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Classification of production systems for industrialized building: a production strategy perspective

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The purpose is to develop a matrix for classifying production systems for construction with various degrees of industrialization. Previous attempts to classify industrialized production systems for construction focus on dimensions such as the design process, the product technology, or the supply chain structure, but none of them acknowledge the importance of how orders are actually won in the market and that different market segments have different requirements. Using production strategy theory as a base, a matrix is developed linking market requirements, via the product offering, to the design of the production system. The matrix positions typical production systems based on their respective degrees of product standardization and volumes relative to the degree of offsite production. Similar to production systems in manufacturing, production systems for construction also deliver manufacturing outputs at different levels, indicating that the choice of production system will affect the competitiveness of the company. The applicability of the matrix is exemplified through three case illustrations of concepts for industrialized building, and these show that the matrix can be used to analyse the production systems' relative strengths and weaknesses. The matrix can also be used as a guide when developing new, or adjusting existing, production systems for industrialized building so that they will match market requirements and offer competitiveness.

Keywords: Construction industry, industrialized housing, offsite production, operational research, production process.

Introduction

The construction industry has for long been suffering from both low productivity as well as high, and rising, production costs (Vrijhoef and Koskela, 2000; Höök and Stehn, 2008). Means have been proposed to resolve these problems, from both industry and academia, but few of them have been successful in the long run (Nadim and Goulding, 2011). Many attempts have been made in developing new, and revisiting old, methods to improve the construction industry (see e.g. Barlow *et al.*, 2003; Gibb and Isack, 2003; Blismas *et al.*, 2006; Pan *et al.*, 2008; Chen *et al.*, 2010), and recently there has been a renewed interest for industrialization to mitigate some of the identified problems in the construction industry. Industrialization includes a higher degree of standardization of both materials and processes, a higher degree of prefabrication and offsite production, platform-based approaches, and moving the value-adding activities upstream in the supply chain (Barlow *et al.*, 2003; Pan *et al.*, 2007; Thuesen and Hvam, 2011). Compared to conventional onsite construction, industrialized production systems for construction have been said to have many advantages (Kadir *et al.*, 2006; Meiling *et al.*, 2012) such as: higher productivity, lower production cost, higher quality and better on-time delivery, to name a few. The trade-off when increasing the degree of industrialization is mainly the reduced variety for the customer. From academia some attempts to classify various forms of industrialized production systems for construction have been presented (e.g. Barlow *et al.*, 2003; Barlow and Ozaki, 2005; Halman *et al.*, 2008), but none of them explicitly treats the trade-offs apparent in industrialization (e.g. the trade-off between productivity and flexibility). Furthermore, the classification matrices and frameworks for industrialized construction found in

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literature neglect the important link between the market requirements (via the product offering) and the design of the production system. Acknowledging this link, and its inherent trade-offs, is crucial when developing production systems so that they can offer competitiveness for specific market segments. The structure of established production strategy frameworks for manufacturing (e.g. Skinner, 1969; Hayes and Wheelwright, 1984; Miltenburg, 2005), offering a well-established way of structuring and classifying various production systems in relation to product and market requirements, is therefore appealing when addressing the issue of classifying production systems for industrialized building. The production strategy theory, for instance, offers guidance on choosing appropriate production systems so as to match the competitive priorities of the company (see e.g. Hayes and Wheelwright, 1979; Hill, 2000). This is important also in construction when more and more companies are turning towards industrialized building.

The purpose is therefore to develop a matrix for classifying production systems for construction with various degrees of industrialization, based on the traditional production strategy framework, linking market requirements, product characteristics, and the design of the production system. In so doing we will consider the fact that varied market conditions and segments can create different, but equally efficient, industry responses (Barlow and Ozaki, 2005), and that these market conditions must be linked to an appropriate design of the production system. In developing the matrix we also address the following research questions:

- What are the most suitable dimensions for classifying typical production systems for construction?
- In what way do different production systems for construction meet different market requirements (i.e. strengths/weaknesses of the identified production systems)?

To address the purpose and the two research questions the research is divided into two phases. The first phase focuses on theory development, based on a literature review and conceptual modelling, and results in our classification matrix. The second phase concerns theory testing and is based on three case examples to illustrate the applicability of the matrix. The initial search for suitable frameworks to aid construction companies in their work with designing industrialized production systems revealed a number of shortcomings leading us to base our theory development on established production strategy theory. The literature review therefore relates production strategy theory to the identified frameworks for classifying industrialized production in construction. Contingency theory is a mainstay in production strategy theory recognizing that production system design must be tailored to different market segments with specific requirements. Therefore literature regarding drivers and barriers for industrialized production was reviewed to be able to identify the competitive priorities in construction. The results of the literature review are used to conceptually develop a matrix for classifying production systems for construction. To illustrate how the matrix can be used for analysing companies' present situation, the second phase of our research identifies three industrialized concepts positioned in different areas of the matrix. These concepts are used as case illustrations to discuss the merits and the limitations of the matrix. These merits and limitations lead to our suggestions for further research to enhance the matrix and develop it into a framework in line with the productions strategy theory.

Research design and method

The first research phase concerns theory development and is based on a literature review and conceptual modelling (logical reasoning). At first a thorough literature review was conducted in order to find the most relevant schemes and frameworks for classifying typical production systems in construction. The major production strategy frameworks and literature describing strengths and weaknesses of offsite production in construction were also reviewed in this phase. The literature review forms the basis for developing a matrix that can be used to classify production systems for construction with a special focus on industrialized building. In the development, suitable classification dimensions were identified, drivers and barriers for offsite construction were clustered and linked to the so-called manufacturing outputs, and the identified classification schemes for industrialized building were compared to the production strategy frameworks. The result is a classification matrix for industrialized construction, offering the possibility to assess different production systems' relative ability to perform in different areas of competition.

The second phase of the research concerns theory testing and started with a review of successful and less successful examples of construction companies that have implemented industrialized production systems in recent years. Among the identified cases three were selected, based on a number of reasons. First of all they have different production systems representing different degrees of industrialization. As suggested by

Eisenhardt (1989) the three cases thereby represent different theoretical categories in the matrix and can thus be used to test the applicability of the developed matrix. Secondly, all three cases were already fairly well documented in published papers, reports and publically available data (annual reports, newspapers, etc.). We thereby had easy access to archival and secondary data when building up our case illustrations. Thirdly, the chosen cases also offered the possibility to collect primary data in terms of onsite visits, unstructured and semi-structured interviews with representatives from the companies developing the production systems in question. To increase the construct validity (Yin, 2009), we also interviewed industry experts and consultants who were active in implementing the production systems of the three case companies to triangulate the findings from archival records and the interviews. The drafts of the case study descriptions have also been verified by the respondents from each of the three case companies. The risks of relying on data collected by other researchers have been discussed (Blismas *et al.*, 2006), but doing this can however provide useful sources of data, and since the data are also publicly available, it allows validation and replication from other researchers (Calantone and Vickery, 2010). There are also examples of published research within the area of construction management that use archival and secondary data for meta-analysis and re-analysis (Kenley, 1998; Blismas *et al.*, 2006). Noteworthy is that the archival and secondary data used in testing the theory development were complemented and verified by primary data, which is intended to increase the validity of the research.

