Mass Customization in a Knowledge-based Construction Industry for Sustainable High-performance Building Production

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Abstract

Today, with recurring resource shortages, striking economic crisis and evolving social standards a new paradigm arises forcing industry not only to focus on competitiveness but also on designing sustainable products and manufacturing processes with equal respect on economic, social and environmental impacts. From that point of view, industrialization has particular advantages compared to conventional construction as it allows addressing various parameters relevant for sustainable construction consequently and in a controlled and predictable way. Industrialized construction could help to reduce material and energy consumption, minimize waste production, improve safety and working conditions, support the supply with affordable housing and enable deconstruction, reuse and recycling. Throughout the recent history of industrialized construction several large-scale industry projects have been conducted and various technologies and high-tech based methods have been applied, each of them addressing a certain sustainability issue. The present paper first gives an overview over those projects, technologies and methods and further develops a framework for future industrialization in construction based on the integration of sustainable best-practices. The framework outlines how different industrialization systems and sub-systems could be integrated to ecologies of factories, intelligent devices, high-tech equipment, resources and human beings by knowledge-based systems to efficiently control economic, social and environmental impacts.

Keywords: industrialization in construction, sustainable manufacturing, mass customization, robotics, reverse logistics
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 where the importance of environmental and social factors finally becomes equipollent to plain 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. Besides a change in organization, new process technologies, microelectronic devices, ICT, flexible automation, robotics and knowledge based logistics are at the heart of that revolution. Industrialized structures and standardized, exchangeable products and processes, which are deployed in most industrial sectors, are a solid basis for a gradual development towards a sustainable economy. However, in construction industry industrialized structures are merely developed and advanced technologies, which are state of the art in other producing industries, are still rejected. Construction industry has the lowest productivity of raw material input [26] [21] and about 40% - 50% [30] of global raw materials are used for the construction of our environment. Construction waste states the largest waste fraction even in highly industrialized countries [21] and the capability of that waste to be recycled with low environmental impact is rather low [31]. Moreover, the working conditions for construction workers in highly industrialized countries as well as in emerging economies as India or China are changing. The number of workers older than 50 is remarkably low and there are nearly no construction workers older than 60, although the retirement age is 65 which means nothing else as that after the age of 50 many construction workers become invalid and/or unemployed [16]. Buildings are among the most expensive goods that we produce [23] and although we have achieved that complex high-tech products as cars and computers are 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 lifecycle performance of our built environment and the fact that in a time of dynamic societies and fast changing needs built environment can hardly be changed, adapted, rearranged or deconstructed [25]. Industrialized structures and technologies in construction could help to enhance resource productivity, reduce waste, improve safety and working conditions, support the supply with affordable housing and enable continuous deconstruction, reuse and recycling. Once industrialized processes are installed, gradual process improvement could be achieved similar to other industrialized sectors and the aspect of modularity of architecture, building structure and industry itself, as an inherent requirement for industrialization, could address the problems of flexibility, deconstruction and remanufacturing. The present paper outlines that prefabrication, logistics, ERP, automated on-site construction, construction robotics, robotic-co workers, systemized deconstruction and other new industrial methods or technologies could be seen as complementary elements able to be co-adapted to create sustainable construction processes and a continuous and controlled flow of information, workforce, energy and resources for on-demand industrially customized buildings. Up to now a multitude of industrialization attempts have been conducted around the globe. Each of them addresses different parameters evident for sustainable construction. Yet, sustainability as we understand it today relies not on single parameters, but on integrative solutions with equal respect on economic, social, environmental and technological impacts. Therefore the present paper first gives examples of specific sustainable practices in construction industrialization and further develops a framework for integrating their advantages to an industrialized, flexible and sustainable building production network by advanced ICT and knowledge based systems.
2. Examples for high performance industrialized construction

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 to introduce industrialized systems or sub-systems. All of those projects, technologies and methods have addressed different issues relevant for efficient and sustainable construction and have therefore focused on dedicated ecological, environmental, social or technological aspects. Moreover, those projects, technologies and methods exemplarily stand for subsequent steps of the technological value chain from customized prefabrication and “production pull” systems to on-site automation and on-site robotic cooperative systems to controlled deconstruction, reverse logistics and recycling. This chapter gives an overview over recently deployed large scale industrialization systems which have efficiently addressed particular parameters relevant for sustainable high-performance building construction.

