KPIs for measuring performance of production systems for residential building: A production strategy perspective

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Title: KPIs for measuring performance of production systems for residential building: a production strategy perspective

Category: Research paper

Purpose – To define Key Performance Indicators for measuring performance of production systems for residential building from a production strategy perspective.

Design/methodology/approach – A literature review is done to identify suitable competitive priorities and to provide grounds for developing KPIs to measure them. The KPIs are evaluated and validated through interviews with industry experts from five case companies producing multifamily residences. Furthermore, two of the case companies are used to illustrate how the KPIs can be employed for analysing different production systems from a manufacturing strategy perspective.

Findings – Defined, and empirically validated, KPIs for measuring the competitive priorities *quality*, *cost* (level and dependability), *delivery* (speed and dependability) and *flexibility* (volume and mix) of different production systems.

Research limitations – To further validate the KPIs, more empirical tests need to be done and further research also needs to address *Mix Flexibility*, which better needs to account for product range to provide a trustworthy KPI.

Practical implications – The defined KPIs can be used to evaluate and monitor the performance of different production systems' ability to meet market demands, hence focusing on the link between the market and the firm's production function. The KPIs can also be used to track a production systems' ability to perform over time.

Originality/value – Most research that evaluate and compare production systems for residential building is based on qualitative estimations of manufacturing outputs. There is a lack of quantitative KPIs to measure performance at a strategic level. This research does this, identifying *what* to measure, but also *how* to measure through 14 defined KPIs divided into four competitive priorities.

Introduction

The majority of production strategy research adopts trade-off reasoning when it comes to competitive priorities, meaning that focusing on and improving one competitive priority (e.g. cost or lead time) will be at the expense of others (e.g. quality or flexibility) (Hayes and Wheelwright, 1984, Hill and Hill, 2009, Miltenburg, 2005). From a production strategy perspective, Jonsson and Rudberg (2015) argue that different production systems for residential building, with different degrees of off-site assembly, also have different strengths and weaknesses in different areas of competition. To be able to design and operate a competitive production system, and to be able to manage trade-offs, the manufacturing output of the production system must be measured and monitored (Womack and Jones, 2003).

   In traditional production strategy literature the importance of performance measurement is emphasized. In Slack and Lewis (2011) it is stated that for a production strategy to be effective, performance must be measured and monitored. Hill and Hill (2009) points out that as part of the continuous reappraisal of strategy decisions, performance must be monitored on a regular basis. In Miltenburg (2005) performance measures are used to make a competitive analysis of production systems also indicating

the importance of performance measurement from a production strategy perspective.

Most research that evaluate and compare production systems for residential building is based on qualitative estimations of manufacturing output performance (see e.g. Arif and Egbu, 2010, Blismas et al., 2006, Gibb, 2001, Halman et al., 2008), and there is a lack of publicly available, well-defined, quantitative, Key Performance Indicators (KPIs) to measure performance at a strategic level. There is research on performance measurement in the residential building industry. Beatham et al. (2004), for example, reviews the use of KPIs in construction and list a quite extensive number of organisations that have developed KPIs for measuring performance. Yet, that list of KPIs are more focused on *what* to measure rather than on *how* to measure performance. The existing KPIs found in literature are also more focused on improving the process on an operational level, rather than on monitoring the performance on the strategic level (Yang et al., 2010). There is also a lack of KPIs defined for the purpose of evaluating different production systems from a production strategy perspective.

The purpose here is consequently to define KPIs for measuring performance of production systems for residential building from a production strategy perspective. The defined KPIs should be able to be used to evaluate and monitor the performance of different production systems' ability to meet market demands, hence focusing on the link between the market and the production function of the firm.

In the following section a brief account on production strategy theory and its use in residential building is provided as a background to the research. Thereafter the research design and the methodologies applied are outlined, followed by the main part of the paper; reviewing the literature to identify typical competitive priorities in residential building and developing suitable KPIs to measure performance at the strategic level. The defined

KPIs are thereafter validated by the means of interviews with experts from different types of case companies and an illustrative case example is provided to show how the defined KPIs can be used in a production strategy context. Finally, a concluding summary is provided identifying the main result and contributions, as well as ideas for further research.

Production strategy in residential building

The essence of a production strategy could be characterised by the pattern of realized decisions affecting the ability of the manufacturing function to meet the long-term objectives and the manufacturing task (Rudberg, 2004). From a theoretical perspective, the content of production strategy is traditionally built around two broad groups: competitive priorities and decision categories (Leong et al., 1990). 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. The use of decision categories is a way of grouping the many decisions that have to be made into typical decision areas such as capacity, facilities, planning systems, etc. In production strategy research a vital issue is the link between the characteristics of the products offered to the customers and the manufacturing process to produce these products (Olhager and Rudberg, 2002). This link is often termed the *process choice* and is a central decision category in production strategy research. The process choice focuses on how the market requirements can be aligned with the ability of the production system to provide competitive manufacturing outputs. Different types of production systems typically have different abilities to provide competitiveness in different areas, wherefore the choice of production system and layout is of utmost importance.

In production strategy theory, the production systems used in the residential building industry are typically classified as project-based (Hill and Hill, 2009). Project-based production systems are furthermore often grouped and treated as one type of production system, or even left out of the scope entirely, due to the unique characteristics of products typically produced in these systems (see e.g. Hayes and Wheelwright, 1979, Hayes and Wheelwright, 1984, Hill and Hill, 2009, Miltenburg, 2005). However, the project-based production systems in the residential building industry do include different types of production systems (Gibb, 2001, Jonsson and Rudberg, 2015) with different product and process characteristics. The product here being the output of production system, including possibly both a factory and the construction site. For a residential building project the output is typically a house, i.e. a typical product would be a house as a whole building. Hence, acknowledging the variety of production systems in residential building could help to provide a better alignment between product characteristics, process characteristics and competitive priorities.

In line with this, Jonsson and Rudberg (2015) developed a matrix for classifying production systems for residential building (Figure 1) inspired by Miltenburg's (2005) production strategy framework for the manufacturing industry. The matrix classifies production systems for the production of multifamily residences along two dimensions: the degree of product standardization and the degree of off-site assembly.
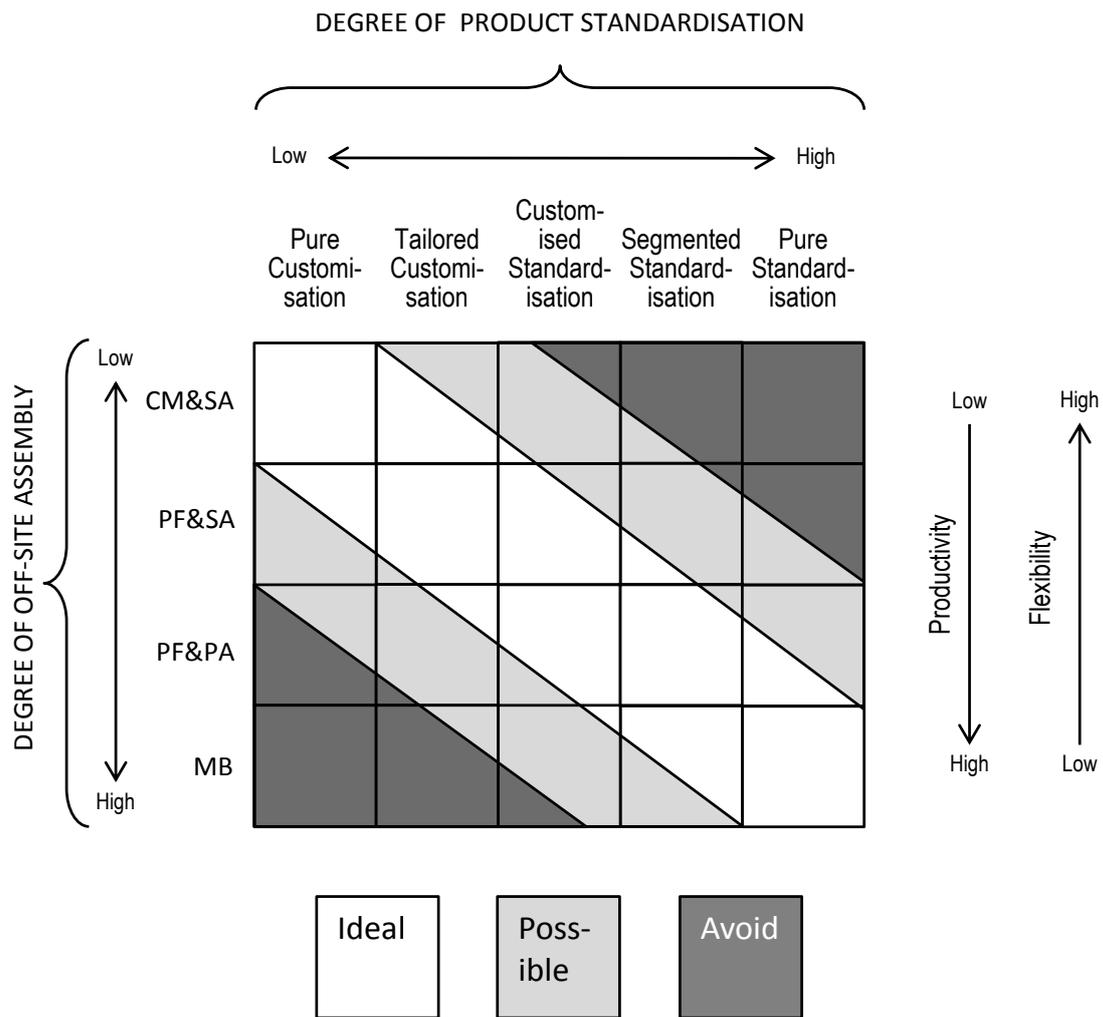
Figure 1 Classification matrix for production systems for residential building (Jonsson and Rudberg, 2015)

