PRODUCTION CONTROL THROUGH MODULARISATION

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ABSTRACT

In Sweden, the industrial housing trade has developed for many years with the salient idea of improving production control through an increased level of prefabrication. However, production variability is a consistent issue as work is still sub-optimised, resulting in a fragmented production process. Consequently, problems arise when prefabricated parts and components are assembled. The building services are often a source of high variability (many different components and subcontractors), leading to reduced production control. The aim of this paper is to present how modularisations can provide prerequisites for production control in service system design.

So far, modularisation has only rendered little attention in Lean construction. In this paper, a modularisation development effort of five Swedish industrial housing companies is reported. To generate a relevant set of modules, several workshops were held together with company representatives and building service consultants. The Design Structure Matrix (DSM) was used to detect the lowest common geometrical denominator of the building service systems as well as crucial connection points and interfaces. Combining the DSM with qualitative module drivers generates a design for service system modules facilitating improved production control.

KEY WORDS

Production control, building services, modularisation, module drivers.

INTRODUCTION

An important theme within the Lean Construction community is production control. The general idea of production control is to protect against uncertainty in production (variation in production tasks, deliveries, etc.) (Ballard and Howell, 1998). Production control, in Lean Construction terms, is generally said to be gained by creating reliable work flows between production units and therefore production control should begin with defining the building at an overall level (customers, components, organisation, etc.). Henrich et al (2006) presented an overview of production control within the construction trade, concluding that the strategy depends on context and setting.

Consequently, the issue to gain production control has been addressed in a number of ways, e.g., in relation to Lean Construction, using tools such as Kanban, Critical Chain and of course the Last Planner system. These tools mainly concern the planning

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and production phases of construction and therefore actively attempts to achieve control by improved management and production planning activities. Lean methods or tools that proactively strive to create prerequisites for production control in earlier stages of the construction process are less common in construction literature.

According to Morris and Donnelly (2006), modularisation is a method/tool that contributes to achieve consistent quality and allow firms to provide a wide range of up-to-date products at affordable prices. For off-site construction, Lennartsson et al (2008) suggested that modularisation is useful in capturing and balancing internal and external values. Modularisation thus seems to have a proactive aim in reducing and better controlling variance (in material and information flows) that can occur during production. In prefabrication, customer values must be declared early. Therefore, any change in design can cause variation leading to production delays; e.g. to gain better control of production. Veenstra et al (2006) emphasised the significance of creating modules for the complex and arduous service system (HVAC, electricity, etc.) work.

The aim of this paper is to describe **how** modularisation can be applied as means to create prerequisites for production control. This paper first provides an overview to the field of production control within lean construction. Then modularisation theory is explored in the sense of how production control can be managed. Finally, a logical chain of empirical studies was conducted in relation to a practical modularisation process within Swedish industrialised housing, aiming to develop modules for building service systems. The goal of the studies was to validate a selection of module drivers proposed for creating prerequisites for production control.

PRODUCTION CONTROL – A GENERAL OVERVIEW

Production is the act to make products (goods and services) while control is used in a variety of contexts to express "mastery" or "proficiency". Thus production control is about gaining mastery over the production process. Production planning and control is a mature research field (Stevenson et al 2005) and the issue to achieve production control in construction is therefore not new. For example, Ballard and Howell (1998) stated that production control is about shielding production from uncertainty, while Henrich et al (2005) reviewed existing production control methods in construction.

van der Bij and van Ekert (1999) stated that *"the production control system comprises a system of tasks, methods, and means, which an organisation uses to agree and maintain the availability of products to the expectations of the internal or external customer with respect to time, quantity, and place"*. Production control in manufacturing can be achieved through (Stevenson et al 2005), e.g., Kanban, Manufacturing resource planning (MRP), Theory of constraints (TOC), Workload control (WLC), and Constant Work In Process (CONWIP). For construction, one of the most recognized and applied production control tools is the Last Planner system™.