Production strategy and construction management

The following sections provide a review of the literature on production strategy as well as an account of classification of production systems in construction.

Production strategy and production systems

Since the seminal paper by Skinner (1969), introducing production strategy as an academic discipline, authors such as Hill (2000), Miltenburg (2005), and Slack and Lewis (2011) have extended Skinner's original thoughts and developed frameworks for linking the business strategy, via market requirements and marketing, to the production strategy. The extensive literature reviews presented in Leong *et al.* (1990) and Dangayach and Deshmukh (2001) show that since Skinner's paper the research on production strategy has focused on the production strategy content rather than the process of developing the strategy. This study also focuses on the production strategy content and as is shown in Leong *et al.* (1990) and Dangayach and Deshmukh (2001) the content of the production strategy is traditionally built around two broad groups: *competitive priorities* and *decision categories*.

The *competitive priorities* are defined as a set of goals for manufacturing, which are used to align the business strategy and market requirements with the manufacturing task. Competitive priorities as means to structure and operate manufacturing have been used extensively in the production strategy literature (see e.g. Hayes and Wheelwright, 1984; Hill, 2000; Miltenburg, 2005). When determining the manufacturing task Rudberg (2004) argues that it is vital to define what the manufacturing function must accomplish in terms of providing so-called manufacturing outputs at competitive levels, i.e. competitive priorities. Consequently, the choice of manufacturing task will position a company relative to its competitors in terms of its competitive advantage.

The actual decisions made to fulfil the manufacturing task are often grouped into a number of *decision categories*. The sets of decision categories differ somewhat between authors, but the literature reviews by Leong *et al.* (1990) and Dangayach and Deshmukh (2001) show that there is an essential agreement on areas that really matter for manufacturing. Typically, the strongest link between market requirements and production strategy concerns the decision category *process choice*, i.e. choosing a production system that delivers manufacturing outputs that support the competitive priorities of the firm. Figure 1 shows the so-called product-process matrix (Hayes and Wheelwright, 1979) in terms of Miltenburg's (2005) production strategy framework, indicating differences in the ability of typical production systems (e.g. job shop, batch flow, etc.) to deliver manufacturing outputs (e.g. delivery, cost, quality, etc.) so as to fulfil the manufacturing task in terms of competitive priorities.

The traditional production strategy framework classifies production systems along two dimensions: products and volumes (PV) in one dimension and layout and material flow (LF) in the other (hence referred to as the PV-LF matrix). Figure 1 positions the typical production systems relative to each other along the diagonal in the PV-LF matrix, and relates them to their respective ability to provide manufacturing outputs at competitive levels. The manufacturing outputs that are typically used in production strategy are delivery (lead time and reliability), cost (product cost per delivered unit), quality (conformance to product specification), performance (features and product performance relative to similar products), flexibility

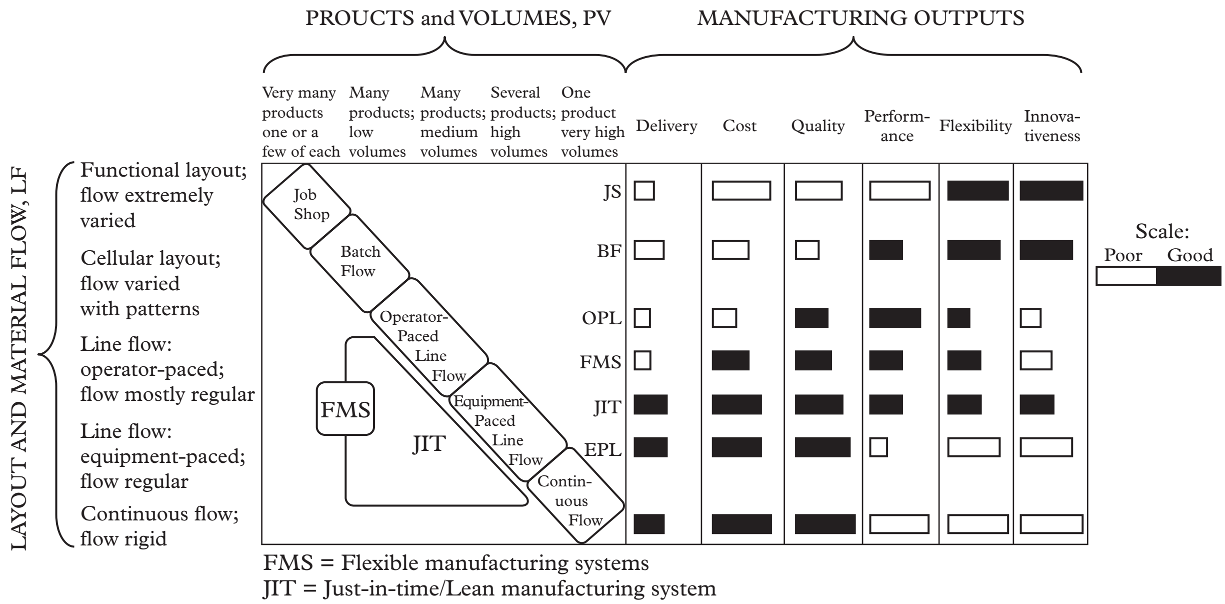

Figure 1 The product-process matrix and manufacturing outputs (Miltenburg, 2005)

(volume and product mix), and innovativeness (ability to introduce new or modified products). As can be seen in Figure 1, the different production systems perform differently in terms of manufacturing outputs. A long black bar represents good performance, whereas a long white bar represents poor performance. This is not an exact science, but rather the bars are intended to show the relative differences between different productions systems' ability to provide manufacturing outputs at competitive levels. For instance, a job shop is much more flexible and it is easier to introduce new products than it is with the continuous flow system (e.g. a pharmaceutical company). Similarly, the unit cost in a line flow system is lower than what it would be to produce the same product in a batch flow system. Thereby, the choice of production system either enhances or limits the possibilities to provide manufacturing outputs at competitive levels, and the process choice must be made wisely based on a thorough analysis of the market and the competition. As can be seen in Figure 1, construction would be positioned far up in the upper left hand corner, but typically project-based production systems are excluded when production systems are depicted in the framework (Miltenburg, 2005). Therefore it is of interest to analyse how production systems for construction can be classified, which is done in the following paragraph.

Production systems in construction

The literature reveals different ways of classifying production systems in construction. Starting with the product design and its relation to the product offer, Segerstedt and Olofsson (2010) introduce a model to classify offsite versus onsite production, inspired by the customer order decoupling point (CODP) (see e.g. Hoekstra and Romme, 1992; Wikner and Rudberg, 2005). The classification in Segerstedt and Olofsson (2010) takes the perspective of the 'customer order *specification* decoupling point', identifying when in time the customer enters the product specification process leading to four different categories: *engineer-to-order* (where only norms and standards are predetermined before the customer enters the process), *modify-to-order* (with predetermined generic product structures, e.g. technical platforms), *configure-to-order* (based on predetermined standard parts and modules), and finally *select-a-variant* (based on standard products with minor possibilities to customize).

