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Design for construction: utilizing production experiences in development

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The design process has a significant impact on the performance and profitability of a housing project. Therefore, decisions made during the design process should take into consideration knowledge and experience from other processes in previously accomplished projects, specifically from the production phase. How to capture and use production experience in housing has not gained enough interest, possibly leading to sub-optimal improvements during the construction process. This motivates research on how onsite production experience from similar previous projects can be captured and used to improve constructability without risking customer values. Based on the concept of constructability, 'design for manufacturing and assembly' and the theory of waste, the method 'design for construction' (DFC) has been developed. The four-step model complements the conventional construction process, and consists of the following steps: (1) specify customer values and similar previous projects; (2) identify onsite waste and cost drivers in previous projects; (3) develop criteria to evaluate constructability; and (4) evaluate constructability of the design. The DFC method is exemplified and tested through a case study, in which it was shown that the method facilitated identification of all problems that were considered in the investigated project. The method also highlighted other project obstacles that potentially could have been solved to improve constructability.

Keywords: Constructability, design for construction, feedback, lean construction, residential.

Introduction

Improvement of constructability in new housing projects requires that onsite production experience is captured, transferred and used in the design process. Knowledge acquisition, development and utilization are often considered crucial for improving company competitiveness (e.g. Chen and Mohamed, 2007). However, according to Goh (2002), it is necessary to consider the experience of all employees at all levels of the organization, not only the experience of the white-collar workers (Dai *et al.*, 2007). The inability to consider acquired experiences from already performed projects for use in new ones is a potential source of low quality and high cost in construction (Love *et al.*, 2010). However, to date, little attention has been paid to how to capture and feed back production knowledge and how to use it in the development of new construction projects in order to increase constructability (Lam and Wong, 2009).

In construction, development endeavours have often been managed through a sequential approach, where the focus has been on either the design or the construction phase (Winch, 2006). Early phases of projects are often considered to have significant influence on the total project and building performance (Al-Reshaid *et al.*, 2005), since it is where the prerequisites for efficient work on site are determined (Fox *et al.*, 2002). Josephson and Saukkoriipi (2005) for example, conducted an extensive empirical investigation of the Swedish construction industry and found that at least 30–35% of construction project costs relate to waste. The waste was primarily caused by design defects (26%) and problems related to construction management on site (25%) (Josephson *et al.*, 2002). Therefore, Bakti *et al.* (2011) asserted that involvement of

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construction knowledge early in the project process is necessary to reduce the risk of creating designs that cannot be efficiently built, i.e. the opposite to constructability (Jergeas and Van der Put, 2001).

Therefore, the objective is to conceptualize principles of how to capture, feed back and use production knowledge in the design phase into one useful model. We begin with a literature review that highlights current problems and knowledge gaps within constructability. Theories from other sectors, i.e. the concept of 'design for manufacturing and assembly' (DFMA) and waste reduction are suggested to solve the knowledge gap problems. The presentation of the conceptualized model 'design for construction' (DFC) is followed by a case study, which is used to illustrate the practical benefits and to facilitate understanding of the last section: the discussion and conclusions from a scientific approach.

Constructability

Constructability means the capability of a construction project to be realized with optimal utilization of construction resources (Bakti *et al.*, 2011). The goal is that, by using appropriate construction experiences in the design and engineering phases of a project facility, the operations on site will be more efficient (O'Connor *et al.*, 1987). According to the Construction Industry Institute (1986), the concept is based on the use of adequate experiences in planning, engineering, management, procurement of resources and field operations when designing the project so the overall performance objectives can be achieved. Their framework of constructability consists of 17 constructability principles, which are grouped under the three main phases of the project process:

(1) The conceptual planning phase, which includes principles where the major idea is to involve construction knowledge and experience in order to execute the project contracting strategy, project master plans and design the site layout.
(2) In the design and procurement phase the focus of the principles is to design, engineer and procure solutions that facilitate the production on site.
(3) The principle for the field operations phase is about the creative use of current construction methods or equipment.

However, what constitutes adequate construction experiences and how these are fed back are not addressed clearly.

O'Connor *et al.* (1987) presented seven concepts which highlight what to consider for improving the constructability from a design and engineering perspective. The concepts can be categorized into three areas: (1) product design, which includes standardization of elements and engineering of modules for prefabrication; (2) production management, i.e. the concepts of construction-driven scheduling, to increase the accessibility of manpower, materials and equipment; and (3) working conditions on site with the concepts of using part designs that are simple to craft, clarified task specifications, and using design solutions robust for adverse weather conditions. It is interesting to note that descriptions of the relations between these concepts, how they can be used together or what kind of experience is appropriate to use are lacking.

Furthermore, these two frameworks serve more as checkpoints or recommendations for appropriate project development and management. Collection and feedback of construction knowledge are not emphasized (cf. Nima *et al.*, 1999). O'Connor *et al.* (1986, p. 463) describe the problems associated with collection and use of experiences that are gained by others—often 'designers are asked to think like constructors and constructors are asked to think like designers'. Therefore, the authors have identified appropriate knowledge-collecting methods from already accomplished projects. Their conclusion was that the most efficient constructability data collection methods involve many project participants and use several data collection techniques, e.g. suggestion boxes of improvements ideas, survey questionnaires, onsite interviews, project documentation and project meetings. However, the collection task will be overwhelming and cumbersome if it is not directed (Imai, 1997), for example through identification of and focus on customer values and company strategy (e.g. Russell *et al.*, 1994).

More recently, Chen and Mohamed (2007) investigated 99 contractors in Hong Kong on how knowledge was managed on site and across different sites. Their conclusion was that the implicit nature of construction knowledge meant that experience was disseminated and shared through meetings, observations and collaboration. The exchange of experiences between employees engaged in onsite and offsite construction of prefabricated house building has also been addressed by e.g. Meiling and Sandberg (2009) and Lin *et al.* (2006). Bakti *et al.* (2011) investigated the relationship between constructability in engineering projects and performance improvement. They found that the performance increased by 15%, but did not consider how the constructability was achieved.