The horizontal dimension in the matrix represents the degree of product standardization, in line with the reasoning in Barlow *et al.* (2003). The dimension is divided into five sections ranging from pure customization to pure standardisation. This dimension has been categorized using Lampel's and Mintzberg's (1996) five customization/standardization strategies. The vertical dimension embodies the degree of off-site assembly represented by four typical production systems, based on the definition by Gibb (2001), but slightly modified in Jonsson and Rudberg (2015). The production system *Component Manufacture and Sub-assembly* (CM&SA) is the traditional approach

for on-site production of residential buildings, with most value-adding activities carried out on-site. *Prefabrication and Sub-assembly* (PF&SA) represent a situation with a high degree of prefabrication off-site and bought in sub-assemblies, but with the majority of assembly activities performed on-site. *Prefabrication and Pre-assembly* (PF&PA) is a situation not only including a high degree of prefabrication, but also some degree of pre-assembly off-site. Finally, the *Modular Building* (MB) entails a high degree of off-site production and assembly, with volumetric modules fabricated to a high level of completion off-site. The only work performed on-site is the assembly of the modules and finishing operations.

The general idea is that the four production systems in Figure 1 perform differently in terms of competitive priorities. For example, the CM&SA is argued to be more flexible but less productive, whereas MB is regarded to be more productive but less flexible. In line with this, the degree of product standardisation should be matched with the appropriate production system so as to meet the market requirements in the most competitive way. Jonsson and Rudberg (2015) therefore argue that there is an ideal position along the diagonal in the matrix, matching the degree of product standardization with the most suitable production system. There are other positions in the matrix than the ideal that may be possible to operate effectively, but positions too far off the diagonal should, theoretically, be avoided. The reason is that such a system most likely will be outperformed by other systems that are better positioned in the matrix. What is missing in Jonsson's and Rudberg's work is however a suitable way of measuring the performance of the different production systems in the matrix. Measuring the performance of production systems provides the possibility to compare different production systems, to monitor changes in competitiveness over time, and to make sure that decisions made

actually materialises into increased performance.

The focus of the research is therefore to determine suitable competitive priorities that can be used to evaluate and compare the production systems in the classification matrix (Figure 1). Furthermore, to be able to actually measure the performance of the production systems, Key Performance Indicators (KPIs) will be developed for each identified competitive priority. Having the matrix, competitive priorities and the possibility to measure KPIs for the different production systems, provide decision makers with suitable tools to aid the decision-making process when it comes to production strategy for residential building.

Research design

The research design is based on a deductive approach (Karlsson, 2009), as visualized in Figure 2. The study starts with a literature review on performance measurement in residential building focusing on two parts. Firstly, at identifying which competitive priorities that are important to consider in a residential building context (*what* to measure) and, secondly, to find out *how* to measure by identifying suitable KPIs for each competitive priority. The literature review also strives to identify means to evaluate the suitability of the KPIs that can be used for empirical evaluation of the defined KPIs. The result of the literature review is used to conceptually develop and define KPIs that could be used with the matrix in Figure 1 in order to analyse and evaluate different production system's ability to meet the market requirements. Thereafter the developed KPIs are tested empirically through the use of experts from a set of case companies active in the residential building industry. The experts are interviewed with the purpose of evaluating, and possibly validating, the suggested KPIs. The results from the expert interviews are

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used in combination with a set of evaluation attributes (Table 2) to refine the KPIs in an iterative research process to reach consensus. The output, and result, of this process (Figure 2) is the suggested KPIs. In the following, each step of the research process is described into more detail.
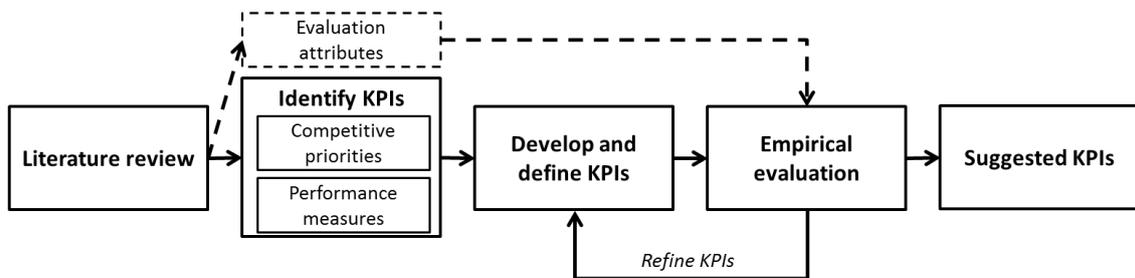

Figure 2. Overview of the research design

The literature review starts with a broad search for papers on KPIs and performance measurement in residential building, resulting in a set of key papers on the topic. Key words used in the search were *KPI*, *performance measurement* and *performance evaluation* in combination with the key words *construction*, *residential building* and *housing*. The databases Scopus Academic search premier, Business source premier, Web of science and Google Scholar were used for the literature search. Forward and backward citation search (Hu et al., 2011) is thereafter used to find other publications and organizations that have developed KPIs for performance measurement in residential building. The review process results in a list of potential performance indicators that are used to develop KPIs within the production strategy context, as exemplified with the matrix in Figure 1. The list of KPIs is then further refined by focusing on KPIs that are suitable to be used for performance measurement on a strategic level, for each competitive priority. Since the focus is on KPIs to be used on a strategic level, performance indicators used on an operational level to evaluate and measure the production process, *per se*, were excluded.

For the KPIs to be useful it is also important that they are grounded in practice. Therefore the KPIs are evaluated empirically through interviews with industry experts from a set of case companies producing multifamily residences. The aim of this research is to build theory and as a part of this process empirical data can be used (Eisenhardt, 1989). To select suitable respondents for the study, persons involved in the residential building sector have been consulted, both from academia and from the industry, and this resulted in a list of potential candidates. When selecting respondents it is important to define a number of criteria whereby candidates are deemed qualified to serve as experts for the interviews (Yin, 2009). In this study the criteria were that the respondents should have worked with developing production systems for residential buildings, that they should represent different types of production systems, that they produced whole buildings and not only separate parts of buildings (e.g. the structural frame or toilet pods), and that they were willing to share the necessary data to be able to evaluate the KPIs for their respective companies. Out of the list of candidates five experts were selected that fulfilled the criteria listed above, all representing different companies. From a production strategy perspective and for the sake of possible comparison between systems, it is important that the KPIs are valid for different types of production systems. Therefore the study takes a stance in the four generic types of production systems defined in in Figure 1 (Jonsson and Rudberg, (2015): *Component Manufacture and Sub Assembly* (CM&SA), *Prefabrication and Sub Assembly* (PF&SA), *Prefabrication and Preassembly* (PF&PA) and *Modular Building* (MB). As such, the unit of analysis in this study is the production system. Table 1 briefly summarises the key characteristics of the companies that the experts in this study represents. All four production systems are represented and also four of the five different degrees of product standardisation. The coverage of possible positions

in the matrix is thereby good, and the KPIs and their suitability will thereby be evaluated from different perspectives.

