PRODUCT DESIGN FOR IMPROVED MATERIAL FLOW—A MULTI-STOREY TIMBER HOUSING PROJECT

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ABSTRACT

Understanding of construction has evolved to include a deeper understanding of its mechanics; in addition to traditional on-site work involving the manufacturing of building products—industrial construction. One of the most important aspects of any industrial process is flow of materials and resources. Using empirical data from a unique multi-storey timber housing project, this paper aims at building a better understanding of how product design affects flow of materials in housing construction.

Even though a high degree of prefabrication was used in the project, the amount of complementary site work caused delays, complaints, and a slow learning cycle. A standardization process was used to shift product 'know-how' from person to product, resulting in increased flow and a reduction of errors. Prefabrication was not the sole solution to the encountered problems, but the controlled and ordered environment in prefabrication provided solutions at early stages.

Instead of working towards solving the main production issues, the management was instead observed working with minor changes (first-aid solutions) to control flow. If industrialized multi-storey timber housing construction is to be successful, product design decisions should be thought through, thoroughly, from start to finish using standardization as a guiding star.

KEY WORDS

Assembly, Logistics, Multi-Storey Timber housing, Prefabrication, Standardization.

INTRODUCTION

The understanding of construction has evolved to include more than on-site, traditional construction work. Construction now includes a deeper understanding of its mechanics, in addition to on-site work, involving the manufacturing of products—referred to as industrialized construction (or simply industrial depending on the context used). The activities involved in manufacturing and on-site assembly are in theory structured under the terms factory and construction physics (Bertelsen, 2004). This new understanding has provided terms to describe and control processes and operations in order to bring a construction product to life, e.g., waste management, work structuring, industrial operations, etc. One of the most important aspects of any industrial process is flow of materials and resources (Bertelsen and Koskela, 2004).

The design of building products (floors, walls, etc.) has an important impact on flow, evident from one of the main construction issues—lack of tolerance consideration from early design, to manufacturing, and construction site work (Tsao et al., 2004). Solving flow issues already at the product design stage was in Björnfot and Stehn (2004) argued as the main path towards leanness in housing construction. Using empirical data from a unique multi-storey timber housing project, this paper aims at building a better understanding of how product design affects the flow of materials in construction. Since this paper contains the early stages of the case study, no quanti-

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fiable aspects of flow have been collected. Instead, the aim is to explain the observed events in a lean construction context. The purpose of this paper is to analyze current practice of product design in a Swedish multi-storey housing project, and to discuss product design strategies for improved flow. Of interest in this paper is therefore to identify processes, or activities, where lack of flow is a problem, and also to propose solutions to these problems.

CONSTRUCTION THEORY AND TERMINOLOGY

Understanding of construction has with the onset of lean construction evolved into two ways of thinking; factory and construction physics (Bertelsen, 2004). ***Factory physics*** is an understanding of construction as a controlled and ordered system where construction products are manufactured under factory conditions and assembled on-site using industrial operations. Construction viewed from site dynamics is far from such a controlled and ordered system. Construction has in recent literature been denoted as complex and chaotic, e.g., uncertainty in production labour productivity (Radosavljevic and Horner, 2002), project network fragmentation (Dubois and Gadde, 2002), etc. These construction 'peculiarities' are well known issues in construction research today. ***Construction physics*** is the understanding of these specific dynamics. In this paper, construction physics is used to denote work and activities performed to maximize value and remove waste on the construction site. Figure 1 illustrates construction and factory physic, and their relation to the main construction phases; this way of understanding construction is in accordance with the '*Transformation-Flow-Value theory*' (e.g., Bertelsen, 2002). The decoupling point (DP), see also Naim and Barlow (2003), signifies a change in thinking for the completion of a construction project, i.e., this is where the characteristics of construction changes from factory to site based production; the further downstream the DP is pushed, the less amount of work is performed on site while the factory production increase in importance. Consequently, increasing the amount of industrialization in a construction

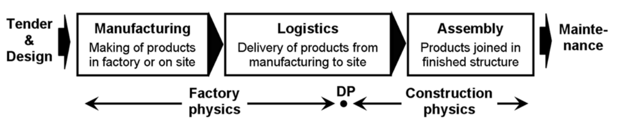


Figure 1: Understanding of construction as a combination of factory and construction physics.

project is achieved by manufacturing more under factory conditions, and/or using industry operations and tools for on-site work.

