CONNECTING LEAN CONSTRUCTION TO PREFABRICATION COMPLEXITY IN SWEDISH VOLUME ELEMENT HOUSING

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ABSTRACT

Lean is about waste elimination and value creation and prefabrication of houses seems to be one way to create structure and decreased complexity and waste generated by variation. However, prefabrication decreases some types of complexity and waste but introduces other ones through new roles of the actors and a shift of focus to manufacturing.

The aim of this paper is to develop an understanding of a prefabrication strategy and to show the increased need for a novel comprehension in lean construction regarding different types of prefabrication deliveries and thus different types of complexity. Complexity as such, in this paper used in a contingency context, cannot be generalized and this study explores the differences in peculiarities of on-site construction, element prefabrication and volume element prefabrication. Peculiarities in volume element prefabrication are found to consist of two connected parts; Product complexity including building element design and product design (built-in knowledge) and process complexity including internal logistics, breadth of required knowledge and integration between product and process design. The sources of complexity in volume element prefabrication are thus connected to the in-house production system, differing from on-site construction and element prefabrication peculiarities connected to fragmentation and uncertainty among actors in the value chain.

KEY WORDS

Volume element prefabrication, Building peculiarities, Product complexity, Process complexity, Timber frame housing

INTRODUCTION

Within lean construction there seems to be two different strategies where structuring of the dynamic and complex construction system is created through reducing complexity and waste generated by variation. The strategies are either to develop the on-site construction process and its product as proposed by e.g. Koskela et al. (2003) or development of the prefabricated product and its process as proposed by e.g. Ballard and Arbulu (2004). We call the latter a prefabrication strategy where the lean ideal is to simplify site installation to final assembly involving every phase in the project delivery process. In Sweden the prefabrication strategy is a trend in progress that has shown to be competitive in housing through factory manufacturing and controlled process flows (Bergström and Westerberg 2004). Prefabrication along with standardisation of products and processes are also shown by others to contribute in construction process improvements (Gibb 2001, Roy et al 2003). However, lessons learned indicate that elimination of waste and complexity through prefabrication cause new problems that have to be tackled to obtain intended benefits (Koskela 2003). On the other hand, this is not an argument that should be a hindrance to further developments of a prefabrication strategy since prefabrication can be more than a complement to

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on-site construction as volume element prefabrication has shown to be in Sweden, Figure 1. A volume element is here defined as a three-dimensional structure, built up by elements and completed in a factory.

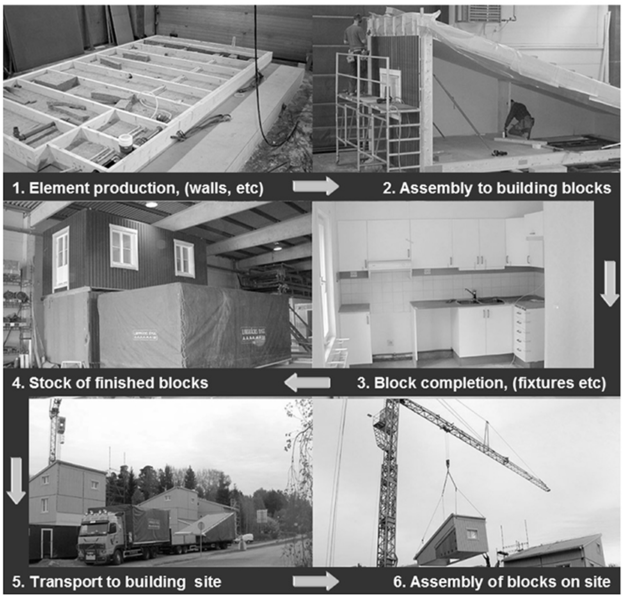

Figure 1: Volume element prefabrication and assembly.

The aim of this study is to develop the understanding of a prefabrication strategy and to show the increased need for a novel view in lean construction regarding different types of prefabrication deliveries. One intention is therefore to chart differences and to describe the relationship in peculiarities of on-site construction, element prefabrication and volume element prefabrication causing waste generation and complexity in products and processes. Complexity as such, is in this paper used in a contingency context, why complexity not is the goal, but a theoretical approach to address differences between construction and prefabrication.