Case	Company type	Production volume [apartments/ year]	Product characteristics (Classification based on Lampel & Mintzberg (1996))	Process characteristics (Classification based on Jonsson & Rudberg (2015))
A	Business concept at large contractor	150	Tower blocks, 4-8 floors, Classified as *Pure standardisation*	On-site production, standardized process, Classified as *CM&SA*
B	Business concept at large contractor	400	Tower blocks and slab blocks, 3-8 floors, Classified as *Customized Standardization*	Prefabricated concrete elements, stairways, structural frame, bathrooms, Classified as *PF&SA*
C	Business concept at large contractor	500	Tower blocks 4-8 floors, slab blocks 4-6 floors, Classified as *Segmented Standardization*	Concrete elements and bathrooms prefabricated by external suppliers, Classified as *PF&PA*
D	Medium sized, family owned company	600	Multifamily residences, 2-6 floors, Classified as, *Tailored Customisation*	Prefabricated modules, high level of completion, Classified as *MB*
E	Joint venture between contractor and home furniture company	600	Slab blocks, 2 floors, Classified as *Pure standardisation*	Prefabricated modules, high degree of completion, Classified as *MB*

Table 1 – Summary of key characteristics for the five case companies in this study.

The actual empirical evaluation and validation of the KPIs are conducted through telephone interviews with the industry experts, consisting of three parts. The first focuses on performance measurement in general within residential building and how each company works with performance measurement within their respective production system. The second part consists of a discussion and validation of the theoretically defined KPIs. It is used to refine some of the suggested KPIs so that they would be in line with already established terminology and KPIs used in the residential building industry. The third part of the interviews focuses on the feasibility of the KPIs, i.e. if the companies has access to all the necessary data to be able to use the suggested KPIs. A summary of the interviews was sent to each respondent to ensure validity.

After the first round of interviews, the results from the interviews were used to refine the KPIs when necessary. To lead this process, a set of attributes for evaluating KPIs were used (see Figure 2). Hence, after the literature derived KPIs had been grounded in practice through empirical data, they were further evaluated using the five attributes described in Beatham et al. (2004) (which in turn is based on the works of Smullen (1997) and Andersson (1996)). These attributes are considered key points for a successful performance measurement (Beatham et al., 2004), and are further described in Table 2.

No.	Attribute	Description
1	Acceptable	It can be understood
2	Suitable	They measure important things
3	Feasible	They are easy to collect
4	Effective	They concentrate on encouraging the right behaviour
5	Aligned	Non-financial metrics must link to financial goals

Table 2 – Attributes used to evaluate and validate KPIs (Beatham et al., 2004)

The results from the interviews and using the five attributes in Beatham et al. (2004) lead to the refinement of some of the KPIs. These refinements were communicated to the experts in a second round of interviews, with the purpose of validating the changes to the KPIs. The five attributes and the second round of interviews identified strengths and weaknesses with the suggested KPIs, which are highlighted in the sections to follow.

To summarize, the suggested KPIs are grounded both in theory and in practice, and are validated against the five attributes in Beatham et al. (2004). They have also been empirically tested on companies covering most positions in the matrix in Figure 1. Yet, the generalizability of the KPIs should be treated with caution, since the number of experts are limited and further studies are needed to strengthen the generalizability.

Competitive Priorities and KPIs in Residential Building

The literature review outlined in this section strives to investigate *what* to measure. *What* takes a stance in the production strategy theory, employing the notion of competitive priorities as means to guide decision-makers in establishing a competitive production system. The following section is devoted to explore *how* to measure performance, defining KPIs for the "whats" identified in this section.

Jonsson and Rudberg (2014) reviewed construction literature to find drivers and barriers for industrialized housing, i.e. production systems for residential building that has a certain degree of off-site assembly, and linked these to the competitive priorities defined by Miltenburg (2005). Jonsson and Rudberg (2014) did show that the most frequently mentioned drivers for off-site production were *Quality, Cost* and *Time*, whereas the largest barrier to off-site production was reduced *Flexibility*. It is therefore considered reasonable to focus on the four "classical" competitive priorities as defined in production strategy (Hayes and Wheelwright (1984), Leong *et al.* (1990)): quality, delivery (i.e. time), cost, and flexibility. Slack and Lewis (2011) make a distinction between *Delivery Speed* and *Delivery Dependability*. This distinction is important since there is a difference between being fast and being on time. Similarly, in the residential building context the same reasoning should be applied on *Cost*, where both *Cost Level* (i.e. being able to produce at low cost) and *Cost Dependability* (i.e. being on budget) need to be evaluated. These competitive priorities (cost dependability excluded) are also described in Slack and Lewis (2011) as generic performance objectives that have meaning for all types of operations and they also argue that these priorities specifically relate to operations' basic task of satisfying customer requirements. In this study the focus is on measuring the production system's ability to meet the market requirements. This is

important to keep in mind since there is a difference between this type of evaluation, related to production strategy, and measuring to improve the process on a "plant" level.

To find KPIs related to *Quality*, *Delivery*, *Cost*, and *Flexibility* a review of literature related to performance measurement in residential building is conducted. Finding KPIs in existing construction literature will facilitate the process of communicating the production strategy framework to fellow researchers and also to practitioners in residential building. Reviewing construction industry literature, it becomes apparent that the competitive priorities *Quality*, *Delivery*, and *Cost* are frequently discussed and there are KPIs developed for measuring all three of them. Table 3 displays a sample of KPIs for residential building as suggested by different sources found in literature. There are other KPIs developed for the construction industry, but within the scope of this study they are either not publically available or deemed not relevant due to, for example, being too operational and not being able to link to the strategic decision-making of the firm. Hence these KPIs have been left out of scope.

	Rethinking construction (Egan, 1998)	KPI Report for the Minister of Construction (Raynsford, 2000)	The MCG Benchmarking Club (Beatham et al., 2004)	CCI Key performance indicators (CBPP, 2014)
KPIs for Quality				
Q1. No. of defects at handover	√	√		√
Q2. Defects		√		√
Q3. Defects at end of defect rectification period		√	√	
Q4. Certificate of making good			√	
Q5. No. of defects during defects liability period			√	
KPIs for Delivery				
D1. Time for construction	√	√		√
D2. Time predictability	√	√	√	√
D3. Time to rectify defects		√		√
KPIs for Cost				
C1. Cost for construction	√	√		√
C2. Cost predictability	√	√	√	√
C3. Cost for rectifying defects		√		√

Table 3 – KPIs for the construction industry previously suggested in literature.

The literature review shows that there is a lack of KPIs to measure the *Flexibility* of a production system in residential building. Flexibility is complex, multidimensional and hard to capture, and over 50 different types of flexibility can be found in the manufacturing literature (Sethi and Sethi, 1990). Flexibility is, however, an important aspect for all manufacturing companies that need to adapt to changing market and customer requirements, a capability that is often deemed crucial for residential building companies. Yet there is an obvious lack of KPIs defined for production flexibility in construction literature, wherefore traditional operations management literature is reviewed for remedy. Important to point out is that production flexibility, which is

addressed here, relates to the flexibility of the production system. Hence, it is a capability of the production system and not a measure of what is offered to the market in terms of, e.g. product range. A company can for example offer a great variety of products to the market without having a flexible production system. However, the flexibility of the production system measures the ability to handle this variety and possible volume variations in an efficient way.

Fredriksson and Wänström (2011) reviewed manufacturing flexibility literature and found *Volume* and *Mix Flexibility* to be most common, which is also apparent by reviewing other production strategy literature (e.g. Miltenburg (2005), Hill and Hill (2009), Slack and Lewis (2011)). Many of the flexibility KPIs are however more suggestions on what to measure, leaving the "how to" aside (see e.g. Hill and Hill, 2009, Slack and Lewis, 2011). Other flexibility KPIs merely indicate what the production system offers in terms of customization (a choice made by the company) and not how well the production system handle the product mix in terms of performance (see e.g. Miltenburg, 2005). Other parts of the operations management literature differentiate between range and response/mobility (D'Souza and Williams, 2000). Range relates to by how much a flexibility capability can be changed, whereas response concerns how fast a change can be realised. Authors also differ between at what system level the flexibility should be analysed and measured. Sethi and Sethi (1990), for example, differ between aggregate, system and component/basic levels, and Palàez-Ibarrondo and Ruiz-Mercarder (2001) differ between plant, shop floor and individual resource levels. Rogalski (2011) summarizes a lot of the flexibility literature within operations management and argues that it is sufficient to measure three types of flexibility: *Volume*, *Mix* and *Expansion* flexibility. Within these definitions *Volume* and *Mix Flexibility* regards flexibility within

an existing production system, whereas *Expansion Flexibility* is relevant when it comes to redesigning a production system. The research presented here, focuses on identifying and measuring KPIs for competitive priorities within existing production systems, wherefore *Expansion Flexibility* will be left outside the scope and left for future research.

