INDUSTRIALIZATION OF CONSTRUCTION – A LEAN MODULAR APPROACH

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ABSTRACT

The concept of industrialization and lean thinking in construction has drawn quite a bit of interest in recent years. Authors have recently begun to critically debate the direct implementation of lean thinking in construction; instead the focus should be related to transformation, flow, and value. This paper is based on a literature review of modularity, lean construction, and buildability. Modularity is then extended to the production phase where simulated assembly scenarios are used to explore and exemplify modular effects during production of long-span timber structures. The literature review suggests that modularity is related to product management, with process management effects, while lean thinking is a process management principle. Both principles are focused on the creation of buildability which is argued to be more of a goal than a means of efficiency. The simulation scenarios indicate possible modular benefits associated with, e.g., organization, out-sourcing, pre-assembly, prefabrication, and development. Modularity is thus argued to advocate management of production in the form of lean construction. The focus for timber construction should be on modularity; i.e., a bottom-up product focused view enabling product value. Such a view has potential to be a driving force in the struggle for industrialization in construction.

KEY WORDS

Assembly, buildability, constructability, industrialized construction, lean thinking, modularity, production, timber structures.

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INTRODUCTION

Industrialization can be seen as a structural means for eliminating, or at least drastically reducing, on-site activities in construction (Koskela, 2003). Industrialization is thus a streamlined process promoting efficiency and economic profit. Regarding the goal of industrialization, there is a wide variety of literature considering the industrialization approach in construction, e.g., supply chain management (London and Kenley, 2001; Naim and Barlow, 2003), lean construction (Gann, 1996; Crowley, 1998), buildability (Poh and Chen, 1998), scheduling (Austin et al., 2000), re-engineering (Winch, 2003), and standardization/prefabrication (Dawood, 1996; Gibb, 2001). Two main principles aiming for industrialization are found in the construction literature above; lean construction and buildability. A third main principle, modularity, is a key issue in the engineering management literature applicable to the manufacturing industry.

In the manufacturing industry modularity has been shown to reduce the number of suppliers from thousands to a few hundred (Crowley, 1998). A good example of industrial success is Volvo Corporation, where the integrated modularity has been guiding the company's transformation (Kusiak, 2002). Modularity is said to be a key concept in the manufacturing industry and has helped lead the way towards widespread industrialization (Gann, 1996). In Björnfot and Stehn (2004) it was argued that industrialization for the construction industry should be linked with modularity, incorporating both prefabricated and standardized products.

The concept of lean construction is concerned with the application of lean thinking in construction (Green, 1999). Authors have recently begun to critically debate the direct implementation of lean thinking in construction (Green, 1999; Naim and Barlow, 2003; Winch, 2003). Reengineering of construction should, instead of applying the whole lean paradigm, focus on its foundation, i.e., transformation, flow, and value (Koskela, 2003). A third principle mentioned together with industrialization in construction is buildability. Buildability has been focused on a wide variety of tasks in construction, e.g., production methods (Fischer and Tatum, 1997), the construction process (Griffith, 1986), and organization of production (Stewart, 1989; Ferguson, 1989). In lean construction, organization of production is termed as work structuring (Ballard et al., 2001).

In Björnfot and Stehn (2004) it was shown how product modularity can guide the design process for long-span timber structures, aiding in the design and providing guidance in optimization problems. Modularity also confers process related effects and can thus ease the implementations of lean construction principles. The motive for the research presented in this paper is to show how modularity in construction can be utilized for an efficient industrialization of construction. The aim of this paper is to explore the industrialization principles; modularity, lean construction, and buildability by attempting to understand their relations and implications on construction. The construction process is in this paper regarded as the transformation process, i.e. flow of information and material in design and production respectively. As simplifications, no analysis is performed of the construction process or its flows, and product value is considered to be a vital part of the value for construction as a whole, without any deeper analysis of its implication. Effects of modularity in construction is finally explored and exemplified by simulating possible assembly scenarios for long-span timber structures, using current production practices. The empirical data used for the simulations is based on a case-study performed at a Swedish design company.

