AUTOMATED ROBOTIC MANUFACTURING FOR BUILDING PREFABRICATION

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ABSTRACT

Established industrial manufacturing methods combined with parametric design have the potential to disrupt the conventional design-to-fabrication processes in the building industry. Currently factors such as increasing cost of labor, stagnated productivity per employee and highly fragmented design-to-fabrication processes in the building industry have not proved to be fruitful influences for the mass production of customizable buildings. Therefore, this qualitative research presents a high level strategy for design-to-robotic manufacturing. Hereby academic publications were used for the literature study and meetings and panel discussions with professionals were conducted. Investigated are three main topics: the parametric design-to-robotic manufacturing process followed by assembly line layouts for scalability and adaptability and factors influencing the adoption and feasibility of prefabrication and robot construction automation. It is argued that parametric (sub)assemblies of building components and modules with automatic generated robot code forwarded to asynchronous multi model or mixed model assembly lines have the potential for flexible, scalable and customizable mass prefabrication as long as the influential factors for adoption and feasibility are met.

KEYWORDS: *Design-to-robotic manufacturing strategy, prefabrication, construction, parametric design, assembly, subassembly, automation, feasibility*

I. INTRODUCTION

The prospects for off-site construction automation in the building industry are promising. Currently factors such as an increasing costs of labor and for decades stagnated number of productivity per employee as well as highly fragmented design-to-fabrication processes have not proved to be fruitful influences for the mass production of buildings to fulfill the need for housing (Barbose *et al.*, 2017; Van Sante, 2019).

Recent software developments in the architecture discipline and a broad range of established industrial manufacturing references of design and production methods call for a radical new design-to-robotic manufacturing process for the building industry. Hereby opening up a new outlook for automated off-site construction plants. With so much technological potential at our fingertips it can be overwhelming to structure and implement the construction automation opportunities. This research paper sets out a high-level strategy for a design-to-robotic manufacturing workflow with construction scalability and adaptability for maximized construction automation in the building industry. Accordingly, an optimized parametric design-to-robotic manufacturing software solution is investigated, followed by assembly line layouts for scalability and adaptability. Moreover, factors influencing the adoption of prefabrication and robot construction automation are investigated.

II. RESEARCH METHOD

The methodological approach in this research is centered on qualitative research methods. Data was gathered based on a literature review of academic publications in the field of robotics and digitization in architecture, automotive and manufacturing. Established and renowned journals and conference publications of Rob | Arch, ISARC, ACADIA, ECAADe and CIRP Annals were analyzed.

Moreover, publications from authorities in robotic industrialization for construction such as Bock and Linner were examined as well as reports from consultancy firms such as McKinsey &

Company for the feasibility and adoption factors for prefabrication and robotic automation.

In addition, valuable data was also acquired from meetings and panel discussions with professionals in architecture, robotics and business development. In order to verify the data from these activities formerly mentioned sources were conducted for comparison.

Accordingly, based on a content analysis of the previously stated sources data was examined to identify patterns and methods relevant for investigation in the corresponding research chapters. Hereby data from different disciplines was combined in order to optimize research findings. This interdisciplinary research approach was chosen because other industries and disciplines have successfully implemented robotic automation for mass customizable production which can function as a reference for the building industry.

III. RESEARCH SCOPE

This research expands upon the established parametric design workflows in the building industry, because the ease of use for designers is essential for a successful adoption. Therefore, robot software that is not developed in relation to the building industry and parametric design such as Robot Operation System (ROS) is not considered in this research.

Moreover, this research is focused on off-site prefabrication of building elements. Since prefabrication improves the performance and efficiency of the product, such as the upholding of quality while saving time through the shortening of building phases, reducing failure costs and increasing workers' safety (Bock and Linner, 2015). In this paper production refers to the generation of basic parts or low-level components such as prefabricated walls. The joining of elements generated within production are referred to as assembly. The term manufacturing includes production and assembly processes (Bock and Linner, 2015).

At last, this research focusses on the application of powerful industrial robots for the manufacturing processes due to the relative affordability, user-friendly programming options and available flexibility for customized tasks. The term "industrial robot" is based on the definition of the International Organization of Standardization: "an automatically controlled, reprogrammable, multipurpose manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications" (2012).