2.1 On-demand individual customization in locally-based minimal-waste factories

Both the productions of Sekisui and Toyota are based on the principles of “pulling” and “lean” [2] production. As only demanded and customized housing products are fabricated overproductions and thus wasted materials or processes are avoided. In a “pulling production” only the effectively needed materials, modules and components are ordered and produced. Further materials, modules and components are organized just in time just in sequence to the final assembly process allowing a lean production with minimized stocks. Today the emerging strategies of “Mass Customization” [6] carry on that ideas and integrate them with other advanced technologies. In conventional construction a huge amount of the used materials and components is still prepared on the construction site causing cut-off waste and unnecessary transportation processes through waste materials. Often the waste produced on the construction site is not sorted and recycled to its full extent. On the contrary, in Japanese prefabrication factories waste is reduced on one hand through on-demand order of compatible elements. On the other hand, waste that is produced during the production is fastidiously collected and sorted in up to thirty different kinds of factory waste boxes. Throughout the whole completion process every piece of waste is immediately fed into a connected recycling system [32]. This is showing that factory production has a distinct advantage in controlling the flow of materials.

Fig. 01 Prefabrication of housing modules with robots, Japan; Fig. 02 Fastidious waste collection and sorting, Sekisui Heim, Japan
and waste. Further especially in building production which is from its nature and history closely related to local habits and resources locally based production plays an important role. A good example how to handle this in an industrialized construction industry can also be found in Japan’s prefabrication industry. Japan is a country with quite contrasting climate regions, which have generated different habits and tastes. In south areas as Kyushu and Okinawa the climate is humid and even sub-tropical, in the winter it merely has below zero degrees and the life style of the people is different from that in the metropolitan areas Tokyo or Chiba. In the north, as for example in Sapporo, winters are cold and snow levels up to 1 meter are normal. Houses need thick insulation, pitched roofs and smaller windows and the taste of the people concerning designs is different. Considering that Japanese people today particularly demand for individuality, different regional preferences are a basic challenge for every company delivering industrialized houses. Therefore the prefabrication company Sekisui Heim offers different types of houses fitting to Japan’s regional, cultural and climatic differences. Customers can choose from these particular types and then adjust them to their individual needs through an off-line configuration system. To get closer to the customers, regional based model parks in strategically important areas [25] have been established each of them showing house types relevant for a specific area. Specially trained local staff is able to consult according to locally based needs. Accordingly, factories are placed in each of those different areas finishing houses to the preferences of the region. So Sekisui Heim’s “Chezdan” [33] house type as well as its’ product variants and individual derivates, have thick insulation, windows, roofs and design styles fitting to colder regions. Chezdan house types are finished in a factory near Sapporo. This strengthens the relation to the customer as factory processes and logistic networks are adjusted to the specific resources of an area. Moreover, this strategy reduces logistic efforts to minimum and locally based craftsmen and suppliers are supported.

2.2 On-site/off-site combined fabrication

From 2002 NCC 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” [20]. This system had been a manufacturing system combining factory prefabrication with a mobile on-site assembly hall. In the off-site factory concrete walls were customized according to customers’ demands and the architects’ plans. Also most of the fit–out work was done in the factory and technical installations as electricity, sub-components, windows, doors, radiators and fixed furniture modules for bath and kitchen were pre-installed. Thus wall and ceiling modules had been completely finalized in the off-site factory and in most cases even wallpapering, flooring and electrical switches had been pre-attached. The completely finalized modules were transported to the construction site just in time and just in sequence and the final assembly took place in a mobile, closed and heated assembly hall that protected the whole on-site assembly from weather influence. All in all, four assembly workers and one assembly foreman were needed per average building and the flow of materials, components and resources was highly controlled through an advanced logistics systems and the combination of controlled off-site and on-site processes.
2.3 Expert Systems for Complexity Management