INDUSTRIALIZATION PRINCIPLES AND THEIR RELATIONS

Paramount to this paper is the construction industry and the conventional "design & build process" (D&B), Figure 1. The process description is based on Swedish conditions and used during construction of long-span timber structures. The explored industrialization principles are related and linked together using the different phases of the construction process. The case study is used to in practice explore the implication of modularity in construction and specifically, its relations to lean construction and buildability.

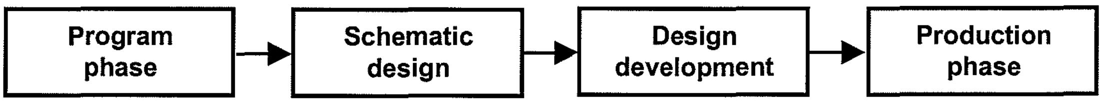

Figure 1: The considered construction process.

MODULARITY

Modularity in construction has frequently been viewed as the use of simple building blocks (Rampersad, 1996), or volumetric pre-assemblies (Murtaza et al., 1993; Dawood, 1996). Today, the sense of the term module has evolved so that a module contains the specifications of a building block and interfaces, as well as considerable functionality compared to the end product (Miller and Elgård, 1998). Based on this definition, the volumetric pre-assemblies are a number of modules fitted together into volumes. The volume is thus a form of modularity, which is a system attribute (Miller and Elgård, 1998). Modularity can therefore not be defined from the modules themselves instead modularity is related to product structure and functionality, and should be used considering the products whole lifecycle (Nørgaard, 2002).

One of the most important aspects of modular products and their realisation is the potential for efficient flexibility and responsive manufacturing through flexibility/agility (Marshall and Leaney, 1999), and reduced process complexity (Marshall et al., 1999). The term mass customization is often mentioned together with flexibility and argued to be a key aspect of modularity (Marshall et al., 1999). The basic drivers behind the wish for modularity, Table 1, are found in (Blackenfelt, 2001) summing up the drivers given in (Miller and Elgård, 1998; Marshall and Leaney, 1999). Nørgaard (2002) uses the product lifecycle when sorting module drivers; however the drivers are basically the same.

Table 1: The module drivers and their relation to the three main problems approached by modularity.

Module drivers		
Commonality Variety Internally planed change Externally driven change Upgradeability Addability Reconfigureability	Concentration of risk Separate development Parallel development Pre-assembly Separate testing Out-sourcing (buy) In-sourcing (make)	Repair Replenishment Component reuse Material recycling Incineration Landfill
Variety versus commonality	**Organization of development and production**	**After sale of product**

In the literature, measured quantitative effects of modularity in construction are rare. There are clearly effects of modularity that are difficult to measure in quantitative terms, i.e. variety and complexity as well as process related effects in development, manufacturing, and production. Murtaza et al. (1993) report construction phase cost savings of 10 % using modularity and Gotlieb et al. (2001) report schedule and cost savings of up to 25 %.

The literature review suggests that modularity is both a product and process attribute, and should be developed by a linked methodology (Marshall et al., 1999). The modular process covers all the modularity effects in the product value-chain; only by performing product modularity can the benefits be realized. For the construction process;

- **Variety** through modularity aims at the reduction of internal complexity and increased external variety, i.e., provide a means for an open building system.
- **Development** aims at the development of new modules for increased external variety. In construction this can emerge as out-sourcing of modules for increased supplier competitiveness or development of multi-functional modules.
- **Production** aims at the design and use of products in such a way that a streamlined production can be achieved.
- **After-sale** aims at the use of modules after structure lifetime, disassembly and recycling of modules as well as extension of structure lifetime by reconfiguring.

THE LEAN METHODOLOGY

The primary goal of the lean concept is the elimination of waste or in other terms, creation of value (Green, 1999). Lean thinking concentrates on the two main conversion activities; design and construction, where information and material flows are the basic units of analysis (Crowley, 1998) - *"lean thinking concentrates on going into the "black box" and studying the processes with the objective of smoothing out interfaces, removing non-value adding activities, or in some cases completely rebuilding the processes and generating new* *processes*" (Halpin and Kueckmann, 2002). The basic purpose of lean thinking is thus the management of conversion processes to promote flow, figure 2.