There are also several papers offering classification frameworks inspired by Japanese housebuilders (see e.g. Gann, 1996; Barlow *et al.*, 2003; Barlow and Ozaki, 2005). For instance, Barlow *et al.* (2003) take a standpoint in the mass customization literature (e.g. Pine *et al.*, 1993; Rudberg and Wikner, 2004) and classify different levels of customization in terms of generic supply chain strategies ranging from pure standardization ('speculative building') to pure customization ('pure self-build'). In some sense their classification combines the product specification process (Segerstedt and Olofsson, 2010) with the supply chain process in a one-dimensional continuum indicating where in the combined process the customer and thereby the customer specification and requirements enter the process. Also the research in Winch (2003) is inspired by the CODP, arguing that when defining the positioning of the CODP an appropriate process choice must follow (i.e. designing a production system). How this matching of the CODP positioning with the process choice should be done is not outlined in the paper. Some guidance on this issue is however provided in Barlow *et al.* (2003), presenting a five-by-five classification matrix designed to link customer requirements to the various supply chain strategies. The matrix shows that the higher the degree of customization, the higher the cost and lead time, which thereby is in line with the classical trade-off between flexibility and cost that Skinner's (1969) production strategy theory rests upon.

The papers by Voordijk *et al.* (2006) and Doran and Giannakis (2011) both focus on modularity in construction and develop classification schemes for this. Doran and Giannakis (2011), as an example, categorize modular construction in three groups: pure modular, hybrid modular, and onsite modular. The first group is the most standardized one that does not accommodate to change, whereas the onsite modular group allows for a high degree of customization. Their research also relates these categories to a relationship/supplier integration matrix indicating key elements in supply chain design for when modular construction is employed. This is however not linked to the performance of the production system. There are also studies that focus more on the actual production system, for example the one presented in Kadir *et al.* (2006) classifying structural building systems in five categories: conventional, cast *in-situ* building system, onsite prefabrication, offsite prefabrication, and composite systems (the latter being a combination of the other four categories). Yet, that research focuses mainly on the frame and concrete production part of construction, and not on production systems for producing whole buildings.

One of the few classifications that actually address how the products, in terms of whole buildings, are produced is provided in Gibb (2001). In that paper, definitions of four types of production systems with varying degrees of offsite production are developed, which are then further elaborated in Gibb and Isack (2003). The production systems are the following:

- *Component manufacture and sub-assembly*: The traditional approach in construction. Raw materials and components are used for building on site.
- *Non-volumetric pre-assembly*: In this concept 'two-dimensional' elements are prefabricated off site and assembled on site.
- *Volumetric pre-assembly*: Volumes of specific parts in the building are produced off site, and assembled on site within an independent structural frame.
- *Modular building*: In this concept much of the production is carried out off site, with modules fabricated to a high level of completion. The only work performed on site is the assembly of the modules and finishing operations.

When going through the literature that tries to categorize, classify and group production systems for construction it is clear that many different main issues are treated, such as: the design process, the product design, the supply chain structure, etc. What becomes apparent, however, is that few of them focus on the production system as such and how an appropriate production system should be designed. Furthermore, most of them neglect how orders are won in the market (i.e. order winning competitive priorities in terms of manufacturing outputs from the production systems). Even though some of the papers, such as e.g. those of Barlow *et al.* (2003), Segerstedt and Olofsson (2010), Winch (2003), do acknowledge the importance of when the customer enters the design and production process, they do not explicitly address the customer requirements in terms of manufacturing outputs and the competitive priorities of the company.

Competitive priorities in construction

This section addresses manufacturing outputs and competitive priorities, starting with analysing drivers and barriers for industrialized building in terms of offsite production. The identified drivers and barriers are thereafter grouped and linked to the typical manufacturing outputs.

Drivers and barriers for industrialization in construction

Besides the issues of standardization and platform-based approaches, industrialization also means that a higher degree of the value-adding activities are performed off site, e.g. through prefabrication of elements and modules (Barlow *et al.*, 2003; Gibb and Isack, 2003; Meiling *et al.*, 2012). Offsite production, as a part of industrialization, has been treated in the literature, and Table 1 summarizes the identified drivers and barriers for increasing the degree of offsite production.

As can be seen in Table 1, the most frequently mentioned drivers for using offsite production in construction are: improved quality, shorter and/or more predictable production time, health and safety issues, lower and/or more predicable production cost and higher productivity. Other drivers for using offsite production are that it facilitates waste reduction, increased possibilities for economies of scale, better project management and human resource management, technical possibilities, continuous improvement,

Table 1 Summary of drivers and barriers for offsite production found in literature

		Gann (1996)	Gibb (2001)	Barlow *et al.* (2003)	Gibb and Isack (2003)	Blismas *et al.* (2006)	Kadir *et al.* (2006)	Pan *et al.* (2007)	Halman *et al.* (2008)	Jaillon and Poon (2008)	Pan *et al.* (2008)	Arif and Egbu (2010)	Chen *et al.* (2010)
Drivers	Quality		•	•	•	•		•	•	•	•	•	•
	Time				•	•	•	•	•	•	•		•
	Health and safety		•		•	•		•		•	•	•	•
	Cost		•		•	•		•	•	•	•		
	Productivity		•	•	•	•	•	•		•			
	Waste reduction		•							•		•	•
	Management	•	•	•						•			
	Economies of scale	•							•			•	
	Human resource management					•		•				•	
	Technical possibilities	•		•									
	Continuous improvement		•										
	More efficient logistics										•		
Barriers	Flexibility	•	•	•	•				•	•		•	
	Freeze design early		•			•		•			•	•	
	Capital investments					•		•		•	•	•	
	Capabilities				•			•		•	•	•	
	Need for higher production volumes				•			•			•		

and more efficient logistics. Turning to the barriers in Table 1, the most frequently mentioned ones are: reduced flexibility, the need to freeze design early, the level of capital investment, the different types of capabilities needed, and the need for high production volumes when investing in fixed assets for production.

