

# Construction Business with Innovative Cellular Structures, Modules and Buildings

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## Abstract

Basically a cellular structure forms a fully functional part of building. A building can be constructed from cellular modules, which can be multiplied up to the full scale modular building. At the moment cellular structure technologies and their applications are well established and play a crucial role in particularly in aircraft manufacturing and marine industries. It is likely that large size cellular structures can have significant impact also on the building construction sector.

Because the cellular structures are relatively new solutions in construction sectors, wide variety of research questions have to be addressed before the technology will have wider impact in the commercial markets. The research needs in the field of cellular structures are very wide covering structural design and analysis, building physics, architectural opportunities, life-cycle economics and building processes. A research effort has been carried out to address all the named research needs.

This paper presents research results of the described effort that are addressing building processes and their management. Particularly, this includes partner network analyses and experiences from case projects. The used research methods included i) analysis of project data bases and ii) interviews about experiences of finalised cellular structure projects. These people were from the cellular structure factory, modular building factory and the actual construction sites.

**Keywords: modular construction, cellular structures, supply chain management, business ecosystem, design principles**

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# 1. Introduction

It was predicted in the early 20<sup>th</sup> century that housing would follow the development seen earlier in the car industry, where industrial production methods had revolutionized the business (Schnaars 2009). However, the production techniques and the productivity development of construction sector didn't follow car industry so quickly. On the other hand some Japanese housing manufacturers have developed industrialized housing solutions (Gann 1996). However, present building construction methods can be considered as industrialized ones merely regarding some special construction services. This seems to be the current status despite of major research and development efforts both by academia and industry itself, look at e.g. (Thuesen et al 2009 and Kazi et al 2009)

Construction sector is often considered very conservative and slow when it comes to diffusion of innovations (Sheffer 2011). One theme where the diffusion of innovations has been slow in practice is modular construction (Lovell & Smith 2010). Modular construction got a lot of attention in 1960s and 1970 s, at the same time when a modular building called Habitat at Expo 67 was built. However, the costs related to modular construction didn't fall as fast as expected, and the hype around modular construction decreased. (Schnaars 2009). Modular construction has gained its popularity, but less quickly than expected in 1960s and 1970s.

The term "modular" has many meanings, since forms and levels of modularity can have great diversity or variety (Starr 2010). In the case of building construction the term modular has also several meanings. For example, a prefabricated element such as a window can be classified as a module (Sheffer 2011). On the other hand, volumetric modules can be room size units (Lawson et al. 2011). Furthermore, modularity can have other types of appearances. Lennartson et al. (2009) have discussed not only about product modularity, but also process modularity and supply chain modularity, which both can have central roles in the production control of modular manufacturing. In this paper modular construction is understood to be a way where off-site construction is utilized widely in a way where dwelling sized modular units are produced.

Modular construction can be done either on-site or off-site. Bayd et al. (2012) have divided off-site construction into four categories: off-site pre-assembly, hybrid systems, panelized systems and modular buildings. In Europe the modular building industry has often resembled more an on-site construction production that has been moved into the interior conditions, than industrial manufacturing business (Linner & Bock 2012).

The published reviews about the advantages and challenges related to modular construction show evidence of numerous drivers towards and against modular and off-site construction. The identified key benefits include cost advantages (economies of scale and learning curve), time, quality, health and safety issues, productivity and predictability (Boyd et al. 2012; Pan & Goodier 2012). Moreover, compared with conventional construction modular construction seems to be more environmental friendly (Quale et al. 2012, Lawson 2010). It is also reported that modular construction can enable shorter on-site and overall project duration. Furthermore the quality targets of end products can be reached in more reliable manner

since the manufacturing can be done in the controlled circumstances (Boyd et al. 2012, Lawson 2010).

There may be cultural differences in the attitude towards modular construction. According to Linner and Bock (2012) an interesting difference between Europe and Japan is that in Japan the modular solutions are often seen as more reliable, customized and better designed buildings than its alternatives. In Europe modular solutions in the construction are possibly more often tried to justify by using cost-efficiency arguments (see Lovell & Smith 2010).