Sekisui Heim, famous for its legendary “Unit-Method” introduced its’ HAPPS (Heim Automated Parts Pickup System) [8] in the 70s 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 products. Today it allows extremely fast and efficient 80% factory production of individual houses. Through HAPPS the customers are free to choose their preferred degree of customer integration. The configuration process is done in several steps guided by trained customer contact staff helping the customers to make decisions as quick as possible (off-line configuration). Once an individual design is fixed the HAPPS automatically generates parts list and coordinates working tasks, logistics, fabrication processes and material flow in a minimal waste factory.

2.4 Semi-automated high-rise construction and human-machine-cooperative systems

Obayashi announced the development of an Automated Building Construction System (ABCS) in 1989 and it has been applied five times up to now. Through these projects, the ABCS has been improved gradually and adapted to various building designs and construction sites. Moreover the automatic level of the system has been lowered gradually to achieve a higher efficiency. In the latest ABCS project finally conventional construction and automated construction have been combined to a new hybrid system. In this project the inner area equipped with the “Super Construction Factory” [9] was constructed by the ABCS meanwhile the outer part of the building was constructed by conventional construction supported and supplied by the SCF logistics and control system. Both SCF and conventional construction created synergies to each other and worked simultaneously. A contrasting approach to on-site automation and semi-automation is at the moment developed by Korean researchers aiming not only at automation but also at introducing small-scale robots capable of supporting construction workers with their tasks in direct interaction and cooperation. The Korean researches have developed their promising approach from the assumption that construction robotic systems normally have to solve problems in unstructured and dynamic construction sites. One of the solutions to address these problems is supposed to be a technology of “human-robot cooperative” [12] systems combining the intelligence of the human worker with the force power of the robotic system [23].

2.5 Reverse logistics and remanufacturing

All buildings of the Japanese Prefab Maker “Sekisui Heim” can be accepted as “trade-ins” [25] for a new Sekisui Heim building. Therefore the deconstruction process is a modified and reversed version of the construction process which was based on unit factory completion and rapid on site assembly of prefabricated units. 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 outdated finishes are dismantled and fed into advanced reuse cycles established around factories. The steel frame units are
further inspected, refurbished if necessary and then equipped with new finishes and fit-outs desired by a customer who has chosen to buy a reused house. On a Web-Platform for “Reuse System Houses” [22] Sekisui organizes a matching of people who want to sell their modular house for reuse and people willing to buy reused house modules for further customization. Renewed units are reorganized and customized in the factory, transported to other customer’s building sites and then assembled on a new foundation in a new site. For Reused and reorganized Houses Sekisui Heim offers the same guarantees, supports and maintenance services as for newly built ones. With a growing number of customers willing purchase a house of the reuse system a community will be formed serving as basis for a highly efficient component circulation, reverse logistics and remanufacturing.

3. Framework for the future development of sustainable and industrialized construction

For future construction industry the question will not be if conventional construction should be kept or industrialized methods should be applied. More important will be that construction addresses all items relevant for sustainable construction bringing together economic, environmental, social and technological issues. From that point of view industrialization has particular advantages as it allows the 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. Sustainable efficiency in construction and building industry in a bigger scale would closely be related to industrialized construction practices and advanced structures for reuse, reorganization or recycling as discussed above. The following chapter derives a framework for integrating and implementing the advantages of those practices with other emerging production technologies being under development in other industries in flexible construction clusters of bigger scale with a focus on advances in robotics and knowledge-based support technologies.