IV. RETROSPECT AND REFERENCES

4.1. The emergence of robotic construction automation

Robotic construction automation gained momentum in the 1970s and 1980s in Japan with the development of on-site robots, automated construction sites and off-site building manufacturing (Bock and Linner, 2015). On-site construction robots were custom-built and made for one specific task. This resulted in costly investments that turned out not to be cost efficient, because factors such as the complex environment of construction sites counteracted the productivity gains. Subsequently the concluding statement was that a structured approach for construction would be more profitable (Bock and Langenberg, 2014). This is achieved with automated construction sites that are still deployed today. The benefit of this system is the improved on-site organization with a high level of integration and continuous material flow (Bock and Linner, 2016). Similarly, off-site building manufacturing approaches have also progressed in Japan. Prefabricated products ranging from building components to modular and customizable housing units can be purchased and are known for their high quality and performance. Most Japanese off-site manufacturing companies did not originate from the construction industry but rather from multinational chemical, electronics or automotive companies, which had already a successful background in production lines and automation (Bock and Linner, 2015).

The economic downfall of Japan in the 1990s reduced the demand for construction which also resulted in limited product development and opportunity to widespread the technology outside of Japan (Bechthold, 2010). Moreover, in the United States little interest and even resistance was shown in the technology back then (Everett and Saito, 1994). Nowadays, Japan is still the most advanced country in terms of the robotic use for construction (Bock and Linner, 2015).

Worldwide robots are applied in various construction sectors for off-site manufacturing. Prefabricated masonry elements can be produced by semi-automatic production systems or fully automatic brickwork robots. However, brickwork construction is often characterized by the high percentage of private builders with a strong orientation to manual labor. This is in contrast to the precast concrete industry which adopted robotized automation on a larger scale. Mass customization is enabled by flexible robotized production systems. Tasks such as setting molds, placing reinforcement bars and mats and distributing concrete are automated for the production of column, beam, roof, floor and wall elements. However, apart from the formerly described horizontal production typology the use of robotics in vertical and volumetric formwork is relatively limited (Bock, 2008; Pan and Pan, 2016). The precast concrete industry has an outlook for an enhanced level of prefabrication by incorporating additional automated functionalities such as placing insulation, windows, electric cabling and applying surface finishes. This also applies to the prefabricated masonry element industry (Bock, 2008). In the case of the timber industry especially larger companies have integrated automated processes for prefabrication of panelized wall, floor and roof elements as well as columns, beams and ceilings. Advanced robotized subtractive operations for milling and cutting offer customizable joinery and element geometries. The additive processes are often automated as well by automatic feed-in of materials, placing of panels, insulation and cladding and structurally joining. Usually the installation of electrical cables, ventilation ducts and fire damper flaps remain manual labor since the requirements are very project specific (Kaufmann, Krötsch and Winter, 2018). The steel industry for prefabricated housing has a high level of automation and robotics similar to the car industry. Panels or modules that can be custom made to client requirements are produced. Robotized subtractive operations such as laser cutting, sawing, drilling as well as robotized additive operations such as welding, applying protective coating and assembling of parts allow a high and constant production quality and capacity (Bock, 2008; Bock and Linner, 2015). Similar to other prefabrication sectors the installation of aforementioned electrical cables and other complex utilities are usually manually fitted.

For the off-site prefabrication industry a variety of robotic solutions are available for order ranging from one-task robots to complete production belts. These products are developed by construction sector specialized system integrators. Generally the solutions offered are either completely automated or require limited manual operation. Moreover, depending on the supplier robotic solutions can also be developed in close collaboration with the customer. (Randek, 2018; Kawasaki, 2019; Weckenmann, 2019; Weinmann, 2020)

The proportion of large-scale prefabrication and robotized manufacturing differ from one country to another. Various reasons such as the technological background, existing inventory of buildings and level of education as well as country policies and availability of low-wage labor have an influence (Bock and Linner, 2015). In the case of Japan the prefabricated house industry of steel has the largest market share which can also be correlated to the large support and promotion of the Japanese steel industry (Matsumara, 2004).

In the past few years in Canada and the United States there has been an increased involvement of multinational technology companies in the off-site construction industry. These firms are investing in startups (Amazon, no date; Autodesk, 2019) or have plans to construct their own manufacturing plants with robotized processes (Sidewalk Labs, 2019). In addition, an off-site construction startup with plans to disrupt the construction industry led by management from successful technology companies received more than a billion in funding (Navitas Capital, 2018). These events can have a similar impact as to what happened in Japan where multinationals from other industries entered construction and used their background to successfully improve the construction processes with automation and robotization.

The use of robotics also enables new applications for off-site building component manufacturing. For example 3D-printing of topological optimized structures (Zegard and Paulino, 2016), hot-wire cutting for more cost effective double curved concrete precast molds (Søndergaard *et al.*, 2016) and detailed milling of complex objects (Aigner and Brell-cokcan, 2009).

However, currently the market share of robots in construction remains little in comparison to other industries as the construction industry is not specified in the annual robot installations overview of the International Federation of Robotics (2019). In the past decade more startups in construction robotics have emerged, often focusing on the development of software to optimize design and manufacturing since these two topics are highly dependent on each other. This is a domain that traditional robot integrators, frequently coming from the automotive industry, have not yet entered (Feringa, Gramazio and Kohler, 2014). This opens up possibilities to form new design-to-robotic manufacturing processes.

