P1102

Integration along the Value Chain in Construction through Robot Oriented 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. Therefore, complementary robot oriented management has to address all value-added steps from off-site fabrication, ERP Logistics, on/off-site combined management, automated on-site assembly, construction robotics to service robotics, automated deconstruction and remanufacturing. The present paper first analyzes best-practice industrialization/automation and Mass Customization projects, which have been tested or applied successfully in larger scales during the last decades. The 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 or value system. Through industrialization and complementary Robot Oriented Management, construction industry would be able to simultaneously address multiple parameters relevant for sustainable economic, environmental and social development. The paper shows, that integrating and managing the advantages of the analyzed best practice examples allows for closed and controlled chains concerning technology, processes, resources and information flow and value creation. Further, Robot Oriented Management would not only be limited to building fabrication but also link systems of controlled deconstruction, component reuse and re-customization to a network for continuous and industrially organized resource circulation.

Key words: Robotics, Value Chain, Construction Management, Closed Loop

1. INTRODUCTION

As in any other industry value creation in construction is a complex process. It starts long before the “design” or “architecture” is fixed and generally ends 60-80 years after the “product” building has been set up and brought into operation. Buildings have an extremely long life cycle and the value which is captured through this long cycle is the reason why development is done, architecture can be set up and finally the building can be constructed. Even the building’s deconstruction plays a role in this process as deconstruction itself states a cost factor which has to be taken over by somebody involved in the value chain – or at least this cost factor is handed over as part of the declining value to the next development after a particular building or ground has been disused.
1.1 Factors leading to Disintegration in Construction

Despite obvious interdependencies, the integration along the value chain in construction is problematic. In general following aspects have a negative impact on integrated thinking:

- Each step (project development, planning, construction, facility management, and deconstruction) is traditionally performed by different players with different backgrounds. Only a few firms have the ability to span more than two of the mentioned steps.
- More and more the architectural part is split into two sections: architecture in terms of design and architecture in terms of detailing the design for construction are each done by specialized architects.
- Architects often overemphasize design aspects with a negative impact on the “producability” of the building and thus on the overall value system.
- Developers are often from financial and civil engineering backgrounds and cannot fully consider necessary architecture and design aspects in their calculations.
- Especially during the construction phase a huge number of sub-contractors are involved and the overall construction task has to be split up in a multitude of subtasks which are complicated to coordinate.
- Most of the sub-contractors are small to medium sized enterprise with low management capability. They use low-quality or no computer programs that are able to support scheduling and organization.
- New tools as Building Information Modeling cannot unfold their full potential as especially construction is mainly based on conventional, crafts based construction making it necessary to re-translate the digital information into “analog” commands.
- The biggest gap in the value chain exists between planning/construction and building operation. Most architects, planners and sub-contractors hand over their products and are not involved in the building’s life cycle.
- Although facility management is advancing and is using advanced tools for computer aided facility management (CAFM) little knowledge exists in using information set up during planning/construction for the building’s (value creating) operation.
- Deconstruction as a value creating parameter is completely neglected.

1.2 Value Creation and Management

Project management and controlling are professional tools which accompany planning and construction phase in order to assure that the parameters setup in the prior phase of project development (the origin of the value creation) are realized as precise as possible in later phases. Changes of cost, quality or the building’s organization and layout make the value calculation done
invalid and thus threaten (annual) return on investment and the vale that can be captured through the building over time. The task of project management and controlling tools is exactly to avoid this through organizational planning, continuous set-actual performance assessment and other management tools. Thus, project management acts as an intermediate between investor/developer on the one side and implementing planning and construction entities on the other side.

1.3 The Answer: Industrialization and Robot Oriented Management

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. Therefore, complementary robot oriented management has to address all value-added steps from off-site fabrication, ERP Logistics, on/off-site combined management, automated on-site assembly, construction robotics to service robotics, automated deconstruction and remanufacturing. The present paper first analyzes best-practice industrialization/automation projects, which have been tested or applied successfully in larger scales during the last decades (chapter 2). The 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 or value system. Further, basic principles for integrating advanced production technology in construction along the value chain through robot oriented management are presented (chapter 3). Finally we summarize our findings (chapter 4).

2. BEST-PRACTICE INDUSTRIALIZATION PROJECTS

Throughout recent history in industrialized construction several large-scale industry projects have been conducted and various technologies and high-tech based methods have been applied. All of those projects, technologies and methods have addressed different issues relevant for efficient and sustainable construction and have therefore, focused on different and dedicated ecological, environmental, social or technological aspects. Moreover, each of those projects, technologies and methods exemplarily represents a certain step of the value chain reaching from customized prefabrication and “production pull” systems to on-site automation, on-site robotic cooperative systems, controlled deconstruction, reverse logistics and recycling. This chapter analyses deployed large scale projects, which efficiently addressed dedicated parameters relevant for sustainable high-performance industrialization and mass customization in construction.
2.1 Off-Site Fabrication in Japan