DIFFERENT MODES OF COMPLEXITY IN CONSTRUCTION

A COMPLEX SYSTEM

A complex system can in a wider context, related to literature in general, be described as "any form of system that comprises many components interacting with each other" (Lucas 2000). Complexity studies are related to what happens when components within a certain system are connected and when stimuli to the system are received. Complex system literature (e.g. Rose-Anderssen et al. 2005) shows that evolution are to be expected in real systems that survive in a changing environment and that a complex system is one in which successive future structure will be created.

In construction the complex system has been studied as connections mainly consisting of relationships between actors and organisations (e.g. Bertelsen 2003) or as demands on physical connections between building components (Björnfot 2004). Complexity in construction has also been connected to uncertainty and interdependence that causes difficulty of implementing planned production workflows (Gidado 1996). Separate and diverse organisations, operations and activities and characteristics of materials and knowledge are factors making construction a process of varying choices from project to project (Baccarini 1996). In this study the whole complex construction system is considered from a general point of view but the empirical part, and hence the system delimitation of the study, focuses on the volume element prefabrication production process. The complexity of this process is in its turn influenced by the complexity of the prefabricated product, an even more delimitated complex sub-system.

ON-SITE CONSTRUCTION

In the traditional construction process a structure is built up by a number of components and subassemblies on-site, Figure 2. Peculiarities of construction are argument to be the one-of-a-kind nature of the construction project, the site production and the temporary organisation (Koskela 2003). The mentioned views of complexity in on-site construction are clearly related to the more holistic terms of uncertainty and fragmentation, problems likewise recognized in studies of the Swedish housing industry (e.g. Fredriksson 2003). Also evident is that the complexity related to construction fall within a system engineering description of complexity that seems to be generic; the connection or interdependence between different elements in a system is far more important than the elements (number of tasks, specialists, components) (Lucas 2000, Baccarini 1996).

PREFABRICATION

It is argued that complexity as such cannot be generalized and nor can it be defined generally since it depends on the context where it is used (Edmonds 2000, Rodriguez-Toro et al. 2004). Complexity of on-site construction of houses cannot be directly compared to complexity of prefabricated housing. Depending on the way products are delivered, conceivable sources of complexity in prefabricated housing arise. One type of product delivery is element prefabrication. The element is manufactured in a factory environment with controlled manufacturing processes—

the so-called *factory physics* (Hopp and Spearman 1996) that in this paper is associated to one single process owner. The element is transported to the construction site where it is assembled together with other elements and sub-assemblies. This part is called the *construction physics* proposed by Bertelsen (2004) and in this paper associated with work on-site where several different actors are involved, Figure 2. Peculiarities within factory physics are managed with lean manufacturing principles while peculiarities in construction physics are managed with lean construction principles (Bertelsen and Koskela 2004). In this study, the concepts of factory physics and construction physics are only used as terminology, describing two different environments, without any further use of the underlying theory.

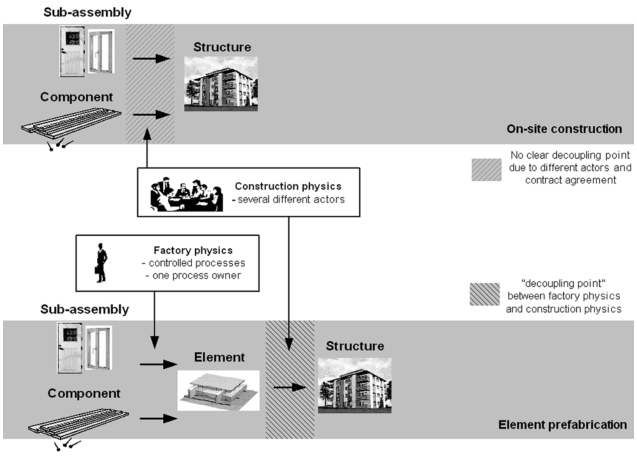

Figure 2: On-site construction respective element prefabrication

In a case study of a multi-storey timber housing project a principal source of complexity for prefabricated elements assembled on-site was claimed to be the level of tolerances between different elements and sub-assemblies (Björnfot and Stehn 2005). The tolerance problems originated from an unsettled definition of the "decoupling point", i.e., the separation between factory manufacturing of elements and the physics of the construction site. The same types of peculiarities in prefabricated construction, namely the lack of an overall view where different actors have different focus, is identified (Warszawski 1990). Thus element prefabrication assembled on-site is partly linked to the same type of complexity as traditional on-site construction, i.e., fragmentation. Longer flow causing higher requirements for cooperation and coordination, longer error correction cycles causing large correction costs, tolerance problems and a higher amount of required design early in the construction process are mentioned as sources of complexity in element prefabrication (Koskela 2003, Björnfot and Stehn 2005).