Drivers and barriers in terms of manufacturing outputs

Even though the literature does acknowledge that there are drivers and barriers for increasing the degree of offsite production as part of industrialization, the construction literature does not make use of the notion of competitive priorities so as to be able to provide guidance on how to design competitive production systems. To be able to do this there is a need to express the identified drivers (strengths) and barriers (weaknesses) in terms of the manufacturing outputs as defined in the production strategy theory. Figure 2 relates the drivers and barriers in Table 1 to the manufacturing outputs as defined in Figure 1. Some of the factors in Table 1 are a 'means to an end' in terms of manufacturing outputs, e.g. increased productivity and waste reduction are means to lower the total production *cost* in offsite production. It is thereby possible to 'cluster' the identified drivers and barriers to resemble the traditional manufacturing outputs used in production strategy. It is clear that offsite production offers competitiveness in terms of *delivery* (time, efficient logistics) and *quality* (quality, continuous improvement, technical possibilities, and better management of the project and production

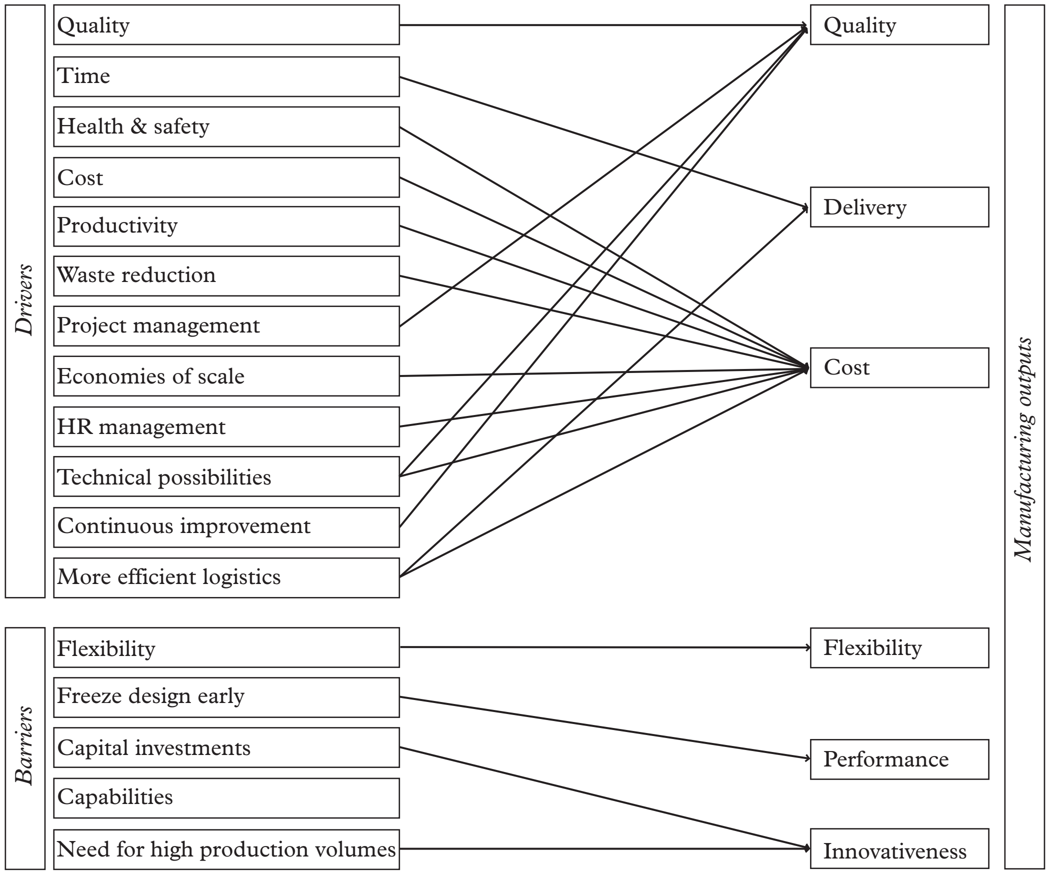

Figure 2 Drivers and barriers for offsite production linked to manufacturing outputs

process). *Cost* is also considered to be improved and it is highlighted in Table 1 by the factors cost, productivity, waste reduction, economies of scale, and efficient logistics. We would argue that the improved health and safety that offsite production offers (as a consequence of a more controllable production environment in offsite production) also reduce cost and so do the improved technical possibilities that industrialization offers in terms of e.g. automation. Better HR management also decreases cost in terms of easier resources planning, the possibility of using more than one shift, etc.

The downside with offsite production in construction is that it is argued to reduce the *flexibility* (flexibility) and *performance* (early design freeze). The literature also highlights that offsite production limits the possibilities for a high level of *innovativeness*. This is due to the fact that offsite production requires high capital investments in fixed assets and the production system is thereby dependent on high production volumes to offset the capital investment. It is thus harder to introduce new products and to change the established production process without jeopardizing the output of the current production system. Finally, lack of capabilities when it comes to offsite production was also highlighted as a hindering barrier. This factor has not been linked to any of the manufacturing outputs since it rather relates to the skills and know-how (i.e. decision categories) that have to be developed to succeed with industrialization. Lack of skills and know-how can be a hindering barrier, but acquiring these and other capabilities can on the other hand drive high levels of the manufacturing outputs of the chosen production system.

In summary, industrialization and a high degree of offsite production are often portrayed in positive terms regarding productivity-related issues, such as higher quality, reduced throughput time, increased economies of scale, less waste, and efficient logistics, to name a few of the identified drivers in Table 1. On the other hand, the downside with industrialization and offsite production often relates to a lower degree of customization and reduced flexibility in production to meet customer requirements. Production systems with a high degree of industrialization are often regarded as having lower performance (e.g. features and options) and being more resistant to product innovations. However, a key issue in production strategy is to design a production system that will meet customer requirements in the most effective way, i.e. dealing with the trade-offs inherent in the process choice (that is, the design of the production system). It is impossible to design a panacea production system that outperforms all other production systems, no matter what context the products are competing in. This is also true for production systems in construction and a higher degree of industrialization is not always the right answer to improve operations in construction. For instance Thuesen and Hvam (2011) argue that offsite manufacturing might not always be the optimal production method and that a well-managed onsite production system can be a better process choice under certain circumstances. When designing a production system a contingency approach (see e.g. Ghoshal and Nohria, 1993) must be followed. That includes knowledge about the chosen production system's ability to perform in terms of providing manufacturing outputs in different areas of competition. Such a contingent approach to classifying industrialized production systems will be described in the following section.

A matrix for classifying production systems for construction

The design of a new, or the redesign of an existing, production system should be done with the intended market segment and customer requirements in mind. The choice of production process also determines the production system's ability to provide manufacturing outputs at the desired levels. So far, the managerial guidance on how to design, or redesign, a production system is scarce, especially when taking a contingency approach including competitiveness and the ability to satisfy market requirements. Figure 3 shows the matrix that we propose for classifying production systems for construction, and for analysing their respective competitiveness in terms of manufacturing outputs. The matrix is inspired by Miltenburg's (2005) production strategy framework, but takes into account the perspective of the four types of production systems presented in Gibb (2001). In our matrix the four types of production systems have been positioned relative to each other in terms of two dimensions: the degree of offsite production (high to low) and the degree of product standardization and manufacturing volumes (low/low to high/high), in line with the reasoning in Barlow *et al.* (2003), Doran and Giannakis (2011), and Segerstedt and Olofsson (2010). Worth mentioning is that whatever production system is used, construction requires that some activities are performed on site (e.g. establishment/foundations, assembly, finishing, etc.). The 'component manufacture & sub-assembly' (CM&SA) resembles traditional onsite construction and can thereby offer a huge variety of products and performs most of the value-adding activities on site. On the other hand, the modular building (MB) offers the possibilities to perform most of the value-adding activities off site, but is limited in the variety (number of different products) that can be offered to the customers. A high degree of offsite production typically means significant investments in fixed assets (i.e. a factory), requiring a higher volume to offset the fixed assets investments. As such, the four production systems identified by Gibb (2001) can be placed along a diagonal as indicated in Figure 3. Each system thereby represents a unique combination of degree of offsite production and product standardization/manufacturing volumes, showing typical differences between the production systems.