4.2. Established design and assembly methods

The automotive industry is known for its high volume car production with advanced robotized assembly lines. In recent years the automotive industry is facing a mass production challenge with the need for a high level of product variety due to the continuously changing market dynamics and the customers demand for customization (Michalos *et al.*, 2010; ElMaraghy *et al.*, 2013). Nowadays, the BMW 7 series has 10^{17} variations (Hu *et al.*, 2008) and different car models are manufactured on the same assembly line (Michalos *et al.*, 2010). The products of the automotive industry are therefore starting to gain resemblances to buildings which are often considered to be unique or customized while assembled from widespread building components. Over time the automotive industry has developed methods to provide highly customizable products. A lot of these methods are derived from product design and assembly methods which are applicable in diverse mass production industries. These methods can therefore function as reference for the design-to-robotic manufacturing strategy in the building industry.

V. DESIGN-TO-ROBOTIC MANUFACTURING STRATEGY

5.1. Parametric workflow

Parametric design allows for automatic generation of building components and manufacturing data in a single workflow (Krieg and Lang, 2019). This is enabled by the graphical algorithm editor Grasshopper which is integrated in the CAD-software Rhinoceros-3D. The parametric design process for manufacturing with Grasshopper contains pre-defined or custom made components which can be connected to each other in an acyclic graph. Each component performs a predefined action based on the connected output of the previous component. The changes are real time visualized and make it possible for the designer to react without having to reset or restart the script (Brell-Cokcan and Braumann, 2010). The short feedback loop enables the designer to quickly iterate through multiple design parameters and visualize the various stages of process from geometrical form to manufacturing simulation.

5.2. Robot design space

This chapter proposes an approach for a fluent integration of design and manufacturing for construction automation with industrial robots. The benefit of a high level integration between the design phase and robotic manufacturing process is the guaranteed level of quality intended by the designer, because the designer is fully informed about the manufacturing possibilities (Menges, 2012). Therefore, knowing how to control and simulate the robot operations during the parametric design process can be considered as one of the most important aspects for a fluent workflow from design to manufacturing for the designer.

Originally industrial robots were not intended to run unique motion paths in changing circumstances (Keating and Oxman, 2013). Programming of the robot's movement typically done for manufacturing are often static and time consuming manual processes that require expert knowledge (Gupta, Arora and Westcott, 2017). These methods are not feasible for construction automation because different design options resulting in high motion path changeover times and thus limiting the adaptability and capacity of the manufacturing process (Stumm, Braumann and Brell-Cokcan, 2016). In addition, the static methods for motion path planning are being utilized at the end of a one-way design to manufacturing workflow. Hereby neglecting an essential feedback loop for the designer. Namely that the robot setup arguably influences the design freedom in the production process as much as the chosen material (Krieg and Lang, 2019). Thus, to efficiently use the production process it is important to design building components with the robot design space in mind, this is known as robot-oriented design (Bock and Linner, 2015).

5.3. Adaptive robot control

Over the last decade flexible and more user-friendly bottom-up approaches with software tools have been developed in the creative industry. Such as inverse kinematic robot motion simulation, automatic generation of robot program language from digital tool paths and the ability to integrate end effector operations in the robot configuration. Recently more robot control research initiatives are focused on connecting real-time robot movement for feedback and control for the designer to aid between theoretical modelling and fabrication (Stumm, Braumann and Brell-Cokcan, 2016; Sharif, Agrawal and

Sweet, 2017).

These software tools are plug-ins for the graphical algorithm editor Grasshopper. There is a variety of commercial and open source adaptive robot control tools available, such as KUKA|prc (Brell-Çokcan and Braumann, 2011), HAL (Schwartz, 2013) and FUROBOT by Fab-Union. Depending on the software tool industrial robots from ABB, KUKA, FANUC and others are supported including external axis, end effectors and tools. Hereby opening up easily accessible and applicable possibilities to integrate robot fabrication in the parametric design environment for designers. However, these adaptive robot control tools do not consider the unique industrial robot characteristics such as robot arm inertia and the actuator capabilities. This is often only implemented in the propriétaire robot program software of the manufacturer, for example Robot Studio from ABB. This should be considered for applications such as gluing where a very precise material distribution is required.

5.4. Subassembly material and operation container

In order to deliver numerous design options the automotive industry has shifted from complex integrated product architecture to modular product architecture. The modular approach enables alternative designs by mixing and matching the different variants of each module and introducing variable scalability of design options (Paralikas *et al.*, 2011). Similarly, a building consists of many different elements. For construction prefabrication a modular approach is not only important for variety, but also essential for on-site assembly. Accordingly, each building component can be considered as a subassembly of a larger assembly (Figure 1).

