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Step-by-Step Modularity – a Roadmap for Building Service Development

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Abstract

Research Question/Hypothesis: Modularity in 3D can serve as a catalyst for change, towards a more industrial practice of building services in housing construction.

Purpose: This paper explores and expands on Fines modularity model and demonstrates it with the development of building services in industrial housing.

Research Design/Method: Empirical data were obtained from a joint product development initiative of a shaft and an inner ceiling, involving five industrial housing companies.

Findings: The proposed framework is applicable in designing building service modules. The framework is applied by identifying and evaluating the key dimension (product, process or supply chain), followed by stepwise evaluation of the remaining dimensions.

Limitations: The research considers development of building services in industrialised housing construction on the Swedish construction market.

Implications: The research provides a roadmap for modularisation in construction, i.e. how to initiate a module development and how to analyse its potential. The methodology provides valuable insights in the complex building service trade.

Value for practitioners: Experiences from an actual product development initiative in industrialised housing are presented, a process in which five companies jointly developed two building service modules. The roadmap works as an action plan, potentially applicable to other complex construction products/components.

Paper type: Case Study

Keywords: Modularity, Building Services, Industrialised Housing, Supply Chain Management

Introduction

Building services (HVAC, electricity, etc.) is a neglected area of innovation in Swedish housing construction; during the latter part of the 20th century only minor technical improvements have occurred. Work is performed with traditional methods and tools, i.e. quality relies on craftsman skills organised in specialised craftsmanship guilds, ranging from plumbers and electricians to speciality designers. Housing companies (contractors and manufacturers) have difficulties in coordinating actors and activities during production. These problems are not exclusive for building services; instead they highlight

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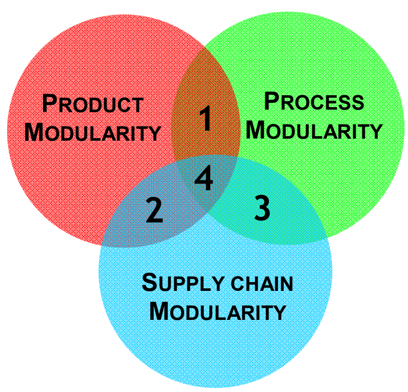
two general issues in construction - an equivocal view on value and poor production control. According to Lennartsson et al. (2008; 2009), these issues can be seen as a lack of value creation and generation for actors within the supply chain; instead of working towards a unified goal they individually optimise the own work. We are convinced that modularity can serve as a catalyst for change towards improved value generation and production control.

Modularity in construction is seen as a management concept concerning design and production, rather than the conventional mass customisation view to offer multiple variants. Construction modularity challenges researchers worldwide through, e.g. tolerances (Milberg and Tommelein 2004), flexibility (Vrijhoef et al. 2002) and open building (Cuperus 2001). Voordijk et al. (2006) applied the three dimensional (product, process and supply chain) model from Fine (1998) (Figure 1) in construction. Fine (1998) investigated concurrent engineering, emphasising that good performance (competitiveness) occur from concurrent product, process and supply chain considerations. Using the model of Fine, Voordijk et al. (2006) was first to provide an overall view on construction modularity. However, modularity was only considered schematically.



Product Modularity

- Performance specifications

Process Modularity

- Technology and process planning

Interactions

1. Recipe, unit process
2. Product architecture, Make/buy
3. Manufacturing system, Make/buy
4. Details, strategy

Figure 1: Overlapping responsibilities according to Fine (1998, p.146).

This paper aims to explore how Fines modularity model can be used and expanded on to guide the improvement of building services in housing construction. Empirical data were collected from a product development process of a shaft and an inner ceiling module for building services. The project consisted of five industrial housing companies working jointly over three years to modularise their building services. The paper presents an expansion of Fine's model, resulting in a step-by-step roadmap for improving modular design of building services in industrialised housing construction.