3.1 Ecology of industrialized sub-systems

Prefabrication of components or units, logistics, ERP, automated on-site construction, construction robotics, robotic-co workers, systemized deconstruction and other new industrial methods could be seen as complementary elements forming a continuous ecology of factories, devices, equipment, resources and human beings. Those different system components should be integrated to create synergies and thus sustainable construction processes [23]. A continuous and controlled flow of information, workforce, energy and resources over the whole life cycle and especially during the construction time could help to create a high efficiency concerning economic, environmental and social issues at once. In the 1980s General Motors invested more than 80 Billions US$ in innovative flexible production systems and appending information technology. Yet General Motors had to face huge economic losses in early 1990s meanwhile compared to its flexibility it could produce only a few different models. GM missed to change product development, modularity, style of management, human resource planning and market strategies in the same way as it updated its production with innovative technology. Today we know very well about the “complementarities of activity” [6] as a
means to achieve economic success. Similar, Milgrom and Roberts state in their management theory that changes in industrial strategies should be done consequently: “Coordinating the general directions of a move may substantially ease the coordination problems while still retaining most of the potential benefits of change. Moreover the systematic errors associated with centrally directed change are less costly than similarly large but uncoordinated errors of independently operating units” [3]. In a similar way, in construction industry, the development of stand-alone intelligent equipment and processes could be more harmful than helpful. Changes in construction industry should be done consequently towards a strategy which equally addresses the whole value chain and combines product design, prefabrication, on-site automation, modular robotics, deconstruction and reuse systems to a synergistic ecology of factories, devices, equipment, resources and human beings.

3.2 Flexible fabrication technologies for mass customization

In recent architecture and construction industry customization is often interpreted as a tool for forming highly differentiated 3D shaped components or buildings. This surely is not wrong and it is an important aspect for architecture, yet it only covers one of a variety of co-adapted sup-processes in that what customization -seen from its original economic or management point of view- really means: Customization is a strategic means for delivering user adapted or even personalized products at same or even lower cost than standardized mass production [6], it aims at enhanced efficiency meanwhile creating user centered innovations. Therefore Customization is not based on the plain control of a single process or CNC machine but on creating new organizational structures corresponding with streaming and intelligent information flows between enterprise, product, machinery, robots, customers and all sub-processes related to these fields. Customizations’ heart is information and communication technology used for forming continuous IT structures on which those information flows are then created. Customization is deeply based on the evolution and interconnection of all computer based technologies. The extension of classic ICT by advances in robotics and intelligence will even create more efficient customization structures. Today the definition of robotics widely differs depending on application area, profession and culture. Sure is that robotics more and more emerges from its’ original application area in classic production industry. Robots are on the way to be used in all parts of our life: from construction, to households, to health, to service. Similarly a change from defining robots as “multifunctional manipulators” which can be programmed to a definition which rather sees robots as “cooperative systems” is taking place [24]. Further the increased demand for flexibility or one-piece-flow production of individual products in complex and dynamically changing production clusters leads to a new design paradigm for robots. For the design of future robotic construction equipment, automation systems and construction robots that can be used on-site or off-site, three main paradigms could be identified:

Human-Robot-Cooperation: 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 accounted as basic requirement for customization and individual product fabrication by industrialized means. Robotic systems of the next decade will rather be “assistants” [24], helping human workers to perform complex tasks, than fully autonomous systems. New interaction concepts, interfaces, numerous concepts for lightweight robots, integrated force-torque sensors and teaching systems are therefore now developed by robotic companies around the world.
Robot-Robot-Cooperation: The next generation of robots is designed to cooperate with each other to perform tasks in dynamically changing and flexible groups of intelligent (robotic) devices. This will mainly be done by distributing processes and tasks over several devices and robots. Moreover robots will increasingly be able to receive information of environmentally embedded Microsystems technology and sources as sensors, actuators and other microelectronic systems distributed in the production environment. Long-term strategies even aim at globally distributed robotic cooperating systems which could be part of decentralized and locally-based small scale production networks. [24]

Modularization and Standardization: Parts and components of robots and specific automation systems that are increasingly needed by a multitude of operators within an industry are usually becoming part of a design evolution making them increasingly modular and interchangeable [24]. As shown by computer industry economic efficiency is closely related to the evolution of shared design rules [29] for modularization and component systems.