PRODUCT AND PROCESS COMPLEXITY ORIGINATING IN CUSTOMISATION

In order to handle complex products even more effectively it is central to establish empirical relationships between product complexity and process complexity, especially since relationships differ depending on customer requirements (Hobday 1998). The product complexity is made up by the product design, i.e. the geometric shape and component interface geometry and inbuilt knowledge. The process complexity are those requirements that a process must meet if it is to convert conceptual design into a physical product. Hence the process complexity heavily depends on the design of the. The complexity of the product tends to increase in proportion to the different strategies employed between standardisation and customisation, Figure 3, (Lampel and Mintzberg

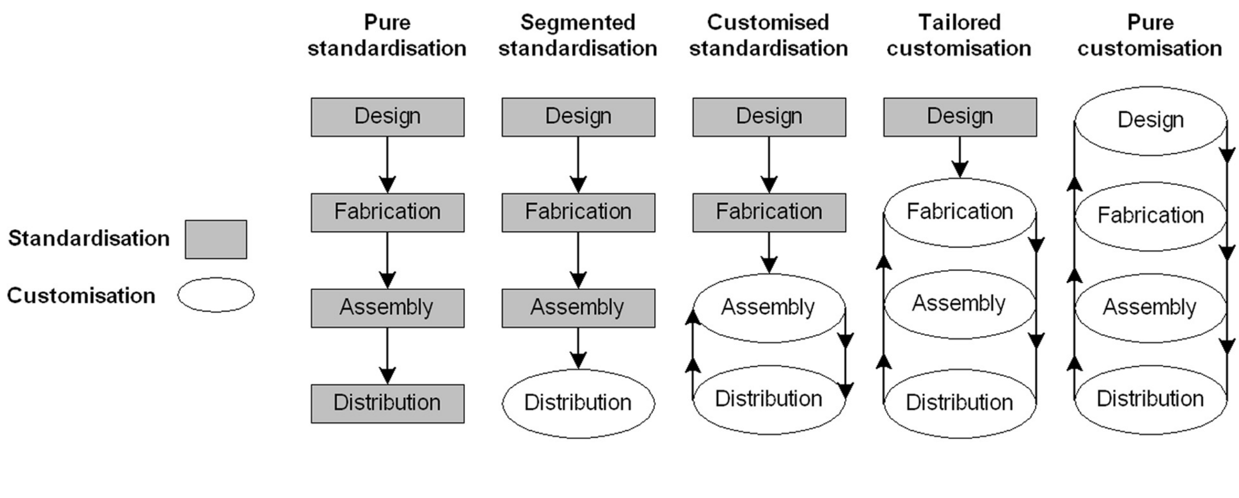

Figure 3: Standardisation and customisation. After Lampel and Mintzberg (1996).

1996) and the number of different products (Hobday 1998). The connection between customisation, increased cost and lead-time in housing is shown by Barlow et al. (2003).

From Figure 3, it is obvious that increased complexity of a delivered product is connected to increased customisation. Customisation influences the number of diversity of inputs and/or outputs, number of separate and different actions, and interactions between individuals or tasks to produce the end product. Likewise, a higher number of internal and external specialists involved in a project, i.e. going from left to the right in Figure 3 will lead to an increased process complexity (Hobday 1998, Kotteaku et al. 1998).