To summarize this discussion, *Volume* and *Mix Flexibility* will be considered, alongside the already identified KPIs for *Quality, Delivery* and *Cost*, as stated above. All these KPIs will be considered on a production systems level for evaluating competitive priorities.

Defining KPIs for performance measurement in residential building

The following section aims at defining KPIs for *Delivery, Cost, Quality* and *Flexibility* that can measure the overall performance of the production system, i.e. focusing on the *how to* measure issue. When defining the KPIs for *Quality*, *Cost* and *Delivery* the KPIs presented in Table 3 are used as a reference. KPIs are developed both on a project level and on a production system level. In other words, KPIs are developed to be able to both measure individual projects produced in a given production system, but also KPIs to be able to measure performance of the production system over time. The KPIs developed for *Flexibility* (*Mix* and *Volume*) are based on Rogalski (2011). When taking a production system perspective, a project by definition cannot be flexible in itself. The project is the output of the production system, i.e. the product or the deliverable, and the output is not a measure of production system flexibility. Hence, only KPIs on the production system level are developed for flexibility.

In the presentation of the KPIs the following notation is used:

i = Project index (running numbers)

N = Number of projects included in a moving average calculation

M = Number of projects that is to be taken into consideration (can be different from N),

ΔCM_i^p = project i's relative deviation from the contributing margin of the optimal project

for a specific production system

A compilation of all defined KPIs derived below is provided in Appendix 1.

KPI for Quality

The metrics for *Quality* in Table 3 (Q1-Q5) all, in one way or the other, try to estimate

the number of defects at handover, during liability period, etc. One problem with these

metrics is that all defects are valued equal, irrespective of the severity of the defects.

Another problem by measuring quality at specific points in the project is that rework and

defects that occurs during the production process is overlooked. Thereby these metrics

fail to fulfil attributes 2 and 4 (Table 2). Another approach is to measure the cost for

rectifying defects (see KPIs C3 in *Table 3*). This way of measuring quality has been used

before (see e.g. Hwang et al., 2009, Josephson and Hammarlund, 1999, Josephson et al.,

2002). The suggested KPI for *Quality* on the project level is thereby based on the cost for

rectifying defects in a project, related to the total project cost. In other words, the KPI

identifies how much of the total project cost was caused by rework (1).

$$Quality \; for \; the \; i{:}th \; project \; \left(Q_i^p\right) = \frac{Cost \; for \; rectifying \; defects \; in \; project \; i}{Total \; production \; cost \; for \; project \; i} \times 100; \; i = 1, 2, \ldots, n \quad (1)$$

To measure performance of the production system over time, a moving average

calculation is suggested based on the quality of individual projects (Q_i^p) that the company

has finalized (2). The number of projects to include in the calculation is dependent on

how many projects a company has over time, and is not specified in this research. The

number should be large enough to level out typical variations between projects, but not larger than that it should be possible to track changes over time in quality performance.

$$Quality, production\ system\ (Q^{PS}) = \frac{\sum_{i=n-N+1}^{n} Q_i^p}{N} \tag{2}$$

KPI for Delivery

Regarding *Delivery Speed* it is important for the companies to decide which project stages (Raynsford, 2000) that should be included in the KPI. For the measures to be comparable they must include the same project stages, e.g. production start to handover, or design start to handover. Another aspect is what the delivery lead-time should be related to, since projects vary in size and complexity. Production time per apartment, per room, per floor area, etc., have been suggested as possible references for comparison. However, comparisons between projects that differs to a great extent must be done with caution. It is, for example, difficult to compare one-room student apartments to five-room, high-end apartment buildings no matter what the delivery time is related to. Here, the suggested KPI for delivery speed of a project (3) measures the production time per gross floor area in the project, which is regarded the most "fair" comparison between projects and concepts. To measure the delivery speed of the production system (4), a moving average is used based on the delivery speed of individual projects.

$$Delivery\ speed\ for\ the\ i{:}th\ project\ \left(DS_i^p\right) = \frac{Total\ production\ time\ for\ project\ i}{Total\ gross\ floor\ area\ for\ project\ i}; \quad i = 1, 2, \ldots, n \tag{3}$$

$$Delivery\ speed, production\ system\ (DS^{PS}) = \frac{\sum_{i=n-N+1}^{n} DS_i^p}{N} \tag{4}$$

Sometimes it is more important for a customer to know when the product is to be delivered, rather than having access to the product at the earliest possible time. Therefore

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Delivery Precision and *Delivery Dependability* is measured. For *Delivery Precision* at the project level the KPI is derived from CBPP (2014) (D2, Table 3). At the project level the deviation between the actual total production time and the production time according to the initial time plan is used to calculate the KPI (5), whereas the delivery precision of the productions system also here is based on a moving average calculation (6). To measure the due date performance it is suggested to use the *tardiness* of a project, which focuses on how long after the due date that a project was delivered. Thereby, projects delivered before the due date are considered on time. Alternative measures would be the *lateness* or the *absolute deviation*. For material deliveries to the factory or to the site the absolute deviation would be the preferable measure, since early deliveries can be as troublesome as late deliveries. However, delivering the finished project ahead of time is not regarded as severe as delivering it late. Hence, the tardiness measure is used in this study for the KPIs on the production system level.

$$Delivery\ precision\ for\ the\ i{:}th\ project\ \left(DP_i^p\right) =$$

$$\frac{(Total\ production\ time - Production\ time\ according\ to\ initial\ timeplan)\ for\ the\ i{:}th\ project}{Production\ time\ according\ to\ initial\ timeplan\ for\ the\ i{:}th\ project} \times 100; \quad i = 1,2,\dots,n \quad (5)$$

$$Delivery\ precision, production\ system\ (DP^{PS}) = \frac{\sum_{i=n-N+1}^{n} DP_i^p}{N} \qquad (6)$$

Delivery Dependability is calculated as the percentage of projects that are delayed from a certain production system (7). Similar to the moving average calculation, the question of how many projects that should be included in the calculation can be raised. There has to be a balance between including enough projects to give a fair judgement of the production system, and still not including too many projects so that the KPI is biased from legacy effects.

$$Delivery\ dependability, prod.\ system\ (DD^{PS}) = \frac{Number\ of\ projects\ delayed\ out\ of\ M\ projects}{M} \times 100 \quad (7)$$

Delivery precision and dependability will not only cover the likelihood for a delay to happen, but will also indicate how much a project typically is delayed using a defined production system.

KPI for Cost

The *Cost Level* is measured as the production cost per gross floor area. Similarly as for the delivery speed KPI, issues can be raised against using the gross floor area as a reference. Yet, when comparing to other points of reference gross floor area seems to be the most "fair" reference. The cost for land, financing and non-production/client related costs are not included in the measure since this typically is not a result of the performance of the production system in use. Also for this KPI it is important to keep track of which project stages (Raynsford, 2000) that should be included in the KPI. The cost level for a project (CL_i^p) is displayed in (8) and the moving average calculation for the production system in (9).

$$Cost\ level\ for\ the\ i{:}th\ project\ \left(CL_i^p\right) = \frac{Total\ production\ cost\ for\ project\ i}{Total\ gross\ floor\ area\ for\ project\ i}; i = 1,2,\dots,n \qquad (8)$$

$$Cost\ level, production\ system\ (CL^{PS}) = \frac{\sum_{i=n-N+1}^{n} CL_i^p}{N} \qquad (9)$$

Besides the cost level, also the ability to stay within the budgeted cost is of importance to both contractors and customers, and will be measured in two parts: the percentage of projects that overrun the budget and the average magnitude of the overrun compared to

the total project budget. Just as for *Delivery Dependability* these KPIs will cover both the likelihood of a budget overrun and the severity of them. Projects with an actual production cost lower than the budgeted cost are considered as being on budget, resembling the tardiness measure for delivery dependability. Also here, budget overruns are considered more severe than projects with a lower than budgeted actual cost. The KPI for *Cost Precision* at project level is derived from CBPP (2014) (C2, Table 3) and calculated as the difference between the actual production cost and the budgeted production cost in relation to the budgeted production cost (10).