Also many barriers for modular and off-site construction have been reported. Even though a central argument for favoring modular construction has been (low) cost (Boyd et al. 2012; Lawson 2011), the cost issue has also been mentioned as a reason, why modular construction has not been more widely utilized than it in fact is (Schnaars 2009). As barriers have been reported to be for example difficulties in transporting manufactured products to site, restricted storage areas on the sites, the need for early done design specifications, limited capacity of suppliers and the lack of experiences (Boyd et al. 2012).

Modular solutions require deep collaboration between different designers, for getting truly modular and practical solutions. Traditionally challenging areas in modular buildings are for example noise management, vibration, heating, ventilation and air conditioning (HVAC) systems. It is seen that in modular construction there is a need for deeper collaboration between designers, manufacturing and construction personnel (Arif et al. 2012)

In the Japanese modular construction industry, automation and new process innovations are reported to be widely utilized, whereas it has been claimed that in Europe the critical mass needed for the most efficient production processes is not usually achieved (Linner & Bock 2012). According to Gann (1996) one key reason behind the success of Japanese industrialized housing might be in the ability to manage the whole supply chain in a way that takes into account the whole supply network, including manufacturing, sales and site erection. In proportion, one potential reason, why modular construction has not always been purely a success story, might be the challenges of supply chain management. Modular product architecture can require different kind of supply chain management solutions than on-site construction (see e. g. Doran & Giannakis 2011; Hofman et al. 2009).

Regarding the overall success industrial experiences over modular and off-site construction are uneven. For special purposes and with a novel business set-up such solutions have proved to be viable and seemingly have lasting operational chances. However, the combination of conventional business arrangements, its expectations and traditions with extensive modular construction seems to result in disappointments in many cases. It looks obvious that an extensive modular construction must be implemented in a way where “the weight of past” of traditional construction business is not present.

This paper presents some results of a joint recent research and development effort by four companies and an academic partner for forwarding modular construction in the residential building field. The overall solution is based on cellular structures, that form cellular modules

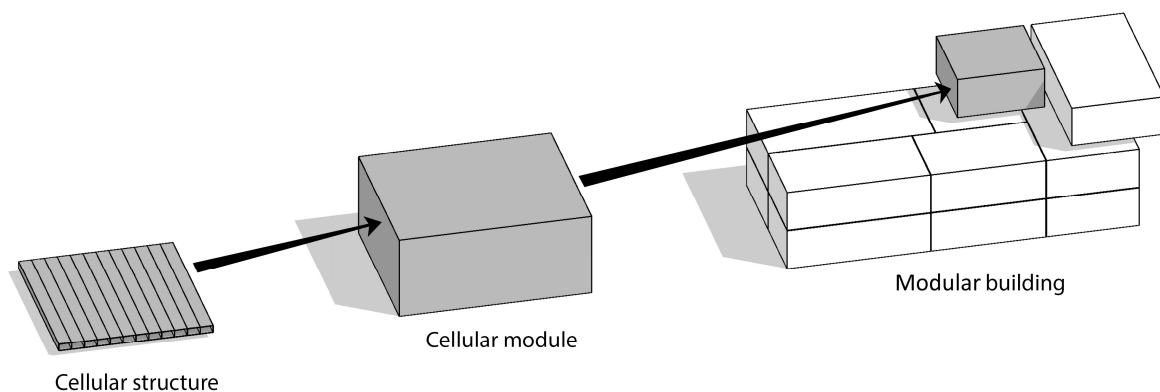
and completes modular buildings. The technology originates from the shipbuilding sector and provides an interesting opportunity for building construction.

## 2. Cellular structures, cellular modules and modular buildings

Modular construction as a concept is not a new idea. The motivation behind this movement is in the promise to gain advantages related to standard procedures. Different approaches of modularity can be identified. Main possible approaches are: i) manufacturing of identical modules (no customization), ii) mass-customization of modules according to the needs of project in question, iii) manufacturing of free-form unique modules. Architectural possibilities are naturally increasing when going towards higher variability of modules. However, all approaches share the production philosophy where industrialized and standardized production is targeted.

