Early Involvement and Integration in Construction Projects: The Benefits of DfX in Elimination of Wastes

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Typical construction processes provide waste: material waste but especially process-related waste. The majority of this waste can be avoided with efficient planning in the front end of projects. The main aim is to describe how the concept of Design for Excellence (DfX) can reduce the most severe waste in construction projects. Based on a literature review of waste and requirements that aid early involvement and integration, we created a survey for analyzing and prioritizing types of waste in the construction industry. We describe how DFX reduces this waste, especially through the use of early involvement and integration. When applied, DfX creates incentives for project stakeholders to eliminate waste automatically through early involvement and integration.

Keywords: design for excellence, lean, waste, early involvement, integration

Introduction

The construction industry has been criticized for very low productivity development compared with other industries (Pekuri, Haapasalo, & Herrala, 2011). Typical construction processes provide waste – material waste but especially process-related waste (Merikallio & Haapasalo, 2009). Process-related waste occurs from activities in the process that do not add value (Womack & Jones, 1996). The majority of this waste can be avoided with efficient planning in the front end of projects.

Construction projects have traditionally been organized in sequential phases in which project tasks follow each other with minimum interaction with other tasks. Project stakeholders participate in other phases only on an as-needed basis resulting in minimal and weak communication. Weak communication leads partially to sub-optimization where work is done mainly to optimize the impact and contribution for the best for one particular participating organization, not for the best for the whole project (Lohikoski & Haapasalo, 2013; Matthews & Howell, 2005).

Early stakeholder involvement and integration have been highlighted as one of the most promising solutions for resolving these waste problems (Aapaoja, Haapasalo, & Söderström, 2013a; Baiden, Price, & Dainty, 2006; Lahdenperä, 2012). This solution has also been mentioned as an essential part of improving productivity in the construction industry in the long run. Integrated project deliveries (IPDs) and relational project delivery agreements (RPDAs) are operating models based specifically on early stakeholder involvement and integration. Contractors, customers, and other stakeholders work together as an integrated, collaborative team in an IPD and RPDA (Ballard, 2008).

Key stakeholders can be addressed in the early phase of a project through the Design for Excellence (DfX) approach. DfX has been applied in the electronics industry in complex product development projects. In DfX, the X stands for an aspect, life-cycle phase, or stakeholder under consideration, such as manufacturing, environment, maintenance, supply chain, and cost (Bralla, 1996; Lehto et al., 2011; Möttönen, Härkönen, Belt, Haapasalo, & Similä, 2009). In DfX, it is important to identify the critical stakeholders (X's) to integrate them early. DfX helps functional integration, creates capability, and acquires the best competence for the project (Ulrich & Eppinger, 2008).

As a more extensive development avenue, the automotive industry has successfully utilized Lean principles for decades, resulting in higher productivity by 15–40% (Bhasin & Burcher, 2006). One of the main avenues of improvement in Lean is to eliminate waste and focus on value creation, early or before waste occurs. Lean thinking has also been applied in the construction industry since the 1990s resulting in a similar type of improvements (Alarcón, Diethelm, Rojo, & Calderón, 2005; Bertelsen, 2004; Sacks, Koskela, Dave, & Owen, 2010).

In this study, based on very versatile and partially miscellaneous background concepts and discussions from different industries (waste, early stakeholder involvement and integration, DfX and Lean), we aim to combine logical reasoning to eliminate waste and then improve productivity in construction. To put it succinctly, *we present the DfX concept as a solution for eliminating the most severe waste in the construction industry.*

The original setup for this research comes from the fragmented and poor productivity construction projects resulting in process waste. From the early stakeholder identification and involvement and eventually integration, we review means for avoiding fragmentation. For these discussions, we aim to present that when applied, DfX automatically forces stakeholders to concentrate on critical issues and prevent waste from occurring. For identifying the most important stakeholders (X), we need to apply discussions from stakeholder management, that is, stakeholder salience. We generated the following research questions:

RQ1 *What are the fundamental requirements for early involvement and integration?*

RQ2 *What are the typical types of waste in construction projects?*

RQ3 *How does DfX respond to these types of waste?*

Literature Review

Waste in the Literature

Lean thinking involves eliminating all waste and focusing on creating value. The automotive industry has successfully utilized Lean principles for years. Lean manufacturing has resulted in increasing productivity in the manufacturing industry by 15–40% (Bhasin & Burcher, 2006). Lean principles have also been successfully applied in the construction industry since the 1990s resulting in similar improvements (Alarcón et al., 2005; Bertelsen, 2004).