$$Cost\ precision\ for\ the\ i\text{:}th\ project\ \left(CP_i^p\right) =$$

$$= \frac{(Actual\ production\ cost - Budgeted\ production\ cost)for\ the\ i\text{:}th\ project}{Budgeted\ produciton\ cost\ for\ the\ i\text{:}th\ project} \times 100;\ i = 1,2,\dots,n \qquad (10)$$

The cost precision for the production system is calculated as the moving average of a set *N* of individual projects, as indicated in (11).

$$Cost\ precision, production\ system\ (CP^{PS}) = \frac{\sum_{i=n-N+1}^{n} CP_i^p}{N} \qquad (11)$$

Cost Dependability is measured as the percentage of projects, out of a set *M*, that do overrun the budget (12). The set *M* has to be determined so that it covers the present performance of the production system, without being biased from recent possible successful projects or from legacy effects.

$$Cost\ dependab., prod.sys.(CD^{PS}) = \frac{Number\ of\ projects\ that\ overrun\ budget\ out\ of\ M\ projects}{M} \times 100 \qquad (12)$$

KPI for Flexibility

Two dimensions of flexibility will be taken into consideration: *Volume* and *Mix*. As mentioned above, the flexibility measures used here cannot by definition be measured for a single project, it must be measured for a set of products (projects) produced by the production system. Hence, the flexibility KPIs will only be defined at the production system level. Unless otherwise stated, the KPIs in the following are based on Rogalski (2011).

Volume Flexibility is defined as: "the capability of a short-term and economical capacity adaption for a given fabrication spectrum inside of the existing technical and organisational limitations of a production system" (Rogalski, 2011, p.30). The KPI for *Volume Flexibility* is measured as the so-called *flexibility space*, which is defined as the deviation between the *break-even-point* and the *maximum capacity* (13)*,* as illustrated in Figure 3 (Rogalski, 2011, p.48):

$$Volume\ flex., prod. system\ (VF^{PS}) = Fexibility\ Space =$$

$$Maximum\ capacity - Volume\ at\ Breakeven\ Point \qquad (13)$$

The maximum capacity indicates the largest possible, but still profitable, output that a system can reach. The break-even point is the production volume at which the revenues cover the total costs. The larger the relative deviation between the break-even point and the maximum capacity of a production system, the larger the flexibility space and hence the higher the *Volume Flexibility*. This means that the flexibility space is a measure of the span of the output *volume* that a production system can deliver efficiently without changing the technological or organisational structure of the system (e.g. building a new factory, increasing the use of pre-fabricated products, etc.).
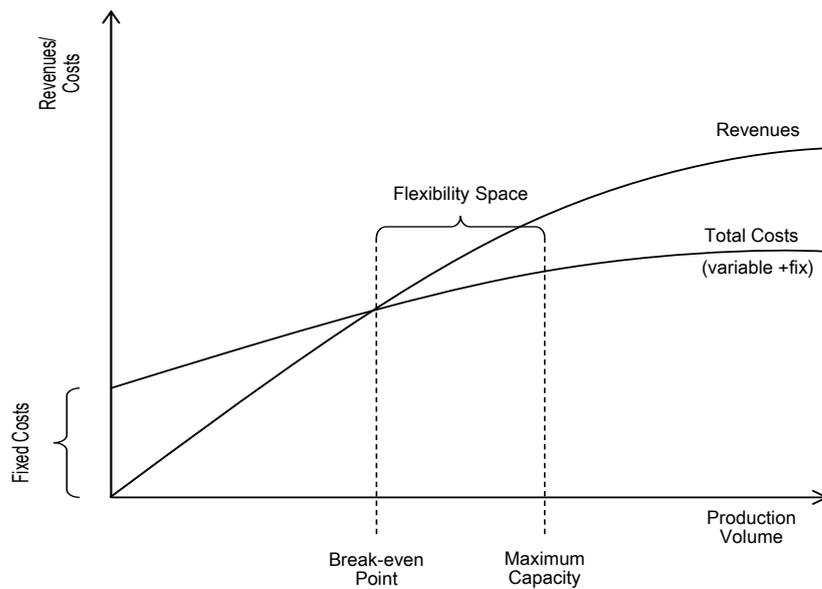
Figure 3 – Illustration of the volume flexibility KPI (Rogalski, 2011, p.48)

Rogalski's (2011) definition of *Mix Flexibility* reads: "The *mix flexibility* characterizes the stability and consequently the mobility of a production system in abandoning single products or variations concerning the production spectrum, without endangering the economical product fabrication." (Rogalski, 2011, p.31).

To measure this, the project profit deviation of the production systems can be used. The idea is to consider the difference between the most profitable product/variant configuration and those configurations that differ from it, see Figure 4. In line with this it is argued that (Rogalski, 2011, p.50): "The lower the average production profit deviation of a system, the higher its mix flexibility. The mix flexibility is therefore optimal when all of the product-specific profit deviations calculated for the system are zero." This means that the flexibility mix measures the ability of the production system to change between different types of products, within a given output volume, without changing the cost structure as compared to the most profitable setting of the production system. A prerequisite is that there is more than one product/variant wherefore this line of reasoning

should not be used to evaluate single-product production systems. A production system that is designed to produce only one product is therefore defined as inflexible in terms of product mix (Rogalski, 2011). Rogalski (2011) focuses on manufacturing production systems that produces products in rather high volumes but here projects will be used instead, which is considered the typical output of a production system for residential building. Also, to avoid bias effects from distributing overheads among projects, the contributing margin (CM) will be used instead of the profit margin for the projects (see Figure 4).
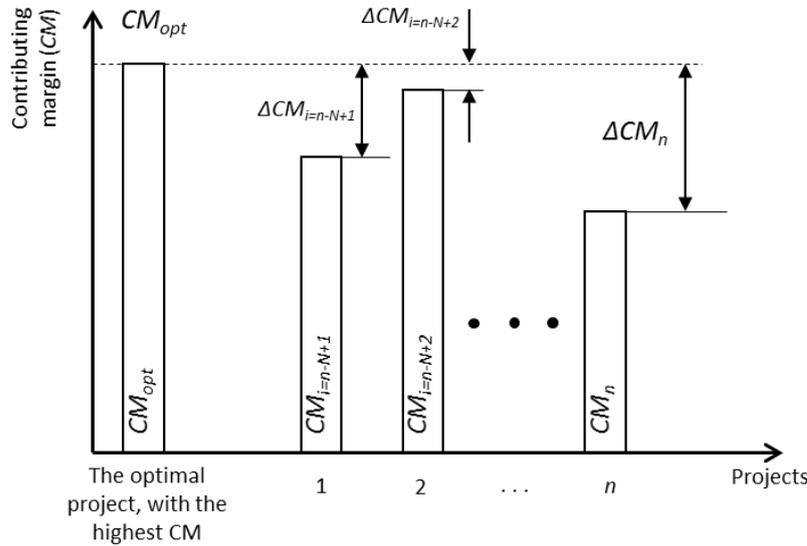

Figure 4- Illustration of the mix flexibility KPI (Rogalski, 2011, p.48).

By using the contributing margin of the most profitable project as a reference, the relative deviation from this optimal project can be calculated for the set of projects produced as a moving average of the deviations in contributing margins of projects (14). The lower the MF^{PS}, the better the mix flexibility of the production system.

$$Mix\ flexibility, production\ system\ (MF^{PS}) = \frac{\sum_{i=n-N+1}^{n} \Delta CM_i^p}{N} \quad i = 1,2,\dots,n \tag{14}$$

Case Validation of the defined KPIs

Below each KPI presented above is validated based on the five attributes (Table 2) presented in Beatham et al. (2004) using data derived from the interviews. A summary of the results from the interviews is visualized in Table 4.

