Using FMEA and AHP methods to prioritise waste types in construction

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Summary

The construction industry sustains poor productivity, primarily because of the large quantities of waste generated during projects. Lean construction is considered to be an answer for better performance and from many industries the link between higher productivity and using lean practices have already been documented. The purpose of lean is to maximise the value to the customer and eliminate all non-value adding activities, otherwise known as waste. This study focuses on waste and its prioritisation. A literature review was carried out to define and classify different waste types relevant to construction. Then, a survey was made for seven Finnish construction practitioners to prioritise different waste types that occur in the construction industry. Failure mode effects analysis (FMEA) and an analytical hierarchy process (AHP), i.e. pairwise comparison, were applied to prioritise different waste types. Results show that poor communication and documentation is the most critical waste type in construction while non-physical wastes in general should be paid more attention to as they have similar negative impacts as traditional waste types but are more difficult to notice.

Keywords: Failure mode and effect analysis, FMEA, analytical hierarchy process, AHP, pairwise comparison, waste, prioritisation, lean construction.

1. Introduction

In Finland, as in many other countries, construction sustains poor productivity. Labour productivity in the Finnish construction industry has improved since the mid-1970s by approximately 0.5–1% per year [1,2]. Ineffective management practices, the growing emergence of subcontracting, and the lack of benchmarking are the factors affecting productivity [3]. The construction industry has a large impact on the Finnish economy, and improvement in construction industry performance would, therefore, have a major economic impact [1].

The concept of lean thinking has been successfully utilised in the manufacturing industry for many years. Lean manufacturing and higher productivity have been documented as being clearly linked, and lean manufacturing has been estimated to improve productivity by 15–40% [4]. Since the 1990s, lean thinking has been successfully applied in the construction industry [5]. Alarcon et al. [6] reported a 7–48% performance improvement after lean implementation in construction companies, while Forbes and Ahmed [7] also described cases of successful lean implementation.

The main purpose of lean thinking is to maximise value to a customer and eliminate all non-value adding activities, which are called ‘waste’. Lean thinking is a broad topic, so this study focused on waste elimination because of the large quantities of construction wastes; these are estimated to be between 30–70% of all activities depending on surveys [1,8–11]. A wasteful activity can cause many problems, such as schedule delays and cost overruns [12], so there is a considerable value to be gained by reducing the levels of wasteful activity. It is also a way to increase value generation for customers and to gain competitive advantage over competitors [13].

The concept of waste is reportedly not well understood by construction personnel [14,15], and this has led to problems in identifying and eliminating wastes. The main problem, in general, is the failure to recognise what constitutes waste [11] because there are no systematic [16] or adequate [17] measurement practices. Waste elimination is a main focal point on a daily basis in lean production. However, the waste elimination process is often misunderstood and is used only at the production level, without understanding the comprehensiveness of lean philosophy. Hence, there is a need to clarify the role of waste elimination in lean production.

Waste classification and prioritisation are important in identifying and eliminating wastes. Classification helps in recognising the different waste types, whereas prioritisation denotes the importance and ranking of waste types. This is important so that resources can be allocated appropriately, thus reducing the most remarkable wastes. Generally, resources are limited so focusing on the most important waste types is essential.

The main objective of this paper is to classify and prioritise wastes in the construction industry. In order to attain this objective, the following research questions must be answered:

- What is the classification of different waste types in construction?
- How waste types can be prioritised and what are the most important waste types in construction?

A literature review was carried out to define wastes and to describe the waste elimination process. Wastes were then classified based on information in the literature and previous studies of waste. Practitioners from various kinds of construction companies were then empirically surveyed in order to prioritise construction wastes and to obtain a comprehensive understanding of the matter. Finally, the results were analysed and their implications discussed briefly before concluding the paper.

2. Wastes in construction

Productivity, waste, and value are interdependent [18]. Productivity is often defined as a relationship between the output produced by a system and the quantities of input factors utilised by the system to produce that output. It is also closely related to the use and availability of resources as well as to value creation [2]. Therefore, it is possible to increase productivity by utilising resources, such as material and labour, more efficiently. Eliminating waste is a way to improve efficiency of resource usage. In lean value is defined through the customer. Value is what the customer wants, and a value-adding activity converts material or information to products or services needed by the customer [7].