Industry Context – Building Services in Construction

The idea of prefabricated building services is as old as the idea to prefabricate buildings; a prefabricated "building service wall" was used in Sweden during the late 1950s, while standardised shaft solutions was used in the 1970s. During the 1980s, efforts were made to prefabricate bathrooms with all necessary building services. The floor plans were often designed with kitchen "wet" side facing the bathroom wall to group all building services in one shaft, simplifying assembly. In the 1990s, the first system solutions emerged as shafts were placed near stairwells, a development driven by new materials, e.g. corrosive, pressure and thermal resistant pipes. The building service wall reappeared, with wall-assembled toilets and joints concealed. Lately, the area has developed technologically, with sprinkler systems and, communication and automatic control systems. However, assembly is performed in traditional fashion, with procured consultants and sub-contractors. See Lennartsson (2009) for a more detailed overview. Figure 2 illustrates the traditional manner of building services, i.e. vertical canals in shafts between floors and between apartments, horizontal canals in inner ceilings.

Figure 2: Left) Assembly of vertical shaft. Right) Building services in inner ceiling.

Industrialised housing, as a production system, attempts to change how work in construction is performed, by production control through increased prefabrication. Companies manufacturing housing industrially strive to take governance and integrate all important functions (design and production); Figure 3 exemplifies such centralised organisation. For industrialised housing, interaction between actors in the process is as important as within traditional housing construction.

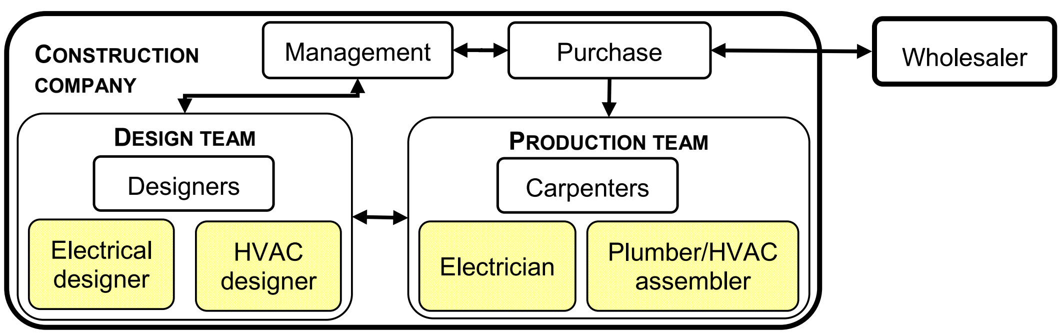


Figure 3: Actors involved in the building services process in industrialised housing.

Case Study – Building Services in Industrialised Housing

Five small to medium-sized (with turnovers ranging from 7 to 42 M€) Swedish industrial housing companies cooperate to design and manage the development of building service modules (shaft and ceiling). The companies perform at least 80 % of their work off-site in factory environments, implying:

- The product strategy is focused on a core product, the building system.
- The production unit (factory) is defined, aiming for 100 % utilisation.

Focus on these prerequisites is essential for these companies. A key to success and survival of these companies is progression in small steps where improvements are made and verified before moving on to other undeveloped areas. The strategy is a consequence of the companies' size as smaller corporations cannot make major and rapid investments.

The selected unit of analysis was building service systems, specifically the design of shaft and ceiling modules. Five studies (see further, Lennartsson 2009) were performed to detect opportunities and obstacles in module design:

- **Market survey –** Overview of available components for the electric system. Data was also collected through interviews with electric system suppliers.
- **Electricity mapping –** Study of traditional electric system assembly at one company through observations of work flow and analysis of potential problems.
- **Plug-and-play system evaluation –** Study of benefit and obstacles of an electrical plug-and-play system through interviews and observations at one company.
- **Flow mapping of building services –** Mapping of all building services within a traditional housing project in order to identify canals and critical interfaces. The investigation covered a study of drawings and interviews in all five companies.
- **Consultant Procurement –** Innovative ideas from Swedish consultants of new building service solutions were studied through a procurement process aimed at evaluating benefits and hindrances. Results from prior studies were also verified.