Lately, industrialization as a concept has been addressed in construction research (e.g., Crowley, 1998; Stehn and Bergström, 2002; Björnfot and Stehn, 2004). The importance of prefabrication and pre-assembly for industrialized construction is described in literature (e.g., Gibb, 2001; Ballard and Arbulu, 2004). Tools used to manage work under factory physics are well developed in the manufacturing industry; one example is Enterprise Resource Planning (ERP) tools. In Sweden such tools are being developed for use in manufacturing of timber frame housing (Bergström and Stehn, 2004). Following the introduction of lean thinking in construction, tools for industrial site work are more frequently discussed in construction literature; the Last Planner system (Ballard, 2000), and work structuring principles (Tsao et al., 2004) are but two good examples.

Work structuring and tools for industrial site work, as well as industrialization involving prefabrication and pre-assembly, aim at the core of lean construction, namely value generation, removal of waste, and improved flow. The seven traditional wastes of construction (overproduction, correction, material movement, processing, inventory, waiting, and motion) and the 8th waste (make-do) are given in Koskela (2004). During a construction project, many participants are involved expecting value generation; tenants' desire satisfying living quarters, contractors desire return on investments, etc. Value is therefore hard to measure in absolute terms; value for one participant is not necessarily of any value for another. The relationship between value, waste, and flow is by the authors summarized as; *if an activity, product design, or process hinders flow, then in some sense it provides less value while generating waste. Waste can be identified by locating flow bottlenecks*. Flow charts can be used to identify waste and flow bottlenecks, e.g., improvement of a house-building supply chain (Naim and Barlow, 2003), and study of a module production system (Arbulu and Ballard, 2004). A flow chart is in this paper used to study the multi-storey housing project.

CONSTRUCTION PRODUCT GENERATION

As the materials are transformed into building products, the value of the product grows. When the product achieves its final place in the structure and is ready for end customer use, the product has attained its maximum value. Figure 2 illustrates a general example of how value is generated in a

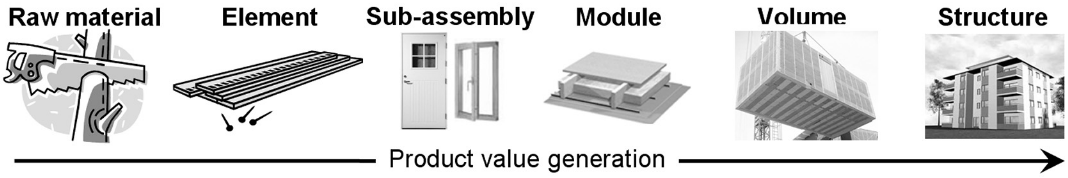


Figure 2: Product value generation in multi-storey timber housing construction.

multi-storey timber structure. Each product involves the use of upstream products, e.g., raw material (timber, plaster, etc.) convey no direct value to the structure by itself, but is in the form of elements (processed raw material), required for downstream products. The highest order of product value in construction is volumes (ready-to-use living space). In this paper, this scenario is called the *'product value chain'*, where value generated is comparable to both streamlining processes (process value) (Starbek and Menart, 2000) and value generated for the end costumer by customization (Naim and Barlow, 2003). A Swedish study of the domestic housing industry indicated a higher return of asset for volume-product companies compared to traditional element companies (Bergström and Stehn, 2004). If return of asset is considered a value for a company, then volumes clearly provide Swedish manufacturers with a higher value than element or module production, as illustrated by Figure 2.

Element and module manufacturers produce products in factories, which are then transported to, and assembled on, site. Volumes are produced through element manufacturing, which are then assembled to three-dimensional volumes complete with installations, surface finishing, doors, wardrobes, etc. The volumes are then transported to the construction site, assembled, and remaining fixed equipment is added. Housing construction using volumes is thus highly dependant on the factory side of construction, which in Figure 1 would push the DP downstream. The design and value generation for each structural component in housing construction can be described using the terminology of Figure 2. Figure 1 can then be used to describe how industrialized the production is and what form of improvements would provide most value for its completion—factory or construction.