Waste was defined by Womack and Jones (1996) as all possible inefficiency resulting from tools, materials, labor, or capital use. Waste includes material loss and cost from unnecessary work resulting in extra cost but no value. Polat and Ballard (2004) observed that waste is everything that does not increase customer value. For customers, this is important because they do not want to pay for activities that do not add value (Liker & Morgan, 2006). Finally, the customer defines what value is and what waste is (Hines, Holweg, & Rich, 2004). Monden (1983) classified process activities into three types: value-adding activities (VAs), non-value-adding but necessary activities (NNVs), and non-value-adding activities (NVAs).

The literature recognizes several waste classifications originating from Ohno's (1988) seven initial types of waste: overproduction, waiting, unnecessary transportation, unnecessary movements, over-processing, inventory, and defects. Formoso, Isatto, and Hirota (1999) revised these classifications to fit the construction industry and added weather conditions, theft, and vandalism. Subsequently, Koskela (2004) added making do and poor constructability (Koskela, 1992), making the wrong product or service (Womack & Jones, 2003), and behavioral waste (Emiliani, 1998). Liker (2004) added people's unused potential, overloading, and unevenness. Cain (2004) proposed other types of waste, such as poor quality of work, poor material management, material waste, non-productive time, suboptimal conditions, and lack of safety. A complete list is compiled in Table 1, where similar types of waste are combined.

Table 1 Types of Waste in the Construction Industry According to the Literature

Type of waste	Authors in the literature	Content in construction
Overproduction	Formoso et al. (1999), Garas, Anis, and El Gammal (2001), Hines and Rich (1997), Liker (2004)	Producing materials, products, or services beyond what is needed or too early, e.g., manufacturing products for inventory
Waiting	Formoso et al. (1999), Garas et al. (2001), Hines and Rich (1997), Liker (2004)	Products or workers have to wait for the next processing step, tool, parts, etc., e.g., because of a machine malfunction
Unnecessary transportation	Formoso et al. (1999), Hines and Rich (1997), Liker (2004)	Transporting materials, parts, tools, or information indirectly to the next working step; e.g., products or materials are moved in and out of inventory between process phases
Inadequate processing	Formoso et al. (1999), Garas et al. (2001), Hines and Rich (1997), Liker (2004)	Ineffective processing caused by unnecessary activities, defective working methods, or poor planning; producing over quality and underutilized capacity
Inventory	Formoso et al. (1999), Garas et al. (2001), Hines and Rich (1997), Liker (2004)	Unnecessary storage of products, materials, or work-in-progress
Unnecessary movements	Formoso et al. (1999), Hines and Rich (1997), Liker (2004)	Unnecessary or inefficient movements made by workers during their job
Defects	Formoso et al. (1999), Garas et al. (2001), Hines and Rich (1997), Liker (2004)	Quality defects, wrong working methods, and needing rework
Making do	Koskela (2004)	Initiating a task without ensuring that all needed prerequisites (materials, workers, information, etc.) are available
Making wrong products or services	Womack and Jones (1996)	A customer's need is not understood, and the wrong product or service is produced for the customer

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Integration

Integration can be seen as a contrast to fragmentation and then an essential part of improving productivity in a project-based industry (Aapaoja et al., 2013a). Organizations, and especially temporary organizations, are open social systems that deal with uncertainty from several sources, where parts of the organization must handle and coordinate problems associated with different tasks and their interdependencies (Tushman & Nadler, 1978). Coordination is an important part of the integration and can be implemented

Table 1 *Continued from the previous page*

People's unused potential	Liker (2004), Macomber and Howell (2004)	Underutilizing people's creativity or skills; workers' ideas and perspectives are not considered
Overloading	Liker (2004)	The workload is too heavy for the worker or machine; it can cause defects and a decrease in safety and quality
Poor constructability	Cain (2004), Lee, Diekmann, Songer, and Brown (1999)	Designing constructs that are difficult or inefficient to build
Inadequate communication and documentation	Alwi (2002), Josephson and Saukkoriipi (2005)	Defective and poor communication, information, or documentation
Safety	Josephson and Saukkoriipi (2005)	Working accidents, poor safety conditions, and dangerous working methods
Other (weather conditions, theft, vandalism)	Formoso et al. (1999), Garas et al. (2001), Josephson and Saukkoriipi (2005)	Waste of any other nature, such as theft, vandalism, or inclement weather

through information systems (Morris, 2013; Thompson, 1967). Then organizations, including temporary organizations, must develop information-processing mechanisms that can be considered integration mechanisms, to deal with external and internal sources of uncertainty.

Uncertainty can exist in the organizational environment, as well as in tasks and task complexity, not to mention time (Mitropoulos & Tatum, 2000; Tushman & Nadler, 1978). According to Turkulainen, Kujala, Artto, and Levitt (2013), organizational task uncertainty can be divided into dimensions: uniqueness, ambiguity, complexity, and dispersion. Several tools and methods can decrease uncertainty, but they must be integrated in the project organizations. Information and communication technology (ICT) systems cannot solve the problems either but can help share explicit knowledge across organizations (Dave & Koskela, 2009).