The matrix also links the positioning of the production systems with the manufacturing outputs that each production system typically provides. The literature review (Table 1) and the clustering of drivers and barriers (Figure 2) show that the manufacturing outputs used in production strategy theory are also valid when it comes to construction. Similar to the production systems in Miltenburg's (2005) original framework, the construction production systems will have different strengths and weaknesses in meeting customer requirements, in terms of e.g. delivery, cost, quality and flexibility. The fact that different production systems perform well in different areas of competition suggests that the choice of production system should be based on an analysis of the market and customer demands. To be successful in producing buildings, the strengths of the production system must fit the requirements of the customer.

As for Miltenburg's (2005) framework, the grading of good and poor levels of manufacturing outputs is not an exact science in absolute terms. Rather, the manufacturing outputs should be considered as relative differences between the production systems in the framework. To exemplify this, delivery lead times are normally longer and less reliable the higher the degree of uniqueness in the product and the lower the degree of offsite production. Hence, the manufacturing output *delivery* typically has lower levels (i.e. poor) for CM&SA, whereas it increases the more standardized the products get and the higher the degree of offsite production. As for the classical cost-flexibility trade-off there are differences along the diagonal in the classification matrix (supported by e.g. Barlow *et al.*, 2003). Concerning cost the very idea with a standardized product produced off site is to have a low unit cost, which can be realized as long as the volumes are sufficiently high. Production systems designed for a

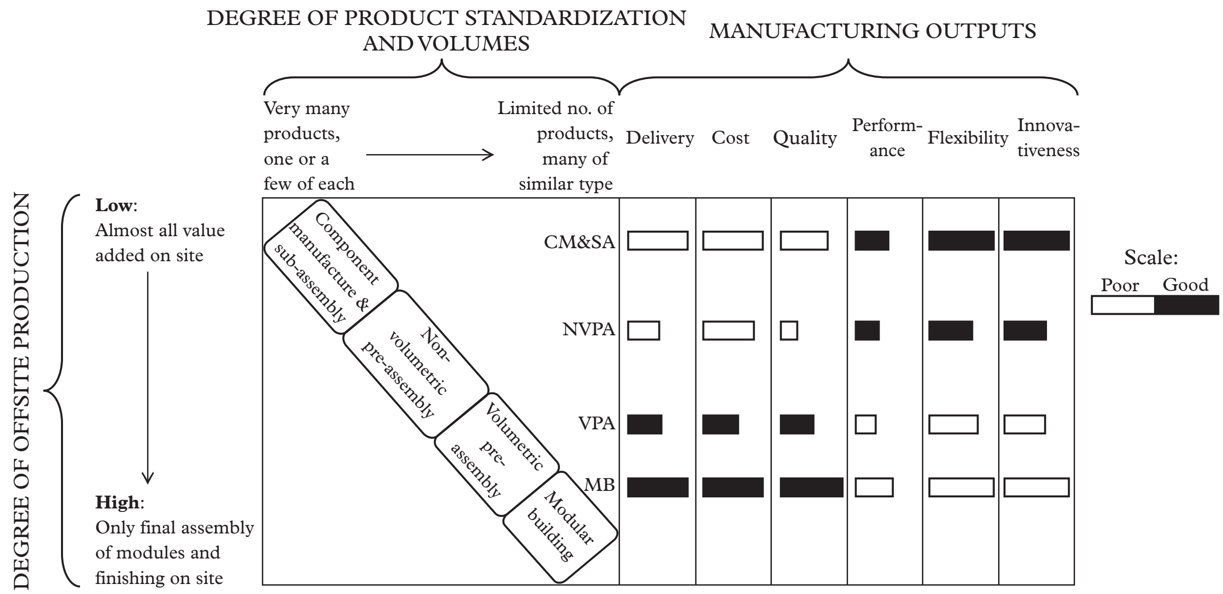

Figure 3 Framework for classifying construction production systems and manufacturing outputs

higher variety with more value added on site can seldom compete on cost for the same type of product. On the other hand, CM&SA can be set up uniquely for a specific project and thereby be very flexible in terms of product mix. It is possible to accommodate volume flexibility incrementally by a stepwise acquisition of resources for each project. This is harder to accommodate in a production system designed to produce high volumes of a limited set of products off site, even though the system can offer some volume flexibility within its capacity limitations and some mix flexibility if it is based on a thought-through modular product design and a flexible manufacturing system. Similar reasoning can be used for the other manufacturing outputs portraying relative differences between the production systems in the framework. It is easier to implement innovations and offer features and customer adapted performance in CM&SA than in a rigid offsite production system.

It must be emphasized that the outputs of the different production systems in Figure 3 are typical ones and can differ between companies depending on how well they manage their system, where they are located relative to the market, etc. Utilizing technical possibilities, well-developed capabilities, etc., can help companies to work around poor manufacturing outputs from some production systems. Also Miltenburg (2005) identifies production systems off the diagonal (just-in-time [JIT] and flexible manufacturing systems [FMS]) that can offer combined competitiveness along many manufacturing outputs if designed wisely. Yet, there are differences embedded in the choice of production system, and when making the process choice and designing the production system these differences must be taken into account, so as to design a competitive production system. In the following we will exemplify these differences for the typical production systems we have identified along the diagonal in Figure 3, and exemplify how the matrix can be used by the means of three case examples.

Case examples of industrialized production systems

To exemplify the framework in Figure 3, and the differences between different production systems, three companies representing different positions in the classification matrix have been picked for the case study research. Traditional construction (CM&SA) is left out of the scope since we focus more on production systems including some degree of industrialization and offsite production. Hence, we have picked one case for each of the remaining three production systems in the matrix. Table 2 summarizes case company information and also indicates the kinds of data that have been used for each respective case.