EMPIRICAL RESEARCH METHOD

The aim of this study is to develop an understanding of a prefabrication strategy. To obtain this the complexity in prefabrication and the relation between the degree of standardisation, customisation, product and process complexity in prefabricated Swedish housing were studied. A multiple case study of the five leading Swedish timber frame house manufacturers, using volume element production, was performed. Personal in-depth interviews, site visits and complementary phone interviews with respondents with comprehensive responsibility and understanding of the companies' product and process design were performed. Interviews were also held with employees in the factory production. Other source materials were documents as construction drawings, process charts and product and process descriptions. The case descriptions are relatively comprehensive to obtain a wide picture of volume element prefabrication in Sweden.

RESULTS

General, salient observations for all studied case companies are first outlined and thereafter the main results and characteristics for each studied company. Common for all studied manufacturers is that they:

- Manufacture "ready-to-use" volumes, integrating elements and subassemblies complete with electrical installations, flooring, cabinets, wardrobes and finishing etc. in a factory. The volumes are transported to the construction site where they are assembled to a complete house, Figure 1.
- Have long-time relations with some selected suppliers of key components.
- Purchase subcontractors and consultants traditionally, but practically always the same actors and individuals, familiar with the manufacturers' routines and working methods, are selected.
- Experience restriction in volume element design determined by transportation limitations.
- Have, in some sense, problems with the design of their factory layout. Most layouts are not designed for volume element production and typically ad hoc solutions originating from an element manufacturing layout, still exists.

In support to these general observations Bergström and Westerberg (2004) shows that the Swedish timber frame house manufacturers, using volume element production has a developed logistics thinking which has yielded methods to handle customer demands of short lead times and high flexibility compared to traditional construction.

FLEXATOR AB

The main products of Flexator are official and commercial buildings as schools, group dwellings, social service and office buildings. The manufacturer offers standard concepts for some of the product types, but yet most of the buildings are customized why projects often, to some extent, are one-of-a kind. Flexator prefer to work in projects where they take care of the whole construction process in design and build contracts where planning and manufacturing of the complete house with installations and wiring together with house foundation and infrastructure is included in the product. This demands a wide and flexible organisation, in its turn demanding projects where the complete organisation is utilized.

Former, standard concepts were a more distinct element in Flexator's product offers, differencing from today when the company are working with customised products. The difference in production is principally the lost repetition effects and by that increased information need. Material suppliers demand more information when components differ from object to object. Information from customers must be gathered early in the process, since the design phase has to be finished before the production phase can start. Problems frequently arise when information from customers is handed over to the production where mistakes in understanding of construction documentation are common. Craftsmen also have to read construction drawings more frequently, compared to earlier when they knew the standard products by heart.

The loyalty to the process in early stages seems to be low as employees states that "the company is too good-natured towards customers, allowing late changes in design leading to deterioration of efficiency in production". Problems are also connected to a need for improved internal logistics in the factory. The production is not optimal as wall and floor elements often have to be turned or moved back and forth. Elements are also stored in a disadvantageous way since the factory is too small.

FINNDOMO GROUP

Finndomo Group has concentrated their production towards dwellings as detached houses for private consumers, terrace houses and larger projects with multi family dwellings. The multi family dwellings projects have been executed in close cooperation with a large Swedish contractor. Since Finndomo often cooperates with the same contractor in projects, they participate in the early design phase and the development of the product. The main benefits here are that the company can develop products fitting directly into their building system, leading to good economy and efficiency in projects.

Customer requirements sometimes differ and a more customised product result in more required information from and to customers and suppliers. Early design phases are also lengthened in time in highly customised projects. On the whole the customisation mainly influence lead time, mostly since customers are late in their decision about choices they can make, but also depending on non-standard component choices that can have longer delivery times than standard components. The most critical point, regarding information flow, is that sales persons have to understand customers choices correct, and then be able to document the information so that other levels in the value chain do not misunderstand the information. To develop the industrial process, material flows and internal logistics have to be developed further. A future vision is that customers' apprehension of volume element prefabrication has to be turned from the mental picture of volumes as booths and barracks, to see the possibilities with flexible, high quality prefabricated houses.

MOELVEN BYGGMODUL AB

Moelven Byggmodul AB manufactures building products from simple booths to office buildings, schools and multi family dwellings. The wide product offers are possible since Moelven owns four different Swedish companies where the different product types are manufactured. Some of the products are sold to municipalities while most multi family dwellings are developed together with a large contractor.