Integration mechanisms link different parts of an organization to accomplish a collective set of tasks (Van de Ven, Delbecq, & Koenig, 1976). According to Okhuysen and Bechky (2009) and Mintzberg (1989), coordination mechanisms, similar to integration mechanisms, are 'the most essential elements of structure' in organizations, including formal and emergent elements. Information processing systems are part of management systems that aid organizational decision-making by gathering, interpreting, and synthesizing information (Laudon & Laudon, 2010; Tushman & Nadler, 1978). Van de Ven et al. (1976) classified information processing into three distinct modes: impersonal, personal, and group. ICT systems were found for these classes (Laudon & Laudon, 2010). However, integration of these systems is essential. Thompson (1967) identified that coordination mechanisms address various interdependencies (pooled, sequential, and reciprocal) in organizations and vary according to the number of interdependencies (Morris, 2013).

In a classification of integration mechanisms, Mitropoulos and Tatum (2000) presented three types: contractual, organizational, and technological. Contractual mechanisms are typically impersonal plans and formalized rules, policies, and procedures: a blueprint or process for action that project management should commonly specify. Organizational mechanisms, in turn, are organizational charts and written policies and procedures; they may also include personal integration mechanisms. Technological mechanisms frequently contain standardized information and communication systems (Turkulainen et al., 2015; Van de Ven et al., 1976). These mechanisms are most likely dynamic and have a higher level of interdependency in complex projects (Morris, 2013).

Early Involvement

The current method of involving different stakeholders in the construction process varies, typically on an as-needed basis. Similarly, the over-the-wall principle prevails where contribution for the project will be in a unidirectional mode, which leads to a sub-optimization in which the stakeholders aim to optimize their performance (Matthews & Howell, 2005) without properly understanding the effect on others. A concurrent discussion about early involvement typically concerns an IPD or RPDA (Ballard, 2008). This type of relational multi – party contracting challenges the traditional system by contrasting the customer needs and requirements against means and constraints (Figure 1) – alternative methods for accomplishing their needs beyond those they have previously considered and to help clients understand the consequences of their desires (Ballard, 2008). An IPD or RPDA is a procurement model for delivering major projects, where the customer and non-owner stakeholders work together as an integrated, collaborative team. The objective is to work in good faith, acting with integrity and making unanimous, best-for-the-project decisions, by jointly managing all risks of delivering the project delivery, and sharing the outcome of the project (Cohen, 2010; Department of Treasury and Finance, 2006; Lahdenperä, 2012; Thomsen, Darrington, Dunne, & Lichtig, 2009), generating together win-win or lose-lose situations.

'IPD integrates people, systems, business structures and practices into a process that collaboratively harnesses the knowledge and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction' (American Institute of Architects, 2008). Early

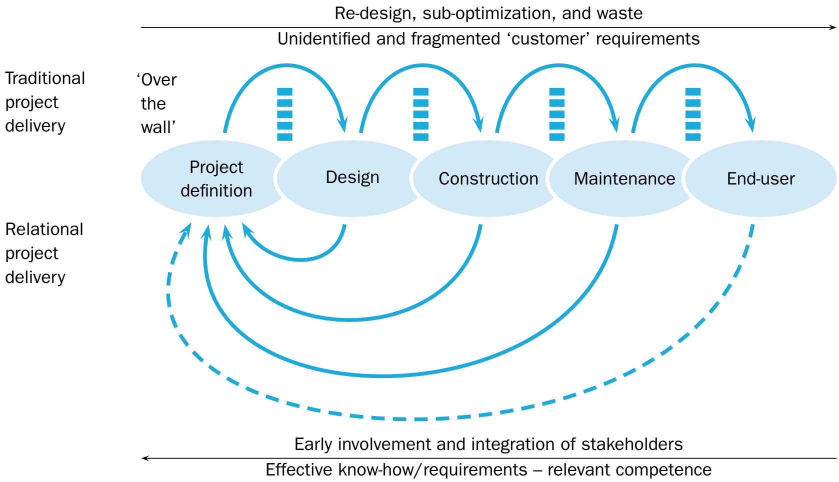

Figure 1 The Ideological Difference between the Traditional As-Needed Basis and Early Integration (Adapted from Aapaoja, Kinnunen, & Haapasalo, 2013b)

stakeholder involvement and integration have been highlighted as one of the most important aims of IPDs (Aapaoja et al., 2013a; Baiden et al., 2006; Lahdenperä, 2012). Handfield, Ragatz, Petersen, & Monczka (1999) emphasized that the more complex the project, the earlier the stakeholders should be involved. Early involvement yields, at least, the following benefits (Dowlatshahi, 1998; van Valkenburg, Lenferink, Nijsten, & Arts, 2008):