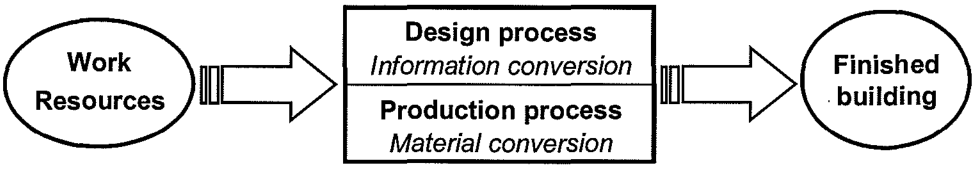

Figure 2: In construction, the lean concept is the management of the conversion process.

The main practices of lean thinking most often referred to in the literature is; just-in-time (JIT) and total quality management (TQM) (Gann, 1996; Green, 1999; Halpin and Kueckmann, 2002). The practices, total preventive maintenance (TPM) and human resource management (HRM) were added by Shah and Ward (2003). A literature survey by Shah and Ward (2003) identified a number of key practices associated with JIT, TQM, TPM, and HRM summing up the above key characteristics, Table 2.

In construction the information conversion process may be related to design development while the material conversion process is associated with production. For the application of leanness in construction (e.g., Ballard et al., 2001; Bertelsen and Koskela, 2002; Koskela, 2003) it is argued that construction should be based on; maximizing value, minimizing waste, and the transformation of inputs into outputs. Lean construction is thus a methodology aiming at streamlining the whole construction process while product requirements are realized during design, development and assembly. The solutions to the value/waste generation proposed in e.g. Ballard et al. (2001) incorporates many of the concepts from the lean practices, Table 2, the modular practices, Table 1, and further many arguments based on the concept of buildability/constructability.

Table 2: Key lean practices in JIT, TQM, TPM, and HRM (adopted from Shah and Ward, 2003).

Key lean practices			
Lot size reduction	Preventive maintenance	Benchmarking	Self-directed teams
Continuous flow	Maintenance optimizat.	Quality programs	Flexible workforce
Cellular manufacture.	Safety improvement	Quality management	
Bottleneck removal	Scheduling strategies	Process measure.	
Reengineering	New equip./technology	Cont. improvement	
JIT	**TPM**	**TQM**	**HRM**

BUILDABILITY/CONSTRUCTABILITY

The terms buildability (European term) and constructability (American term) both describe a similar area of interest in construction (e.g., Griffith, 1986; Tatum et al., 1986; Fischer and Tatum, 1997). The definitions of buildability found in the literature are most often concerned with the design of the building, i.e., the most common definition; "*the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for* *the completed building*" (Griffith, 1986; Poh and Chen, 1998). This definition suggests that there is more to buildability than the product which also Griffith (1986) observes, linking both technical and managerial aspects to buildability.

An interesting connection is the relation between buildability and manufacturability, the design for assembly (DFA), and the design for manufacturing (DFM) methodologies. Manufacturability can be seen as buildability in manufacturing (Sharma and Gao, 2002). DFA and DFM, are methodologies aiming at reduced complexity in assembly, and reduced assembly costs; therefore their relationships to modularity is strong (Rampersad, 1996). Based on the above definitions it is not unlikely that buildability has its origins in the manufacturing industry. The relationship between the three methodologies and the diversity in their definitions does not provide any clear guidance on what buildability really is, as an example; buildability has also been associated with quality (Pheng and Abeyegoonasekera, 2001). Though, it is clear that buildability has a distinct relationship to productivity. This relationship is not fresh. For example, Poh and Chen (1998) describe a method for evaluation of buildability aimed at an increased productivity.

The main argument in the buildability literature is the use of standardization and prefabrication for increased buildability (Stewart, 1989; Ferguson, 1989; Poh and Chen, 1998). Prefabrication and standardization have advantages as well as disadvantages (Bock, 2001). Even though both standardization and prefabrication are important for an industrialization of construction, they will by themselves not revolutionize construction; instead they should be seen as an effect of the buildability approach.