Construction experience feedback

According to Jergeas and Van der Put (2001), the most significant factor of constructability is labour experience, which encourages the comprehensive use of onsite expertise in the early phases of projects. In their empirical survey, they concluded that the major obstacles to achieving the benefits of constructability efforts were the lack of collaboration and the fact that individuals moved between different projects. However, Dai *et al.* (2007) asserted that most studies of performance improvement within construction have been conducted with a top-down approach and thereby emphasized primarily white-collar workers' knowledge of construction in the design phase of projects. Even if many studies mention the construction or field operation knowledge, the main concern is the experience at management level. There seems to be an assumption that craftsmen have enough know-how themselves, and are able to handle and solve all construction issues that appear (cf. Gann, 1996).

A potential reason is that the involvement of many different parties in the development of construction projects, as emphasized by concurrent engineering (Gunasekaran and Love, 1998), is problematic in practice due to the temporary and novel nature of project organizations (e.g. Kamara *et al.*, 2001). Another reason may be that lack of standards and processes (Roy *et al.*, 2005) for sharing knowledge and valuable practice within the construction process are obtruding realization of improvement efforts (Styhre and Gluch, 2010). By using formal management procedures, implicit experience can be more easily transformed and explicitly stored (Aggestam, 2006), and made available for use in management and performance improvement efforts (Jensen, 2005); an example from the manufacturing sector is found in Barlow (1999).

Industrial improvement methods

In manufacturing, numerous improvement philosophies and methodologies have been developed and used to increase product and production performance, e.g. the lean production concept and the method 'design for manufacturing and assembly' (DFMA). These improvement methods are based on standardization and repetitiveness of the production processes, which can be monitored, controlled and continuously improved (Womack *et al.*, 1990; Barlow, 1999). This is not the normal process for housing development, where formal management procedures are rarely followed within projects (Roy *et al.*, 2005). Instead, production is based on skilled craftsmen whose methods and operations are seldom controlled (Dai *et al.*, 2007). However, according to March (2009) and Winch (2003) residential housing projects are relatively homogeneous products and the production processes are rather iterative. Anumba *et al.* (2007) argue that similarities between the iterations of design, development and production of products in manufacturing and housing motivate the use of methods that support interaction of different knowledge disciplines in the design phase.

Both of these methodologies are about providing the stakeholders of the product realization process with relevant knowledge to enable improvement. For example, lean concepts suggest that in order to realize high performance products, the development process should be based on deep knowledge about customer values, current production operations and conditions, and how the new product design affects both of these areas (Kennedy *et al.*, 2008). DFMA is focused on creation of production improvements through product design, and it complements lean product development concepts by describing how to make detailed generic production knowledge available to other disciplines, i.e. DFMA makes relevant manufacturing and assembly knowledge available for product designers in a set of predefined guidelines (Ulrich and Eppinger, 2008). The purpose is to evaluate a product design systematically and iteratively from both its ability to satisfy customer needs and its manufacturability, and thereby improve both the product design and production processes. In a sense, DFMA is a way to create an organizational learning process, transform individual knowledge into organizational knowledge (feed forward), and interpret, develop, integrate and institutionalize it into products and processes (Castaneda and Rios, 2007). The new knowledge is then supposed to be fed back to the operational individuals in the organization (Kamara *et al.*, 2003). Therefore, if the DFMA method can be adapted to the conditions of construction, it could be an appropriate approach to capture and utilize onsite experience and conditions for conventional housing, thereby increasing project performance.

Design for manufacturing and assembly

Design for manufacturing and assembly (DFMA) is the process of designing products to optimize all manufacturing functions, and to ensure minimized cost, maximum quality, delivery time reliability and customer satisfaction (Belay, 2009). The term 'Design for X' or DFX is sometimes used when the generic method is discussed, where the X stands for the specific aspect under consideration, e.g. manufacturing, assembly, automatic assembly, quality, etc. (Mottonen *et al.*, 2009); however, in this paper the term DFMA will be used. DFMA integrates past experiences from production and customer needs into product design, with the main goal of improving business performance.

The DFMA method utilizes knowledge from several professions, such as design and production, and uses several different types of information, e.g. sketches, blueprints, product specifications, production experiences and production cost drivers (cf. Takezawa *et al.*, 2005). If existing processes are to be utilized, the product should be designed for the production process; however, if new processes are to be implemented, then the product and the process should be developed concurrently. This requires a detailed understanding of the production process, and one of the best ways to achieve this is to develop products in multifunctional teams (Belay, 2009). Hamidi and Farahmand (2008) explained that DFMA is like a feedback loop between the design and the manufacturing functions, i.e. the designers develop and describe the design, and the manufacturing engineers check whether the designed product can be effectively produced with its current capabilities, or how processes have to be changed. The manufacturing knowledge is then fed back to support the designers in making the necessary corrections to develop an economically profitable product. The DFMA process consists of five main steps, which are preceded by a proposed product design with specific functions, quality and customer values:

(1) Estimate total manufacturing cost.
(2) Reduce cost of parts.
(3) Reduce cost of manufacturing and assembly.
(4) Reduce cost of production execution, management and supplies.
(5) Consider the impact on other factors and evaluate whether the design is good enough.

Waste reduction through DFMA

The theory of lean production states that every process and operation consists of value adding work, necessary waste and pure waste. In order to maximize the value adding work and increase product quality, companies should focus on reducing waste along with adding value through product development (Russell *et al.*, 1994; Kennedy *et al.*, 2008). In literature on lean production, waste is commonly divided into eight subtypes (see Table 1). Ohno (1988) and Koskela (2000) argue that waste types 1–5 are mainly addressed at the production management level, which in the case of construction includes project manager, design engineer and site manager. Types 6 and 7 are mostly addressed at the operational level, e.g. by craftsmen, but controlled by supervisors such as foremen. According to Liker (2004) waste type 8 is addressed at both levels. Morgan and Liker (2006, p. 19) state that 'Waste created by poor engineering that results in low levels of product or process performance … is the most destructive waste'. Berglund and Westling (2009) have shown, by exemplifying the waste types at different functions within the company,

Table 1 Different types of waste, typical manufacturing manifestation and examples in the context of housing