- Early knowledge about the end-users leads to greater client satisfaction regarding the product's function and usage.
- Leads to the lower likelihood of developing poor designs, and a higher probability of improved construction operations and less scrap.
- Enables creation of innovative solutions and intensive exchange of ideas.
- Leads to procedures that are synchronized and run in phases.
- The more the stakeholders know about:
  1. the client's or end-users' actual usage of products, the more efficient the stakeholders' operations are regarding meeting the buyer's needs and purposes;
  2. the exact objectives of design specifications, the more the stakeholders can meet or revise those specifications by adjusting its capabilities.

DfX and Stakeholder Management

In the electronics industry, DfX has been applied in complex product development projects (Bralla, 1996; Lehto et al., 2011; Möttönen et al., 2009).

Table 2 Business Benefits Supported in DfX Realization

DfX characteristic	Potential benefit
Cost	Profit in price competitive markets
Quality	Consistent and low defect rates; optimal product performance; reliable products
Services	Effective after-sales service; effective product support and maintenance; customization of products and services; availability of products
Delivery	Fast delivery; on-time delivery; time-to-market
Flexibility	Design changes; rapid volume changes and introduction of new products
Manufacturing	Selection of appropriate processes and materials; appropriate modular design; use of standard components
Supply chain	Optimal lead-time and product diversity
Assembly	Economical assembly; effective parts handling and insertion
Testability	Optimal test coverage; faults revealed and reliability improved; controllability; observability
Environment	Sustainable development; overall environmental impact minimized

Notes Modified from Lehto et al. (2011).

Early involvement and integration can be seen as a necessity from the project success point of view (Aapaoja et al. 2013b; Distanont, Haapasalo, Väänänen, & Lehto, 2012). However, all possible stakeholders cannot be involved early because the number of stakeholders would be too large. DfX is a structured approach to systematically addressing key stakeholders in the early phase of product development, functional integration, and capability creation.

At the permanent organization level, there are few examples of how these X's have been defined and balanced for collective knowledge and contribution in the early phase of product development (Kinnunen, Aapaoja, & Haapasalo, 2014). A comparative study (Aapaoja et al., 2013a) revealed that the construction industry has not utilized collective capabilities, or involved stakeholders, optimally. In principle, comparative X's exist in the construction industry, but the names are different. It then only requires stakeholder analysis for each type of project.

Theoretically, these X's are the most important stakeholders. Bourne (2005) defined a stakeholder as an 'individual or group who have an interest or some aspect of rights or ownership in the project.' Stakeholders can also 'contribute in the form of knowledge or support, or can impact or be affected by the project.' Briefly, they have a stake in the project or the results. Management, or more accurately, 'orchestration,' of these stakeholders involves identifying, analyzing, and planning actions systematically in order to communicate with and impact the process of these stakeholders to aid decision-making in projects (Aaltonen, Kujala, & Oijala, 2004; Donaldson & Preston, 1995; Project Management Institute, 2004). However, it is easy, even in smaller projects, to end up defining tens or even hundreds of stakeholders, and decision-making becomes impossible. Aapaoja and Haapasalo (2014) created a framework for identifying and classifying stakeholders in construction projects. This framework adapted Mitchell, Agle, and Wood's (1997) stakeholder salience (consisting of the attributes legitimacy, urgency, and power) and Olander's (2007) impact and probability matrix to identify the key stakeholders.

DfX includes features of concurrent engineering (CE), such as manufacturing, quality, logistics, assembly, packaging, reliability, service, and so on (Bralla, 1996). Life-cycle considerations are important, because project management commits as much as 70% of the total life-cycle costs of products in the early design stages. One of the main aims of DfX is to reduce costs, but it also provides cost and other information to designers (Anderson, 2006; Asiedu, 1998; Rabino & Wright, 2003). DfX has been seen as a potential means for improving communication and creating capabilities for addressing competitive goals (Lehto et al., 2011; see Table 2).

Requirements for Early Involvement and Integration

IPD, typically applied in complex projects, can be considered an extreme form of inter-organizational integration. The most attractive forms of relational contracting are reducing fragmentation and improving efficiency and performance in complex construction projects (Chen, Zhang, Xie, & Jin, 2012; Davis & Love, 2011). Fragmentation in the construction industry has resulted in adversarial relationships between stakeholders, in the disintegration of the construction process in general, and in deteriorating performance on demanding projects (Jefferies, Brewer, & Gajendran, 2014; Noble, 2007). Some researchers (Chen et al., 2012; Lahdenperä, 2012; Rutten, Dorée, & Halman, 2009) have developed several collaborative project arrangements to improve integration through the early involvement of stakeholders, transparent financials, shared risks and rewards, joint decision making, and agreement. The literature identifies at least three forms of collaborative arrangement: project alliancing (originally in Australia), integrated project delivery (the Integrated Form of Agreement in the United States), and partnering (Lahdenperä, 2012; Walker & Lloyd-Walker, 2015).