In this paper a floor structure is used as a case example. The floor structure is a module built-up from multiple elements and sub-assemblies, integrating many technical systems—i.e., joists or slabs for load-carrying, ducts and cables for installations. If the floor structure is manufactured as a module, then the demand on manufacturing is high (the DP moving downstream). If the floor structure is manufactured as sub-assemblies then the on-site assembly process will increase in importance (the DP moving upstream).

CASE STUDY: MULTI-STOREY TIMBER HOUSING PROJECT

A multi-storey timber housing project is studied, Figure 3. An interesting aspect in this case study is the material and structural system choice, massive timber elements in both floors and walls, Figure 4. Before 1995, multi-storey timber structures were prohibited due to restrictive Swedish fire regulations. Consequently, there is presently a lack of timber construction knowledge among Swedish contractors, consultants, engineers, and architects. The uniqueness of the case is further amplified as product development and experience feedback has progressed hand-in-hand with actual construction.

Figure 3: Illustration of the buildings.

Figure 4: Cross-laminated massive timber slab.

The multi-storey timber housing project involves five buildings of six floors each (a total of 95 apartments over 8.600 m^2 [≈ 93.000 sq. feet]). The case study involves the construction of the first three houses (numbered 1 to 3 in Figure 3). The project is a design-build project where the main contractor procures suppliers, consultants and other contractors. Practical experience was obtained from personnel responsible for design and handling, i.e., interviews with construction workers, site supervisor, project management, and manufacturer personnel. Other data used was documentation from manufacturing and assembly. The main interest during the interviews were collecting experience of floor structure handling and assembly; what are the main problems encountered using the current design of the floor structure, and how can the design be improved to ease flow?

CASE STUDY RESULTS

The floor structure, Figure 5, consists of load-carrying system (massive timber slabs, and T-joists), floor (slabs are used as finished floor surface), and sub-ceiling (a three layer cross-work of timber beams, insulation, and two layers of plasterboards). The product design and material flow results are summarized in a flow chart, Figure 6. The flow chart, illustrates work done under factory conditions and construction site work. Length of flow arrows is just a form of illustration and has no relation to any measure. Value generated (compare with Figure 2) is evident by following the flow (arrows) from *Timber* to **Finished Floor** (raw material to module). The DP for this project is identified as the state when the floor structure arrives ready to be assembled on the construction site.

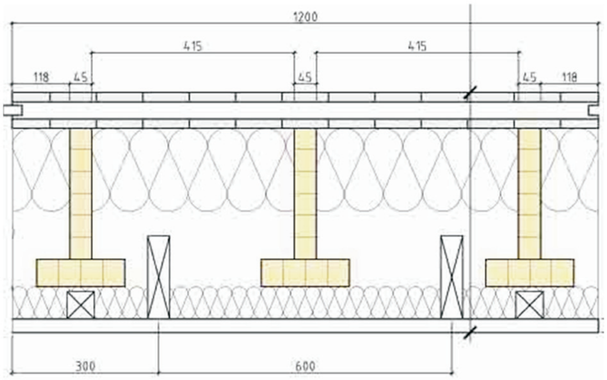


Figure 5: Floor structure drawing.

MANUFACTURING

The manufacturer is one of northern Sweden's largest sawmills and one of Europe's leading and most modern glulam producers. For the manufacturer, the current project is a breakthrough for a new technique and a new way of thinking concerning construction using massive timber elements. Due to the low use of massive timber elements, it is only recently they upgraded their factory production to include a higher degree of automation. The decision to move towards more automation was by the manufacturer crucial to secure delivery for the current project. The contractor project manager stated; *"the manufacturer advertised an undeveloped product, not ready for*