No	Waste type	Description (manufacturing)	Example in construction
1	Overproduction	Making more than is immediately required	Completing operations earlier than necessary, e.g. painting of walls in rooms that are not completed
2	Waiting	Waiting for parts, information, instructions and equipment	Blueprints are not finished when onsite operations need them
3	Transport	Moving people, products and information	Inappropriate distances between storage, workplace offices on site owing to little logistic planning
4	Over-processing	Tighter tolerances or use of higher quality in materials than necessary	Including more functions within the product than the customer wants
5	Inventory	Storing parts, pieces, and documentation ahead of requirements	Unnecessary large storage of materials and components on site
6	Motion	Bending, turning, reaching and lifting	Inappropriate work conditions, e.g. unnecessarily heavy and high lifts
7	Defects	Rework, scrap and incorrect documentation	Rework of operations and construction material affected by climate
8	Unused employee creativity	Underutilizing capabilities	Not considering onsite experiences from earlier projects in new projects

that all eight types of waste can occur at any organizational level; however, the root cause for each type can be traced to either management or operational activities for each level.

An economically successful design is about ensuring high product quality while minimizing the manufacturing cost. According to Ulrich and Eppinger (2008) this is achieved by minimizing the number of parts, and by maximizing the ease of handling parts and the ease of assembly, which are the key principles of DFMA. By following these principles, as well as by coordinating with non-production disciplines and dealing with quality defects, customer value can be increased and the complexity in production management reduced. By reducing the number of parts, the number of onsite activities is decreased and the total production time can be reduced (cf. O'Connor *et al.*, 1987), i.e. the risk of waste occurring can be reduced. The total value adding production time consists of handling time and operation time, so when these are reduced the risk for waste types 6 and 7 decreases. Also, reduction of the number of parts reduces the complexity of planning and performing these activities, and the need for monitoring and controlling them, thus increasing the ability to reduce waste types 1–5.

According to Shingo (1989), single improvements at operational level do not necessarily improve the whole process. The interaction between operations and management has to be considered in order not to sub-optimize the total production (Bryde, 2008). Hence, collaboration between different professions during the development process is a central part of the DFMA method (e.g. Bogus *et al.*, 2006). The generic and detailed DFMA rules used by designers are logically based on previously gathered experience from production. These rules can also be amended with company- or project-specific rules that are directly derived from previous projects, limiting the risk for waste type 8. As shown above, DFMA utilizes deep production knowledge and experiences from multiple disciplines to reduce the complexity and amount of waste at both management and operational levels, which in turn leads to a reduction of the total manufacturing cost.

Scientific approach

The 'design for construction' model concerns capturing and transferring tacit knowledge, making it explicit for development of future project settings. Deep and qualitative empirical data are required to validate a model that considers this, which makes suitable the use of a case study approach (Yin, 2003). Therefore, the DFC method is validated through a qualitative evaluation of both the functionality of each step of DFC in its real-life setting, and by analysis of its potential to generate solutions that have a higher degree of constructability than conventional methods are able to create (cf. Patton and Appelbaum, 2003).

The most appropriate way to validate the DFC is to repeat already completed projects with the use of DFC. The functionality of the model's steps can then be analysed and the result be evaluated in comparison with the constructability of the actual housing project outcomes. An appropriate case study project would be a conventional project developed with considerable efforts to achieve a high level of constructability. In such a case, it is of particular interest to assess to what extent the achieved design developments, in the real project, correlate with the evaluation criteria, determined by the use of DFC. Further, the efforts that were put in to improve the design, in the real project, should be weighed against the efforts required to perform the DFC method.

The identified case study project was a passive house project, which the contractor perceived as a hindrance for high project performance. Therefore, the company made comprehensive efforts during product design to increase its constructability; in fact, the building design was developed and improved three times before production started. In line with Yin's (2003) recommendations, the chosen data collecting methods were document analyses, 15 semi-structured interviews, and 10 onsite observations (see section on empirical implications for details). The DFC model requires similar previous projects to be assessed; in this case, 10 similar projects were used for comparison during the DFC analysis. The major difference was that these projects had not considered the constructability aspects in the design phase. This strengthens the choice of the case study project for testing the model, i.e. validation of the DFC method should be made with a project where efforts have been made to improve constructability. If not, we cannot validate that the DFC has the potential to systematically improve constructability more than the typical process to make improvements in building design.

Moreover, the case serves as an opportunity to consider the empirical implications of the adoption of the method. To illustrate how the DFC concept is useful and increases the constructability in practice, two hypotheses were formulated and investigated: (1) all design improvements implemented by the company are highlighted by the DFC method; (2) the DFC method points out improvement areas that the design team were not aware of. Later, these results could be the foundation for future hypothesis testing based on empirical data from numerous projects in numerous companies (cf. Eisenhardt and Graebner, 2007).

Design for construction

Design for construction (DFC) is based on the same principles as DFMA, i.e. the improvement of a product design's constructability should to a great extent be based on minimizing the number of components, parts and materials that need to be processed, assembled and handled on site (Ulrich and Eppinger, 2008). The overall goal is to improve production efficiency by developing the working conditions for the craftsmen and making production management less complex and more accurate (cf. O'Connor *et al.*, 1987). The foundation of DFC is that many individual housing projects have similarities and consist of some operations that are repeated (Winch, 2003). The repetitiveness should also increase between similar projects regarding the characteristics of customer segment, building type, building quality, production strategy and structure design (Anumba *et al.*, 2007). DFC focuses on identifying problems and waste from projects where similar buildings were produced, and then using this knowledge to design the new project in a way that old problems do not reoccur or at least occur to a lesser extent. The reason for this is the assumption that similar product solutions create some types of waste more frequently than others (cf. Imai, 1997). This ensures that relevant onsite production experience can be captured and used in the design process in order to evaluate the product design's ability to satisfy constructability without sacrificing customer values, and thereby improving the new project. The method should be seen as a complementary process to the ordinary project process (Russell *et al.*, 1994); the four steps of DFC are carried out during the concept and design phases in a construction project (cf. Nima *et al.*, 1999). The following sections explain each step within DFC and its relation to the project process.