If a standard concept is compared to a customised project the standard house is said to be far more rational to produce. A standardised concept demand less time for design, planning, purchasing of materials and sub contractors, and the employees know how to make the product. The difference between a standard house and a customised house is mostly based on the difference in required information in the value chain. Purchasing of materials is one activity that is highly exacting in a customised project and the same goes for the information flow between the purchasing division and the design team. Customisation carrying different volume sizes also render long set up times in production and several material switches. The production today is highly customised, but Moelven vision to render a more effective production process to decrease costs. A possible solution mentioned is to work with standard concepts and offer customisation through options (extras) to obtain higher repetition effects in production. It is important for the company to participate in early design phases to be able to influence the house design to fit the building system. A future vision is therefore to spread knowledge about volume element prefabrication to customers and architects.

LINDBÄCKS BYGG AB

Products offered and manufactured by Lindbäcks are student lodgings, hotels, multi family dwellings (mainly four storey houses) and senior dwellings. Products are flexible and the only limitation is the physical dimensions set by transportation and structural demands for the volume elements. Contrary other studied manufacturers, the factory layout do not seem to be a major problem for Lindbäcks. Though products are highly customised Lindbäcks use the same type of system solution independent of product design. Every project is unique and suited after customers demand, but for e.g. student lodgings repetition effects are gained since house design is standardised within and between every project. Degree of customisation influence the efficiency in production and increased information flow is said to be one key issue. Material that cannot be bought via annual agreements calls for extra work and more information to and from material suppliers. Another type of information is increased need for customers understanding of effects of late decisions in the process, influencing economy in projects. A strategy is to train sales staff to reject late changes in design to obtain an efficient production. Increased customisation and information flow also influence employees in production since much changes lead to decreased project learning.

However, the company has observed a decreased efficiency due to employees getting into a rut when projects exceed a number of 100 to 150 flats. The ambition and the future vision is that the company to a higher extent has to control the information flow. To reduce waste occurring in defects in production it seems to be important that information about new projects not are handed over from the design phase to production before all information is absolutely completed and correct.

NORVAG BYGGSYSTEM AB

Norvag Byggsystem AB primary manufacture official and commercial buildings as schools, pre-schools and office buildings, but the company has also tried to widen their market towards dwellings. Norvag has developed suggestions for multi family dwellings, student lodgings modules and a module for electricity hypersensitive persons. Except these standard modules, Norvag is solely working with highly customised projects. All products are fundamentally unique, but the building system is always the same, i.e., the company has a standard design for e.g. walls. The most common procedure is that the company adjusts their system after a customer's design of an ordered house but the most effective is if they can design a house by themselves.

It is emphasized that the production is managed with focus on customer value and not with focus on internal production efficiency since the flexibility and customisation is the core value to retain customers. Nevertheless the repetition effects and project learning is important since customers also demand short lead times and low costs. The design phase is a critical phase since the design has to be correct from the beginning to avoid mistakes in production. To develop the process improved internal logistics are mentioned as important. Another important issue when manufacturing customised products seems to be the information flow from the design team to employees in the production plant.

ANALYSIS AND DISCUSSION

The systems engineering statement that the connection between elements is far more important than the elements themselves, (Lucas 2000, Baccarini 1996) has been analysed. On-site construction, element prefabrication and volume element prefabrication show different peculiarities, position and importance of the decoupling point between factory physics and construction physics, Figure 4.

In traditional on-site construction there are no distinct decoupling point between factory physics and construction physics (except for smaller sub-assemblies as e.g. windows and doors). Instead the connection of importance and also the connection where problems arise are the interactions in the temporary organisation of the one-of-a-kind project (Koskela 2003).