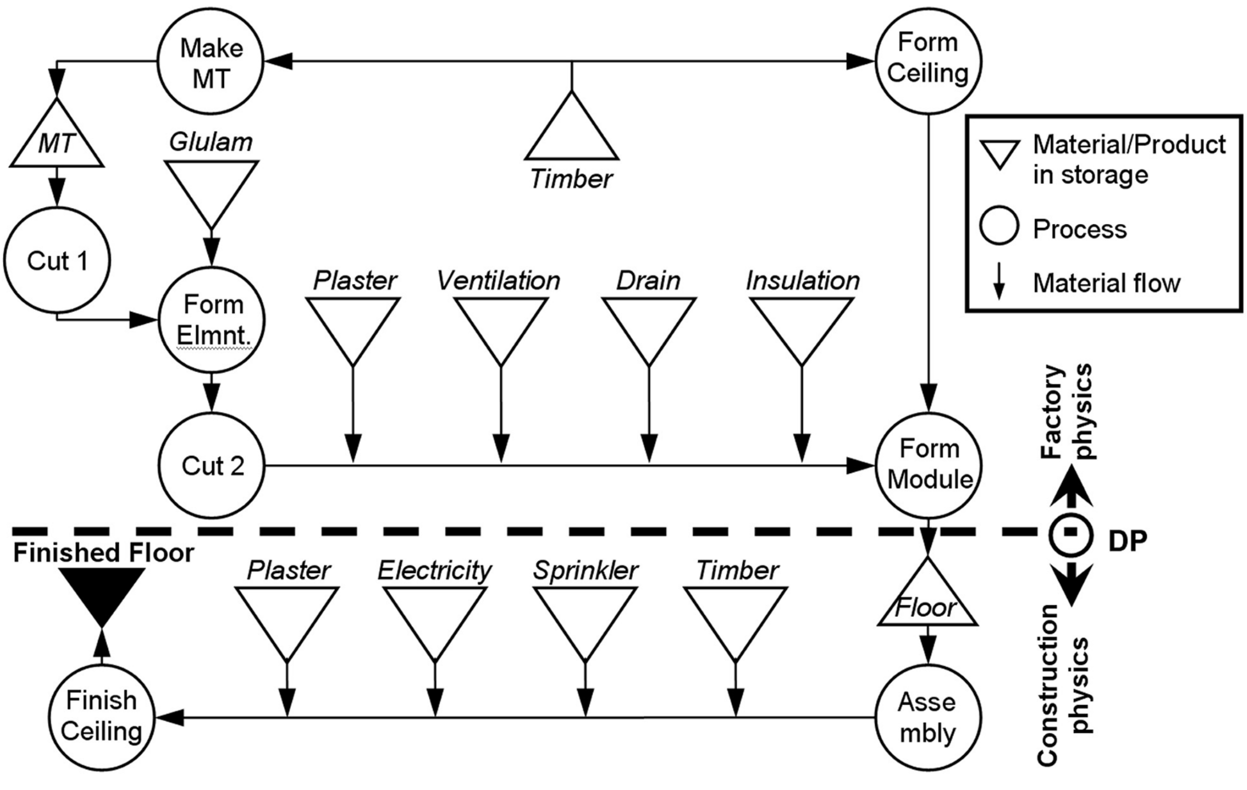
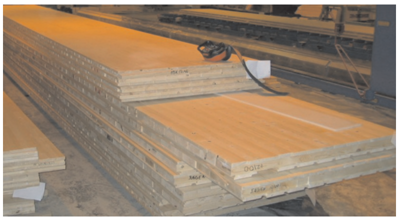
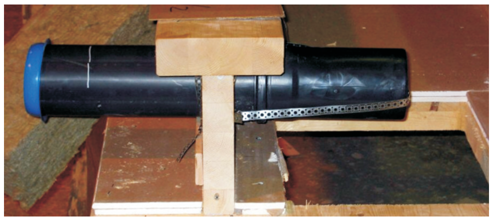


Figure 6: The floor structure flow chart. Processes are described in Table 1.

Table 1: Description of the processes used in the floor structure flow chart (Figure 10).