SUMMARY AND CONCLUSION

The differences found between the three disciplines can be argued to be minimal and their goals the same, i.e., an industrialization of construction. Many authors also seem to mix the principles. Table 3 illustrates the applications of the three principles for the construction process based on the similarities and differences summarized as:

- **Modularity** is both a process and a product discipline offering a wide variety of advantages in the whole construction process. In construction, modularity is applied at the product level and realized in design development and production.
- **Lean construction** is a process management discipline offering management during the whole construction process, aiming at streamlining production.
- **Buildability** is a process and product based principle. In contrary to modularity; buildability is more of a goal than a means for product and process efficiency.

Table 3: The application of modularity, lean construction and buildability in the construction process.

Methodology	Used in...		Provides effects in...
MODULARITY	*Schematic design*	→	*Design development*
	Design development	→	*Production*
LEAN CONSTRUCTION	*Program phase*	→	*Schematic design*
	Schematic design	→	*Design development*
	Design development	→	*Production*
BUILDABILITY	*Schematic design*	→	*Design development*
	Design development	→	*Production*

Based on the literature review and the summarization we argue that the following four characteristics are the core of industrialization in construction, Figure 3;

- the **effects** provided by product modularity promotes buildable designs,
- the **use** of the lean construction philosophy promotes a buildable process,
- lean construction advocates, but **does not** necessarily promote, modularity, while
- product modularity **does** promote a lean construction process.

Two ways of viewing the construction process is top-down or bottom-up (Figure 3). The majority of recent production and construction literature in this area is concerned with streamlining processes, i.e. the implementation of lean thinking which emits a top-down view on construction. In the mechanical industry products are often tailored towards the end customer while the production is volume based. The production of new products is also often based on previous products, enabling reuse of previous technologies and processes. Economic profit in the mechanical industry is therefore based on streamlining processes and enabling their reuse, i.e., a top-down view. In contrary to the mechanical industry, the construction industry is project based with single product production where every structure is viewed as unique and tailored to the end client. The construction industry, and its reuse of technology, can be compared to the design of new products in the mechanical industry, but due to the project based site production the characteristics of the production system may change, causing new problems to emerge (Koskela, 2003). Therefore we, in this paper, argue that the timber construction industry should emit a bottom-up view where the design of the product guides the production processes, i.e., value (or buildability) for the product in design is a requirement for overall product and process value, and in the end; a requirement for end costumer value. Product modularity has in theory been shown to provide many process based benefits; we further argue that modularity is a key concept in the struggle for industrialization in timber construction, and possibly for construction in general.

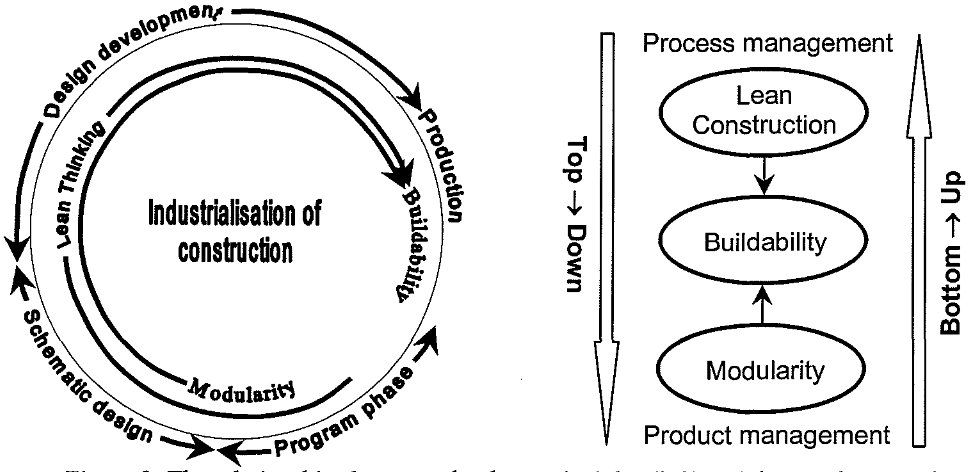

Figure 3: The relationships between the three principles (left) and the top-down vs. bottom-up views in construction (right)