Other used tools to gain production control in construction are e.g., Critical Path Method (CPM), Critical chain (CC), Line-of-Balance (LoB) and Kanban. Common for these tools is that they are developed to function in on-site project environments. Additional tools capable of addressing production control in early stages of construction (essential in the case of prefabrication) are Poka-Yoke (PY) and Set-based design (SBD). SBD can be applied in early phases of construction to proactively achieve production control through an improved design process, i.e., the design process is controlled so it facilitates a streamlined production process, minimizing waste. In Figure 1, the methods mentioned above are related to each other and to the construction process phases of design, manufacturing and production.

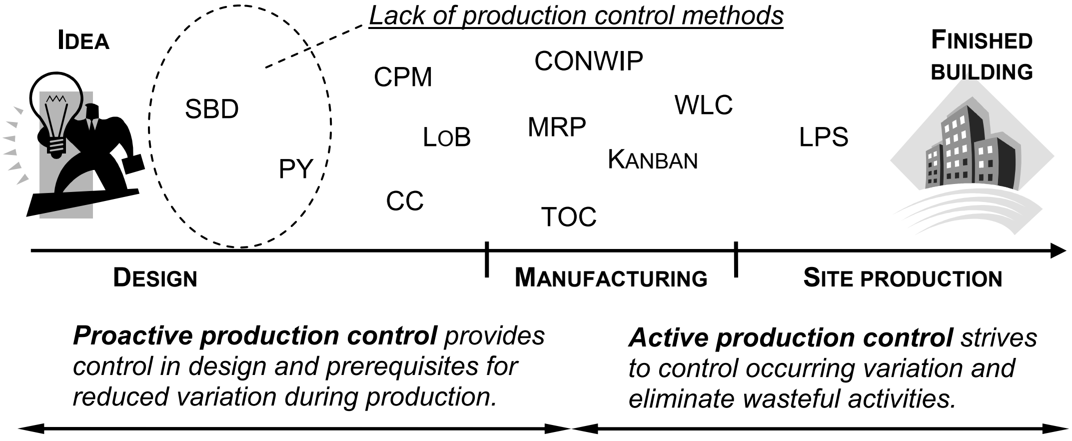


Figure 1: Common Production Control Methods and their Relation to the Construction Process

As illustrated in Figure 1, there seems to be a lack of production control methods or systems that can be applied early in prefabrication to provide proactive control of production events. This paper proposes that modularisation can play such a role in the design phase. However, it is important to emphasize that modularisation does not have the goal to actively control production. Rather, modularisation should be seen as a facilitator of production management, since expected variances can be controlled.

PRODUCTION CONTROL THROUGH MODULARISATION

Modularity (or modular design) is an approach that subdivides a system into smaller tangible entities (modules) that can be independently created and used in different systems to drive multiple functions (Voordijk et al, 2006). Modularisation is the undertaking to design a modular system. Most modularisation initiatives in construction are found within this area. However, in prefabrication, modularisation is argued as means to create standardised parts, produced in optimised processes, i.e. the essence of modularisation is not modular division, rather a standardised way of thinking all through the process (Lennartsson et al 2008).

Bertelsen (2005) stated that the purpose of modularisation is to reduce production variability by turning the building into a product that can be prefabricated in permanent facilities using established Lean methods and tools. Erixon et al. (1996) refer to this as ‘products in products’ and ‘factories in the factory’. For example, Court et al (2008) report on modular initiatives within Lean Construction reducing variation and minimizing waste in assembly, while Brookes (2005) noted that tangible components are easier to coordinate and misfits can be avoided.

As was argued in Lennartsson et al (2008), a successful modularisation effort will capture and define customer values (both internal and external) implying that variations within the supply chain can be better controlled (Voordijk et al, 2006). Using modular products, it is, possible to design a production process that provides a wider range of variants depending on what the customer demands (Morris and Donnelly, 2006), i.e., increased product variety with reduced process variation.