Inter-organizational integration is vital for organizations to promote a collaborative culture and improve project performance (Aapaoja & Haapasalo, 2014). Ibrahim, Costello, and Wilkinson (2013) characterized seven key practices for alliance team integration: team leadership, trust, respect, single team focus on project objectives, collective understanding, commitment from the alliance management team, the creation of a unique and co-located alliance team, and the free flow of communication. These practices are very similar those that Aapaoja et al. (2013a) identified as the cornerstones for creating an integrated team.

DfX is a management approach for coordinating design requirements of internal functions and external supply chain partners – stakeholders. Aside from the requirements coordination role, one of the main benefits of DfX is getting requirements on equal terms for the project and its outcome – especially in the beginning of the project. DfX works also as a communication tool to achieve functional (stakeholder) integration and as a compilation to manage requirements (e.g., Lehto et al., 2011). Through DfX a project can discuss on contradictory requirements and avoid mistakes and overlapping in its later phases.

Waste in the Finnish Construction Industry

Research Methodology

This study follows mainly a conceptual research, when it focuses on the concept or theory that explains or describes the phenomenon of DfX and wastes being studied. It, however, has features of an explorative study forming avenues for further research e.g. in the area of stakeholder management related to DfX utilization in construction processes. The role of empirical data is to explain and verify the major wastes to be eliminated with DfX concept.

Our research aims at answering to the research questions presented in the introduction (Figure 2). We first analyzed the literature on waste, especially wastes in the construction industry, to provide specific waste definitions for this industry. Then we reviewed the literature on integration, early involvement, DfX, and stakeholder management to provide insight into the fundamental requirements for early involvement and integration (RQ1). The literature is based on earlier systematic literature reviews in our earlier studies. We have used an integrative approach to combine the aforementioned areas for this study. We have used only the most relevant references to avoid unnecessary extension in the list of references, because the aforementioned areas are somewhat based on different types of literature.

We present the results from a survey carried out to identify and describe the types of waste in construction. On the survey, practitioners were asked to define the most severe types of waste and to rank them by importance. We created a waste priority number (WPN) based on a failure mode effects analysis (FMEA) in order to rank the types of waste, and then applied an analytical hierarchy process (AHP) for pairwise comparison. FMEA relies on identifying potential failures, analyzing root causes, and examining failure impacts so that these effects can be reduced (Abdelgawad & Fayek, 2010). Because of the divergent nature of the different types of waste (e.g., intangible and immeasurable), the types of waste were also ranked with the AHP

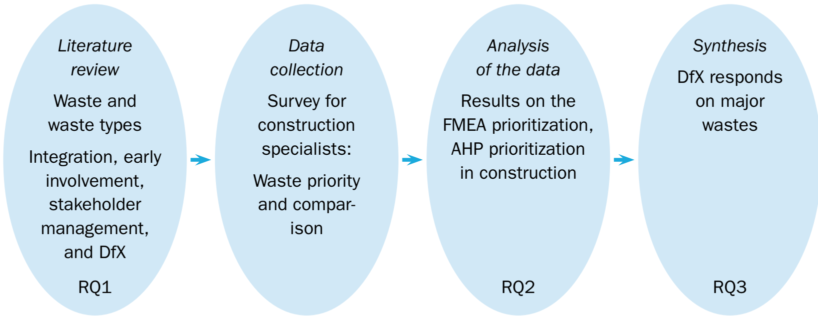

Figure 2 Our Research Process

method (RQ2) to validate the priority and weight of different wastes. The AHP aims to aid in the decision making for problems that involve multiple criteria, entailing a hierarchical formatting of the problem by establishing a pairwise comparison matrix (Saaty, 1980). Finally, we analyze the most severe waste with the benefits of DfX (RQ3).

Data Collection

We deployed a survey among Finnish construction specialists (Table 3) to rank types of waste in the construction industry (Table 1). We applied FMEA for the waste priority number and an analytical hierarchy process (a pairwise comparison). The interviewees' provided data for prioritizing the wastes and answered on pairwise comparison on different waste pairs. We selected the interviewed specialist from the Finnish construction companies representing different roles in the construction process (Table 3). The selected companies were participating in the same development entity and had a good understanding on productivity development in the construction industry. Therefore we had good access to information and a reliable relationship with these specialists.