	Attribute 1 Acceptable	Attribute 2 Suitable	Attribute 3 Feasible	Attribute 4 Effective	Attribute 5 Aligned
Quality	+	+	o	+	+
Delivery Speed	+	o	+	+	o
Delivery Dependability	o	o	+	o	o
Cost Level	+	o	+	+	+
Cost Dependability	+	+	o	o	+
Volume Flexibility	o	+	o	+	+
Mix Flexibility	-	o	o	o	+

Legend: + fulfils attribute well, o acceptable, - issues in fulfilling attribute

Table 4 – Summary of how well the defined KPIs adhere to the validation criteria (Beatham et al., 2004) in Table 2

Quality

One of the case companies already measured quality this way, but only for one type of defect. Another of the case companies had plans to implement a similar KPI in the near future. This indicates that the KPI fulfil attribute 1 and 2. A possible barrier was however noted, that it can be difficult to collect the necessary data to be able to calculate the KPI (attribute 3). However, Case B and D possessed all the necessary data indicating that also attribute 3 is fulfilled, whilst case A and C only measured the production cost. The KPI is a financial metric (attribute 5). Furthermore, if the cost for rectifying errors and defects is measured and can be compared between different production systems, it can be useful when designing/choosing production system and hence fulfil attribute 4. In summary, the

KPI complies with all attributes (acceptable, suitable, feasible, effective and aligned), but companies must make sure to track and collect the necessary data for the KPI to be applicable.

Delivery Speed

None of the case companies had any problems understanding the KPI for delivery speed (attribute 1). The case companies thought it was a suitable KPI even though the experts from Case A and C argued for using production time per apartment instead of gross floor area when calculating *Delivery Speed* (attribute 2). This is of course possible (see further reasoning above and under KPI for *Cost* below), but to be able to compare different projects and production systems, and for consistency, gross floor area is suggested in this research. Some of the companies highlighted the importance of including the design phase when measuring delivery speed, indicating the importance of defining which project stages to include in the measure (Raynsford, 2000). The cases acknowledged that the KPI can be translated to financial goals by using cost estimations for design and for production (attribute 5). Only case D currently possessed all the necessary data to be able to calculate the KPIs, but all cases considered it possible to retrieve the necessary data to be able to use the KPIs (attribute 3). When designing a new production system or redesigning an already existing production system it is important to know how different decisions affect the delivery speed (attribute 4).

Delivery dependability

Case B, D and E did not consider *Delivery Dependability* to be a problem and argued that delays are never caused by the production system. However, by reviewing literature it is

apparent that delays is a problem in residential building (see e.g. Assaf and Al-Hejji, 2006) indicating the importance of measuring delivery dependability on both project and production system level (attribute 2). Case B and D possess all the necessary data to calculate both precision and dependability, and all cases would be able to retrieve the data if they would chose to use the KPIs (attribute 3). Since possible delays can be linked to financial goals, e.g. through late delivery penalties or by using the real estate's alternative cost for lost rental income, we consider that the KPIs for *Delivery Dependability* comply also with attribute 5.

Cost Level

The KPIs for *Cost Level* seem to be fairly established within the residential building industry, and are hence consistent with all the attributes in Table 2. Yet, similar as for delivery speed, some of the case companies highlighted the fact that measuring cost per gross floor area can be misguiding when comparing different houses. They argued that it is generally cheaper to produce a five room apartment, measured per gross floor area, compared to a one room apartment. Their suggestion was to measure cost per apartment instead. However, a similar argument could be raised against using cost per apartment. Also, some of the respondents preferred cost per gross floor area to cost per apartment (or other reference measures). The most important issue to raise is that if a comparison is to be made, the same way of measuring the KPI must be used. All the case companies however considered the suggested KPI to be relevant and they also possessed all the necessary data, i.e. *total production cost* and *total gross area* for each project, to calculate the KPIs. We therefore consider the suggested KPIs for *Cost Level* both valid and feasible in practise.

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Cost dependability

One case company had been investigating possible KPIs for *Cost Dependability* and stipulated that the suggested KPIs could be the solution, indicating that the KPIs are both acceptable and suitable (attribute 1 and 2). Case B and D possess all the necessary data and the remaining experts considered it possible to calculate the KPIs if implemented (attribute 3). Considering that it is a financial measure, attribute 5 is fulfilled by default. This KPI gives a possibility to monitor the ability to produce within budget. If many of the projects that are produced within a production system overrun the calculated cost, it is reasonable to believe that management takes action to find the reason for the overruns and to solve the problem (attribute 4).

Volume Flexibility

Even though all interviewees considered that it took some time and reasoning to understand this KPI, we consider that the KPI for *Volume Flexibility* complies with all attributes in Table 2, especially for for the production systems *PF&SA, PF&PA* and *MB* (Jonsson and Rudberg, 2014). For *CM&SA* it is difficult to define a clear break-even point and the maximum capacity, wherefore data collection (attribute 3) will be a challenge compared to an industrialized production system utilizing an off-site facility. Still, this line of reasoning can be applied also for *CM&SA*. Company B was the only one currently addressing flexibility KPIs and they considered the KPI to be relevant and applicable.

Mix Flexibility

Concerning *Mix Flexibility* all companies considered the KPI to be difficult to understand, but that it complies with attribute 2-4. It is regarded possible to collect the necessary data, the KPI is clearly linked to financial measures, and it encourages to focus on profitable projects within the limits of the production system. As mentioned above, company B was the only company actively trying to measure flexibility. They considered the KPI relevant, but questioned the use of contributing margin since this might be dependent on factors external to the production system. Instead, they suggested that overhead cost could be used in the calculation. If the production system can deliver many different types of projects with only low deviations in overhead costs (e.g. cost for design), the production system can be considered to have high *Mix Flexibility*. The definition of overhead costs are not always clear and even though the overhead costs might be stable between different projects and product variants, direct costs might be added affecting the profitability of the output of the production system. Hence, contributing margin is still the preferred measure in this research, but the issues raised calls for further research on the subject. Considering the difficulties in determining capacity levels, the risk is that the KPIs might not be acceptable (understood), and the concerns with using the contributing (or profit) margin in the calculations, calls for further research on the flexibility KPIs (both *Volume* and *Mix*), to safeguard that they comply with all attributes for all of the addressed production systems.

Case Illustration and Discussion

To illustrate how the defined KPIs can be used in combination with the classification matrix (Figure 1), companies B and E are classified, analysed and discussed. Case B and E are used for this purpose since they represent different, but still "ideal", positions in the

classification matrix. This makes the illustration clear and easy to relate to theory. Another reason for using case B and E is access. Case B and E were the cases where most data could be collected to be able to calculate and estimate the suggested KPIs. Furthermore, the purpose of this section is not to compare and analyse all cases, *per se*, but rather to illustrate how the matrix and KPIs could be employed. Mapping the cases in the classification matrix shows relative differences in how the market is approached (i.e. the degree of product standardisation) and the production system in use (i.e. the degree of off-site assembly), see Figure 5. Both production systems are located fairly well on the diagonal of the classification matrix and should thereby, theoretically, be able to meet the demands from their respective targeted markets in an effective way. However they should have strengths, and possibly weaknesses, in different areas of competition since they are different both in terms of product and process characteristics. As an example, case E should be able to deliver with shorter lead-time and at lower cost, having a production system designed for producing standardised products. On the other hand, case B should be able to handle flexibility, both volume and mix, in a better way since the production system is designed for a lower degree of product standardisation. The KPIs presented in this paper can be used to evaluate the two cases and to identify and measure differences between the cases. Even though most of the case companies argued that they would be able to track the necessary data for all of the KPIs, this unfortunately does not mean that it was possible to track historical data for all projects. Hence, some of the KPIs were possible to calculate, whereas other KPIs had to rely on qualitative estimations rather than calculated KPIs based on real data. However, using the KPIs, calculated or estimated, still provides a good ground for analysing the case companies' respective production system and market offer.
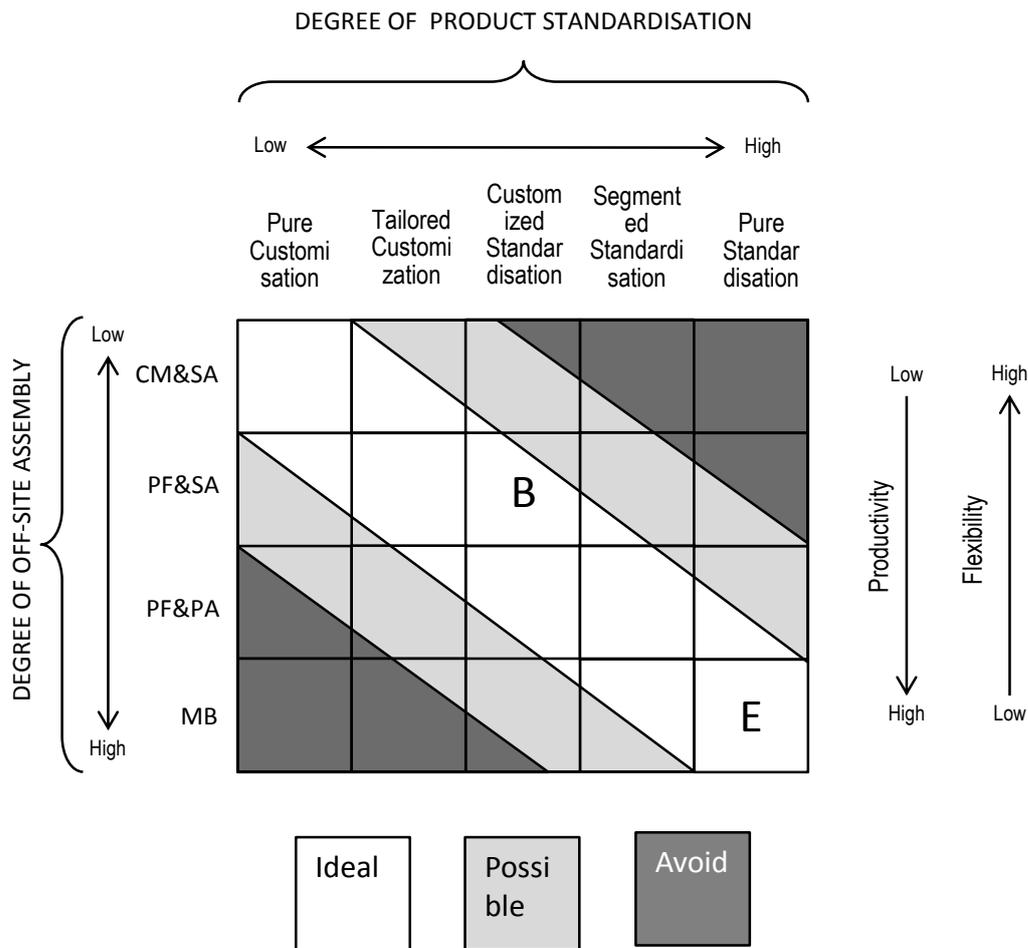
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DEGREE OF PRODUCT STANDARDISATION