In lean thinking, waste is linked to the term ‘a non-value adding activity’. However, it is difficult to identify waste if the value to the customer is unknown [19]. Womack and Jones [20] define waste as ‘any activity, which absorbs resources but creates no value’. More specifically, waste is any inefficiency that results in the use of equipment, materials, labour, or capital in larger quantities than those considered as necessary [21]. It also includes additional costs caused by both material losses and unnecessary work [22]. Monden [23] classified an organisation’s activities into three types:

- value adding activities
- non-value adding but necessary activities
- non-value adding activities.

The waste elimination process (Figure 1) consists of phases and support activities. The process starts with acknowledging waste and establishing a control system for measuring and identifying it. The idea of lean is to make waste visible, for example, by creating continuous material and information flows when waste and problems cannot hide in inventories. Instead, any stoppage on flow is a signal of emerged waste. However, making waste visible is the most challenging phase in waste removal because construction personnel generally fail to recognise it [11]. In addition, waste identification has not usually been systematically carried out in construction which further hinders its reduction [16].

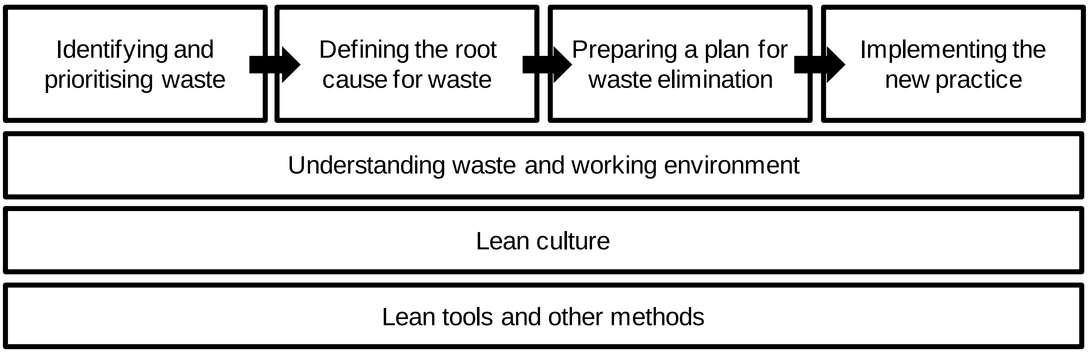

Figure 1. The waste elimination process.

In the following phase, waste can be identified by measuring or through expertise of individuals. Developing a systematic waste measurement system is important, because some of the wastes are not easily observable. The identification of wastes, analysing their causes, and measuring their level of importance provide useful information that allow management to act to reduce their negative effects in advance [14]. Yet, tools must always be selected to fit the problem at hand and the working environment they are used. The difficulty of waste elimination is that same problems tend to continually appear, which indicates that the root causes are not understood well enough [27]. Thus, it is important to identify the real causes of waste instead of just eliminating visible problem with obvious, but often non-optimal, solution. Only by eliminating the root cause can the visible problem be permanently removed.

Following completion of a root cause analysis, a waste elimination plan is prepared. There lean advocates obey consensus based decision making where different options and viewpoints are thoroughly considered before rapid implementation. To avoid making the same mistakes again and to make the improvement permanent, the new solution and working methods should also be standardised. This contributes to the building of a (lean) culture where problem solving and waste elimination become inherent to all employees.

Although lean tools can be used in many phases in the process, selecting and using the right tools for the given situation remains the most essential thing. Actually, the whole waste elimination process should always be formulated with the understanding of lean culture and methods, the type of waste and its impacts, and the working environment. For waste elimination to be successful, lean thinking must be adapted at the strategic level in a company's management to understand and define customer value, and waste elimination must be institutionalised on an operational level [28]. This contributes to a complete strategy where waste elimination is not an isolated activity.