It seems, modularisation can provide production control from many perspectives. Voordijk et al (2006) discuss modularisation as a three-dimensional concept concurrently considering the product, the process and the supply chain. It can be argued that modularisation strives for production control in these three areas through:

- **Product modularity** specifies the product so that materials, components and other resources required for production is known and can be controlled, i.e. degree of component independence and interface standardisation For example; if ten different connected components each have 5 % risk of erroneous tolerances, then there is 40 % risk of failures in assembly.
- **Process modularity** refers to management of production, establishing and controlling production methods, i.e. how the product is made. The industrialised housing trade is aiming for high degree of prefabrication, which demands a higher degree of planning and preparation than on-site building.
- **Supply chain modularity** refers to who does what, i.e. decides participants involved so responsibilities and delivery requirements are known and can be controlled and monitored. For example; if each supplier to an assembler have a delivery accuracy of 90 %, then there is a 10 % risk of at least one component missing during assembly if not relevant buffers are set.

According to Erixon et al (1996) the first step in a modularisation process is to specify the product using Quality Function Deployment (QFD). Then technical solutions are selected in respect to manufacturing goals. In the third step, modular concepts are generated with aid of module drivers (Table 1), defining reasons to perform a modular division and works as a link between module requirements and the production system.

Table 1: Overview of the Generic Module Drivers Presented by Erixon et al. (1996)

Generic Module Drivers			
A	**Carry over.** Solutions can be carried over to new product generations.	G	**Process/Organisation.** Special know-how, pedagogical assembly, lead times.
B	**Technology evolution.** Guard for technology shifts during product cycle	H	**Separate Testing.** When functions can be separately tested.
C	**Planned design changes**. Controlled by customer demands.	I	**Purchasing.** Delivery as a "black box" to reduce logistic costs.
D	**Technical specification.** Concentration of variant changes.	J	**Service and maintenance.** Ease of management as separate modules
E	**Styling.** Influences from trends and fashion.	K	**Upgrading.** If upgrades are expected.
F	**Common unit.** Sub-function with similar physical solutions.	L	**Recycling.** Concentration of recyclable material to one module.

The fourth step in the modularisation process evaluates concepts and tests interfaces. The interfaces are a key consideration as they influence the characteristics and flexibility of the final product. The fifth and final step concerns the improvement of the specified modules in respect to assembly strategies. Modular division through module drivers has been applied in practice in various environments in manufacturing. In construction, Veenstra et al. (2006) put forward a driver regarding a variable to capture the risk or need for components to change over time.

Considering all of the presented module drivers is an arduous process since they are so numerous and also hard to fit to construction, e.g. in construction, carry over is rarely spoken about. However, considering the three distinct areas (product, process and supply chain) that above was argued to provide production control, three of the module drivers emerge as influential in facilitating production control:

- **(F) Common Unit.** As industrial builders depend on the whole construction trade to accept their prefabricated components, it is necessary for all participants to adapt to these components. Therefore, it is important to find functions present in several product variants and provide them with the same design. Variants in demand can then be produced with fewer components.
- **(G) Process/Organisation.** Modular products manufactured in main and supportive processes, facilitate a production system that will help lower lead times and improve quality. Cultural issues in prefabrication lead to strained supplier relations as contractors and housing manufacturers have short term relations with subcontractors and suppliers (Höök and Stehn, 2008).
- **(I) Purchasing.** It is important to gain control of material and components in order to lower wholesaler influence. Properly defined modules allow material deliveries in “black boxes”, lowering costs for logistics and providing more power for the companies in price negotiations.

CASE STUDY: BUILDING SERVICES IN INDUSTRIALISED HOUSING

Five small to medium sized Swedish industrial housing companies (Table 2) have agreed to cooperate in order to facilitate design and management of building services (Lennartsson et al 2008). The companies base their production on a high degree of prefabrication (> 80 % work in off-site production facilities) considering modularisation as a feasible method to find product solutions that appeal all participating companies; the building service modules should fit the different production systems.

Table 2: Overview of the Five Involved Housing Manufacturers

Company	**Turnover** (MEUR)	**Building system**	**Product strategy**
1	42	Volumetric units	Student-dwellings, apartments
2	42	Volumetric units	Apartment buildings, offices
3	7	Volumetric units	Single family residences, schools
4	18	Volumetric units	Student-dwellings, apartments
5	14	Element structural	Multi-storey residential housing

Early in the project, three studies (Figure 3) were conducted to gain understanding of building services issues. *Market Exploration* proved that wholesalers control the market with a catalogue of more than 100,000 articles. The study suggested a plug-and-play system as a viable path of development. In *Map Electric*, the current process was mapped to spot improvement. In *Plug & Play*, was decided to test the feasibility of a plug-and-play system. The evaluation highlighted a resistance to change at building services subcontractors, who emphasised problems and obstacles rather than advantages. This supported the idea of a joint industry venture for modularisation.