Theoretical Context – Modularity in Construction

Modularity research in construction is uncommon. Halman et al. (2008) conducted a survey of platform approaches, concluding that restrictive regulations, trade-offs in variety vs. price and collaboration among actors must be addressed. Björnfot and Stehn (2004) argued that modularity support the practice of Lean Production in construction. As a continuation, Björnfot and Stehn (2007) stated that buildability is enhanced by modularity in design through fitting between elements while issues such as Just-in-Time, scheduling, quality and flexibility are facilitated. The Open building concept (Vrijhoef et al. 2002) is based on modular principles with the purpose to offer variety. Another aspect of modularity is interface standardisation, where a key issue is tolerances (Milberg and Tommelein 2004). Voordijk et al. (2006) approached Fines (1998) product-process-supply chain concept (Figure 1) to assess and to provide guidance on the degree of modularity.

Modularity in Three Dimensions

Erixon et al. (1996) suggested a concurrent engineering methodology to develop modules focusing on capturing customer demands and values with aid from Quality Function Deployment (QFD). However, with fragmented supply chains, as the view on value delivery differ and value is hard to define and quantify, modular development solely based on customer requirements is difficult to achieve in construction (Emmitt et al. (2005). Consequently, a more general approach to construction modularity is appropriate. Erixon et al. (1996) evaluated modular development from a product and process perspective. However, as already mentioned, Fine (1998) argued that the key to good performance is to master the third dimension, the supply chain.

Fixson et al. (2005) asked; *Do products design organisations, or do organisations design products?* The question highlights the importance of strategic positioning in modular development; in what dimension is our core competence? The product, process, or supply chain? A framework for the three strategic choices (Figure 4) has been developed from Fine's modularity model (Figure 1). It is important to underline that the key dimension must be determined before modularity can be approached in the remaining dimensions, which then can be approached independently without any predetermined order.

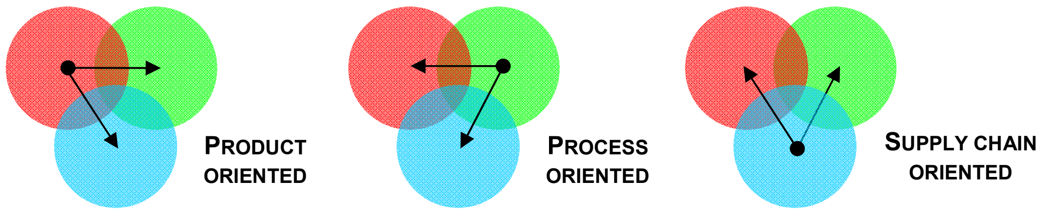


Figure 4: Different strategic choices in module development.

In for example Fine (1998), multiple examples of modularity strategies, ranging from computers to aircrafts, are provided that can be positioned in this framework. To fully utilise the framework, it is essential to grasp the contents in all dimensions. It is important to note that Fines original idea was to anticipate and adapt to sudden shifts and turns on the market, i.e. the clockspeed. However, in construction the clockspeed plays a less important role. Within this context, the model provides prerequisites for construction companies to gain control over the three dimensions. In the following sections, research in the three module dimensions is interpreted to identify key issues that must be addressed.

Product Modularity

The product dimension depends on product architecture (Fine 1998, p.135); inter-changeable components, upgradeable components, interface standardisation and system assessment. Based on these characteristics, the following statements were developed:

- **A modular product facilitates interchange of components**

An interchangeable component is more modular (Fine 1998). Erixon et al. (1996) includes this characteristic as a driver for modular division facilitating service and maintenance.

- **A modular product facilitates upgrade of components**

Modular components are individually upgradeable (Fine 1998), i.e. system functionality is enhanced by upgrading the function of specific modules or adding components providing wider selection of product variants (Halman et al. 2008). Variation of the end product is possible while design and production within product families are fixed (Erixon et al. 1996; Jørgensen (2001). According to Vrijhoef et al. (2002) modules can be produced to a certain extent before individually customised.