Traditionally, buildings have been constructed using practices where on-site methods have had a dominating role. However, many kind of prefabricated solutions have gradually become more popular. This has resulted in prefabricated production technologies where complete building elements are formed from prefabricated components. For example, building façade elements can be composed from prefabricated components (skeleton, insulation, windows). Modularity can go even further. Modular construction refers to the use of volumetric modules that are objects in three physical dimensions forming a complete space such as room or even a completed dwelling.

A cellular structure is defined as a structural component targeting the minimization of the amount of used material to reach minimal weight and minimal material cost. A honeycomb shaped structure is an example of such cellular structure. Modular construction represents a new kind of skeletal structure (compare Hong et al. 2011). The basic idea is that the modules can bear the load of the other modules, and thus separate supporting structures are not required. Modular construction is also a special case of modular construction where even multi-storey buildings can be made from volumetric modules, the size of which can comprise a whole dwelling unit (Figure 1).



**Figure 1. Concepts of cellular structures, cellular modules and modular buildings.**

### **3. Concells research and development project**

#### **3.1 Research approach and methods**

The Concells research project consisted of five work packages covering various knowledge gaps of cellular structures, modules and buildings. The research was carried out in collaboration of an academic research body and four companies, including engineering and architecture offices. As a leading company was a relatively new and innovative construction company, that has developed patented products related to modular construction. This company utilizes hot galvanized steel panels in its cellular structure products. Other firms involved were from the area sectors of architecture, engineering and HVAC.

The research and development effort within the Concells project has been particularly around technical and architectural questions related to modular construction. Because the core firm of modular construction supply chain is a part of the larger ecosystem of companies, also its partners are important in developing and learning. In this project we have studied things related to business networks.

The research itself included two case projects and one so-called virtual project that was designed and analyzed in co-operation with architects, engineers and researchers. Two case projects were residential building projects where the gained results and experiences were analyzed.

#### **3.2 Case projects**

Two modular building construction projects from Finland were under close evaluation in the Concells project. The both cases represent residential buildings where the apartments are built in a way where one module is a complete one dwelling. Later on in this paper the case projects are termed as case A and case B. The first case project (A) comprised three 2-storey apartment houses, altogether 53 dwellings. This project was originally designed as a concrete building but the engineering drawings were afterwards revised for modular apartments made from cellular steel structures. The client was a tenement company owned by the city in question.

Second case project (B) is a 5-storey apartment building. The building was designed as a modular solution from the beginning of the project. The size of apartments was between 37-73 square meters (Figure 2). Furthermore both dwelling and staircase shafts were manufactured and installed as factory made prefabricated modules. In this case also an underground garage made from concrete was built, due to the demands of the parking slot regulations set for the area's buildings plan by the local city.



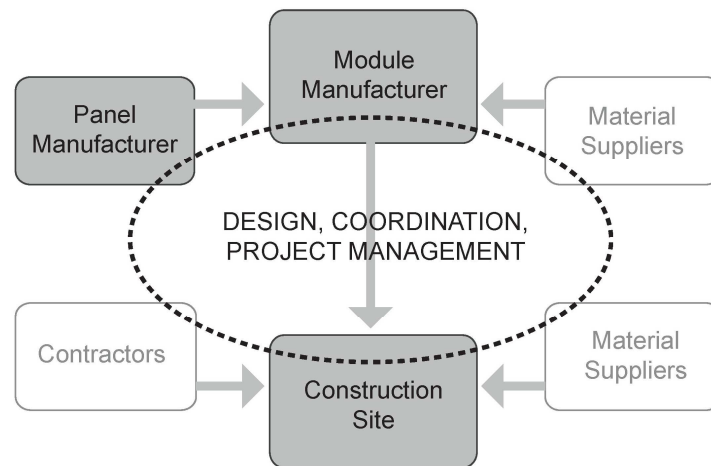
**Figure 2. Installation of cellular modules for the case project B.**

### **3.3 Research data**

In the two case projects research data were collected in interviews covering the following three parts of the supply chain: at panel (cellular structure) manufacturer, module manufacturer and construction site (see the supply chain from the figure 3). Interviewed persons were project managers, production managers or other managers. Project managers had knowledge of their own projects (A or B) and the other interviewed had experience about both projects. The interviews were planned and discussed with purchasing experts in the core firm of the supply chain, thus also their perspective was notified.