Data Analysis Method

Traditional FMEA determines a risk priority number (RPN) for the failure modes as a multiplication of severity, occurrence, and detection (Abdelgawad & Fayek, 2010). Instead of the RPN, we created the WPN with the same logic; for simplicity, all three attributes are equally weighted from 1 to 10. Severity means the effect of the waste on the project: the higher the number, the more severe the type of waste in question. Occurrence refers to how often the waste occurs: a value of 10 means continuous occurrence while 1 means a very rare occurrence. The detection means how easily we can identify waste: 10 means that waste is tough to determine, and its root

Table 3 Interviewees' Demographics

Title	Trade	Size of bus. unit	Work experience
Project Engineer	Contractor	4	2
Executive Director	Design	4	3
Executive Director	Project Management	4	5
Account Manager	Design and Maintain	3	3
Consultant	Construction Consultant	1	4
Executive Director	Developer	1	5
Project Manager	Contractor	4	2

Notes Size of business unit (employees): 1 = 0–10, 2 = 10–50, 3 = 50–200, 4 = 200+. Work experience (years): 1 = 0–5, 2 = 6–10, 3 = 10–15, 4 = 15–20, 5 = 20+.

Table 4 Pairwise Comparison Scale Applied in the Interview

Weight	Definition
1	Equal importance
3	Weak importance of one over another
5	Essential or strong importance
7	Substantially higher importance
9	Absolutely higher importance
2, 4, 6, 8	Intermediate values
Reciprocals of above	Reciprocals (1/2 to 1/9) of the above weights can be used when necessary

Notes Adapted from Saaty (1980).

causes and consequences are hard to control within the current system. The WPN increases as the occurrence of this type of waste may have unpredictable and uncontrollable outcomes. A value of 1 means that the waste can be easily identified by individuals or by the existing control system. We collected the data through interviews (Table 3), and every informant gave values for each type of waste and each attribute. During the interviews, informants were able to ask additional specific questions if needed.

In the pairwise comparison, the respondents compared and prioritized two alternatives. This method identifies the extent or ranking of the compared factors. A pairwise comparison included several steps, starting with the construction of the matrix (size $n \times n$, where n is the number of waste). Then the respondents compared two factors in the interview using the relative scale measurement shown in Table 4. Finally, the informants compared each type of waste against the others. The system assigned reciprocals automatically in each pairwise comparison (Al-Subhi Al-Harbi, 2001; Saaty, 1980).

After all the comparisons had been made, the priority vectors (eigenvectors) were calculated: Each element of the matrix was divided by its column

Table 5 Random Index (RI) Values

(a)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
(b)	0	0	0.52	0.88	1.11	1.25	1.34	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.58

Notes (a) size of matrix (*n*), (b) random consistency. Adapted from Alonso & Lamata (2004).

total, and then the priority vector was obtained by finding the row averages. Then, the consistency of the comparison was determined by using the eigenvalue (λmax) to calculate the consistency index (CI), CI = (λmax – n)/(n – 1). After that, the consistency ratio (CR) was calculated by dividing the CR with the appropriate value of the random index (RI; Table 5). If the CR does not exceed 0.10, it is acceptable but, if it is higher than that, the judgment matrix is inconsistent and should be reviewed and improved (Al-Subhi Al-Harbi, 2001; Saaty, 1980).

Waste Priority Number in the Finnish Construction Industry

The final WPN can vary from 1 to 1000 per type of waste. A higher WPN means a more important type of waste; a smaller WPN means that particular waste is less important. The types of waste are presented in the order of the WPNs in Table 6. According to the FMEA prioritization and WPN analysis, the most severe types of waste are inadequate communication and documentation, people's unused potential, defects, making the wrong product or service, and unnecessary movements.

If we think about eliminating waste, detecting it is a major factor. In the WPN, detection has a significant role, and the use of detection in the formula changed the order of some types of waste. Communication and documentation remained number one, while the role of defects, overproduction, making do, and overloading increased. The interviewees saw the importance of different types of waste differently, so there was no direct correlation between the answers. Different roles and responsibilities in projects also revealed slightly different types of waste.

Pairwise Comparison of Types of Waste

In the pairwise comparison, types of waste were compared with each other. There was no clear correlation between different interviewers' answers, and the correlation between the pairwise comparison and the WPN analysis was weak. There was more correlation between the impact factor of the WPN analyses and the pairwise comparison. Inadequate communication and documentation, making the wrong product or service, and defects all were the most severe in both methods.