Process	**Activity**
Make MT	 Massive timber elements (width: 1200 mm [≈ four feet]), are fabricated using three to five glued cross-laminates. The fabrication process is similar to the manufacturer's fabrication of glulam, which is well known and used within the company for a long period of time.
Cut 1	Using a CNC machine, the elements are provided dimensions according to drawings, and sockets for installations and sanitary areas are cut. Tolerance problems emanating from this stage are reported as uncommon. 
Form element	 Glulam beams are glued to the massive timber elements forming beams with T-shaped cross-sections supporting the massive timber elements. The formed elements are then glued together two and two forming elements up to a width of 2400 mm [≈ eight feet].
Cut 2	Holes and notches are cut into the beams for installations. This work is currently performed by hand using handheld machinery. Hand-work is prone to human error, and tolerance errors have been reported from this stage. 
Form ceiling	 A cross-work of timber is formed to support and make room for the sub-ceiling. "Blocks" of timber are added to support the modules in transportation.
Form module	Plasterboards are added to the pre-cut elements, while drains and ducts are added by specialised installation contractors. A layer of insulation is added before the ceiling is assembled, producing a module ready for shipping and on-site assembly. 
Assembly	 The modules are assembled straight from trailers, using a tower crane. The modules are joined to walls using steel-plates and nails or screws. After assembly the ceiling is cut lose from the floor. Tolerance errors discovered at this stage was identified as related to human errors in detailed design or fabrication.
Finish ceiling	On site the sub-ceiling is complemented; A layer of timber is attached, cables for sprinkler and electricity are added by installation contractors, and then insulation and two layers of plasterboards are added. All work is performed from below. At this stage, installation tolerance issues have been the main concern. 

use in a construction project. They were in belief they were contracted as suppliers only, when they had clearly been contracted with overall responsibility for their products (manufacturing to assembly)."

The manufacturing process has been constantly streamlined during the project. Today, manufacturing of the floor structure is performed in a semi-automatic process using computer aided machinery, and classic construction work, Figure 7. The manufacturing processes (*Make MT* to *Form Module*) are described in Figure 6 and Table 1. Timber required for manufacturing of elements and T-joists are brought straight from the manufacturers own sawmill and stored at the factory. The installation work is performed by a contracted installation crew. Cutting and notching the elements is done in a computer aided machine (*Cut 1*). The manufacturer factory supervisor stated; *"the CNC machine provides the slabs with measures according to provided drawings. Tolerance mistakes are mainly due to errors in the detailed design stage."*

Figure 7: Use of handheld machinery

Assembly problems related to manufacturing has been most common during assembly of the first house, the manufacturer factory supervisor stated; *"at the start of house one, we had problems with efficient manufacturing of the floor structures, since it's a new product for us and we didn't have a fully developed manufacturing process."* These errors are mostly related to the massive timber elements having the wrong dimensions, therefore requiring extra cutting work on site, resulting in assembly delays. The numbers of errors related to manufacturing were substantially reduced for house two and three, as shown in a register of construction site faults maintained by the contractor site supervisor.

Another common error related to manufacturing is the cuts and notches used for complementary site work on installations—a general consensus among the site workers are; *"the cuts and notches are much too small for reasonable work rate, and low tolerances on notches makes it very difficult for us to uphold the strict demands on fire and sound insulation. It is not uncommon that the ducts and pipes assembled at the factory are placed up to a few decimetres from their intended place."* Feedback between site workers and factory workers have solved many of these issues, though there are still, as of house three, complaints regarding installation work on site.

LOGISTICS AND HANDLING

The assembly of the floor structure for a whole floor is performed in two stages during two sequential days. Approximately half the floor is assembled in each stage. The manufacturer is responsible for transporting the floor structure modules to the construction site. The modules for each assembly stage were supplied just-in-time using **one** truck and trailer; the transports were pulled from the factory by the assembly schedule. This has been carefully organised in detailed design to minimize transportation, the manufacturer factory supervisor stated *"we have worked with a limit for the height of the modules to ensure they can be delivered to the site on one truck and trailer. This is the main reason why not more parts of the sub-ceiling are integrated already at the factory."* The off-loading was supervised by four workers and a tower crane, one worker connects the modules on the truck (using straps as shown in Table 1—*Form Module*) and the remaining three assemble the modules. *"The transportations and off-loading of modules has worked as intended for all three houses"* is a general consensus among all involved parties. Though, the straps used to off-load the modules are problematic, since these have to be removed and the holes must be carefully insulated to cover sound and fire demands.