Case NVPA

This concept was a major effort to rethink the entire production of buildings. With a vision to reduce production cost and time, this large contractor invested €30 000 000 in the new concept (development, facilities, technology, IT, etc.). The goal was to produce multi-family houses up to eight floors to meet an expected demand for affordable living. The concept

Table 2 Overview of case company data

Case	Company type	Production system	Production volume	Data sources	Note
NVPA	New business unit at large contractor	Non-volumetric pre-assembly	391 dwellings 2006–08 (capacity > 1000 dwellings pa)	Unstructured interview, semi-structured telephone interview (Apleberger *et al.*, 2007; Andersson *et al.*, 2009)	Closed down in 2007
VPA	Concept owned by real estate company	Volumetric pre-assembly	1360 dwellings 2003–08	Unstructured interview, semi-structured telephone interview (Svensson, 2004; Boverket, 2006; Apleberger *et al.*, 2007; Andersson *et al.*, 2009)	Closed down in 2008
MB	Medium sized, family owned company	Modular building	7100 dwellings 1994–2011	Onsite visit, unstructured interview, semi-structured telephone interview (Apleberger *et al.*, 2007; Andersson *et al.*, 2009)	Still running as of June 2013

was designed to be able to meet a broad variety of customer demands; the prerequisite was that the choices were made early in the process. The customers made their choices in design in the sales phase (Andersson *et al.*, 2009), but after a certain point the customers were not able to make any changes. In terms of the customer order specification decoupling point (Segerstedt and Olofsson, 2010) this would resemble a situation between the engineer-to-order and the modify-to-order, meaning a fairly low level of standardization.

The offsite production system was inspired by the car and shipbuilding industries, and elements were complete with installations (e.g. radiators and electric switches) and surfaces (e.g. wallpaper, paint and floor tiles) when leaving the factory. The production of elements was undertaken in three separate production lines: ceiling/floor, walls and kitchen. Stairways, balconies, bathrooms and the roof were delivered directly to the construction site from external suppliers. The majority of the prefabricated elements were transported to site in flat packages. The goal was to prefabricate 90% of the buildings off site (foundations excluded). Assembly on site was performed in a large, temporary, weatherproof assembly hall (Apleberger *et al.*, 2007; Andersson *et al.*, 2009), and the only activities, besides assembly, performed on site were the facade and complementary work on the roof.

This concept is categorized as *Non-volumetric pre-assembly* in Figure 3. Traditional onsite construction (CM&SA) was considered the main competitor, and within this context the order winner was argued to be *delivery*; the total production time was halved compared to traditional construction processes. However, in addition a large reduction of cost was postulated as a competitive advantage compared to traditional onsite competitors. Consistent and high quality was also a factor that was considered important (i.e. an order qualifier). Comparing NPVA to other industrialized concepts, the main advantage was the performance and the flexibility offered. As long as the choices were made early in the process the system offered a large variety of product types and features.

NVPA could not live up to the expectations in terms of production pace. The realized production volume was far from the break-even production volume (Andersson *et al.*, 2009), meaning that the production unit cost became much higher than expected. NVPA thereby showed a loss for three consecutive years before it was shut down in 2007. It had been operational in less than three years and only produced a total of 391 flats in 16 multi-family houses. NVPA was an effort to make a revolutionary change in the production process and internally NVPA was promoted as a concept to make the same improvements that took the car industry 20 years to realize, but in only five years. Even though the company made large investments in both money and patience, it was not enough to make it work (Nagenius and Kaldner, 2010).

Case VPA

The starting point for this concept was a competition concerning 'the future of building'. A joint venture between the winner and the runner up was arranged and that resulted in this new concept for production of multi-family houses up to five floors. After some smaller pilot projects and development of the building system, an order to build 1200 dwellings was received, meaning that the production system could be tested in full-scale production. Of the 1200 dwellings 90% were rental units and 10% were condominiums. This concept also focused on affordable living and the reduction of production cost was very important (Boverket, 2006).

The building system consisted of an independent structural framework of steel where modules were mounted. Since the supporting steel frame carried the load from surrounding modules, the modules were designed only to support their own weight. This was an important factor since the construction offered the possibility to introduce product variants and customer-specific features (i.e. performance) in the standardized structure. The aim was to produce 50% of the building off site and the modules were produced off site to a high level of completion. The main activities performed on site were the facades, complementary work with bathroom fixtures and kitchen appliances and work with the connection between the modules. The idea when it came to the design of the building was to produce the interior parts of the building in an industrial way while the exterior was built in a more traditional way to blend in with the surroundings (Apleberger *et al.*, 2007; Andersson *et al.*, 2009), thereby being able to offer more product variants without affecting the production system off site. The production system was therefore designed for a fairly high level of standardization producing fairly high volumes per product type, while still offering some variation in both exterior and interior product features.

This concept is categorized as *Volumetric pre-assembly* in Figure 3. The main differences from the production systems in the lower right hand corner of the matrix, like the MB case described below, are the degree of offsite production and the independent structural framework supporting the modules. VPA thereby offers a greater possibility of introducing product variants and features as compared to MB, and the production system as such offers a higher degree of flexibility. The order winner for this specific concept was *cost*. The ambition was to reduce production cost to be able to offer the end customers affordable living. The main competition was the traditional onsite production and flexibility, quality and delivery were considered order qualifiers.

VPA could, however, not reduce the production cost enough to be able to compete with onsite production and the concept was closed down in 2008. In the pilot projects the production cost was around €1250/m^2, but when the production volume increased they could not reach that cost level. The main problem was that VPA only managed to produce 35% of the building off site, which naturally increased the actual production costs for the buildings and reduced the competitiveness of VPA. Furthermore, when VPA had to do more of the value added on site a lot of coordination problems arose. The insufficient coordination between the plant, in which the modules were produced, and the construction site delayed the project and further increased the production cost. Another problem resulting from the lower than expected degree of offsite production was the installations undertaken by subcontractors and the coordination between the building system and the installations. The problems with coordination between different parts of the production system made it hard to reduce the work on site as the project was running. Hence, VPA never managed to reach the level of volumes that the production system was designed to handle.

Case MB

This company builds multi-family houses with two to six floors. Its turnover as of 2011 was just over €50 000 000, and the firm has some 165 employees. The company considers that it does not have standard products; each house is designed based on customer demands. There are limitations in the design though: the product is based on a technical platform and the technical solutions are reused to a large extent, which limits the end customers' ability to affect the design (Andersson *et al.*, 2009). There are also operational limitations such that the modules have a maximum width of 4.15 meters due to transportation regulations. Therefore, the company must be considered to produce fairly standardized products in high volumes, even though it does manage to offer some product variation thanks to a thought-through product platform and a production system that can handle the necessary flexibility to offer variation within the technical platform.

The modules are prefabricated to a high level of completion off site, and about 80% of the work is performed off site leaving 20% to be performed on site (Meiling *et al.*, 2012). The offsite manufacturing phase is divided into three main stages: element production (floor, walls and roof), module assembly and module completion. The complete modules are covered and transported to the construction site where the building is assembled by small in-house groups that specialize in the onsite phase of the production. The building system has no independent structural frame; the modules themselves are carrying the entire load.