RESEARCH METHOD – CASE STUDY

The case study is based on two phases: interviews and a theoretical survey of the production of long-span timber structures. The case company has three employees and has been competing in the Scandinavian construction market since 1986. The company focuses on long-span structures, offering design and assembly of the structural system. The managing director (MD) has 30 years of experience as a designer. The MD was interviewed with the aim of collecting general information about the assembly operations during the production of long-span timber structures. Long span timber structures were chosen for the easy to comprehend structural system and the straight-forward assembly process. The survey is based on a general type of long-span timber structure used for ice hockey. The aim of the survey was to collect core quantitative production knowledge and experience relating to the case company production practices. The production was studied by reviewing time schedules, quality control plans, drawings, and other documents of interest as well as a rich supply of photographs.

THE GENERAL LONG-SPAN TIMBER STRUCTURE

The specific long-span timber structure, width and length, 36×65 m^2 (118×213 sq. feet), considered in this paper was constructed in southern Sweden during 2003. All quantitative data was compared to the MD´s broad and general knowledge of the production of hundreds of similar structures. The described assembly process can thus be argued as a general process for the production of long-span timber structures in Sweden. The considered structural design is shown in Figure 4.

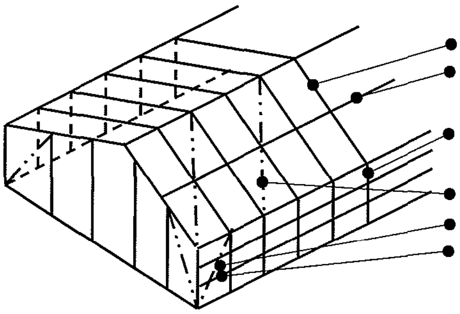

Figure 4: The sub-systems used in this case study

RESULTS FROM THE CASE STUDY

In production there are two general types of resources used; workforce (labor) and machinery (equipment). For long-span timber structures the machinery used are tower cranes and sky-lifts, Figure 5 (picture 4 and 5). The activities during production are divided into three stages. *Sub-assembly* is the activity in which the elements are assembled into a finished module. *Placement* is the activity in which the module, or its constituent elements, is moved on the construction site. *Final assembly* is the activity in which the module is connected to other modules within the structure.

