increasingly important. However, JIT deliveries are often difficult to realize and are usually associated with inventory at the fabrication shop or at the construction site. Therefore, this paper presents the concept of mobile on-site factories as a possible solution. Through mobile and industrialized production cells, both lead-time as well as inventory can be reduced. The main result of this paper is given by deducing a set of generally applicable Design Parameters for On-site Factories using Axiomatic Design as methodology. This Design Parameters can be summarized as follows:

- DP1 Industrial processes and environment
- DP2 Use of flexible production modules
- DP3 Mobile and easy transportable factory design
- DP4 Autonomous supply and operation.

Through the systematical top-down decomposition of Functional Requirements in several levels, more concrete Design Parameters could be deduced. Parallel to this the analysis of dependencies between FRs and DPs and an iterative revision of the design leads to a reduction of the complexity of the manufacturing system design. Further research will follow now, designing and implementing a prototype of a mobile On-site Factory in collaboration with industrial partners and associations.

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