In Figure 3, this concept is categorized as *Modular building*. The order winner for this specific case is delivery, but the importance of cost reduction is also highlighted, especially when it comes to campus apartments and leasehold flats. The customers are typically public actors and they value the reduced production time on site since it leads to less disturbance for the surrounding community. Also the design lead time is in congruence with the time the customer needs for selling the required amount of dwellings before production starts. The other manufacturing outputs are considered qualifiers for MB, typically concerned with the regulations of the National Board of Housing, Building and Planning (quality, performance) and the competition with traditional onsite construction (quality, flexibility, innovativeness).

This firm only produces buildings on turnkey contracts which means that it has control over the whole process from design to complete building. Other contract forms are not an option since it has to make sure that every part of the process is in line with its production strategy. The company has worked with lean production for many years, so as to reduce waste and streamline production, but also focusing on the design and administrative processes. The company is still running.

Case summary

Table 3 summarizes the key characteristics from the three cases. As can be seen they have three different types of production systems and they do differ in terms of the degree of offsite production and in terms of product standardization and production volumes. In other words, they have different positions in the matrix presented in Figure 3. They also compete on somewhat different order winners (i.e. focus on different manufacturing outputs). Yet, considering the different positions in the matrix the order winners are still quite similar. This and other issues will be further discussed in the following section.

Discussion and implication

The following section discusses the case examples in relation to the classification matrix and outlines implications for research and for practice.

Case discussion

Only MB is still active (as of June 2013), and there are many reasons why the other concepts were closed down. The classification matrix presented in Figure 3 can be used to shed some light on the issue, even though the process choice of the companies might not be the only answer to success or failure of the concepts analysed. Yet analysing the process choice and the corresponding order winners relative to how the production system was actually positioned in the matrix does offer interesting insights. It also demonstrates how the matrix can be used to design, and analyse, production systems in construction.

Case NVPA was developed as a separate concept within a large contractor and as such it had to compete not only with other contractors, but also with the traditional way of building houses within the company. The concept was also an attempt to radically change the way of doing business in construction, and as such there were many new requirements when it came to capabilities, production, assembly processes, logistics, etc. When the company was losing money on the concept, it did not have the endurance to trim and fine tune the new concept to make it profitable. The reasons why it was losing money can partly be explained with the aid of the matrix in Figure 3. NVPA focused on cutting lead time and costs compared to onsite construction, while offering a higher degree of flexibility than other competing industrialized concepts. It was offering a high variety for the customer, but still aiming at producing 90% of the value-adding off site (although it only reached 60%). As such, it was offering a product with high variety in terms of many product variants in low volumes per product type. But instead of matching the product standardization and volume dimension (cf. Figure 3) with a corresponding degree of offsite production, it

Table 3 Summary of key characteristics for the three case examples

Characteristic	NVPA	VPA	MB
Type of product	Multi-family houses up to 8 floors	Multi-family houses up to 5 floors	Multi-family houses up to 6 floors
Type of production system	Non-volumetric pre-assembly	Volumetric pre-assembly	Modular building
Degree of product standardization	Low	Medium-high	High
Volumes/product type	High[a]	Medium	Medium-high
Degree of offsite production	High (90%)[b]	Medium (50%)[c]	High (80%)
Order winning manufacturing output	Delivery, cost, flexibility	Cost	Delivery, cost

Notes: [a]Designed for high volume, but only produced in low volumes.
[b]Only reached 60%.
[c]Only reached 35%.

designed a production system focusing on cost with a very high level of completion off site. In terms of the matrix in Figure 3 it was 'off the diagonal match' by being far below the diagonal. In other words, it was trying to offer 'flexibility-related' manufacturing outputs (performance, flexibility and innovativeness) with a 'productivity-related' production system (delivery, cost and quality). It was also trying too hard to satisfy the customer (instead of maybe turning 'wrong' orders down), so that it was not loyal to the concept and allowed for late design changes making it even harder to keep costs down and to accommodate the constantly changing product types in production. NVPA thereby ended up in a panacea production system trying to do well in almost all manufacturing outputs, which resulted in a mismatch between market requirements and the design of the production system. Therefore, it underperformed in all outputs and was outperformed by competing production systems. It did not reach any of the goals or volumes that were set out when the concept was designed.

Case VPA was focusing heavily on cutting cost compared to onsite construction and the concept that was created out of a joint venture only focused on industrialized building. According to the framework in Figure 3, the initial design of the production system was correctly done, matching medium-high product standardization and volume with approximately 50% value added off site. This should allow for some 'flexibility-related' outputs besides the main focus on 'productivity-related' manufacturing outputs. Yet it never reached the 50% level (rather 30–35%) and as such ended up above the diagonal match in Figure 3. It was trying to provide low cost but had too low volumes to offset the cost of fixed assets. Also, a correct positioning is not enough if a company does not acquire the right capabilities to make the concept work. Here, the failure to reach volume off site put higher than expected requirements on coordination between the factory, the subcontractors, and the site. VPA had designed a production system that was lacking the necessary knowledge, know-how, and resources to make the production system work with such high degrees of value added on site. In terms of manufacturing outputs, its desired order winner was cost, but being off the diagonal match in the matrix it could not reach the expected cost level. Meanwhile it was also underperforming in delivery and quality due to the coordination problems as a result of the higher degree of value added on site.

Finally, case MB is positioned in the lower right hand corner and focuses mainly on delivery and cost. It has a high portion (80%) produced off site and it has limited both the targeted market segments and the product variety offered to its clients. The product is fairly standardized, although the product platform does offer some possibilities to offer variants and features (performance). The production system is also flexible enough to handle the limited variation that is offered to the market. Hence, it is correctly positioned according to Figure 3 and it has a clear view of its customers (only public clients), and what type of buildings (dwellings, student flats, retirement homes and hotels) its concept is suitable for. MB is also very loyal to its concept and even though it offers somewhat unique designs, those designs are unique within the frames of the concept. Its processes are also standardized from the very first contact with a client to the delivery of the complete building. MB has evolved over time, and the company has had the time to develop and acquire the right resources, competences and capabilities to make its concept work.

Managerial and research implications

The framework for classifying production systems for construction and industrialized building (Figure 3) can be used to examine the three case examples described above. It shows that NVPA was designing a system that was matched with neither the right process choice nor the manufacturing outputs that could be provided at competitive levels with the production system. VPA and MB seem to be, at least initially, better positioned in the matrix, but VPA was not able to develop the necessary capabilities to handle the production system it ended up with. As for all production systems, offsite production requires commitment and hard work to achieve the benefits. Some literature (e.g. Gann, 1996; Gibb, 2001; Barlow *et al.*, 2003; Jaillon and Poon, 2008) indicates that offsite production helps management to stay focused on the manufacturing task, which is well exemplified by case MB. Yet, if it fails to do so, like case VPA, the concept most likely will be yet another example of failed attempts to offer industrialized building. Proper management is also a necessity when trying to mitigate, or reduce the effects of, the barriers identified in literature. Another matter that management has to deal with is the change in capabilities required when manufacturing off site as compared to crafting buildings on site, since large contractors, like the contractor behind NVPA, typically are used to onsite production.