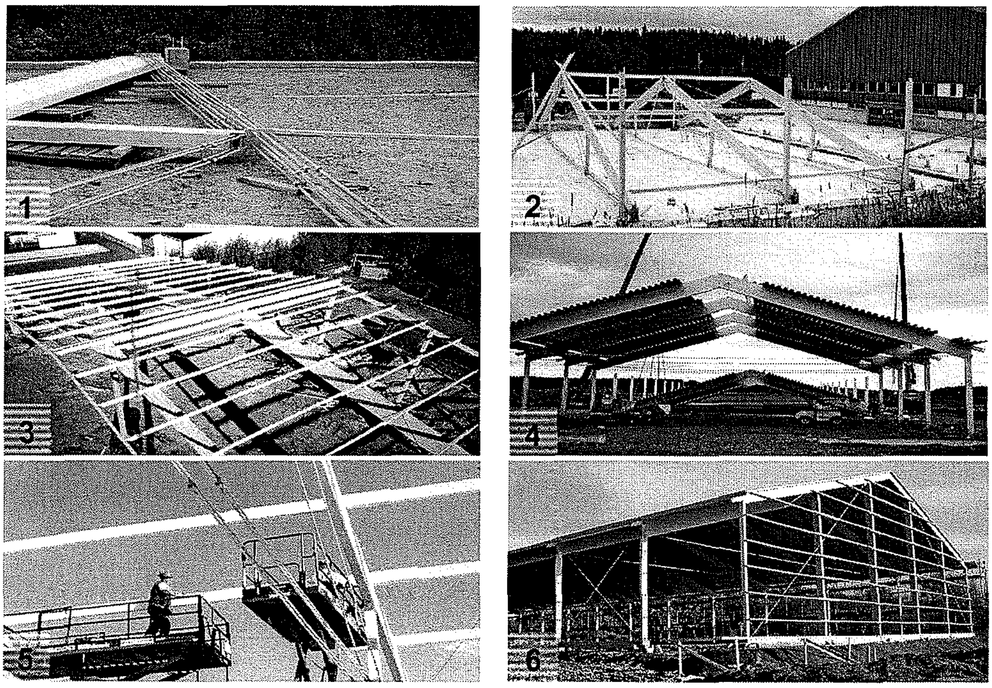

Figure 5: Illustration of the assembly process for long-span timber structures.

THE ASSEMBLY PROCESS FOR LONG-SPAN TIMBER STRUCTURES

In general, the assembly process of the structural system for long-span timber structures takes four weeks. The current sequential assembly process is presented in Table 4. The foundation is cast in place by a separate contractor prior to the start of the assembly. In Table 4, *Sub-system* denote the sub-system being worked on, *Activities* denote the activity performed, *Resources* denote the resources used, and *Time* denote the elapsed time.

Table 4: The sequential assembly process for long-span timber structures.

	Description	Sub-system	Activities	Resources	Time
1 ↓	Set up on site. All required material is delivered to the site on day one.	(set up)	Set up	3 men 1 tower crane	1 day
2 ↓	Organisation of materials; beams, bracers, steel details, etc., Figure 5 (1).	All	Placement	3 men 1 tower crane	1 day
3 ↓	Sub-assembly of roof modules on ground, Figure 5 (1).	Roof	Sub-assembly	3 men	4 days
4 ↓	Sub-assembly, placement, and final assembly of façade columns, Figure 5 (2).	Column	Sub-assembly Placement Final assembly	3 men 1 tower crane 1 sky-lift	1 day
5 ↓	Lift up and temporary bracing of roof modules on ground, Figure 5 (2).	Roof	Placement	3 men 1 tower crane 1 sky-lift	2 days
6 ↓	Preparation of final assembly with roof "packages", Figure 5 (3).	Roof-purlin Stab. in roof	Sub-assembly Placement Final assembly	3 men 1 tower crane 1 sky-lift	3 days
7 ↓	Placement and final assembly of roof "packages", Figure 5 (4).	Roof	Placement Final assembly	3 men 2 tower cranes 2 sky-lifts	1 day
8 ↓	Sub-assembly, placement, and final assembly of gable columns and gable beam.	Column	Sub-assembly Placement Final assembly	3 men 1 tower crane 2 sky-lifts	1 days
9 ↓	Complementary assembly of roof-ridges and stab. in roof, Figure 5 (5).	Roof-purlin Stab. in roof	Sub-assembly Placement Final assembly	2 men 2 sky-lifts	2 days
10 ↓	Assembly of the stab. in façade and gable, Figure 5 (6).	Stab. in wall	Sub-assembly Placement Final assembly	2 men 2 sky-lifts	1 day
11	Assembly of wall-purlins, Figure 5 (6).	Wall-purlin	Sub-assembly Placement Final assembly	2 men 2 sky-lifts	3 days

ANALYSIS AND SIMULATION

The first two days during assembly are generally required for set up on site, unloading of materials, and organization of workforce and materials. The step-by-step assembly process in Table 4 indicates a sequential type of production. Viewing the sub-systems as natural modules in the traditional step-wise assembly process has many potential advantages. Detailed time schedules based on modules and activities may be created by ordering the assembly process after modules (Figure 6). The time schedule is created by performing a day-by-day study of Table 4 and taking note of the current sub-system under work and the activity performed. The time schedule should be read row-wise, i.e., each row contains information about the required activities and time spent on each sub-system. The resources required for each activity can then be obtained from Table 4, e.g., the sub-assembly of the roof system requires four days during which three men are occupied (step 3 in Table 4). Simulations, using the time schedule, of probable scenarios during the assembly of long-span timber structures are used to exemplify the possible effects of modularity in construction and how modularity can confer both construction leanness and buildability.