In the design-to-robotic manufacturing strategy subassemblies are parametrically described in material and operation containers with inputs and outputs that affect the configuration of the subassembly. For example dimensions, load bearing capacity, fire resistance and aesthetics. Accordingly, the subassemblies are stored in a database of product families. A product family architecture is a grouping of similar subassemblies which possess underlying design and assembly processes or have the potential to share the same materials. In this way design and production changes are kept at a minimum which is beneficial for the simplification of the assembly process (Tseng, Jiao and Merchant, 1996; Gupta and Krishnan, 1998).

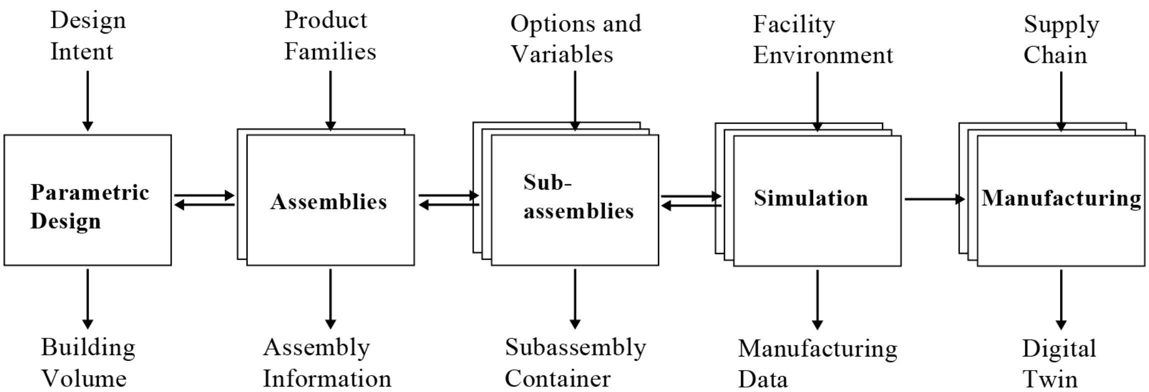

Figure 1. Integrated design-to-robotic manufacturing strategy with short feedback loops

In addition, the robot operations can be automatically generated. Although there are subassembly options and variables, the types of operations performed by industrial robots remain the same for each feature. What changes are the locations of the operations and the number of operations that have to be performed. The industrial robot operations can be grouped into three main categories: materials handling, materials shaping and structural joining. Each of the main operations consist of multiple elementary operations. For example drilling, cutting and gripping (Saidi, Bock and Georgoulas, 2016). In an efficient workflow each of the elementary operations are predefined in function blocks and follow an object-oriented approach. A function block contains one specific industrial robot operation routine. Each function block has a link to its parents task and links to possible child-tasks. This allows to generate task sequences that are related to each other. For example pre-drilling holes followed by screwing to avoid splintering of the material when structurally joining parts (Figure 2). This approach allows for an adaptive process of calling operation sequences. These sequences can be linked to generated subassemblies whereby the number and locations of the operations are determined. Hereby a database with various function block taxonomies is defined that can be used as a catalog for operations. Accordingly the function block sequences are linked to the subassembly material and operation container.