When focusing heavily on the 'productivity-related' manufacturing outputs (i.e. cost delivery and quality), this is often done at the expense of the 'flexibility-related' manufacturing outputs (i.e. performance, flexibility and innovativeness). However, as indicated in Figure 1, JIT- and FMS-inspired production systems are positioned below the diagonal, but can still be competitive when combining the productivity focus with a flexibility focus. A similar attempt to overcome the barriers with reduced flexibility (due to a rigid production system) and performance (in terms of e.g. early design freezes) in industrialized building is the mass customization approach, mainly adopted in Japan (Barlow *et al.*, 2003; Barlow and Ozaki, 2005; Linner and Bock, 2012). In construction, this approach controls the cost through constraints on the variety of choice, even though it appears to offer extensive choice (Barlow and Ozaki, 2005). The technical possibilities that offsite production offers (e. g. thought-through platform techniques) can also help keep the 'flexibility-related' outputs at acceptable, or even competitive, levels without jeopardizing productivity and cost. Case MB has worked hard on developing a technical platform that can offer the clients a variety of choice, while still being able to have high productivity in design, production, assembly and delivery processes. The technical platform covers both product and process requirements, wherefore the production system can be designed to offer the necessary flexibility within the frames of the product platform. As such, MB has developed capabilities allowing it to offset some of the barriers that come with the industrialized building concept and has actually also approached the mass customization type lower left hand quadrant in Figure 3. A move towards this area of the framework must however be made with caution and the company must make sure to develop capabilities allowing it to be off the diagonal, or else it might end up in a panacea situation like NVPA and thereby lose both competitiveness and profitability.

Industrialized building is moving value-adding activities upstream in the supply chain, whereby the overhead costs and set-up costs become significant compared to the more traditional production system. Holistic and methodical assessments of the applicability and overall benefit of different production systems in construction have been found to be deficient and make the higher capital investment when producing off site a barrier for many contractors (Blismas *et al.*, 2006; Pan and Sidwell, 2011). The matrix presented in Figure 3 can be of help when analysing the relationship between product standardization/volumes and the degree of value-adding offsite/suitable production system. To cover for the additional investment cost, a certain break-even volume has to be reached and the higher the investments in fixed assets the higher that break-even volume will be. Therefore the variety in the product offer must be limited to increase production volumes and to offset high capital investment in fixed assets. Another barrier linked to this is the project-based structure of the construction industry. If every project is viewed as a single event that has to cover its own expenses it is hard to make profit on the concept since it requires a certain production volume. Therefore, the industrialized building concept needs time to evolve and develop, and companies must be loyal to the concept and aware of its limits. Clearly defined market and product segments are a must, otherwise the industrialized builders might find themselves in projects and businesses not suitable for what the production system was designed for.

The original product-process matrix (Hayes and Wheelwright, 1979) was developed based on a series of case studies and conceptual ideas. The matrix has since then been further developed theoretically (Hayes and Wheelwright, 1984; Hill, 2000; Miltenburg, 2005; Slack and Lewis, 2011), but also tested and verified empirically (Miller and Roth, 1994; Safizadeh *et al.*, 1996; Ward *et al.*, 1998). Even though some variants of the original matrix (e.g. Hill, 2000) mention project-based manufacturing, none of them treats the 'extremes' (i.e. project-based and continuous flow production systems) in any depth. This is especially true for project-based production like construction, which is not even mentioned in Miltenburg's (2005) framework. Yet, the logic and structure behind the product-process matrix is appealing also for construction. Our research therefore extends Miltenburg's (2005) framework and adds the missing upper left hand corner. We propose a matrix that can be used to classify production systems for construction with a special focus on industrialized building. Our matrix follows the same logic as does Miltenburg's (2005) framework, but we focus on an area not treated in Miltenburg's (2005) work.

Conclusions

The purpose was to develop and present a matrix for classification of production systems in construction and to evaluate different production systems' ability to perform in different areas of competition. The matrix presented in Figure 3 is the main result, but in the process of developing the matrix we also addressed two research questions.

For the first research question, we argue that the dimensions suited to classify the different production systems are: the *degree of industrialization* (i.e. how much of the value is added off site), and the *product variety and volume per product type*. The choice to separate the different production systems from each other based on how the buildings are produced (i.e. on or off site and in small or large volumes) makes it possible to consider and compare the manufacturing outputs between the suggested production systems. It becomes clear that there is no production system that can outperform all other production systems in all areas of competition, and the choice of production system should be based on what the identified market and customer segments consider important. Furthermore, the framework itself can be used to guide companies that are in the process of entering, or changing the degree of, industrialization in construction.

Turning to the second research question, it is evident that classifying the different production systems in a structured framework exposes the classic trade-off in operations management (Barlow *et al.*, 2003): the dichotomy between maintaining efficient processes (i.e. 'productivity-related' outputs) and offering a high degree of choice for the customers (i.e. 'flexibility-related' outputs). Typically, all different production systems have strengths and weaknesses that must be catered for. One example is production cost that normally is higher and less reliable the higher the degree of uniqueness in the product and the lower the degree of offsite production. Hence, the manufacturing outputs in Figure 3 differ between different production systems and the process choice must be made based on what the market requires and an understanding of how the company wants to compete, i.e. defining the manufacturing task in terms of competitive priorities. However, the different production systems do not perform well or badly by themselves. Just as it is possible to fail if a concept is managed poorly it is possible to improve the weaknesses of the system by acquiring the right capabilities and competences, something which requires commitment and strong leadership.

The main contribution of the research is that it:

- provides a structured matrix so as to classify and compare different kinds of production systems and how they fit different market conditions and requirements;
- illustrates the different facets of industrialized production systems and their relative strengths and weaknesses;
- introduces a contingency-based and market oriented approach to the design of production systems for industrialized building, linking market requirements, via the product offering, to the design of the production system;
- provides cases that exemplify how the framework can be used and how the different production systems suggested can be compared.

The research presented here is an attempt to develop a production strategy framework adjusted to the construction industry. The theories and models on classifying production systems for construction in literature and the framework presented in this study are of a rather basic and typical nature. However, simple models and classification schemes are useful aids when reflecting upon core attributes in construction and industrialized building, for both managers and academics (see e.g. Ghoshal and Nohria, 1993). Thus, the classification matrix described can be used as a sound guide for construction companies in their search for competitive production systems for industrialized building. To further strengthen and verify the results more case studies would be needed. In this research we deliberately selected three cases to represent each of the three industrialized production systems identified by Gibb (2001) and Gibb and Isack (2003). Further research would benefit from selecting cases more randomly, classifying them in the matrix and undertaking cross-case analysis to both verify and develop the matrix. More research is also needed to better define the manufacturing outputs and to find tools to define and measure the outputs relative each other and relative various production systems in construction. More longitudinal case studies would also be valuable so as to be able to identify success and failure factors for various production systems relative to their position in the classification matrix. Finally, an investigation of capabilities needed to successfully operate industrialized production systems on, and maybe also off, the diagonal match in the matrix would be valuable.

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