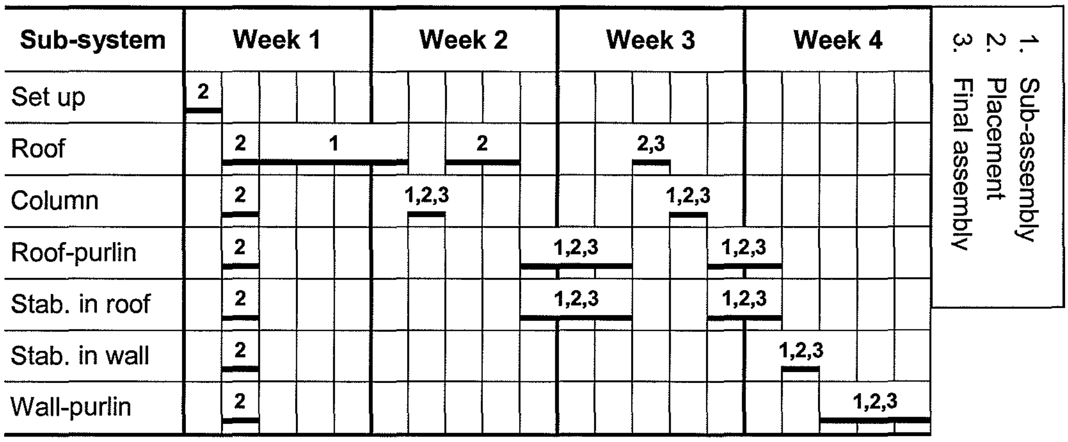

Figure 6: Time schedule sorted by modules, based on Table 4.

- **Set up**. Some components of the roof module are misplaced or were never delivered. Time schedule loss is incurred and one tower crane which has to be on site from day one is left idle (step 1 and 2 in Table 4). *By having each component checked and attached to a module the chance of misplacing items and thereby incurring delays is reduced.*
- **Roof module**. During design, considering the time schedule, it is decided to out-source the roof module for design, manufacturing, and sub-assembly enabling supplier competitiveness and possible cost savings in the program phase. In assembly, the prefabrication of the roof module result in time schedule savings of four days (step 3 in table 4). The cost savings in site production can also be compared with partial prefabrication and on-site pre-assembly. *By the modular approach issues like out-sourcing, pre-assembly, and prefabrication can be used and analyzed in a new light enabling both time and cost savings.*

- **Column module**. The columns are delivered to the site with steel details attached. The sub-assembly part of the column modules is therefore reduced and the time and resource savings incurred can instead be used to work on the placement of the roof system (in Figure 6; work is reallocated from the column to roof during week 2). *A modular approach can enable the reallocation of resources on the construction site.*
- **Roof-purlin module**. A new connector innovation is developed with plug-and-play characteristics, resulting in rapid final assembly. This reduces the overall time required for assembly of the roof "packages" as well as the complementary assembly of the module resulting in time and resource savings. *A modular approach may further streamline the assembly by the development innovations.*

Similar scenarios may be created for the other sub-systems. Possible effects of a modular approach; organization, out-sourcing, pre-assembly, prefabrication, and development, are all ways of streamlining production - a way towards an industrialization of construction.

CONCLUSIONS

The goal of industrialization in construction is the reduction of on-site activities (Koskela, 2003). As shown during the simulations, one of the benefits of modularity is the reduced complexity in choosing whether to remove activities, or to reallocate resources. Modularity was theoretically shown to aid in a lean process and to create buildability by promoting a high productivity. The modular approach enables easier management of the lean main practices by just-in time deliveries, scheduling, quality, and flexibility etc. Buildability is, by the modular approach, promoted already during design by enabling accurate fit between elements within a module and between the modules themselves (Björnfot and Stehn, 2004). Buildability during production is further enabled by the simplified organization of materials and resources.

Due to the adverse participant relations and the segregated construction process, the Swedish timber construction industry is, at this date, not mature enough to handle the implementation of lean practices as is. The focus for timber construction should therefore instead be product modularity, i.e., a bottom-up product focused view. Such a view has potential to be a driving force in the struggle for industrialization of construction.

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