In Japan customized fabrication has a long history. 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 work in the Japanese socio-economic system. Additionally, they feared phases of economic recession, which lower production batches even more. Under those circumstances and derived from those needs the famous “TPS” (Toyota Production System) was born (Ohno, 1988). The system’s basic idea is to turn around the conventional one-directional information and production flow. In TPS, therefore, the information about the demanded product is directly sent to the final assembly station. From there (by means of Kanban), components are ordered and previous processes are controlled. The system orders only parts that are actually demanded for a certain individual car (“Production Pull System”). Thus Toyota could build up a production which is strongly connected to customers’ real needs. Finally, the system turned out to work better the lower production batches became (Ohno, 1988). Sekisui Heim, famous for its legendary “Unit-Method” introduced its’ HAPPS (Heim Automated Parts Pickup System, Fig. 2) (Furuse and Katano, 2006) in the 70s and started to deliver industrialized houses with individual floor plans.

![Image](https://via.placeholder.com/150)

*Figure 2. Functionalities of Heim Automated Parts Pickup System (HAPPS) Sekisui Heim, Japan.*

2.2 Modular and Flexible On-site Automation

Since 1990, about 20 automated high-rise Automation sites 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. 4) combining semi- and fully automated storage systems with transport and assembly equipment (Fig. 5) and/or robots to erect a building almost completely automatically (Fig. 6, 7) (Linner and Bock, 2009). 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 (Bock, 2007). 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 non-rectangular buildings (Fig. 9) (Ikeda and Harada, 2006). 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 (Fig. 8). Today also European construction firms have adopted flexible site-automation systems (e.g. Skanskas, Fig. 10, 11).

**Figure 4.** Super Construction Factory of Automated Building Construction System (ABCS, Obayashi) in operation.

**Figure 5.** Z-Carry, Robotic Subsystem of Automated On-site Building Production with AMURAD System, Kajima, Japan.

**Figure 6.** AMURAD System, Robotic Device for automatic positioning of columns; floors are assembled in the ground floor and then pushed upwards subsequently.

**Figure 7.** FACES Automated Construction System (Goyo) of the company Penta Ocean in operation, Japan.

**Figure 8.** The SMART High-Rise Construction System is a modular, changeable and reconfigurable on-site factory kit.
Figures 9. Today semi-automated high-rise construction systems are capable of erecting individually designed and non-rectangular buildings, Tokyo, 2008.

Figure 10. Pilot Test of new automated construction method: An automated system assembles the floors in the ground floor level. Hydraulic presses raise floors and buildings step by step. Skanska, Sweden, 2009.


2.3 Flexible 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 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 façade inspection or painting robots (Fig. 12–13). In Japan in total over 400 different robots were developed and used on building sites. In Germany since the 1990s various robots have been created for supporting interior finishing and refurbishing work in order to increase productivity of building stock modernization (Bock and Linner, 2009).
2.4 Systemized Deconstruction

Within 11 months, three high-rise buildings in the center of Tokyo recently were 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 (Fig. 14). As the deconstruction thus 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%) (Bock, 2009). This example shows that the consequent deployment of advanced on-site technologies could be crucial for sustainability in construction/de-construction in the future.
2.5 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 (Fig. 16) which is based on subsequent unit factory completion of modular units on the conveyor belt as described before. For deconstruction first joints between steel frame units are eased, and then the house is transported to a special dismantling factory unit by unit. There the out-dated finishes are dismantled and fed into advanced reuse cycles established around factories. The bare steel frame units are further inspected and renovated and then 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 Heim, website), Sekisui organizes a matching 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 a new site (Fig. 15). Thus the system allows e.g. that a house once purchased by parents or grandparents could be relocated and reorganized to serve children or grandchildren. For remanufactured homes Sekisui Heim offers the same guarantees, supports and services as for newly built houses.

3. INTEGRATION ALONG THE VALUE CHAIN BY ROBOT ORIENTED MANAGEMENT

Future sustainable industrialization and robot oriented management in construction has to address all value-added steps from off-site fabrication, ERP Logistics, on/off-site combined management, automated on-site assembly, construction robotics to service robotics, deconstruction and remanufacturing. High-tech construction would then allow addressing economic, environmental, social and technological issues simultaneously. Here industrialization has particular advantages, as it allows gradual implementation of new technologies for reducing energy, material and waste consumption and for upgrading working conditions, health and low wages. Further, industrialized
processes, methods and technologies are crucial for developing affordable and thus sustainable housing. In this chapter, we present a framework for industrialization and robot oriented management, which was derived from the above analysed best-practice examples. The examples analysed showed that industrialization, flexible automation and construction robotics could be integrated with all value-added steps. Integrating and managing the advantages of those practices would allow for closed chains concerning technology, processes and information in the building construction process. From the analysis done in section 2 the following basic principles enabling an integration along the value chain could be derived:

3.1 Implementing Human-Robot-Cooperative Systems

The next generation of robots will work in the direct operating range of human workers in order to achieve a maximum of 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. Conventional construction robotic systems, guidance or remote-controlled system, have to solve complex problems in unstructured and complex construction sites. A solution to address these problems is the strategy of “human-robot cooperative manipulation”. Robots are capable of high speed motions and power assistance, whereas humans are slow and weak concerning heavy construction work. On the other hand, humans are much more flexible and adaptable concerning thinking, orientation and operational behaviour. The strategy of “Human-Robot-Cooperative-Manipulation” (Lee, Lee et. al., 2007) 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 (Fig.17).