The project process and the DFC steps

The context of DFC is the private housing process which in general can be divided into four main phases (cf. Construction Industry Institute, 1986).

(1) *Concept and project development*—the project idea and the functionality of the product are defined in relation to a particular geographical market demand. The customer values are identified and used as a basis for the product design. Necessary building permissions are applied for and the sales of the dwellings start. This phase creates a base for evaluation of the product design's ability to meet customer values in the specific project. This phase also guides the search for similar projects to investigate and benchmark.

(2) *Design, project cost estimation and production planning*—the detailed building design is specified and the project cost is estimated. The onsite construction is planned including resource allocation, time and logistics scheduling, and orders for purchase and project material are prepared. The deliverables from this phase include blueprints, lists of resource needs, bills of quantities, current material prices, production time schedule, detailed activity structures, and specified resource plans, etc. All deliverables are specific for the building design and the project conditions.

(3) *Construction*—craftsman-based production is performed on site, supervised by the project management team to complete the finished building in accordance with the identified customer values.

(4) *Delivery and occupancy*—the finished dwellings are delivered to the customers after quality inspections.

DFC uses the first project phase to identify customer values and similar performed projects (step 1); the cost driving factors on site are identified in the already performed projects (step 2); these factors are then analysed and deduced into evaluation criteria (step 3). The evaluation criteria can be used to support the design process in order to develop a construction-friendly project draft. The draft is then evaluated as to its ability to achieve constructability and customer values (step 4). Figure 1 shows how the DFC steps are accomplished in relation to the ordinary project process. The DFC method has an iterative nature, so if the suggested design does not fulfil the identified requirements, the building design can be further improved until it reaches a satisfactory level with regard to the evaluation criteria. DFC is also iterative from one project to the next, i.e. previous DFC experience should be fed back and used to create design rules that can be generalized for a company or project type.

Step 1: Specify customer values and similar projects

The theory of lean production asserts that specific customer values should always be the foundation for improvements. The general customer values should be clearly stated and described in the housing company's strategy and business plan. In the design phase the general customer values are configured into specific project conditions that, in addition to an analysis

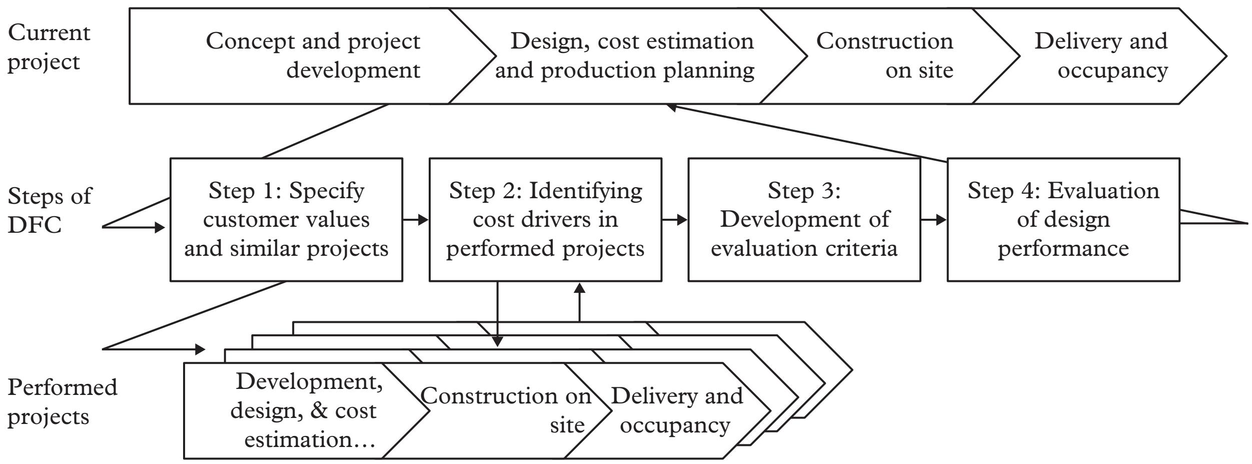

Figure 1 The four steps of DFC, their placement in the housing project process, and DFC's connection to performed projects

of the local market and local building codes, can be practically used as evaluation criteria to guide the design process. Lam *et al.* (2004) argue that critical success factors are often project specific; however, projects that exhibit similar characteristics also tend to share success factors (Winch, 2003). Consequently, housing characteristics like conceptual design, location of the estate and identified customer values determine the already completed projects that could be interesting to investigate from a constructability approach. More detailed choices could be made on customer segment, product type (multi-storey houses or small houses), function requirements, quality parameters (e.g. energy efficiency), production methods (conventional or prefabrication construction), and construction design type (framework and material). The first step in DFC follows basic benchmarking procedures (Anand and Kodali, 2008), i.e. to identify specific areas to investigate in order to find relevant cost drivers and waste.

Step 2: Identifying onsite waste and cost drivers

The key focus in DFMA is to reduce the production cost, mainly by reducing the number of parts, with the aim of reducing the number of assembly operations and the complexity in production management. The concepts of constructability developed by O'Connor *et al.* (1987) recommend similar efforts to make the site construction more simple and efficient. Reduction of parts is generally not a driver in the design phase, probably due to the lack of deep production knowledge and of how specific design choices drive cost on site. In order to increase project profitability and predictability, the product design must also be evaluated on how well the desired product characteristics can be achieved with the minimum of problems and waste on site. In the case of craft-based production, every design solution can be achieved in different ways depending on the skill of the craftsmen (e.g. Gann, 1996). This means that there are more or less efficient ways of performing certain activities and that the variation has a great effect on the product quality. The reduction of variation in how different craftsmen perform a specific production process is key to ensuring that the total product quality meets customer requirements (O'Connor and Davies, 1988). The second step of DFC identifies typical problems and waste on site by using the data collecting methods that are suitable for constructability issues (O'Connor *et al.*, 1986): documentation and interviews for already performed projects, and onsite observations in current ones. Use of these kinds of methods is motivated by the fact that it is tacit skills that were creating the eventual problems (cf. Goh, 2002). The eight types of waste can work as a guide for what to look for (Goodson, 2002). Essentially important problems to discover are those which cause waste at both operational level and project management level (Ohno, 1988). By analysing where, why and how the problems occurred (Johnsson and Meiling, 2009), each problem is sorted into three categories of desired product characteristics (cf. O'Connor *et al.*, 1987):