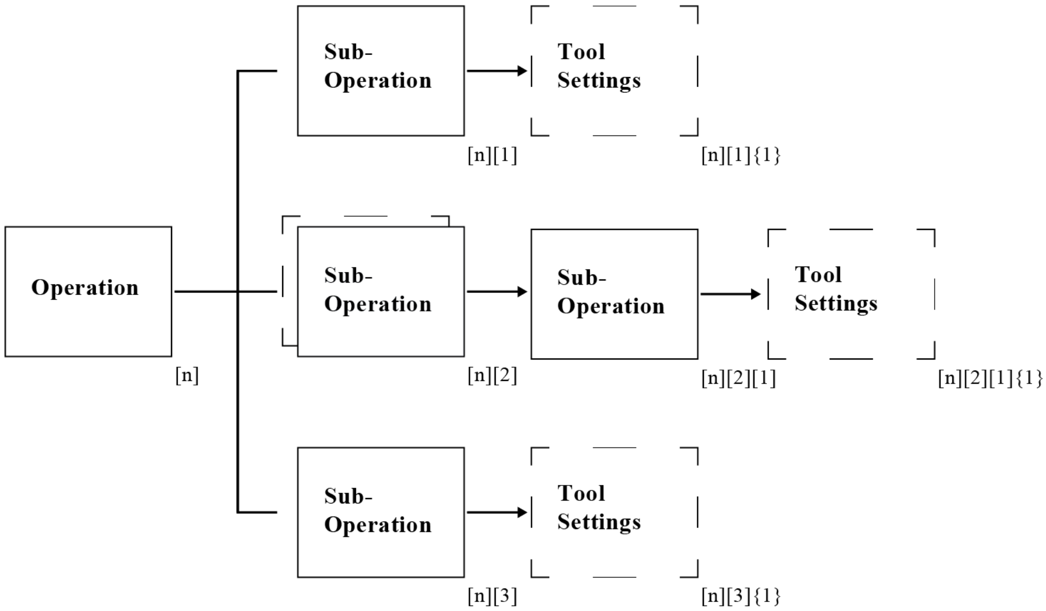

Figure 2. Taxonomy of function blocks for robot operations

5.5. Parametric subassembly variables and options

Adjusting variables of a subassembly in a predefined parametric design-to-manufacturing process only has an effect on the configuration of the subassembly, since the sequence of the parametric design-to-manufacturing process will remain the same. New design options on the other hand request each separate sequences in a parametric design-to-manufacturing process. The sequence has to be manually created in advance in order to implement it. The amount of design options can therefore increase the complexity of the design-to-manufacturing process (Figure 3). In order to avoid frequently adding new parametric sequences and adjusting the manufacturing configuration because of the introductions of new design options it is important to define ahead what options should be provided.

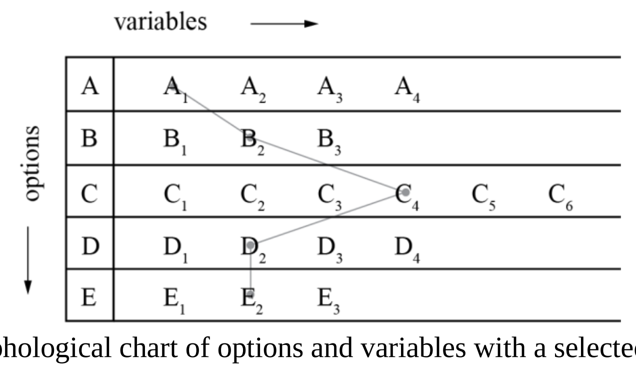

Figure 3. Morphological chart of options and variables with a selected configuration

5.6. Design for assembly

The order how different subassemblies are assembled have an important influence on the quality of the final product and the assembly process (Hu *et al.*, 2011). Therefore, the manufacturing sequence must be considered in the initial stages of the design-to-manufacturing strategy. For complex manufacturing sequences advanced algorithms have been developed to assist with finding optimal configurations (Dini *et al.*, 1999; Li *et al.*, 2011).

VI. SCALABLE AND FLEXIBLE ROBOT ASSEMBLY

6.1. Supply network

Bock and Linner (2015) described a tier framework for supply chains in the building industry based on an original equipment manufacturer (OEM) model from the manufacturing industry (Figure 4). Each tier relies on the previous tier and adds value in every step. The model explains the general material flows as well as information during manufacturing of the products. In general, structured environments for manufacturing are thus essential to foster the creation of building components. Therefore, the whole supply chain has to be considered since each value added step holds the potential to prestructure and simplify processes for the next step.

A reliable supply of products is critical for the continuity of the workflow. Production disruptions can have severe operational and financial consequences. Accordingly, optimizing supply processes can have a manifold positive impact. Nowadays, strategic modelling of the supply chain is aided with advanced frameworks to gain insights in supply decisions such as redundancy and costs (Arashpour *et al.*, 2017).