At the beginning of this project (house 1), none of the contractor work crew was familiar working with massive timber floor structures integrating structural system and sub-ceiling. The only know-how of the system was in the hand of the manufacturer's personnel. Therefore, the manufacturer factory supervisor was initially forced to spend time teaching the work crew how to handle the *new* system. The supervisor spent a total of six weeks (three assembly cycles) on site transferring his knowledge to the work crew. This enabled feedback of notches, tolerances, connectors, etc. to be brought back directly to manufacturing. All construction site personnel agreed that *"the manufacturer factory supervisor's role was critical for the success of this project. Without his aid we* *would still be standing out there trying to understand the drawings."*

ASSEMBLY AND COMPLEMENTARY WORK

The structural assembly of each floor was performed during a nine day assembly cycle. The modules were fastened on the walls using steel-plates with nails or screws, Figure 8. Handheld machinery (most common; nail guns) was used for the fastening operations. Screwing was, when possible, preferred over nail guns by the site workers due to safety reasons and noise. With the floor structure assembled, complementary sub-ceiling work was performed; adding the third and last layer of timber to the sub-ceiling cross-work, followed by electricity and the sprinkler system (Table 1—*Finish Ceiling*). Then, missing insulation and plasterboards were complemented.

Figure 8: Typical floor-to-wall connection

In assembly, the drawings have been difficult to understand, as was also the case in logistics and handling. The expertise of the manufacturer factory supervisor helped solve many of the issues with the assembly cycle. During early assembly, the fit between factory and on-site assembled installations was an issue. Direct feedback between site workers and the manufacturer factory supervisor solved many miss-fits in installation work, Figure 9. One of the most problematic assembly operations was the connection between floor modules and walls. These operations were commonly complained upon, it is by the site workers often stated that *"a smarter way of fastening the modules is a must; the way we have to work now is simply not possible in the long run."* Even though the assembly process has been continuously improved from house one to three, the assembly schedule has remained mostly untouched. It was agreed on that assembly could be made faster, but the site workers expressed a need to have plenty of time for assembly work due to the rigorous demands on connection work still remaining.

The complementary work on the sub-ceiling is pointed out as an important issue, both from a work environment, and a technical perspective. Complementary work on installations is problematic, as one site worker expressed; *"there is very little space to work in and the tolerances allowed are minimal, best would be if complementary work on installations could be minimized by prefabrication."* Often asked for by the site crew is pre-assembled plasterboards. No reason for not integrating plasterboards in factories was given by the interviewees. Assembly of plasterboards in factories would circumvent another issue, storage on site. For this project the plasterboards for both walls and sub-ceiling are stored at their place of use within the houses. Due to limited space, the plasterboards are often a hindrance when performing complementary work.

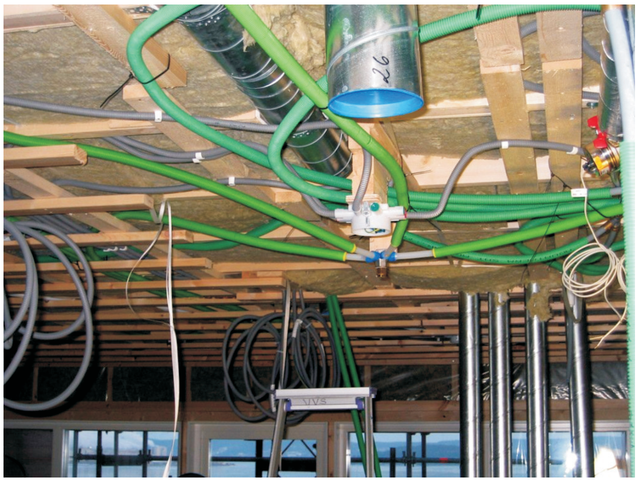


Figure 9: Complementary site work on installations in sub-ceiling.