Together with the case companies, it was decided to perform a *Competition* to explore new innovative building services. An open call went out to all consultants, contractors and designers in Sweden with the task to develop service system solutions suited for industrialised housing. The thorough inquiry included specification of the current production systems (*Overall Mapping*) and specified necessary characteristics and technical solutions, e.g. a prefabrication level of 80 %. However, all proposals lacked a systems view since not all required service systems were included. After the competition, solutions were discussed to identify implementation possibilities. Results (product, process, and supply chain) from the studies are presented below.

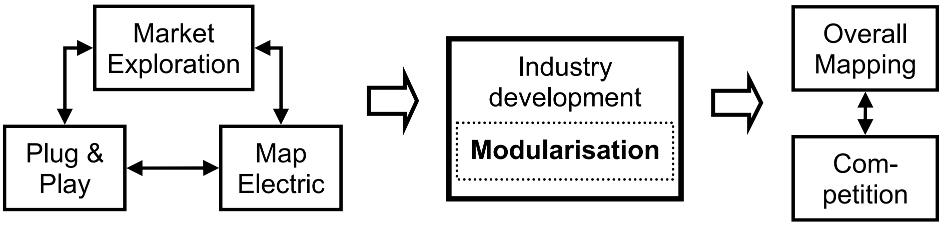


Figure 3: Empirical Studies Conducted to Validate Proposed Module Drivers.

SERVICE SYSTEMS – THE PRODUCT

A Design Structure Matrix (DSM) was used to map the building services in a generic building (Figure 4) valid to all case companies. Seven types of media must be provided for each apartment; Heating *[1]*, Hot *[2]* and Cold *[3]* water, Drainage *[4]*, Ventilation *[5]*, Weak Current (TV/Telecom/Computer *[6]*) and Power Supply *[7]*.

	A	B	C	D	E	F	G	H
Feed **A**	A	1267						
Central Feed Unit **B**		B	123 67					
Basement **C**		1	C		123 67			
Roof **D**				D				
Shaft **E**			14	5	E	123 67	123 67	
Access Balcony **F**						F	123 67	
Traffic Volume **G**					145		G	167
Volumetric Unit **H**							15	H

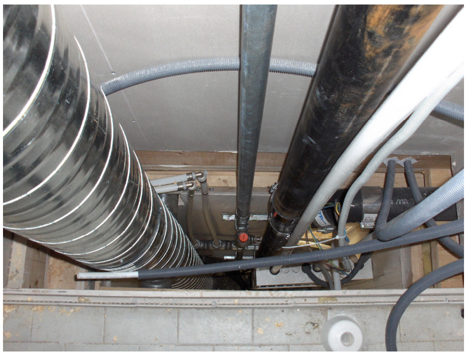


Figure 4: Left: DSM Illustrating Service Systems in A Generic Building. Right: Illustration of A Vertical Shaft with Different Media (Ventilation, Power Supply, Warm Water, etc.) Seen From Above.

The different systems distribute media to the user units within the building. These are closed systems consisting of ducts, pipes and wires. The categories of the DSM (Figure 4) represent different spaces within the building where building services are present and required. Reading the DSM row-wise shows media going out of an entity while reading the DSM column-wise reveals media coming from another entity. For example, services enter a building through an *external feed (A)*, travel through the *Central Feed Unit (B)* into the *Basement (C)*, through vertical *shafts (E)* to horizontal feeds in *Traffic Volumes (G)* and then to living quarters inside volumes *(H)*.

As many service system components as possible are assembled at production facilities; wires and sockets are installed in walls and roofs, while pipes are placed in floor elements. In addition, interior slots are assembled to hold ventilation ducts. Excluded from off-site work is canalisation (shafts) to reach higher floors, and to connect shafts to volumetric units. These couplings are made on the construction site.