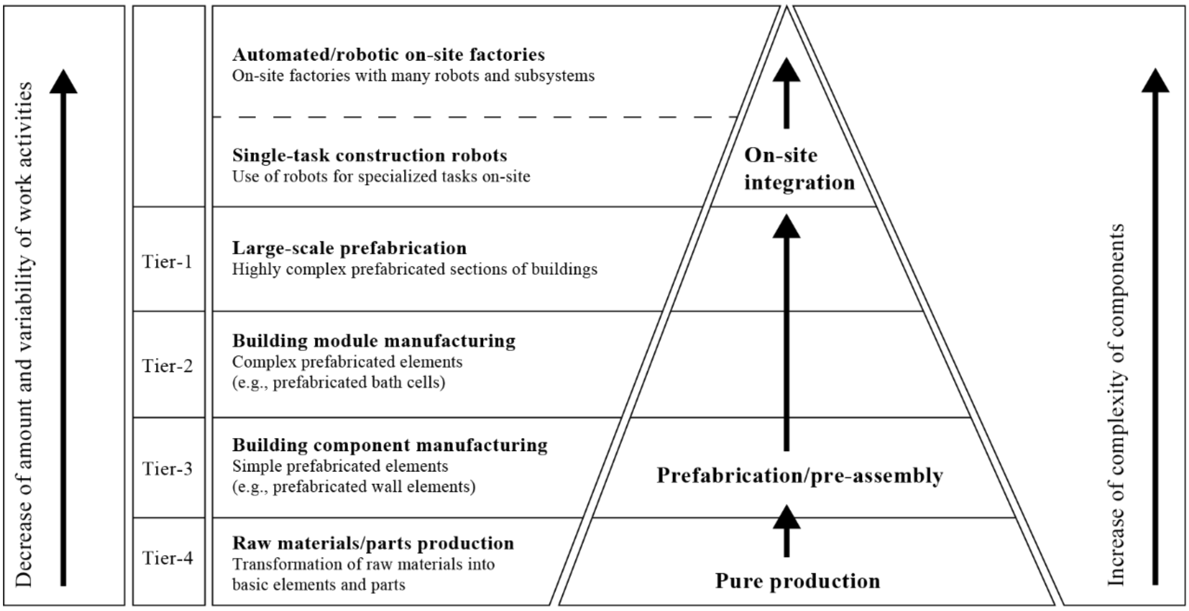

Figure 4. OEM-like integration structure in automated/robotic construction as reproduced in source from (Bock and Linner, 2015)

6.2. Assembly line balancing

Construction prefabrication ranges from tier 1 to 3 and concentrates on assembly of parts. Assembly lines are flow-oriented production systems which consist of stations arranged along a conveyor belt or similar mechanical material handling equipment. At each station certain operations are repeatedly performed. Optimally partitioning the assembly work among stations with respect to some objectives such as cycle time and number of stations is known as assembly line balancing problem (Scholl and Becker, 2006). In general, determining the assembly line configuration is complex, because there are many factors involved. For example machine utilization, investment cost, resource energy consumption, availability, annual production volume and product options. Therefore, the assembly line configuration is often developed by experts with the help of advanced simulations generated by algorithms (Hu *et al.*, 2008; Michalos *et al.*, 2015). Accordingly, numerous feasibly assembly line configurations exist depending on the weight of factors. Ultimately the assembly line configuration has a profound impact on the level of productivity, flexibility and cost of manufacturing (Lafou *et al.*, 2015). And therefore needs to be considered carefully.

Assembly lines can be primarily classified in synchronous and asynchronous configurations based on the type of line control (
Figure 5). The parts in a synchronous system move from one station to the next at a constant pace.

Therefore, synchronous systems are more appropriate for mass production with high production volume of a single product. Asynchronous systems on the other hand are more commonly used in assembly systems with multiple subassemblies. Hereby is the main assembly setup often serial and connected with feeders from other serial subassembly lines. The workpiece is passed to the next station when it is not blocked (Hu *et al.*, 2011; Lafou *et al.*, 2015).

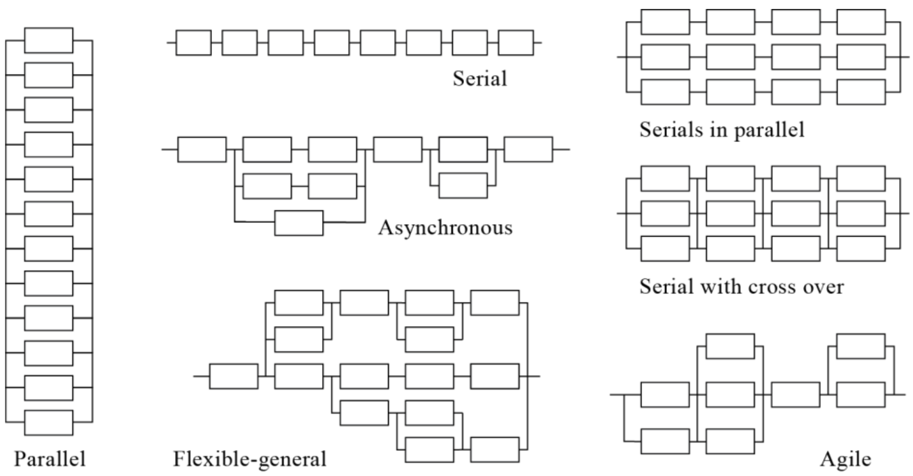

Figure 5. Different assembly system configurations as reproduced in source from (Hu *et al.*, 2011)

In order to cope with market fluctuations and product variations several approaches have been developed (
Figure *6*). A multi-model assembly line produces a sequence of batches with intermediate setup operations. Each batch contains units of only one model or group of similar products (Boysen, Fliedner and Scholl, 2007). Scholl's 1999 book explains that a mixed-model assembly line produces the units of different models in an arbitrarily intermixed sequence (as cited in Boysen et al., 2007). Each approach has its own in challenges in terms of balancing and sequencing.