DISCUSSION AND CONCLUSIONS

As shown in Figure 6, lean construction theory involving factory and construction physics was successfully used to describe the observed production events. Due to a general lack of timber construction knowledge among Swedish construction participants (Björnfot and Stehn, 2004), Swedish multi-storey timber housing projects are often prone to flow bottlenecks and waste generation. This project is no exception. Even though a high degree of prefabrication was used (modules), the high amount of complementary site work caused delays, complaints, and a slow learning cycle. These issues stress the importance of construction physics considerations in prefabrication decisions. In this project, it is clear that the design of the floor structure had a large impact on material (and resource) flow. Table 2 presents examples of product design observations obtained from the case study, highlighting the importance of careful product design.

It should be noted that neither of these performed actions had any major impact on the flow chart structure (Figure 6), i.e., the relation (amount of work) between factory and construction physics is unchanged. Even with the performed actions, the main issue related to the sub-ceiling remain, i.e., complementary work from below. The performed actions instead served as a means to remove waste resulting in improved

Table 2: Examples of performed product design actions for improved flow.

	Problem	Performed Action	Improvement in Flow
Cut 1	Even using CNC, poor design documents lead to elements delivered to site with wrong dimensions.	More attention was given to manufacturing and tolerances already at the detailed design stage.	Reduced extra site work spent manually cutting, or re-ordering elements due to size issues.
Cut 2	Handwork using standard handheld machinery is prone to human errors and mistakes, which are especially evident in complementary site work.	Site installation workers have been in close contact with factory installation workers and manufacturer factory supervisor.	Reduced amount of site work correcting installation placement errors. Has also reduced the time spent adding insulation or plaster related to the corrections.
Assembly	The drawings are difficult to comprehend, and the amount of plates and fasteners used cause bad work conditions and parts missing in assembly.	In the design stage the number of steel-plates and fasteners required for assembly was significantly reduced.	Reduced the amount of work in uncomfortable positions, and reduced the amount of emergency orders on missing parts.

flow within, and between, processes (in Figure 6 this improvement is not quantifiable). More fundamental actions are required to fully benefit from the prefabrication. Table 3 proposes solutions to two of the main identified product design issues and their expected impact on flow.

The *Finish Ceiling* solution would induce a major change in the floor structure flow chart; division of the floor structure into floor and sub-ceiling, Figure 10 (the processes before *Cut 2* are omitted for visibility). In contrast to the flow chart used in this project (Figure 6), the empirical data suggests a flow chart where the DP is moved even further downstream, indicating more work under factory conditions and assembly being the only remaining site activity. While moving work from the site to factories would ease assembly, manufacturing and logistics would instead be introduced with an increased workload. Prefabricating more is not the sole solution to all problems in this project. But compared to the variability of site production (Bertelsen, 2002), a holistic product design where more of the product completion is performed in factories would provide a controlled

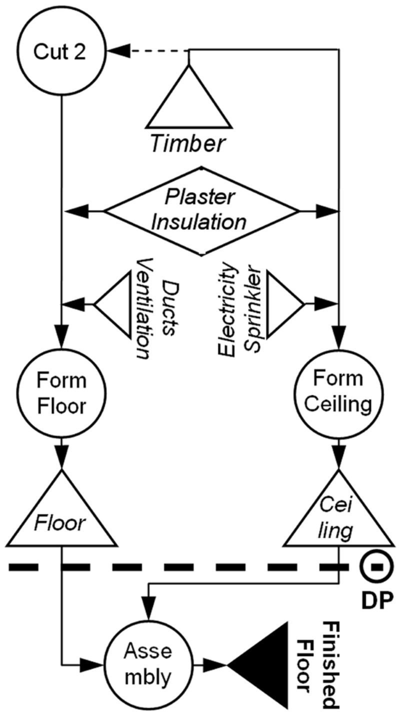


Figure 10: The proposed revised floor structure flow chart.

Table 3: Examples of remaining product design issues and proposed solutions.