3.3 Product design for distributed fabrication

A holistic product conception is determined by a planned and integrated design of the production system’s performance from supply chain to production line. With the system architecture of the final product or building, not only its’ visible shape but also its’ modular structure and thus the ability to be fabricated with certain processes, technologies or production networks are determined [1]. In that context, today, CAD programs could be developed further towards “Virtual Assembly Platforms” [27] which are already under development in automotive industry. Those virtual platforms could be used for digital and production oriented architecture helping to design and virtually test the interdependencies of the applied building products, processes and resources. Further, extended program functions are needed which support variant development and variant management of highly customizable industrialized building component systems. With the introduction of industrialized processes and new co-operative equipment in construction industry, virtual commission planning for lines, flexible production cells or on-site construction processes as well as the virtual modeling of human actions or inter-actions on the construction site – which are already state of the art in other advanced industries, f. e. “body-in-white-assembly” [34] in automotive industry – have to be addressed for fully using industrialization’s potential. Those technologies could reduce construction failures, enhance safety and moreover help to design healthy and acceptable off-site or on-site working environments for the future construction workers. Further, the development and gradual implementation of ERP systems in construction should have high priority. As explained above, buildings fabricated industrially in the factory or on-site by automation and/or robotics should be finished individually according to customer demands, and regional styles. Therefore it is an important process to select and pick up about 30,000 components correctly for single house, out of about 350,000 components building up the solution space and feed them to the production line just in sequence [25]. Thus parameter based ERP system should be implemented supporting the whole workflow: customization, planning, receipt of order, logistics, fabrication and delivery. Integrated ERPs could help to generate parts and component structures and parts lists from CAD floor plans. Based on the information generated from the CAD models also detailed location information concerning parts, components, cables could be generated to build up a object oriented virtual house. Out of that construction ERPs could schedule logistics and fabrication just in time and in sequence of
Around a combined industrialized off-site/on-site production, construction companies could install a systemic supply network. This supply network could be bound together by an advanced modular product architectures and Construction ERP systems scheduling and controlling material supply, processes, workers, automated machinery and modular and distributed industrial robots. Considering that people today particularly demand for individuality [6], different regional preferences state a basic challenge for every company delivering industrialized houses. Therefore companies prefabricating elements or housing units should supply different types of building components fitting to regional, cultural and climatic differences with locally-based factories integrated in a distributed and flexible factory network [4].

Customers or other companies purchasing components could then choose from these types and adjust them to their individual needs. To get closer to the customers and the regional materials, regionally based factories in strategically important areas should be established. This strategy could minimize transportation efforts enormously. Bigger component suppliers or prefab makers could run several factories each of them producing predominantly the types of houses required in the surrounding region. Yet, basic production layout could be similar in different factories and thus also the basic product structures and production processes. In general, production structures are shifting from centralized to more modularized and decentralized structures, as those are more flexible and offer the possibility to deliver highly customized products. Moreover, the principle of distributed fabrication has already successfully been practiced by the automotive industry where huge car companies (OEM) contract small and medium enterprises (Tier-n) to deliver subcomponents and subsystems. The advantage of the implementation of a distributed, but industrialized fabrication concept in the construction industry would be, that highly specialized companies or craftsman may use their modular (robotic) high-tech equipment not only for one specific product but for several products for many customers or various building fabrication networks. The introduction of a decentralized fabrication system would allow that small scale construction enterprises could be supported. Also, this would offer the ability to react flexible on various customer demands. Equipping small scale enterprises with flexible and ICT-based construction equipment and further deploying advanced supply chain communication could thus be seen as basic enablers for distributed industrialized building fabrication.