(1) Components and part design (indestructibility)
(2) Production ease (constructability)
(3) Production execution and management (operation and coordination)

Step 3: Development of criteria to evaluate constructability

The next step in the DFC method is to develop evaluation criteria, which are to be used by the design team to evaluate how well desired product characteristics can be achieved without incurring unnecessary costs in production. This requires evaluation criteria for each of the desired product characteristics (Ulrich and Eppinger, 2008). The classification of the root problems into three categories, performed in DFC step 2, is carried out by methods such as root cause analysis and cause and effect analysis (Hines and Rich, 1997). The identified customer values in the project development phase should also be analysed and condensed into specific customer values that are more easily assessed by the designer. DFC suggests that problem analysis is conducted in relation to the estimated project cost in order to come up with feasible evaluation factors and solution areas for the problems. This procedure should be performed in multi-disciplined groups (Anumba *et al.*, 2007), e.g. in workshops where representatives from all project lifecycle stages are involved (O'Connor *et al.*, 1986). The result from the analysis is a number of evaluation criteria for each category of the product characteristics. These are then used in the design process and in the next step in DFC to evaluate the constructability of the design draft.

Step 4: Evaluation of the design's construction performance

DFMA suggests calculating an assembly index for each part in order to see how production cost, time and quality are affected. In construction it is more difficult to obtain accurate numbers on these parameters; therefore, the evaluation of the design's construction performance in DFC is based on logical argumentation, linking the constructability to the desired product functions. The purpose of the evaluation is to clarify to what extent the design can achieve the predefined criteria. Each identified criterion is evaluated individually as desired, acceptable or unacceptable. Owing to differences in relevance, each criterion must be weighted in order to contribute to an appropriate extent when the performance index is calculated. Each criterion is given a factor of relevance (R): 2 if important, 1 if relevant; and a grade (G): 2 for desired, 1 for acceptable, and 0 for unacceptable. By multiplying the factor of relevance (R) and the grade (G) the total points (P) is obtained for each criterion. To highlight the strong and weak aspects of the design, an index is presented for each desired product characteristic and there is an overall performance index. The index (I) was given by dividing the summary of obtained points ($P_{obtained}$) with the maximum possible points (P_{max}) (see Equation 1). If the characteristics of the solution are exactly as desired, the index is 1, and if the index is less than 1 (minimum 0) it indicates that product is not perfectly designed for constructability. See Table 3 for an example of the indexes.

$$Performance\ index\ (I) = \frac{\sum P\ (Obtained)}{\sum P(Max)} \quad (1)$$

The process of giving each evaluation criterion a certain relevance and grade is subjective and will probably be project specific. Therefore it is really important to derive the consequences for the waste and problems, and the root cause analysis and cause and effect analysis should be the foundation for the weightings. The index should be used to clarify the progress of the development of the product design and to get an indication as to when the desired product characteristic is achieved. The project's design team has then to decide whether each part's product design is good enough and weigh additional design costs and the potential to reduce production cost. If the decision is no, the product does not fulfil

Table 2 Categorization of identified problems on site

Components and part design	Production ease	Production execution and management
Large piles of broken materials and components (due to fragile materials)	Many components and parts to assemble	Insufficient production management information
A lot of rework, due to non-robust part solutions	Complex and time consuming assembly operations	Production plans were scarce and out of date
Unsafe movements because of unwieldy materials and components	Unnecessary transportation of resources	Unanticipated operational requirements and tools
Over-processed parts (sub-optimized product concept)	Additional quality controls and inspections	Large stocks of materials and components
	Unfamiliarity in fixing errors	Negligence as to instructions and information (waiting)
		Lack of routines for quality control

Table 3 Case-specific evaluation criteria, relevance factors and grades for each wall solution

		Solution 1		Solution 2		Solution 3	
	Relevance (R)	Grade (G)	Points (P)	Grade (G)	Points (G)	Grade (G)	Points (G)
Components and part design (indestructibility)							
Fragile components/materials regarding handling	2	2	4	2	4	2	4
Non-tender construction solutions	1	2	2	2	2	2	2
Indestructibility of part design regarding the airtightness	2	0	0	0	0	0	0
Moisture insensitivity of components (material choices)	1	1	1	1	1	2	2
Moisture proof part (modules) design	1	0	0	1	1	1	1
Moisture proof connections and attachments	2	1	2	1	2	2	4
Foolproof splices in the moisture barrier	1	0	0	0	0	0	0
$P_{(max)}$	20		9		10		13
Components and part design index			0.45		0.50		0.65
Production ease (constructability)							
Number of material layers	2	0	0	0	0	2	4
Minimized numbers of different types of machines and tools	1	1	1	1	1	1	1
Size of internal parts	1	1	1	1	1	1	1
Positioning of parts	2	1	2	1	2	1	2
Maximized tolerances	1	1	1	1	1	1	1
Multifunctional connections/alignments	1	0	0	0	0	0	0
Installation space	1	1	1	2	2	2	2
Degree of completion (reduction of operations)	2	0	0	0	0	1	2
$P_{(max)}$	22		6		7		13
Production ease index			0.27		0.32		0.59
Production execution and management							
Foolproof assembly of small parts on site	2	1	2	1	2	1	2
Foolproof assembly of prefabricated modules	1	1	1	1	1	1	1
Weather independent assembly	1	1	1	1	1	2	2
Instructions for assembly of airtight parts	2	0	0	0	0	1	2
Additional need of specialists	1	0	0	0	0	0	0
Need of special skilled craftsmen	1	1	1	1	1	1	1
Stability during assembly	1	1	1	1	1	1	1
Safety for workers	1	1	1	1	1	1	1
$P_{(max)}$	20		7		7		10
Production execution index			0.35		0.35		0.50
End-customer value (product functions)							
Protected moisture barrier	2	1	2	2	4	2	4
Interior attachments	1	0	0	0	0	0	0