- **A modular product facilitates standard interfaces**

Standardised interfaces between components are a key characteristic of modularity (Fine 1998; Erixon et al. 1996). Baldwin and Clark (2000) argue for interdependence within and independency across modules; isolation of complexity by defining a separate abstraction that has a simple interface. The interface hides the complexity of the element and indicates element interactions with the system. Pandremenos et al. (2008) emphasise the importance of module interface definition according to assembly sequence prerequisites.

- **A modular product facilitates easy system assessment**

Easy assessment and localisation of failures is a modular characteristic (Fine 1998) related to interchangeable components, i.e. with failures isolated, specific components are replaceable. The interpretation is that, division of a larger system into more tangible parts reduce complexity (Erixon et al. 1996; Baldwin and Clark 2000). Veenstra et al.

(2006) address the issue by defining a product platform to better translate functional requirements into traceable technical specifications.

Process Modularity

Process modularity is approached from two dimensions, *space* and *time* (Fine 1998, p.143). A process is integrated in either or both space and time, or dispersed in both. When activities are spread over multiple time intervals or takes place on dispersed locations, process modularity increases. Consequently, a modular process is comparable to a modular product where standardised components instead are operations with standardised linked interfaces (hand-offs). To reflect this similarity, three statements have been developed:

- **A modular process facilitates use of common production technology**

This statement is related to *space*. According to Voordijk et al. (2006), process modularity in construction refers to management of production and establishing and controlling production methods, i.e. how the product is made. Jiao et al. (2007) discuss the concept of process platforms, implying process commonality, i.e. common tools and machines.

- **A modular process facilitates parallel assembly**

A statement linked to *time*. As noted by Pandremenos et al. (2008), the ability to modularise in time need defined module interfaces due to assembly sequence requirements. An advantage from modular division is the reduction of lead times through parallel assembly (Erixon et al. 1996). Jiao et al. (2007) discuss the division of assembly in a main line used for common operations and a line for variants.

- **A modular process facilitates the use of standard work**

A statement related to *space*. Bertelsen (2001) assesses process modularity in terms of craftsman skills and number of operations, where complex systems should be modularised. Reijers and Mendling (2008) approach modularity from an operations view where sub-processes are defined either by refining functions or segmenting processes.

Supply Chain Modularity

Supply chain modularity is interpreted by Fine (1998, p.136) as degree of proximity: modular supply chains exhibit characteristics such as geographically dispersed actors, autonomous management, diverse cultures and low connectivity electronically, while integral supply chains have geographically concentrated actors, common ownership, common business and social culture and are linked electronically. Based on this view, three statements of modular supply chain characterisation have emerged:

- **A modular supply chain facilitates large physical distances**

According to Fine (1998), physical distance between involved actors in the supply chain imply additional challenges for the success of any product development or production process, i.e. fundamental logistics problems concerning material planning and facility allocation. Modular supply chains support efficient production in such conditions.

- **A modular supply chain facilitates independent organisations**

Organisations should decide their level of dependency in terms of knowledge and capacity (Fine 1998). Doran et al. (2007) share this view, emphasising that core and non-core competencies are crucial in supply chain modularity. According to Bertelsen (2005), modules should be designed in terms of functions possible to assign to specific work groups or subcontractors. Through outsourcing, quality becomes the responsibility of the supplier, who therefore will become more interested in development. A restraining factor is the influence of diverse business customs and laws (Fine 1998). A survey by Halman et al. (2008) points out legal restrictions as an obstacle to modularisation.

- **A modular supply chain facilitates communication independency**

In-person and electronic communication provides challenges related to commonality of language, commonality of communication technology and diverse ethical standards (Fine 1998), i.e. modular supply chains should be organised in a way to minimise the need for communication, in turn it will reduce the risk of misunderstandings.

A Step-by-Step Approach to Modularity

As argued above, a modularity initiative should be commenced by establishing the key competence dimension (Figure 4), before considering the remaining dimensions. As development is best performed in small steps, an iterative step-by-step methodology to modular development is proposed (Figure 5). First, empirical data is extracted from the key dimension (**Step 1**) and analysed with the modular framework (**2**). The analysis results in modular characteristics (**3**), which are assessed by considering obstacles to modular development (**4**). Then, remaining dimensions are considered (**5**) by applying the framework, step-by-step, dimension by dimension.