![Figure 17. Concept of human-robot cooperative manipulation able to create highly flexible cooperative systems for complex tasks in factories or on construction sites (Lee, Lee et. al., 2007).](image_url)
3.2 Reducing Complexity: Robot Oriented Design

In integrated industrialized construction, the product structure is the most crucial and most complex item of the whole process chain (Bock, 1988). It is impossible to successfully apply the building structure known from conventional buildings. Systemized and modularized building structures have to be developed in close cooperation with the needs of fabrication, logistics, customization and robotic and cooperative applications. Further 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. Further the structural elements (e.g. steel structure) should be clearly separated from the infill (cables, electricity, appliances) and from the façade elements and interior finishing. Then facade elements and interior finishing could be designed more or less individually, whereas structure and infill could be standardized.

![Figure 18. Robotic Construction Automation System Technology. Model of the first Korean automated construction site. The orange frame is part of a vertically moving on-site factory. To the frame robotic devices, robotic transportation systems and assistance technologies are attached. The whole system is based on principles of Robot Oriented Design. Seoul, 2010.](image)

To the product structure all other processes, technologies, and business strategies are strongly related. An open building structure is fundamental to dynamically integrating and applying new and also modularized ecologies of technologies, microelectronic systems, devices and services.

Additionally, Body-in-White assembly simulations (Wang, Chen et. al., 2004), which are state-of-the-art in aviation industry, car manufacturing and ship building industry, could not only assist in developing industrialization and robot oriented design but could significantly reduce time and error cost in final construction operations. The principles of Robot Oriented Design are currently applied at the first Korean automated construction site (Fig. 18).
3.3 Towards Robot Oriented Management: “Production” Flow and 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. Moreover, construction products are still inflexible, showing a highly interdependent component structure. 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. Moreover, today, the demand for expressive and diverse buildings requires an even more advanced building typology. This perspective considers not that up to now architecture has only tried to achieve industrialization by changing construction to serialized prefabrication. However, today new approaches as mass customization allow an industrialized fabrication of individual construction products from infill elements up to whole units and houses. Customization is a strategic means for delivering user adapted or even personalized houses at same or even lower cost than standardized mass production (Piller, 2006). It aims at enhanced efficiency meanwhile creating user adapted products. Therefore, customization is not only based on the control of a single process or CNC machine but on creating new organizational structures over the whole value chain corresponding with information flows between enterprise, product, machinery, robots, customers and all complementary sub-processes. Moreover, Mass Customization allows fabricating houses to order by industrial means minimizing the input of resources, workforce and energy.

3.4 Addressing Eco Issues through Robot Oriented Management

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: Zero Waste Factories, Japan, website). An essential economic and ecologic factor in most industries today is the implementation of factories with low or even no environmental impact (Williams, Westkämper et. al., 2009). Additionally, with the implementation of industrialized and modularized structures, eco-processes once established could be improved gradually. Eco-factories are often established through applying Environmental Management Systems (EMS) (US Environmental Protection Agency, website) that are complementary with advanced resource control technologies. Therefore, factories are increasingly able to manage the closed-loop circulation of all resources and materials efficiently. Further, technologies for using renewable energy, solar modules and cogeneration systems are gradually deployed in industrial facilities to generate electricity and heat for the production, meanwhile waste and heat recovery systems allow a passive-house-like energy
circulation within the factory. The research aims here into the direction of more or less autarkic factories, which even could process their own waste to generate resources and energy. Moreover, the reduction of waste through continuously improved and demand oriented production “pull” processes and advanced production equipment is another aspect, which shows the advantages of switching material-intensive processes from the construction site into the controlled environment of an off-site or on-site factory. Further, systems for reverse logistics, remanufacturing and recycling as discussed before could be closely linked to eco-factories creating closed-loop manufacturing structures for sustainable resource, material and component circulation (Fig. 19).

![Figure 19](image.png)

**Figure 19.** Towards closed-loop component circulation in construction through automation and robotics: Reverse logistics, remanufacturing and recycling could be closely linked to eco-factories creating closed-loop manufacturing structures for sustainable resource, material and component circulation throughout the whole building lifecycle.

### 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 paper, examples have been given which outline
best-practices in sustainable industrialized construction. Further, basic principles for integrating advanced production technology in construction along the value chain through robot oriented management have been presented. Through industrialization and complementary Robot Oriented Management, construction industry would be able to simultaneously address multiple parameters relevant for sustainable economic, environmental and social development. The paper shows, that integrating and managing the advantages of the analyzed best practice examples allows for closed and controlled chains concerning technology, processes, resources and information flow and value creation. Further, Robot Oriented Management would not only be limited to building fabrication but also link systems of controlled deconstruction, component reuse and re-customization to a network for continuous and industrially organized resource circulation.

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### 5.1 Websites

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