(Continued)

Table 3 (*Continued*)

		Solution 1		Solution 2		Solution 3	
	Relevance (R)	Grade (G)	Points (P)	Grade (G)	Points (G)	Grade (G)	Points (G)
Disassembly ability	1	2	2	2	2	2	2
Lifetime quality of the moisture barrier	2	1	2	1	2	1	2
Maximum numbers of outlets for electricity	1	2	2	2	2	2	2
Minimized service and maintenance	1	2	2	2	2	2	2
$P_{(max)}$	16		10		12		12
Customer value index			0.63		0.75		0.75
Product design performance index			0.42		0.48		0.62

Notes: The factor of relevance (R) was set to 2 if important, 1 if relevant; and the range of the grades (G) to 2 for desired, 1 for acceptable, and 0 for unacceptable. The index (I) was given by dividing the summary of obtained points ($P_{obtained}$) with the maximum possible points (P_{max}).

the requirements and a new design loop should be performed.

Empirical implications

The case study project

The investigated project, named 'Beckomberga', consists of two multi-family, four-storey houses based on the Swedish passive house standard (Sveriges Centrum för Nollenergihus, 2012), which is very similar to the European criteria (Passivhaus Institut, 2009). The developer and contractor is one of the largest construction corporations in Scandinavia. This project was chosen because of its unusual focus on iterative product design, i.e. the company developed and improved the product design three times before production started. Each design draft was completed including all required documentation. Since all design drafts could be evaluated and compared, this case was suitable to illustrate the DFC method. The case study was limited to a new light wall design that was designed according to the Swedish passive house standard and its impact on onsite production.

Project accomplishment

Within the Beckomberga project, the design team consisted of the client (in-house), contractor, architect and structural engineer. The project process and the design phase were carried out in accordance with normal company routines. Both the project organization and the project process accomplishment were typical for housing within Sweden. In the project development phase the company focused on maintaining customer values similar to those for its 'conventional' housing projects, fulfilling national building codes and municipality regulations, and Swedish passive house standards. The project also followed the normal routines for production cost estimation, using a database with different types of material cost and standard times for all production activities, e.g. time needed to assemble one square metre of internal wall. The design phase deliverables were a list of resource needs, bill of quantities, current material prices, overall production time schedule, activities structures and resource needs. Owing to the passive house concept almost all construction parts used in the building were identified, except some ordinary insertions and alignment parts, e.g. screws.

The design team had chosen a traditional load bearing structure of concrete slabs and steel columns with light walls as complement. To achieve passive house standard, the traditional exterior walls required additional insulation, which the design team developed based on previous experience. In the first solution, the moisture safety solution was commonly used within the construction sector, but at that time publicly questioned. The dimensions of the wooden studs were also considered to diverge too much from the company's traditional walls. Hence, a second solution was developed with dimensions similar to a traditional wall, which included an additional layer of insulation. Within this design, the installation space was separated from the façade construction and it was made deeper so the risk of penetration was minimized. The façade was designed to be more moisture proof by including an air gap for ventilation. However, this solution was not economical with regard to the specific requirements for multi-storey buildings. A third and final wall solution was developed, where the wooden studs were replaced by sheet metal studs. Because of the sheet metal studs and construction aspects, the geometric dimensions were once again changed to suit construction on site. The third design solution was used in the project realization and had about the same number of parts (see Figure 2), but the project manager decided to purchase the wall design as modules produced by a prefabricator. This decision extensively reduced the numbers of operations on site, but was in fact an unintended benefit; the main driver was the cost. For example, the windows were installed in the façade elements before they were delivered to the construction site, which removed several complex operations from the construction site and made the management less complex.

It is interesting to note that the design team did not show much interest in how operations on site were conducted in detail and lacked knowledge of the exact order of assembly, how parts are assembled, and how long certain operations take. Site managers, who were assumed to fulfil the management role with the most interest in and experience of this, were not members of the design team. However, the investigation showed that not even the site managers had detailed understanding of these issues—they only knew that the output of certain operations is dependent on who performs the task, weather conditions and some other circumstances.

The application of DFC on the Beckomberga project

The following steps of the DFC model were conducted by the authors with support from the project team. The descriptions include details of how empirical data were collected for each step.

Step 1: Identifying customer values and similar projects

The characteristics and location of the Beckomberga project were similar to the company's traditional market for its 'conventional' housing projects, and thereby included the normal customer values (see Table 3, category 'End-customer value'). The conceptual ideas and the choice to develop it as a passive house