Figure 5 - Cases B and E mapped in classification matrix to illustrate the use of KPIs for comparing different production systems for residential building.

Starting with quality, both cases acknowledged that they have some issues with rework and both of them actively work to mitigate these problems. Yet, none of the cases currently kept track of the cost for rectifying defects wherefore it was not possible to calculate any KPIs. From the interviews it was not possible to detect any major differences concerning quality issues between the cases. Turning to the cost KPIs it was easier to retrieve data. Case E has approximately EUR 200 lower production cost per gross area than does Case B. The interviews also showed that case E was able to provide more dependable budgets, but the lack of data made it hard to calculate any KPIs for this. Similarly for delivery, it was possible to get enough data to calculate delivery speed, but

not for calculating dependability. The delivery speed KPI showed that case E was approximately 2.7 times faster than Case B (calculations included design and production time for both cases).

Hence, so far the KPIs indicates that case E performs better for the competitive priorities cost and delivery, which is in line with what theory suggests according to the matrix in Figure 5. Theory also suggests that the trade-off for lower cost and better delivery is reduced flexibility (indicated by the arrows in Figure 5). None of the cases possessed enough data for calculating the flexibility KPIs, but the interviews still provided enough data for a qualitative estimation. Case B can deliver a wider range of products than case E, which is apparent from the position of the two companies on the x-axis in the classification matrix, and has a production system adjusted to handle this variety efficiently. Mix flexibility is difficult to evaluate without hard data. Within the limited range of products produced by case E most projects show similar margins. However, if they would increase their product range towards the same offer as case B, the profitability for the projects offering more customized products would most likely suffer.

In terms of volume flexibility, case E is limited by the factory's capacity and the break-even volume is higher due to the high investments in facilities and machinery. Hence, the flexibility space is smaller for case E than what it is for case B, wherefore case B has a higher volume flexibility. In summary, and without any calculated KPIs for flexibility, case B seems to be able to handle flexibility, both volume and mix, in a better way, which is also in line with what is shown in the classification matrix.

The above illustration shows how the KPIs can be used, in combination with the classification matrix, to evaluate and compare different positions (i.e. production

systems) in the matrix. The matrix developed in Jonsson and Rudberg (2015) provides a way of classifying production systems for the production of multifamily residences, but it does not provide a way of analysing the performance of the positions, or production systems, in the matrix. The KPIs developed within this research offer the possibility to actually measure the performance of the production systems identified in the matrix. As such, the research presented provides a more profound analysis of the strategic performance of the production systems.

Summary and conclusions

The purpose was to define KPIs to measure the performance of a production system for residential building at a strategic level, so as to be able to evaluate the production system relative the market and competitors in different areas of competition. The research is based on a production strategy perspective and the defined KPIs should be used to measure differences in performance between different types of production systems at a strategic level. *Quality*, *Delivery*, *Cost* and *Flexibility* were identified as the competitive priorities to consider when evaluating production systems. *Delivery* was further divided into *Delivery Speed* and *Delivery Dependability* and *Cost* was divided into *Cost Level* and *Cost Dependability*. Finally two aspects of *Flexibility* were deemed necessary to consider, *Volume* and *Mix*.

KPIs for each of the four identified competitive priorities were defined, which is the main result of this research. In literature there is a lack of well-defined quantitative KPIs and most performance evaluations are based on qualitative estimations rather than quantitative calculations. With the defined KPIs, a production system's performance can

be measured in a standardized and structured way, which facilitates comparison between production systems and monitoring performance over time.

In summary, the main contribution of this research is:

- Identification of important aspects to consider (i.e. what to measure) when evaluating production systems for production of multifamily residences at a strategic level, the aspects being the competitive priorities *quality*, *delivery*, *cost* and *flexibility*,

- Definitions of quantitative KPIs (i.e. how to measure), grounded in theory and validated by practitioners, for each of the four competitive priorities resulting in 14 KPIs in total (a list of all KPIs provided in Appendix 1).

Even though that the KPIs have been validated by industry experts representing different types of production system, more empirical work has to be done to further validate the KPIs. Further research would hence benefit from collecting data and put more effort into actually calculate performance for a number of production systems. The case illustration in this research is first step along this avenue, but a more complete and extended version of the case illustration is a much needed research endeavor. This will further test the applicability and validity of the KPIs and also be a first step in investigating how the characteristics of different production systems affect the ability of a production system to perform in a competitive way. Further research also needs to address the *Flexibility* KPIs, especially *Mix Flexibility*. The industry experts found this KPI to be difficult to understand and the current way of calculating this KPI could be misleading if the range of the product offer is not taken into account. Hence, the *Mix Flexibility* KPI must be able to capture differences in flexibility between different production systems so that the KPI is applicable and have practical relevance for

residential building companies. Further research should also investigate those parameters of the KPIs that are partly dependent on market and client considerations, such as the budgeted cost of a project. The way that the budgeting is done can affect the KPI, irrespective of how the production system performs. If the budgeting differs a lot between different projects produced by a production system, this will of course affect the KPI even though this is outside the control of the production system. Similar issues can be raised for the estimated production time plan and delivery date. These issues have not been treated here, but would preferable be a part of further research on testing and validating the suggested KPIs.

References

Anderson, R. (1996). A Practical Application of the Business Scorecard to Align Business Goal and Performance. *Business Intelligence Conference on Business Performance Measurement.*

Arif, M. and Egbu, C. (2010). Making a Case for Offsite Construction in China. *Engineering, Construction and Architectural Management,* 17:6**,** 536-548.

Assaf, S. A. and Al-Hejji, S. (2006). Causes of Delay in Large Construction Projects. *International Journal of Project Management,* 24:4**,** 349-357.

Barlow, J., Childerhouse, P., Gann, D., Hong-Minh, S., Naim, M. and Ozaki, R. (2003). Choice and Delivery in Housebuilding- Lessons from Japan for Uk Housebuilders. *Building Research & Information,* 31:2**,** 134-145.

Beatham, S., Anumba, C., Thorpe, T. and Hedges, I. (2004). Kpis: A Critical Appraisal of Their Use in Construction. *Benchmarking: An International Journal,* 11:1**,** 93-117.