SERVICE SYSTEMS – THE PROCESS

The production process is divided into two parts; in the factory, wires and pipes are assembled into floors and walls. Then the panels are assembled to volumetric units, wires and pipes are connected, and sockets installed. In the second phase installations are completed on-site. The power supply production process was documented using a stop-watch and video-recorder. This study highlighted the many different activities taking place in building service assembly resulting in high lead times as the risk of errors grow with increasing activities and relations (between physical components and subcontractors). Table 3 displays an excerpt from the mapping study illustrating five common assembly errors and an estimation of needed correction time (estimation by the subcontractors). The assembly activities have a cycle time of five minutes or less.

Table 3: Errors and Correction Times (1 unit = 5 minutes) for Subcontractors in Power Supply Assembly. Boxes are Sockets and Switches for Electrical Assembly while Duct Holes are Used for Ventilation Ducts.

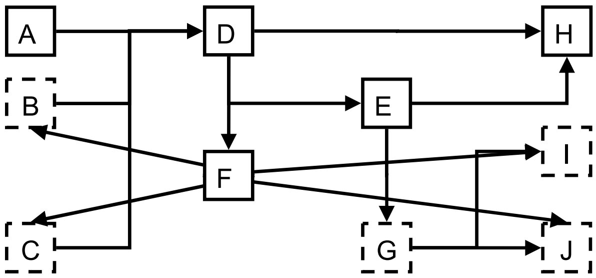
#	Type of error	Subcontractor					Total
		Elec.	HVAC	Carpet	Paint	Carpenter	
1	Box misplaced in ceiling	12			6		18
2	Box behind kitchen inter.	12			4	12	28
3	Box behind tiles in bathroom	12		24		12	48
4	Radiator pipes misplaced in floor		24	12		12	48
5	Duct holes misplaced in slots		18				18

Correctional time is derived from additional activities carried out by the subcontractors, e.g. misplaced boxes require a new installation and correction of the erroneous placement. Errors can be traced to incorrect drawings, as they are passed on between designers and subcontractors without validation. Errors lead to increased production times with up to 48 times (Table 3), not including delays of other activities that can obstruct assembly of correct units. This leads to an increase in overall lead times that cannot be predicted (a challenge to any production control system).

SERVICE SYSTEMS – THE SUPPLY CHAIN

Figure 5 displays the supply chain for one of the case companies in factory production. Dotted parties represent external resources, while the remaining parties are “owned” by the company. As displayed in the figure, several actors are involved in the building services that are not in-house personnel and the arrows show the many different ways information and materials are transferred between participants. Figure 5 should at this stage only be viewed as an example of the complexity in relations.

Information and material flows must be considered in terms of securing delivery of drawings and materials on agreed times. Different designers are independent and don’t have regular contact with each other. The fact that designers and subcontractors are procured on short-term contracts on a project to project basis pose additional problems in relations, i.e. drawings are distributed to factory personnel and procured subcontractors without synchronisation or validation, and if necessary materials are provided by subcontractors, they will charge for full material coverage.



A. Structural designer
B. Power designer
C. HVAC designer
D. Management
E. Purchase division
F. Procurement
G. Wholesalers
H. Factory personnel
I. Subcontractor Power
J. Subcontractor HVAC

Figure 5: Illustration of Information and Material Flow During Building Services Assembly in the Factory.

Evaluation of the plug and play system proved possible cuts in lead times up to four times. Moreover the results showed the need of a better coordinated supply chain as wrong components were delivered, and agreed-on delivery times were exceeded. One reason was poor design made in a hurry. There is also ambiguity in the regulations when it comes to the demand for inspections in the joints where the plug and play system is to be connected. Commonly, the regulations are interpreted in such a way that these joints cannot be built in behind the plaster boards in the walls, which was why it was decided to keep the joints unveiled in this case. Additionally, the subcontractor opposed this kind of system, as the current situation provides power to the building service trade where subcontractors can charge maximum work hours.