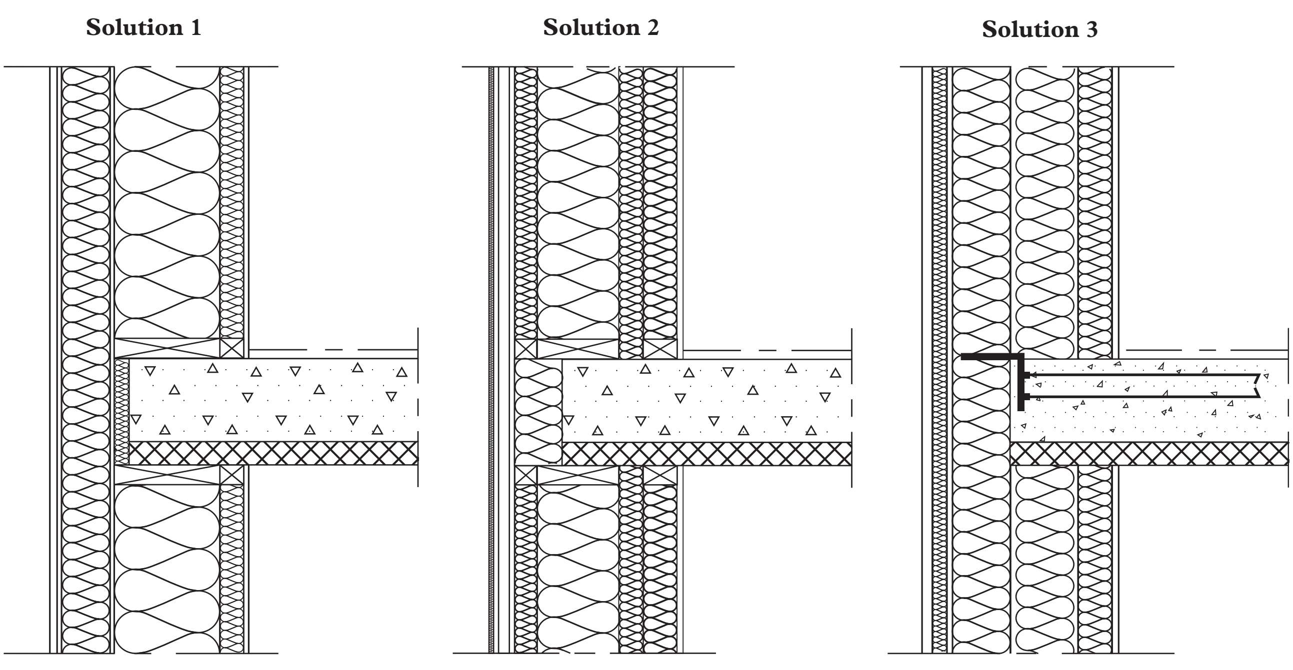

Figure 2 The three suggested wall designs in the 'Beckomberga' project
Note: Solution 3 was the final solution and used in project realization.

concept meant comprehensive documentation, which made it easy to identify similar projects. Six passive house and four 'conventional housing' projects were chosen because of the similarities of building type (multi-family houses), structure design (material and type), and building qualities (passive house standard).

Step 2: Identifying onsite waste and cost drivers

The chosen projects were examined through 15 deep semi-structured interviews that focused on problems and cost drivers in onsite construction. The interviewees were project managers, site managers, foremen and engineers. Documents such as regulations, blueprints, procedures, checklists, and inspection documentation were collected and analysed. Most of the documents from the other projects illustrated the construction itself and not how it should be done in detail. The procedures for inspections were scarce which resulted in insufficient documentation, and thereby did not give adequate input for the DFC evaluation. Onsite observations of how the actual work on site was managed, within all the projects, showed that similar design solutions were crafted in different ways; each craftsman decided how to perform a certain operation in a given situation. The documents and especially the blueprints were just a guide for what to achieve, not how to do it; the skills of the craftsmen thereby affected the amount of material used, operational time and the quality of the final product. The study, conducted 2009–2010, identified 15 types of onsite waste, which were classified into the three categories of product characteristics (Table 2). Although many craft operations were accomplished in different ways, most problems were common for all kinds of housing projects. However, the passive house projects had a lot of additional problems compared to conventional housing, which was due to fragile construction materials.

Step 3: Development of criteria to evaluate constructability

The root cause and effect analysis of the problems in Table 2 showed that some problems generated waste on both operational level and project management level. For example, piles of junk consisting of the same types of broken material indicated problems with fragile materials and solutions, which caused a lot of waste at both operational and managerial level. For operations it created rework, i.e. more time and material was needed; for management it forced rescheduling of the production, delays for subsequent operations, and re-coordination of the supply chain for material on site. Project management tried to avoid problems by keeping a larger stock of material on site, which generated unnecessary transportation of materials and craftsmen, and increased the risk for high inventories at the end of the project.

The development of criteria for evaluation of the building design's constructability and its ability to achieve customer values was based on previous steps. The Beckomberga project group included one construction manager, one architect, two onsite managers, one structural engineer, one installation engineer and one energy engineer. The group gathered to discuss the problems in passive house projects and work out the desired product characteristics. By using 5Why and Ishikawa diagrams the workshop resulted in 29 identified evaluation criteria for the light exterior wall, 23 for the constructability, and 6 for how well the wall design could realize the end-customer values (see Table 3).

Step 4: Evaluation of the building design's performance

The relevance and grade for each evaluation criterion was determined by the Beckomberga project group. The criteria relevance were discussed from the analysis of each criterion in step 3, and included to what extent the criterion affected the production ease, risk of failure and consequences for product quality. In Table 3 the three wall solutions in the Beckomberga project are evaluated and compared; note for example that the relevance of the criterion for fragile material was set to 2. It proved difficult to achieve objectivity in the evaluation process, especially when grading each evaluation criterion, which means that the grading result is rather project specific and cannot easily be compared between projects. Table 3 shows the three wall designs that were iteratively developed without the guidance of DFC. The three designs were subsequently evaluated based on the 29 evaluation criteria (left column), which were developed when using the DFC. It shows that if the DFC method had been used for the Beckomberga project the number of development iterations could have been reduced, that the DFC analysis directs attention to the issues addressed in the iterations, and that the final and constructed wall solution could have been even more buildable.

Discussion

The key to increasing construction efficiency is to capture production experience, feeding it forward and using it during the design, i.e. making implicit production experience explicit (e.g. Chen and Mohamed, 2007; Pathirage *et al.*, 2007). The empirical case study showed that lack of interest in production, little control of processes, and insufficient feedback from onsite experiences to the design phase are obstacles for improvement of the project and production efficiency, which confirms previous results presented by e.g. Lam and Wong (2009). In practice, the architect, design engineers and onsite managers lacked knowledge of exact number of parts, order of assembly, how parts are supposed to be assembled, and how long an onsite operation takes (cf. Bröchner *et al.*, 2002). In fact, not even onsite managers had detailed knowledge of these issues—they only knew that the output of certain operations is dependent on who performs the task, weather conditions and some other circumstances. In reality it was the operating craftsman who decided how to perform a certain operation, thereby affecting the amount of material used, operational time and the quality of the product (cf. Dai *et al.*, 2007). In construction this is a traditional delegation of responsibility (Stinchcombe, 1959), which limits management's ability to control and improve the construction process (Taylor, 1967).