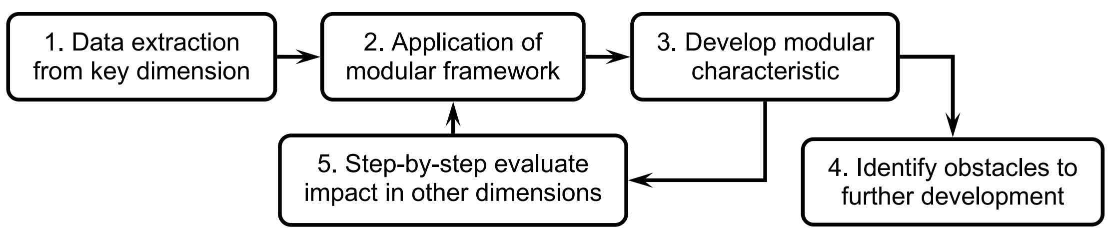


Figure 5: Roadmap for evaluation of modularity in construction.

Data Analysis for Development of Building Service Modules

This section analyses the gathered data utilising the roadmap proposed in the preceding section. The data were collected, from the previously described cases denoted A-E. First the roadmap is demonstrated with an example, followed by results and analysis from the three dimensions respectively. The results are summarised in Table 1.

Roadmap Demonstration

Experiences were extracted from a product determined from the outset, i.e. a shaft and a ceiling for building services, adaptable to different building systems and different production systems. Consequently, the decided key dimension (**Step 1**) regarding the building services is the product. Using the modular framework (**2**) in the product dimension shows that there is no uniform view on material and component manufacturers and that wholesalers are dictating business with a thorough cumbersome catalogue of articles (obtained from study B, C and E). Therefore, an important modular characteristic (**3**) is *material standardisation*, which specifies a narrow set of material which would in turn provide control to the building company. An obstacle (**4**) to obtain this standardisation is the demand on actors in the supply chain to only assemble with allowed components (**5**) that would avoid misfits and faulty assembly. In the advance, there is also a possible risk with dependency to certain material suppliers (**5**). The remaining modular dimensions are analysed in the same fashion.

Modular Characteristics – the Product Dimension

The current practice use conventional systems, e.g. water-based heating (Study D). However, development increases demands on energy saving (E); e.g. solutions for preheated supply air and heat recovery from shower water. Therefore, base modules should be designed with only necessary system components and interfaces designed for possible additives e.g. sprinklers. Figure 6 illustrates the shaft and ceiling and has been developed outgoing from ideas and views submitted in study E.

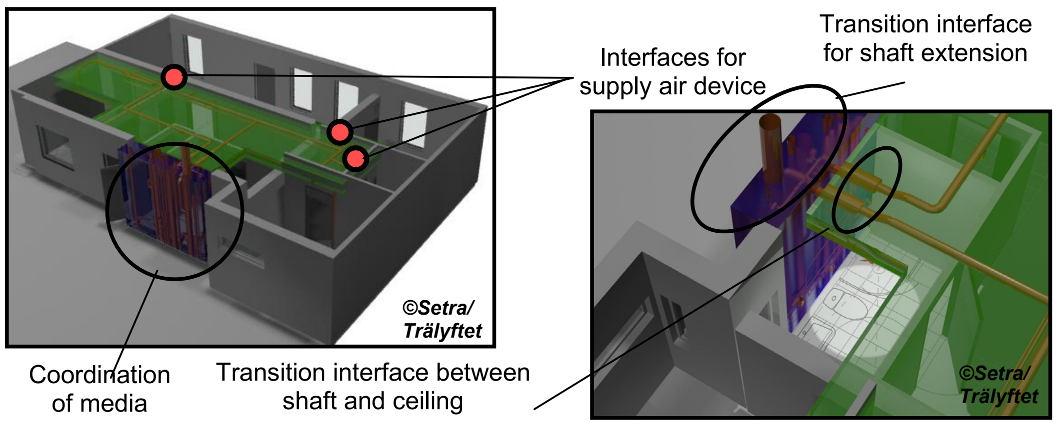


Figure 6: Conceptual image for shaft and ceiling modules in a universal dwelling.