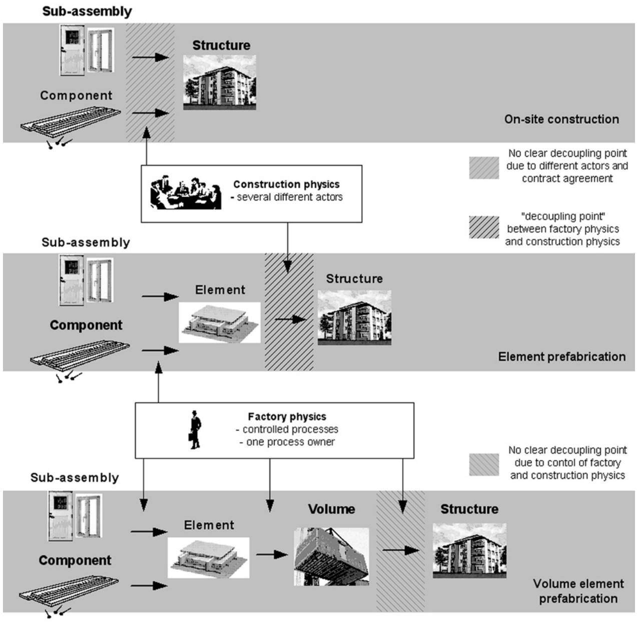

Figure 4: On-site construction, element prefabrication and volume element prefabrication

In element prefabrication the tolerance problems originating from e.g. poor communication are shown by Björnfot and Stehn (2005). These problems point to the importance of handling the complexity in the connection, or the decoupling point, between factory physics and construction physics where the product from the element manufacturer is handed over to the contractor. Complexity is reduced when standardisation is obtained (Lampel and Mintzberg 1996) why the only right way seems to be to standardise the connection, the communication, to reduce mistakes and to overcome the complexity. In building projects, using element prefabrication, the initial design decisions are important—changing a prefabrication decision on-site is often difficult due to long lead times (Koskela 2003).

As in on-site construction, there is no decoupling point of distinct importance between factory physics and construction physics in volume element prefabrication since the whole process, and thus the information flow, is handled by the volume element manufacturer. The process is located within factory physics though volume elements are assembled on-site. Some of the studied companies often cooperate with a large contractor that e.g. makes the foundation to the houses. This decoupling point does not however seem to be a problem causing complexity. Instead other "connections between elements" are related to peculiarities and problems in volume element prefabrication. One typical problem encountered is the need of better internal logistics e.g. regarding the flow of material in the production. High customisation demand increased information to customers so that they can understand what in their decisions that cause longer lead times and higher costs. Also important for the case companies are that correct information from customers is procured. The multiple case study shows that the fragmentation is eliminated for volume element prefabrication and if e.g. tolerances yet are a problem for a volume element manufacturer, the problem originates from a poor control of the in-house production system and not because of fragmentation. This discussion indicates that relevant sources of complexity of prefabrication of houses using volume element production is related to the in-house production system, i.e., progress within factory physics. The case study results imply that lessons for volume element prefabrication can be learned principally from lean manufacturing since the development areas are more related to factory physics managed with lean manufacturing principles rather than lean construction principles.

The design phase is a limitation for the volume element manufacturers as it demands large efforts at the same time as the design phase have to be completed in early stages before the production phase starts. In a lean project delivery system the product and the process are designed together (Ballard and Howell 2003b). Thus a development area, and also the area that most likely can decrease costs and lead-time, seems to be integration of product and process design. To decrease costs and lead times it is also evident that an increased knowledge about building systems of volume element prefabrication for architects and customers is needed. Advantages would arise if the manufacturers did not have to adjust an already designed house to their building systems, entailing double design phases and not the best conditions for an efficient prefabrication strategy.

This study indicates a strong link between degree of customisation and peculiarities, and thus complexity in volume element prefabrication as shown by Hobday (1998).

- The degree of customisation determines the element design; influencing the type of integration between elements and the number of different elements. Through Figure 3 it is possible to understand the studied companies'customisation/ standardisation strategy and it is obvious that choice of strategy is important, since it influence the process complexity. Flexator and Norvag are the companies that act with a clear "Pure customisation" strategy in Figure 3, while Lindbäcks, Moelven and Finndomo have strategies more to the left in the figure.
- The element design, i.e., the product complexity, influences both material and information flow and the breadth of required knowledge, i.e., the process complexity. Low loyalty to a settled product design in late phases affects the process complexity and makes prefabricated products much less effective. Two interdependent sources are causing this. Customers (e.g. contractors, real estate trustees etc.) that do not understand the product and the effect of late changes. Employees (e.g. designers, salesmen) at the manufacturers have to have loyalty to the system and not accept late changes. An obvious input to a successful prefabrication strategy is thus not to accept late changes.
- The kind and degree of in-built knowledge, i.e., product design of the delivered product, influence the complexity. A high product complexity where the whole construction process is handled requires a flexible organisation with several different skills and varying knowledge involved in the process.