In order to avoid these problems the presented DFC method identifies specific customer values for a project and determines similar projects, step 1. In step 2, typical problems and waste are identified in the chosen similar residential projects. In the studied projects numerous obstacles that were common to all the projects were identified, even though problems with fragile materials were a bigger problem in passive house projects. This confirms the assumption that there are similarities between housing projects described by e.g. Winch (2003), but contradicts Lam *et al.* (2004) who found that critical success factors are often project specific. When the DFC was applied in the Beckomberga project, experiences from six passive house projects and four traditional house projects were used (step 2), which seemed excessive in hindsight. However, an appropriate number of projects to study is difficult to specify and it is probably dependent on specific project characteristics, in particular the complexity of the project. In addition, it is likely that the number of previous projects that need to be assessed will be reduced if generic design rules have been established by using DFC in previous housing projects.

In step 3, the identified problems are classified according to each problem's most obvious inherent attributes, i.e. in the product, production or the management categorization (cf. Table 2). The categorizations should be considered as helping to focus the root cause analysis in order to derive evolution criteria. The analysis should be undertaken by persons with various competencies to analyse the problems from different angles (e.g. Anumba *et al.*, 2007). In step 4 the product design is evaluated as to its ability to satisfy all the developed criteria. An important factor in the evaluation is the relevance of the criteria. Here evaluation is done from a waste creating approach, meaning that a criterion that may create many types of waste or severe negative effects is very important to consider in the design phase (O'Connor and Davies, 1988). In the case study, fragile material caused multiple types of waste in all four categories of product characteristics; the relevance for this criterion was therefore set to 2. As mentioned before, the grading procedure is rather project specific and should therefore be performed in groups consisting of various competencies to reduce bias.

From Table 3 it is apparent that the wall design was improved in practice without utilizing DFC. Nevertheless, if the DFC method had been used the number of iterations could potentially have been reduced and the improvement for production could have been greater. In the studied project, only nine of the 29 criteria were improved after the two design iterations. Most improvements were based on the major differences between passive house and conventional construction, e.g. the improved requirements on moisture safety. When looking at the most important criteria for developing constructability, only three of the eight were improved, and only two of them to the desired level, which is similar to findings described by Lam and Wong (2009). Reasons for this could be the lack of systematic procedures to monitor, evaluate and improve designs from a constructability approach (cf. Meiling and Johnsson, 2008; Bakti *et al.*, 2011). However, this corroborates the first hypothesis: by using the DFC all improvements made by the project design team were identified.

The DFC method could also identify weaknesses in the product design that were not considered by the design team, cf. the second hypothesis. Three examples are:

(1) The final wall design used plastic foil as a moisture barrier that was considered an unacceptably fragile solution from a construction perspective, partly because the material was fragile, and partly because the joints were supposed to be sealed by tape.
(2) The numbers of unique fasteners necessary to assemble the wall on site.
(3) The numbers of parts needed to be assembled.

The last two points are consistent with the DFMA principle that the number of components affects the efficiency of assembly, which in turn impacts on production management. The decision to prefabricate the modules was based on the general perception that prefabricated modules are cheaper to purchase than to produce on site, but no comparison of the production cost was made. Thus, the reduction of parts was in fact an unintended benefit. A better basis for design decisions requires production cost estimation tools, which require detailed production knowledge. In addition to economic incentives, the use of prefabricated modules was also driven by stricter quality requirements and an increased demand for control.

The possibility to generalize these findings is rather limited due to the case study approach; furthermore note that the empirical exemplification did not investigate how the design improvements affected operations on site. Nevertheless, the research indicates interesting results for future development and hypothesis testing. One of the main findings of this study is that the lack of detailed production knowledge in the early phases prohibits improvement of the project's constructability. There are several explanations for this, e.g. that construction is centred on craft-based production (Clarke and Wall, 2000), and that there is a culture of viewing every construction project as unique (Bröchner *et al.*, 2002). Another less obvious but important finding when using experiences from already performed projects for the benefit of new ones is that continuous development in construction companies is not performed within a single project, but between projects. This confirms that the cyclic nature of improvement processes (Jensen, 2005) is also relevant for housing (Roy *et al.*, 2005), and that it can be achieved at project level with the help of DFC as shown in the case study. The most efficient application for DFC would be to apply the method in the development of standardized product models or technical platforms. A standardized technical platform offers repetition (Styhre and Gluch, 2010), which means that the product or solution could be further improved between projects (cf. Construction Industry Institute, 1986; O'Connor *et al.*, 1987). In a similar way Meiling and Sandberg (2009) argue that industrial housing has more to gain from production feedback than conventional housing, due to the differences of standardization and uniqueness of projects between the two production logics. However, this research indicates that many conventional housing projects have similarities and, therefore, have a lot to gain by using DFC.

Conclusion

The limited understanding of how to capture and transfer onsite production experience from already performed projects and use it in the design process of new ones prohibits the improvement of constructability. The presented model 'design for construction' (DFC) provides a way to improve the interactions between the production and the design phases. In the construction literature the value of using experiences and conditions on site has not gained enough interest when aiming for performance improvement and constructability, especially regarding the craftsmen's situation. The foundation of DFC is to identify similar projects and to recognize frequent problems and waste that have occurred on site. The purpose is to correlate new design selections to previous production problems, evaluate and redesign, so that unnecessary waste will not be designed into the next project.

The current findings are limited to a case study of a single housing project; however, it still contributes to the general understanding of improvement management. In practice, the method can facilitate direct improvement of the current project where it is used, and it enables generic production knowledge to be used by designers in future housing developments. The DFC method complements other research studies by emphasizing the importance of the craftsmen's experience, and that it is necessary to consider the experience of the employees at all levels of the organization to improve company competitiveness. The use of DFC indicates that when using experiences from similar and already performed projects for the benefit of new ones, continuous development does not occur within a single project, but between projects.

These findings will serve as a base for future studies. To verify the generality and explore the possibilities of the DFC method, the following issues are critical: (1) identification and use of customer values as a basis for evaluation of the development of desired product characteristics is assumed to be possible and desirable; however, this needs to be verified and further developed; (2) development of an appropriate procedure for waste analyses and translation of waste into criteria that are useful during design; and (3) investigation of how the craftsmen's work is and can be management is imperative for the implementation of DFC.

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