The figure highlights modular hotspots; ventilation ducts in the ceiling with flexible interfaces facing different rooms adaptable to different floor plans (C, E). Media in the shaft should be coordinated with respect to buildability, maintainability (upgradeability and exchangeability) and safety (bacteria growth elimination in water pipes) (E). As the interfaces are present in nearly all product variants, interface definition including tolerances for continuous monitoring is crucial. The following characteristics emerge:

- **Material standardisation** (B, C, E) - mixing of components from different manufacturers can lead to compatibility issues such as short circuits.
- **Functional interface** (C, E) - the shaft and inner ceiling are components that contain critical functionality for transportation of different media.
- **Interface standardisation** (A, C, E) – standard exterior module geometry with interior adaptable to different demands on media (contemporary and future).
- **Accessibility** (D, E) – shafts should be accessible for maintenance from public areas, so service can be performed without interference in residential areas.
- **Safety** (D, E) – Adherence to building regulations to avoid growth of bacteria and fire protection improvements with consultants, interpreting rules diversely.

Modular Characteristics – the Process Dimension

The companies individually manufacture prefabricated housing (D). The process is separated in two parts; in the factory, wires, pipes, etc. are assembled into floors and walls, then interfaces are completed on site (B). For building services, several activities and hand-offs are performed (electric assembly contains 14 distinct activities) increasing the risk of errors (B). Estimations indicate up to 48 times additional production time, meaning work groups must be relocated to handle these errors (B, C). Occurring errors were traced to unverified drawings delivered to production (B, C). The situation implicates delays and nuisance among craftsmen. Unverified drawings can be interpreted as poorly designed interfaces. A related issue is faulty assembly leading to lost *production control*, as the correctional time is difficult to calculate. In the process dimension, these characteristics appeared:

- **Activity interface** (B, C) – isolation of the modular production process, meaning a minimum number of interfaces and a minimum number of iterations.
- **Activity standardisation** (B, C) – standard work protocols for assembly that only allows a standardised set of activities reducing the risk of faulty assembly.
- **Design validation** (B, C) – verification of quality by, e.g. validation of drawings before delivery to production units and identification of critical tolerances.

Modular Characteristics – the Supply Chain Dimension

The actors focus on maximising own values (B). Subcontractors generally express negative attitude derived from current conditions where they work isolated and calculations are made on single projects using piecework debit (B). Within the prevailing culture, competence is fixed to subcontractors but without incitements to push the development (B, C, E). Consequently, the builder depends on subcontractor competence, reinforcing their power.

In the other end of the supply chain consultants are engaged closing deals with several clients (D, E). They are often small firms without surplus capacity, increasing the risk of faulty drawings (D, E). Furthermore, material suppliers aim at maximising own profits (E). Currently, component manufacturers and wholesalers dictate business on the building service market as building companies lack necessary knowledge; a catalogue exceeding 100,000 articles is difficult to grasp. The following characteristics emerged:

- **Actor interface** (B, C) –actors have different interests. It is important to resolutely define the goal and motivation of each actor involved.
- **Actor standardisation** (B, C, E) – distinctively define what work is to be performed by each actor will prohibit consultants and designers to interfere on their areas respectively.
- **Outsourcing** (E) – purchase of standard materials in “black boxes” and production can be outsourced to third-party suppliers.