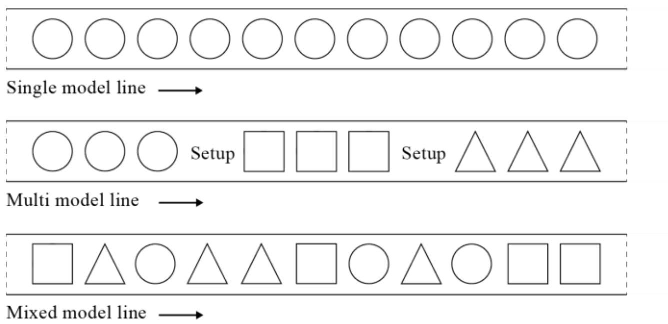

Figure 6. Product variations on assembly lines

6.3. Robot configuration

There are several factors that need to be considered when deciding on an industrial robot. These are cost, reach, payload, maximum speed, repeatability, accuracy and degrees of freedom (Gupta, Arora and Westcott, 2017). Moreover, depending on the operation special considerations need to be taken for example when working in moist environments or working alongside humans.

Flexibility in robot operations can be achieved with automatic changes of end effectors and function blocks. However, this process increases the robot's passive times. This factor needs to be considered during assembly line balancing (Michalos *et al.*, 2010). Moreover, maintaining the material flow such as glue can increases the complexity of automatic changes of end effectors. Another option is to install multi-tool end effectors which are fixed on the robot. In this case multiple tools are integrated in one end effector. This reduces the passive operation times and decreases the complexity of the process, although the number of different operations is limited.

VII. FROM PROJECTS TO PRODUCTS IN AN INDUSTRIAL SCALE

7.1. Traction for prefabrication

The success of the described design-to-robotic manufacturing strategy relies on careful optimizations of the prefabrication process. Such as the choice of materials, 2D panels, 3D modules or hybrids and mastering challenges in design, manufacturing, technology, logistics and assembly (Figure 7). Moreover, achievements of scale and repeatability are influential too (Bertram *et al.*, 2019). Nonetheless, the benefits of prefabrication are manifold. Since prefabrication improves the performance and efficiency of the product, such as the upholding of quality while saving time through the shortening of building phases, reducing failure costs and increasing workers' safety (Bock and Linner, 2015).

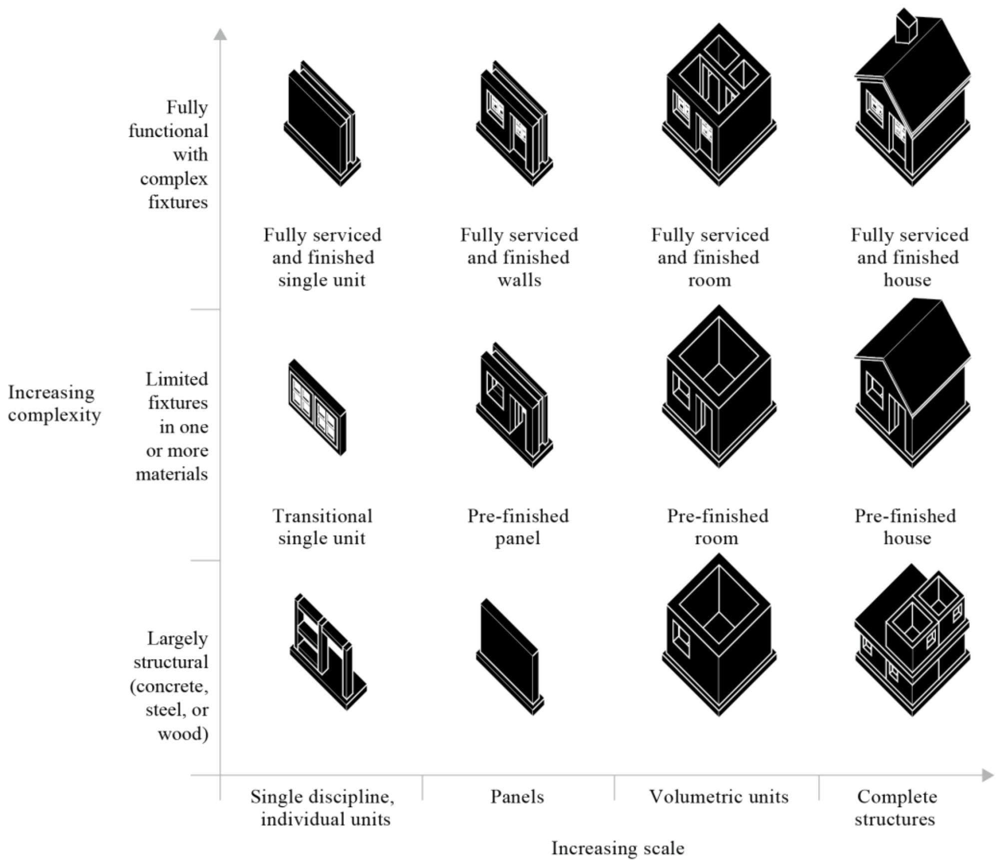

Figure 7. Complexity and scale of prefabricated construction as reproduced in source from (Bertram *et al.*, 2019)