	Problem	Proposed Solution	Expected Improvement
Assembly	An easy way of off-loading modules is sought. The straps cause unnecessary complementary site work. The steel-plates used for assembly should be even more reduced, and placed at location where work can be performed efficiently.	Fasten the steel-plates to the modules already at the factory, and find an innovative way to connect these to walls on the site. The steel-plates can also be designed to serve a purpose in off-loading of modules.	Prefabricating and finding innovative connections would significantly reduce re-work on site. Possible problems encountered are related to transportation, storage, and handling of elements containing jutting steel-plates.
Finish Ceiling	This is the main project issue. Working conditions on complementary sub-ceiling work can be described as awful. Limiting or totally removing work from below is a strong wish among site workers.	Divide the floor-structure in two parts; floor and sub-ceiling. If the sub-ceiling is assembled first, this enables work to be performed from above. This would also enable the whole sub-ceiling to be prefabricated.	Working from above is a preferred working position and provides increased quality in complementary work if required. Problems are related to manufacturing, which may be difficult handle due to reduced stability.

and ordered environment with opportunities to solve site waste generation issues already at an early stage.

Each problem identified, and each proposed solution, is a standardization process to continuously improve the floor structure by removal of waste and improvement of flow. Continuous improvements are an important part of lean thinking, and are usually integrated with innovation strategies (Knuf, 2000). All encountered problems can be identified as traditional construction wastes; the main waste in this project being corrections. Each action to solve these problems serves as a driver to shift product knowledge from practitioners to product. This shift of knowledge is important in standardization processes; buildability/constructability is a good example of where standardization serves as a driver for site productivity (Björnfot and Stehn, 2004). The initiator for the shift of knowledge in this project was the manufacturer factory supervisor. Know-how transferred to the construction site workers eventually resulted in an understanding of handling and assembly. The manufacturer site supervisor was the coordinator continuously improving the work and design of the floor structure, while the construction site workers provided input for the standardization of the product and process, Table 2. The proposed innovations (Table 3) were mainly provided by the project management and the manufacturer factory supervisor. Figure 11 illustrates the participants' roles in product development for this project. In each row, the relative area of each process (standardization, continuous improvements, and innovation) illustrates the amount of work performed by the participants. A better developed floor structure design would have allowed the management to give more attention to finding innovative solutions, instead of developing first-aid solutions to make it work at all.

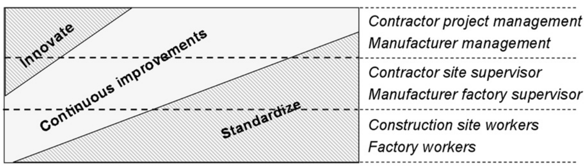


Figure 11: The manufacture's and site personnel's roles in the floor structure development process.

Concluding this paper, the results highlight the importance of the DP for industrialized construction. Failure to utilize a holistic process view in prefabrication often ends up with problems, i.e. unnecessary complementary site work where the advantages of prefabrication are lost. The project has to live with the initial prefabrication decision—changing a prefabrication strategy on the run is often difficult due to long lead times (Koskela, 2003). The main observations in this case study are summarized as;

- ***Think holistic.*** The substantial complementary site work in this project is a result of poor product design decisions in early design phases. As a result, the main advantages of prefabrication (control and order) are lost. Product design decisions should be thought through, thoroughly, from start to finish. In this project first-aid solutions was employed to improve flow but the main issues still persisted.
- ***Standardized thinking.*** In this project each module could have varying dimensions, resulting in unnecessary lead times in fabrication and errors in assembly. The findings indicate that prefabrication without a '*standardized way of thinking*' (more related to mass customization than mass production) is prone to issues; obvious from the managements' decision to add part of the sub-ceiling to the floor, without realizing the amount of added work in site assembly.

The above points are not new to the construction community; still failure to utilize these facts is all too often documented. In this project the management, responsible for setting fundamental changes into motion, was instead observed as working with minor changes (first-aid solutions) to control flow. The main reasons for this are most likely related to a combination of using a relatively new product, participants not used to working together, and a paced time-to-finish without time for any changes during production. But these conditions are apparently more of a rule than an exception in construction.

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