Table 1: Modular characteristics overview for building services

	Modular framework (Step 2)	Modular characteristics (Step 3)	General obstacles to characteristics (Step 4)
Product (Step 1)	1. Component interchange	Material standardisation, Accessibility	• Influential Unions. Every trade belongs to a union who work to achieve benefit for their own members (in construction, there are at least 10 related unions). Separate goals lead to individualism and therefore, cooperation is difficult to achieve. • Wholesaler Market Control. The large catalogue makes standardisation difficult to achieve as subcontractors often use their own set of material leading to a mix of components and risk of misfit in assembly. A narrow set of components is required. • Restrictive Regulations. Housing companies depend on the construction trade to accept their prefabricated components. It is necessary for project participants to adapt to these prerequisites. However, rigid regulations give little space for innovative solutions, required to adapt technical solutions to rules and the values of individual participants. • Resistance to Change. The traditional culture is evident in many instances in everyday construction. One source of income for subcontractors are rework due to faulty plans. This gives subcontractors a strong market position. They are therefore resistant to change and often emphasise problems and obstacles rather than advantages and innovations. • Fragmented Supply Chains. Individually procured consultants and subcontractors lead to problems when, e.g. drawings from a consultant are not validated before delivered to the subcontractor and the production facility, which can result in rework.
	2. Component upgradeability	Accessibility	
	3.Interface standardisation	Interface standardisation, Material standardisation	
	4. System assessment	Functional interface, Accessibility, Safety	
Process (Step 5)	5. Production technology	Activity standardisation	
	6. Parallel assembly	Activity interface	
	7. Standard work	Activity interface, Design validation, Activity standardisation,	
Supply chain (Step 5)	8. Physical proximity	Actor interface, Outsourcing	
	9. Organisation independency	Actor interface, Outsourcing	
	10. Communication reduction	Actor standardisation	

Discussion

The design of the shaft and inner ceiling has several characteristics facilitating modularity (Table 1). The product dimension is naturally the most modular since development began with a product-oriented approach. During the process, hindrances for further modularisation emerged, e.g. the large number of unions implies fragile organisations, as disagreements in a sole association may result in production slack (compare with airlines that are dependent on numerous unions that single handily can paralyse a whole operation). Interestingly, Hofman et al. (2009) presents similar hindrances from a Dutch joint development venture of industrialised housing.

During the design process, standardisation and module interfaces emerged as critical in module development. In the joint venture, comprising five companies having different building systems and corporate strategies, it was essential to find commonality across the industry. Therefore, the modules only contain required components that can be subjected to enhancement with additives. The interfaces must also be designed to fit generic building systems. The product design also exhibits modular characteristics related to the process and supply chain, i.e. standardised component interfaces lead to standardised process and supply chain interfaces.

The issue with standardisation is a common theme within modularity literature in terms of mass customisation and platform designs. It is important to punctuate that the issue not only concerns the apparent product design, but also the process and the supply chain, described by Björnfot and Stehn (2007) as *"it is not the division of the product into modules that is be the essence of modularisation in construction, rather it is the standardised way of thinking all through the process"*. The essence of this statement emerges as fundamental in the development of building services modules.

Interface design is a well-recognised characteristic of modularity, e.g. Erixon et al. (1996) suggest early interface definition for concurrent product development. The analysis shows that interfaces should be addressed in all dimensions, physical connections as well as value-adding activities and hand-offs between actors, possible to monitor with preset tolerances. Interface considerations provide support for building companies in strategy discussions (area 4 in Figure 1), e.g. interference of module designs with building system design and procurement strategies for key actors in the supply chain.

Conclusions

This paper assessed how Fines modularity model can be expanded to provide guidance in development of building services for industrialised housing. The proposed methodology is to apply an expanded framework of Fines three dimensional model in a step-by-step manner. Data from five studies were analysed and the conclusion is that the model is applicable in designing building service modules. The main contribution from this research is the roadmap, i.e. how to initiate a module development process (Figure 4) and how to analyse its potential (Figure 5 and Table 1); in this particular case providing valuable insights in the complex building service trade.

Industrialised housing implies fixed prerequisites in the product and process dimensions, i.e. the building system and production units. Therefore, the supply chain has the highest degrees of freedom. The results also indicate that actors are attached to a prevailing construction culture (Höök and Stehn 2008), but stepwise modularity has the potential to dissolve these constraints. Fine et al. (2005) quantify trade-offs in modular design, an approach that may make continuous monitoring of key module interfaces possible, e.g. material intensity and hand-offs.

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