### 3.4 Eco-factories, deconstruction and resource circulation

Eco-factories are factories that produce at high efficiency and in accordance with environmental needs: carbon neutral, powered by renewable energy, zero-waste. An essential factor in most industries today is the implementation of factories with low or even no environmental impact [18]. Moreover, with the implementation of industrialized structures eco-processes once established could be improved gradually. Eco-factories are often established through introducing so called “Environmental Management Systems” [28] combined with other advanced resource control technologies. Therefore factories are increasingly able to manage the 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 vision here goes into the direction of more or less autarkic factories which even could process their own waste. Moreover, the reduction of waste through continuously
improved production processes and advanced production equipment is another aspect which shows the advantages of moving material-intensive processes from the construction site into the controlled environment of the factory. Further, systems for reverse logistics, remanufacturing and recycling as discussed in section 2.4 could be closely linked to those eco-factories creating structures for hyper-sustainable resource and component circulation.

3.5 Towards a knowledge-based construction industry

In most high-tech based industries knowledge-based information and software systems are crucial for making complex decisions. Once information and communication structures, sensors, RFID tagged components [15] and networks are introduced in construction industry intelligent decision making software could be deployed to control, manage and operate a distributed, flexible and complex network of modular high-tech equipment, locally based factories and other resources. In an industrialized and decentralized construction industry, as described above, it would be difficult to adequately coordinate the inevitable multitude of complex operations and to make rational decisions without the help of intelligent knowledge based systems [5]. As ICT in an industrialized industry becomes an inherent part of most processes, knowledge-based decision support systems could make real-time use of the operation data or help to analyze them for further decisions or operations [14]. Appropriate decisions in complex industrialized networks would enhance the efficient flow of information, materials, components, energy and other resources. In construction industry knowledge based systems could also be used to organize, classify and analyze data from previous projects and activities as well as different building variations and their related lifecycle performances, in order to support sustainable short-term and long-term decisions on system architecture, modularity and construction processes.

4. Conclusion

New organizational structures, new process technologies, microelectronic systems, ICT, flexible automation, robotics, human-machine-cooperative systems, tagged equipment and building components and knowledge based logistics are key enablers of a necessary shift from economic growth to sustainable economic development. Industrialized structures would be a solid basis for a gradual development towards a sustainable construction industry. Therefore in this paper examples have been given which outline best-practices in sustainable industrialized construction. Further a framework for future industrialization has been presented, which suggests to combine several industrialization methods to a synergistic 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 proofed stand-alone industrialization solutions. Those state of the art industrialization methods could be integrated and developed further to large scale sustainable building fabrication networks producing sustainable buildings with determined economic, environmental and social impact. In the presented approach, production oriented architectural design structures, appropriate modularization and standardization of building structures, logistics, equipment and processes would serve as fundamental integration tools. Customized and demand oriented industrialized prefabrication could then be able to supply...
construction sites with individual elements and a modular pool of flexible automated systems, robots and robotic co-working systems could support a limited amount of trained workers to do positioning, joining and finishing operations. Knowledge-based construction ERP systems could support overall organization as well as a lean and demand oriented industrialized construction based on just-in-time and just-in-sequence resource supply. Locally based and distributed factories grant identity, support small and medium sized enterprises and reduce logistic effort. Moreover, integrated industrialization should not only be limited to the fabrication but also link systems of controlled deconstruction and component reuse to a network for continuous component circulation. Advanced tools for resource planning on the enterprise level (ERP) and knowledge based systems on the level of management, greater networks and real estate could support appropriate decisions in complex industrialized networks and thus enhance the determined and sustainable flow of information, materials, components, energy and other resources. With the gradual implementation of a compatible ecology of industrialization sub-systems, construction industry would have the chance to simultaneously address various parameters relevant for sustainable economic, environmental and social development consequently and with greater efficiency than with conventional construction methods. Industrialization could help to reduce material and energy consumption, minimize waste production, improve safety and working conditions, supply affordable housing and enable deconstruction, reuse and recycling. Moreover processes once systemized and industrialized have the potential for continuous adaptation and improvement. Further research will focus on the detailed design of building structures and modular building platforms designed for knowledge-based production in flexible networks of small and medium sized construction enterprises.

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