In Figure 3, there is a pairwise head-to-head comparison of the types of waste. The analysis indicated that poor communication and documentation

Table 6 List of Types of Waste According to the Waste Priority Number

Type of waste	WPN	Severity	Occurrence	Detection
Communication and documentation	328	8.0	7.0	5.9
People's unused potential	251	6.9	5.6	6.6
Defects	238	7.0	7.0	4.9
Making wrong products or services	207	6.9	5.3	5.7
Unnecessary movements	201	4.8	7.3	5.7
Inadequate processing	187	6.0	5.5	5.7
Making do	186	6.4	7.0	4.1
Overloading	176	6.7	6.6	4.0
Poor constructability	152	6.7	5.3	4.3
Overproduction	148	7.1	6.6	3.1
Waiting	146	6.0	5.9	4.1
Unnecessary transportation	144	4.9	7.1	4.1
Safety	51	6.5	2.3	3.3
Inventory	45	4.3	6.2	1.7
Other (weather conditions, theft ...)	30	4.7	4.8	1.3

Notes WPN = severity × occurrence × detection.

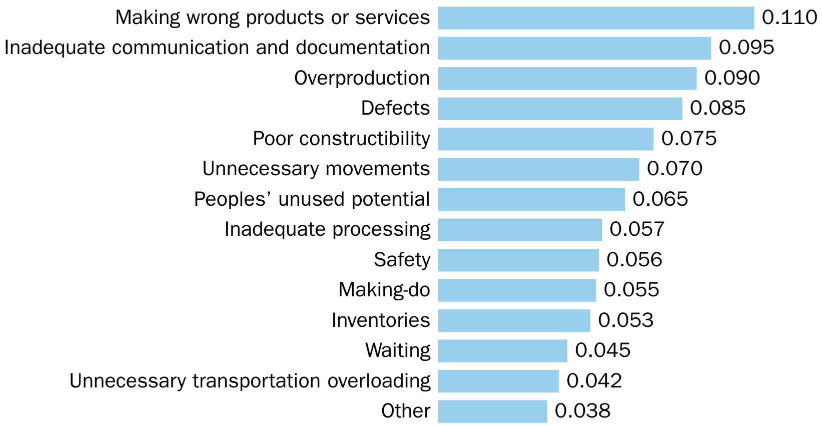

Figure 3 Head-to-Head Pairwise Comparison of Types of Waste

is the most severe type of waste in the construction industry. The main reason is the fragmented nature of the construction industry, and non-material waste should receive more attention.

The two estimation methods led to different rankings of types of waste. Table 6 and Figure 3 show that inadequate communication and documentation, defects, and making the wrong products or services have the best correlation. Both estimation methods ranked these types of waste as among the four most severe types of waste. Likewise, unnecessary transportation, another type of waste, was less essential according to both approaches.

The two estimation methods ranked some types of waste very differently. People's unused potential was the second severe type of waste according to the waste priority number but the seventh in the pairwise comparison. Overproduction was the third most severe using the pairwise comparison but tenth in the waste priority number ranking.

We combined the results of the two methods by adding together the two estimation methods' rankings and arranging the sum numbers from smaller to bigger. The five most severe types of waste are: (1) inadequate communication and documentation; (2) making the wrong products or services; (3) defects; (4) people's unused potential and (5) unnecessary transportation. It is evident that all major types of waste except defects result in waste.

The Use of DfX to Reduce Waste in Construction Projects

Design for X contributes to the early involvement process. Early involvement provides benefits, such as a more efficient design and improved construction operations. When stakeholder needs can be defined early enough, it is easier to plan and design the project and to share the overall objective, scope, and limitations, as well as the features it provides. The project's mission statement can then serve as common understanding for stakeholders. If stakeholders contribute to this document, they are also more committed to it.

Lean principles focus on eliminating all waste and creating value. In the literature review, we listed types of waste and then, in the study, we estimated the importance of each type of waste. As a result of two different analyses, we found the five most severe types of waste: inadequate communication and documentation, making wrong products or services, defects, people's unused potential, and unnecessary transportation. DfX is a tool for managing (originally) design requirements that come from all project stakeholders. With these needs and requirements, and especially early involvement, stakeholders' knowledge and competence can be utilized in the early phase. DfX has a requirements coordination role, but it also receives requirements equally for the project and its outcomes.

In this logic we have not yet specified what are the specific X's – stakeholders. As it is evident that key stakeholders – X's – have to be involved in the beginning, it is yet more important to recognize these stakeholders project specifically. The possibilities of influencing the project success and value creation are perceived as the best during the early phases of the project. Stakeholder involvement is generally project-specific, that is, what works in one situation may not be appropriate in another. Therefore we cannot, yet, propose all relevant stakeholders. It is one of the main tasks of project management to identify, classify and prioritize the stakeholders who are the most salient, and to be able to contribute to the project's success by eliminating wastes.