7.2. Feasibility parameters for robotic automation business case

In order to make robotic prefabrication automation feasible the return on investment is crucial. Therefore, it is important to choose the right level of complexity to meet current and foreseeable future needs. Consequently, manufacturing processes that can be easily modified and adapted to maximize flexibility and economies of scale have a great benefit not only for the return on investment, but also for the development of new products (Tilley, 2017). Hereby contest technological developments the performance characteristics of assembly systems. Moreover, a target group analysis has to be conducted in order to understand the product requirements of potential clients (Wamelink, 2019). This is essential because a high initial investment in the manufacturing facility and product development is required before being able to market it to customers.

To define a business case for robotic manufacturing for prefabrication automation the facility as well as depreciation, financing, operating expenditure, and machinery cost on each project must be determined (Bertram *et al.*, 2019). More specific, costs can be specified in variable and fixed. Variable costs include raw materials, labor and energy cost while fixed cost include investment, tooling, building, maintenance and overhead costs (Paralikas *et al.*, 2011). Bock and Linner (2015) specified parameters classified in soft and hard items. Soft items comprise personnel/labour management, supplier management, production plan control, costing, sales and general management. Hard items comprise production capacity, factory network, selection of production technology and vertical integration. Thus, a thorough analysis has to be conducted in order to understand the financial aspects of the business case.

VIII. DISCUSSION

This fundamental research sets out a high level strategy for design-to-robotic manufacturing. At present-day it is an unproven method for building construction. Notably for the digital workflow and assembly line configurations it is recommended to conduct further practical research. Prior to the practical research it is advised to define a clear product concept substantiated with a target group analysis. Based on the product the optimization formulation for the design workflow and the assembly line balancing problem can be identified. Hereby it is recommended to conduct empirical research consisting out of experiments and case-studies. Accordingly the quantitative results will lead to a better understanding of the possibilities and implications of the processes. It is essential to perform this thoroughly in order to develop a feasible business case for the product.

Moreover, a qualitative research about off-site manufacturing processes in Japan can be fruitful for further development of the design-to-robotic manufacturing strategy. Japan is currently the most advanced in the use of robotics, but also in mass customization and after service in prefabricated construction. Accordingly, in Japan the client's most influential reason to buy a prefabricated house is because of the high quality and performance (Matsumara, 2004).

It is expected that the role of the architect within the design-to-robotic manufacturing process will change. Hereby opening up the possibility to guarantee a high quality level of the final product because the architect can have control over the design process as well as the manufacturing process, although the design options have to be restricted to manufacturable assemblies in the facility. In order to avoid falling back to mass production of monotonous buildings the social impacts must not be overlooked. Therefore, the architect's role is to guard the processes on behalf of this. Moreover, new disciplines previously unfamiliar in the construction industry such as robotic engineers and data scientists will likely trigger the innovation spiral for productivity, products and services. Therefore it is recommended for future research to investigate the social effects of the design-to-robotic manufacturing strategy on the practice of construction and its practitioners.

IX. CONCLUSION

The current building industry has an increasing costs of labor, a for decades stagnated number of productivity per employee and highly fragmented design-to-fabrication processes. These negative influences obstruct the mass production of buildings to fulfill the need for housing. Presented in this research is a design-to-robotic manufacturing strategy based on established industrial manufacturing methods combined with parametric design. Hereby opening up an adaptive and scalable approach for customizable prefabrication automation in an industrial scale. Parametric design allows for automatic generation of building components and manufacturing data in a single workflow. Consequently integrating the design and manufacturing processes for the designer that allows for a higher quality product due to the controlled environment and ability to simulate the manufacturing process. By using (sub)assemblies and product families with parametric options and variables a broad range for customization of the product is achieved while still being able to manufacture it from the same assembly line. The asynchronous assembly line is configured for mixed or multi model assemblies and therefore offers a high level of flexibility, scalability and adaptability. However, market adoption for prefabrication and automation is essential in order to become feasible. Moreover, a thorough target group analysis has to be conducted in order to understand customer specific requirements. This is important since there are high initial investment costs involved in the product development as well as manufacturing facility. These factors must not be overlooked in order to define a feasible business case.

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