DESIGN OF A MODULAR SERVICE SYSTEM

The DSM detected suitable interfaces for modular division. The analysis shows that vertical *Shafts (E)*, *Traffic Volumes (G)* and the basement holds all seven media types. *The Shaft (E)* is, in a way, already a module with set boundaries, but all assembly is performed on-site which causes interferences and delays. There is a need to coordinate the media flowing in the shaft, e.g. separate media that affect each other such as hot and cold water. Development of a prefabricated shaft module is proposed. The *Traffic Volume (G)* and the *Basement (C)* both have horizontal canalisation of media, with similar opportunities to create a prefabricated inner ceiling module.

PRODUCTION CONTROL THROUGH *COMMON UNITS*

The module driver *common unit* manages a frequent problem in assembly of building service, pipe dimension errors. Often pipes with diameters of both 15 and 16 mm are used that can be accidentally mixed increasing risk for leakage, i.e. it is difficult to secure a tight joint between two pipes of different dimensions. A reason is the use of components from different brands. Instead, specifying a narrow set of discrete dimensions for pipes (e.g. 15, 18, 21 mm) only allows for correct jointing lowering the risk of faulty assembly. Further, the problem relates to how subcontractors are procured; as subcontractors normally work in different projects at the same time for different contractors using own materials, thus mixing of components is unavoidable.

PRODUCTION CONTROL THROUGH *PROCESS/ORGANISATION*

Process/Organisation relates to how and where value adding activities will be performed. High levels of on-site assembly require much on-site coordination (e.g. on-site work structuring of subcontractors), while a large degree of prefabrication demands better planning in design, e.g. assembly errors from poor design can be costly due to the level of standardisation. The case companies are focused on the latter view. In order to gain production control with respect to process and organisation it is desired that shafts and ceilings are manufactured parallel to the main process with a specified and minimised set of materials and required activities in order to reduce interface, mismatches, e.g. piping dimensions, faulty drawings, etc.

PRODUCTION CONTROL THROUGH *PURCHASING*

Purchasing can facilitate production control by further narrowing allowed materials used, e.g. pipe dimensions. Material purchase can then be made in respect to the needs and boundaries of the modules by specifying standardised bill of materials that lower inventories and waste while improving material forecasting. As a consequence, the purchasing division can focus on procurement of fewer components, as previously mentioned. Control of required materials prohibit subcontractor to make the purchase in order to lower costs and avoid risk of mixing materials from different brands.

DISCUSSION AND CONCLUSIONS

In this paper, the main incentive put forward for a modularisation initiative is to provide prerequisites for production control. With this means that modularisation is applied early in the construction process at the product level to proactively reduce variation during production and in the supply chain. The case study results highlight the importance of interfaces in products, processes and within supply chains for production control. An example of a product interface is the high risk of errors in piping connections, while unconfirmed drawings passed on to subcontractors is an example of a poor process interface and also show evidence of fragmented supply chain interfaces as subcontractors are often procured on a project to project basis.

Prerequisites for production control are achieved in practice through three module drivers (*common unit*, *process/organisation* and *purchasing*), in this case resulting in development of shaft and inner ceiling modules for building services. The proposed module drivers are interrelated as specification of a narrow set of components affect purchasing in respect to how supply of materials is secured. Further, modules work in collaboration with Poka-Yoke as module interfaces, by design, shield from erroneous assembly through standardized pipe dimensions and interfaces, thereby improving production control. These results are in line with those presented by Fine et al (2005) who state that modular products tend to have modular processes and supply chains.

Hofman et al (2009) noted that suppliers tend to be reluctant to adopt new standards. Similar results were obtained in the evaluation of the plug-and play system where the electricians emphasised the problems rather than lifting up the advantages and possibilities. The case study findings are also in line with Halman et al (2008) who stated that modularisation initiatives within construction need to address issues with restrictive regulations, which lead to the ambiguity in interpretation of regulations as was highlighted in the evaluation of the plug and play system.

Modularisation has possibilities of becoming a potent tool in the design phase in order to facilitate other production control methods within the construction industry. Production control can be further facilitated through better adaptation of the product into the production process, i.e., opportunities to apply the Line-of-Balance technique as well as coordination and monitoring on-site with support from Last Planner.

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