The purpose of the interviews was to collect information especially about (1) what has been successful, (2) what kind of problems have appeared and (3) what kind of surprises have appeared in the modular building projects. Thus the basic purpose was to analyze earlier or current projects, and to document, what were the lessons learnt. So that the same failures are not repeated, and good things are reinforced in the future projects.

In addition to the interview a partner analysis was carried out. The data for this was provided by the supplies and procurement managers.

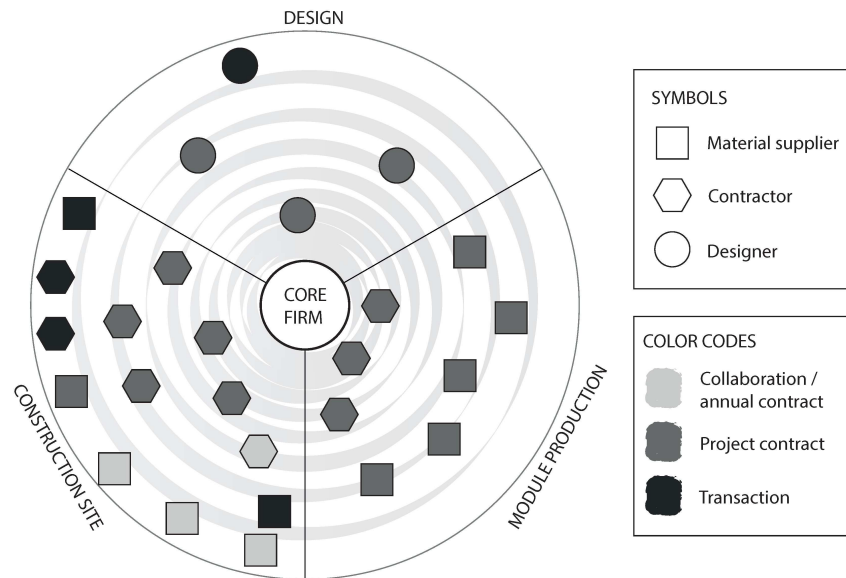


**Figure 3. Supply chain in modular construction. The interviewed organizations are presented as gray.**

## 4. Results

Clear differences between project A and B were identified regarding the logic of supplies and their management. In the project A even many basic small purchases were done by the core firm both in the case of module production and construction sites. In the project B there were many lessons learnt from the earlier project A related to the supply chain management. The content of the contracts was therefore developed, and also many suppliers and other partners were changed. In both cases the project management was in the hands of the core company, but many other tasks were outsourced to the specialized companies.

The following figure 4 explains the profiles of partners (other companies such as engineering companies, subcontractors, special contractors and suppliers) involved in the case project B. The total number of companies involved in both projects is noticeable. The project A included 140 partnering companies, and 26 contract relationships. The project B included 90 partners and 22 contract relationships. One should notice that the project A preceded the project B, and the number of partners was consciously reduced based on the gained experience.



**Figure 4. The most important partners in the project (B). Each figure represents a company. The nearer the figure is to the core firm the more revenue it had in the project. The subcontractors are not included in the picture.**

From the construction site perspective the overall experience was that modular construction is rather similar to conventional construction operations, but installation phase is significantly faster. The most important differences are in the design phase and in the manufacturing process.

## 5. Significance of gained results for construction management

Some factory production related bottlenecks were identified in the case projects. This covered the organization and management of manufacturing processes themselves. The batch production type of factory operations can result in a situation where the site cannot have continuous flow of modules for installation. Apparently, this can be a significant cause for lower productivity and, finally, the total *project duration* is not in the target level. However, it seems clear that the construction process on site can be much shorter in modular construction than in conventional projects. The case projects included several waiting periods on sites due to the bottlenecks elsewhere.