Inadequate communication and documentation means defective and poor communication, information, or documentation. It was the most severe type of waste according to the waste priority number and the second important one in the pairwise comparison. DfX focuses on documentation in the early involvement process. According to Lehto et al. (2011), there are document systems involved with DfX. Requirements from various stakeholders are collected and documented and then communicated to designers, but also for other stakeholders in the project. Then excuses about 'not knowing' vanish. The proper use of DfX requires better communication between interested parties and an appropriate documentation system of requirements (see e.g. Lehto et al. 2011). The more the stakeholders know about the objectives of the design specifications, the more the stakeholders can work together and adjust specifications (see e.g. Van de Ven et al., 1976; Aapaoja et al., 2013a). Early involvement also allows creative solutions and innovative exchange of ideas. The more the stakeholders know about the customers' or end-users' actual use of the products, the more efficient the stakeholders' operations are regarding meeting the buyers' needs and purposes.

Making wrong products or services occurs when the customers,' or other stakeholders,' needs are not understood, and the customer gets a bad product or service. Project management can use DfX for different purposes. DfX forces or allows designers to contact all the chosen stakeholders during the design phase. In construction projects, project management can collect requirements from all interested parties and balance them using stakeholder salience (see e.g. Aapaoja et al., 2013a; Aapaoja et al., 2013b). 'Requirement' has a negative connotation in the construction industry, but in the information and communication industry, requirement has a positive connotation: If someone sets requirements, he should know what to develop.

Defects typically include quality defects and wrong working methods, which cause rework. DfX gives project managers tools for documenting the required qualities or features of the product for designers and then provides documented guidelines for production to avoid defects. It is possible to discover the defects before the production phase and, thus, the process is scrutinized from the stakeholders' point of view and balanced with stakeholder salience (see e.g. Halttula, Aapaoja & Haapasalo, 2015). Project managers can minimize construction defects if contractors can influence the design work and if they require efficient tools to be used in the design so as to minimize the number of mistakes and rework during the construction phase. Improved communication and documentation decrease defects, and thus prevent poor quality from snowballing further.

People's unused potential takes place when the project underutilizes people's creativity or skills because the project managers do not consider workers' ideas and perspectives. DfX pays attention to all stakeholders' needs, which makes it possible to listen to opinions of larger crowds within the project but does not guarantee that all people participating in the project are using their full capacity nor that they are in a position to give information to the project managers.

Unnecessary transportation means transporting materials, parts, tools, or information indirectly to the next working step. For example, products or materials are moved in and out of the inventory between the process phases. DfX collects the requirements from the stakeholders that the project managers have chosen. It enables planning to consider production requirements so that the production phases and work methods do not generate unnecessary transportation. In the design phase, it is important to include requirements from maintenance operations – a stakeholder. For instance, there has to be enough space for maintenance machines to operate optimally and to care for temporary inventory space for snow in winter maintenance.

Conclusions

In the literature, DfX has been seen as a philosophy that balances all stakeholder needs for 'the best for the project.' It is natural that people should work for the best for the project and think holistically. However, this works optimally only in theory. So where can DfX provide benefit? In practice, limited scope and amount of information cause bias. Cost, quality, and time in the current construction business do not allow automatically 'best for the project' thinking – traditional commercial models drive for sub-optimization (see e.g. Merikallio & Haapasalo, 2009). If we use and further develop DfX as a tool that is part of formal protocols, it is evident that it automatically hits on the most severe types of waste and then improves the project success. Therefore, DfX can eliminate the most severe types of waste in the construction industry.

This study does not specify, what are the specific X's – stakeholders, because stakeholder involvement is project-specific. It is actually one of the main tasks of project management to identify, classify and prioritize the stakeholders in the very beginning of project planning that can be most salient and able to contribute on the project success by eliminating wastes.

DfX is a practical approach that helps project managers include early involvement and integration in the process. According to this study, DfX reduces some of the most severe types of waste in construction projects. The important thing is to make sure that there are incentives for the project to collect the relevant requirements from later phases of the project. If a construction company collects more money from change orders due to design mistakes instead of trying to avoid them, there is something wrong, in the sense of sustainable long-term business.

Relational project delivery agreements include incentives for balanced gain and pain. It is also possible in a traditional design-bid-build project to provide incentives that support the proper use of Design for X in construction projects. DfX supports early involvement and integration, because it forces stakeholders to communicate but also documents when things become more explicit. Project managers can study the stakeholder salience and balance the requirements in DfX so that the best work is performed for the project.

However, the construction industry is still in the early phase of genuinely applying integration. We have only slightly opened up the possibilities of DfX in early involvement; clearly, more development is required, and additional practical applications of DfX must be defined. It is the responsibility of the following studies to outline who really these most salient stakeholders are – not only those generic ones that have been typically defined in national norms and standards.

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