Blismas, N., Pasquire, C. and Gibb, A. (2006). Benefit Evaluation for Off-Site Production in Construction. *Construction Management and Economics,* 24:2**,** 121-130.

Cbpp, C. B. P. P. (2014). Construction Industry Key Performance Indicators. Centre for Construction Innovation.

D'souza, D. E. and Williams, F. P. (2000). Toward a Taxonomy of Manufacturing Flexibility Dimensions. *Journal of Operations Management,* 18:5**,** 577-593.

Eisenhardt, K. M. (1989). Building Theories from Case Study Research. *Academy of Management Review,* 14:4**,** 532-550.

Fredriksson, A. and Wänström, C. (2011). Production Network Flexibility. *NOFOMA.* Harstad.

Gibb, A. G. F. (2001). Standardization and Pre-Assembly- Distinguishing Myth from Reality Using Case Study Research. *Construction Management and Economics,* 19:3**,** 307-315.

Halman, J. I. M., Voordijk, J. T. and Reymen, I. M. M. J. (2008). Modular Approaches in Dutch House Building: An Exploratory Survey. *Housing Studies,* 23:5**,** 781-799.

Hayes, R. H. and Wheelwright, S. C. (1979). Link Manufacturing Process and Product Life Cycles: Focusing on the Process Gives a New Dimesion to Strategy. *Harvard Business Review,* 57:1**,** 133-140.

Hayes, R. H. and Wheelwright, S. C. (1984). *Restoring Our Competitive Edge: Competing through Manufacturing*, John Wiley & Sons.

Hill, A. and Hill, T. (2009). *Manufacturing Operations Strategy*, Palgrave Macmillan.

Hu, X., Rousseau, R. and Chen, J. (2011). On the Definition of Forward and Backward Citation Generations. *Journal of Informetrics,* 5:1**,** 27-36.

Hwang, B.-G., Thomas, S. R., Haas, C. T. and Caldas, C. H. (2009). Measuring the Impact of Rework on Construction Cost Performance. *Journal of Construction Engineering and Management,* 135:3.

Jonsson, H. and Rudberg, M. (2014). Classification of Production Systems for Industrialized Building: A Production Strategy Perspective. *Construction Management and Economics,* 32:1-2**,** 53-69.

Jonsson, H. and Rudberg, M. (2015). Production System Classification Matrix: Matching Product Standardization and Production-System Design. *Journal of Construction Engineering and Management,* 141:6.

Josephson, P.-E. and Hammarlund, Y. (1999). The Causes and Costs of Defects in Construction a Study of Seven Building Projects. *Automation in Construction,* 8:6**,** 681-687.

Josephson, P.-E., Larsson, B. and Li, H. (2002). Illustrative Benchmarking Rework and Rework Costs in Swedish Construction Industry. *Journal of Management in Engineering,* 18:2**,** 76 - 82.

Karlsson, C. (2009). *Researching Operations Management,* New York, Routledge.

Lampel, J. and Mintzberg, H. (1996). Customizing Customization. *Sloan Management Review,* 38:1**,** 21 - 30.

Leong, G., Snyder, D. and Ward, P. (1990). Research in the Process and Content of Manufacturing Strategy. *Omega International Journal of Management Science,* 18:2**,** 109-122.

Miltenburg, J. (2005). *Manufacturing Strategy - How to Formulate and Implement a Winning Plan,* New York, Productivity Press.

Olhager, J. and Rudberg, M. (2002). Linking Manufacturing Strategy Decisions on Process Choice with Manufacturing Planning and Control Systems. *International Journal of Production Research,* 40:10**,** 2335-2351.

Pelàez-Ibarrondo, J. J. and Ruiz-Mercader, J. (2001). Measuring Operational Flexibility. *In:* The fourth SMESME international conferennce, 2001 Aalborg /Denmark.

Raynsford, N. (2000). Kpi Report for the Minister for Construction. Norwich.

Rogalski, S. (2011). *Flexibility Measurement in Production Systems, Handling Uncertainties in Industrial Production,* London, Springer.

Rudberg, M. (2004). Linking Competitive Priorities and Manufacturing Networks: A Manufacturing Strategy Perspective. *International Journal of Manufacturing Technology and Management,* 6:1/2**,** 55-80.

Sethi, A. K. and Sethi, S. P. (1990). Flexibility in Manufacturing: A Survey. *The International Journal of Flexible Manufacturing Systems,* 2**,** 289 - 328.

Slack, N. and Lewis, M. (2011). *Operations Strategy,* Harlow, Pearson Education Limeted.

Smullen, J. (1997). *Balanced Scorecards and Activity Based Management: The Practical Applications*, FT PrenticeHall.

Womack, J. P. and Jones, D. T. (2003). *Lean Thinking - Banish Waste and Create Wealth in Your Corporation,* New York, Free Press.

Yang, H., Yeung, J. F. Y., Chan, A. P. C., Chiang, Y. H. and Chan, D. W. M. (2010). A Critical Review of Performance Measurement in Construction. *Journal of Facilities Management,* 8:4**,** 269-284.

Yin, R. K. (2009). *Case Study Research Design and Methods,* Thousand Oaks, Carlifornia Sage Publications.

Appendix 1: KPIs for measuring production system performance in the residential building industry

Competitive priority	KPI
Quality	$Quality\ for\ the\ i{:}th\ project\ \left(Q_i^p\right) = \dfrac{Cost\ for\ rectifying\ defects\ in\ project\ i}{Total\ production\ cost\ for\ project\ i} \times 100;\ i = 1, 2, \dots, n$ (1) $Quality, production\ system\ (Q^{PS}) = \dfrac{\sum_{i=n-N+1}^{n} Q_i^p}{N}$ (2)
Delivery Speed	$Delivery\ speed\ for\ the\ i{:}th\ project\ \left(DS_i^p\right) = \dfrac{Total\ production\ time\ for\ project\ i}{Total\ gross\ floor\ area\ for\ project\ i};\ i = 1, 2, \dots, n$ (3) $Delivery\ speed, production\ system\ (DS^{PS}) = \dfrac{\sum_{i=n-N+1}^{n} DS_i^p}{N}$ (4)
Delivery Dependability	$\dfrac{(Total\ production\ time - Production\ time\ according\ to\ initial\ timeplan)for\ the\ i{:}th\ project}{Production\ time\ according\ to\ initial\ timeplan\ for\ the\ i{:}th\ project} \times 100;\ i = 1, 2, \dots, n$ (5) $Delivery\ precision, production\ system\ (DP^{PS}) = \dfrac{\sum_{i=n-N+1}^{n} DP_i^p}{N}$ (6) $Delivery\ dependability, prod.\ system\ (DD^{PS}) = \dfrac{Number\ of\ projects\ delayed\ out\ of\ M\ projects}{M} \times 100$ (7)
Cost Level	$Cost\ level\ for\ the\ i{:}th\ project\ \left(CL_i^p\right) = \dfrac{Total\ production\ cost\ for\ project\ i}{Total\ gross\ floor\ area\ for\ project\ i};\ i = 1, 2, \dots, n$ (8) $Cost\ level, production\ system\ (CL^{PS}) = \dfrac{\sum_{i=n-N+1}^{n} CL_i^p}{N}$ (9)
Cost Dependability	$Cost\ precision\ for\ the\ i{:}th\ project\ \left(CP_i^p\right) = \dfrac{(Actual\ production\ cost - Budgeted\ production\ cost)for\ the\ i{:}th\ project}{Budgeted\ produciton\ cost\ for\ the\ i{:}th\ project} \times 100;\ i = 1, 2, \dots, n$ (10) $Cost\ precision, production\ system\ (CP^{PS}) = \dfrac{\sum_{i=n-N+1}^{n} CP_i^p}{N}$ (11) $Cost\ dependab., prod.\ sys.\ (CD^{PS}) = \dfrac{Number\ of\ projects\ that\ overrun\ budget\ out\ of\ M\ projects}{M} \times 100$ (12)
Volume Flexibility	$Volume\ flex., prod.\ system\ (VF^{PS}) = Flexibility\ Space = Maximum\ capacity - Volume\ at\ Breakeven\ Point$ (13)
Mix Flexibility	$Mix\ flexibility, production\ system\ (MF^{PS}) = \dfrac{\sum_{i=n-N+1}^{n} \Delta CM_i^p}{N};\ i = 1, 2, \dots, n$ (14)