*Off-site and on-site constructability* and its relations to design processes and their management turned out to be rather multidimensional and challenging viewpoints. The design philosophy in modular construction is clearly different than in traditional construction projects. In the modular construction the product design should be done in a way where modular feasibility is enabled in all phases from off-site manufacturing until the final stages of on-site construction operations. Generally, design management is an activity where the overall project objectives form the most importance reference point to evaluate outcomes of design processes and guide the actual processes further. In the case of modular



construction it is the manufacturing knowledge (off-site production, deliveries, on-site assembly) that needs to be incorporated within design management. Based on the studied case projects it seems possible that there will be always a good share of conventional on-site constructions activities in modular construction projects. For example, these can include earthworks, foundations, parts of load bearing structures, façade finishing and roofing. Thus, there will be a need to manage successfully the interplay between the results from off-site production and their assemblies on site together with some traditional construction operations taking place in an almost or totally overlapping manner.

*Technical tolerances* are a wide subject. In the modular construction the technical tolerance errors can be accumulated in panel manufacturing (including both own and tolerance errors of materials), module manufacturing, on site (including also the effects of weather) and dimensions transformations of modules during transportation. Such tolerances seem to be much more critical in modular construction than in traditional construction since chances to fix potential tolerance problems afterwards on construction site conditions are more limited in modular construction. In off-site manufacturing such fixing operations are possible, that errors will be copied many times (in several cellular modules) before the error is found. Therefore in the case of modular construction proactive supervising is important related to technical tolerances and also to other potential manufacturing defects.

Compared with traditional construction, modular construction requires more detailed and carefully designed solutions, e.g. complete shop drawings. *The management of information flows* is particularly important due to this reason. More detailed product and production data is also needed in earlier phases than in conventional on-site construction. In the case projects several new kind of challenges were identified such as difficulties to optimize the purchases and their costs. This was due to the lacking or late arrival of material data from designers. Incompletely synchronized information flows caused notable rework and changes in the studied case projects.

Ability to avoid *moisture problems and their management* can be an advantage of modular construction, because most of the manufacturing process is done indoors where weather doesn't affect. However, in both projects there appeared to be moisture problems on sites. Thus even though the cellular modules are produced in interior conditions, it is possible to have water problems on site, if too little attention is paid on moisture management. However, in the case projects some solutions addressing moisture problems were identified in collaboration with module manufacturer. Thus the moisture problems don't seem to be unsolvable and lasting challenge for modular construction.

*Spatial efficiency*, in terms of the square meters that can be sold, can be currently a somewhat lower in modular buildings compared to traditional buildings. This is due to additional joints and their space requirements between modules. When using traditional performance indicators the spatial efficiency can prove to be a competitive disadvantage. Thus, it seems that this is then matter of presenting new kind of performance indicators that are highlighting the new kind of benefits provided by the modular construction.

Finding *capable and committed partners* can be very difficult when entering new business such as modular building construction. This is due to the lacking business ecosystem. As this modular building ecosystem we mean organizations and individuals which provide foundation for successful deliveries of such buildings from project initiation through the life-cycle of the delivery. Furthermore it is assumed that the ecosystem can provide knowledge and resources for the actual facility management as well. New companies have to market their technology and convince both the potential buyers and contractors in the situation where for example costing can be challenging, due to limited amount of reference projects related to modular construction in the building sector.

## 6. Conclusion

The cellular structures have their origins in the shipbuilding sector. Thus this emerging new business line has clear distance and differences to the traditional construction and its culture. It does not have its weight of past and it can be very interesting chance to create a significant impact to the building construction. However, challenges are notable. Our research observed several critical points, from which some are clearly different than in traditional construction. In particular, the overall process expectations are closer to manufacturing than construction. For construction management this presents another field of knowledge of importance. Based on this knowledge and relating observations from case projects several principles have been presented in this paper that needs to be incorporated within the management of modular construction projects.

## 7. Acknowledgements

The research effort forming the basis of this paper enjoyed a most fruitful and positive support and co-operation with Neapo Ltd., Suunnittelulinja Ltd, Hedman & Matomäki Ltd. and Ramboll Ltd. The main financing body of the Concells research and development project was Tekes (the Finnish Funding Agency for Technology and Innovation).

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