Summing up the different peculiarities leading to different types of complexity between the three different ways of delivering a product (on-site construction, element prefabrication and volume element prefabrication) is shown in Figure 5 below.

CONCLUSIONS

This study shows that it is not appropriate to generalize management of construction without considering the difference in complexity between on-site construction and different types of prefabricated product deliveries. Therefore it is proposed that a novel view within the lean construction concept is needed to more clearly incorporate tools and methods in a lean manufacturing context considering e.g. innovative prefabrication deliveries as volume element prefabrication. Peculiarities in on-site construction as e.g. the temporary organisation, and two or more production locations in element prefabrication are related to fragmentation causing complexity. This study shows that peculiarities in volume element prefabrication are connected to product complexity through choice of customisation/standardisation strategy, element design and in-built knowledge in the product. The product design influence in its turn the process complexity which in volume element pre-

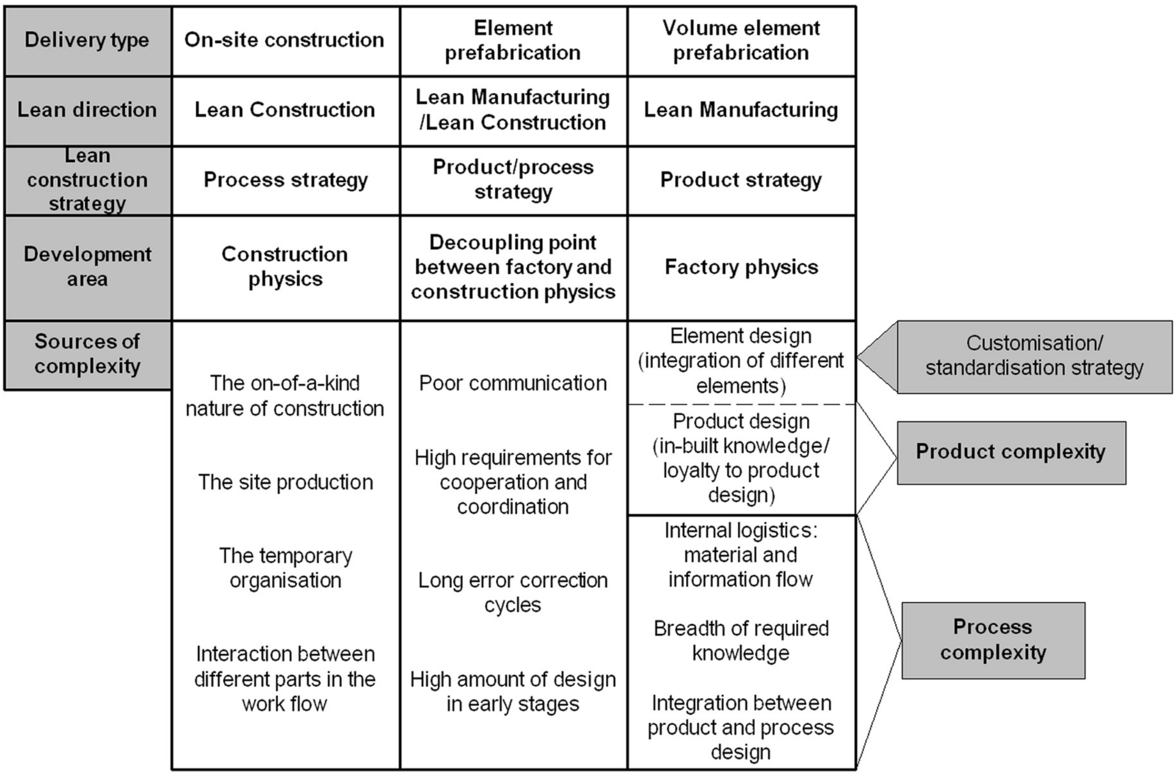

Figure 5: Peculiarities and complexity depending on product delivery

fabrication shows peculiarities as internal logistics, breadth of required knowledge and integration of product and process design.

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