2.1 Waste classification

Wastes can be classified in different ways. One well-known classification is Ohno's seven wastes: overproduction, waiting, unnecessary transportation, unnecessary movements, overprocessing, inventories, and defects [24]. Formoso et al. [21] revised these seven wastes to fit the construction industry. They also included weather conditions, theft, and vandalism. Subsequently, additional waste types have been proposed, such as making-do [18], poor constructability [22], making the wrong product or service [20], and behavioural waste [27]. Liker [25] mentioned unused peoples' potential, overloading, and unevenness as waste types. Cain [29] proposed waste types, such as poor quality of work, poor material management, material waste, non-productive time, suboptimal conditions, and lack of safety. Inadequate methods [26], systems and structures [10], documentation [14], and inadequate information [30] have also been identified as waste types.

As a result of the literature review a classification with 15 waste types were made (Table 1). Some similar waste types were combined into one, which was perceived in waste definitions.

Table 1. Waste types in the construction industry.

Waste type	Definition
Overproduction	Producing material, products, or services beyond what is needed or too early, e.g. manufacturing products to an inventory [21]
Making wrong products or services	A customer's need is not understood and the wrong product or service is produced for the customer [20]
Unnecessary transportation	Transporting material, parts, tools, or information indirectly to the next working step, e.g. products or material are moved in and out of inventory between process phases [21]
Inadequate processing	Ineffective processing caused by unnecessary activities, defective working methods, or poor planning; producing overquality and underutilised capacity [21]
Inventories	Unnecessary storage of products, material, or work-in-progress [21]
Unnecessary movements	Unnecessary or inefficient movements made by workers during their job [21]
Defects	Includes quality defects, wrong working methods, and needing rework [21]
Making-do	Initiating a task without ensuring that all needed perquisites (material, workers, information…) are available [18]
Waiting	Products or workers have to wait for the next processing step, tool, parts, etc., e.g. because of a machine malfunction [21]
Overloading	Workload is too heavy for the worker or machine. This can cause defects and a decrease in safety and quality [25]
Poor constructability	Designing constructions that are difficult or inefficient to build [22]
Communication and documentation	Defective and poor communication, information, or documentation [14,30]
Safety	Working accidents, poor safety conditions, and dangerous working methods [10]
Peoples' unused potential	Underutilising peoples' creativity or skills. Workers' ideas and perspectives are not considered [25]
Other (weather conditions, theft, vandalism)	Waste of any other nature, such as theft, vandalism, or inclement weather [21]

3. Research methodology

A survey was carried out to identify the most important waste types in construction. From the literature review, 15 different waste types were identified and included in the survey. In the survey, practitioners were asked to rank waste types by importance. Because of the divergent nature of the different waste types (e.g. intangible and immeasurable waste types), the ranking was made by prioritising waste types as described below.

Two methods were used for prioritisation: failure mode effects analysis (FMEA) to calculate the waste priority number (WPN) and an analytical hierarchy process (AHP). FMEA is a technique based on identifying potential failures, analysing root causes, and examining failure impacts so that these impacts can be reduced [31].The AHP was established to aid in decision making for problems that involve multiple criteria [32]. Applying this concept entails a hierarchical formatting of the problem – establishing a pairwise comparison matrix in accordance with a pairwise comparison scale.

Within the context of the traditional FMEA, the degree of criticality of a failure mode is determined by calculating the risk priority number [31]. In WPN analysis, the idea is to evaluate the impact, frequency, and perceptivity of waste types by using a value from 1 to 10 and to multiply these values among the types. The WPN then illustrates the importance of the waste type. Impact refers to the effect of the waste in the operation, and the higher the number, the greater the impact. Frequency means how often the waste occurs; a value of 10 means continuous occurrence while 1 is very rarely occurs. Perceptivity refers to how easily waste can be identified; 10 means that waste is very difficult to identify and its root causes and consequences are hard to control within the current system. WPN is thus increased as occurrence of this kind of waste may have unpredictable and uncontrollable outcomes. A value of 1 means that waste can be easily identified by individuals or by the existing controlling system.

In the pairwise comparison, the respondents are forced to prioritise between two alternatives. By comparing factors, it is possible to identify the extent or ranking of the compared factors. A pairwise comparison includes several steps, starting with the construction of the matrix (size n × n). Then the respondent compares two factors at once by using the relative scale measurement shown in Table 2. Each alternative is matched one-on-one with each of the other alternatives. Reciprocals are automatically assigned in each pairwise comparison [32,33].

Table 2. Pairwise comparison scale [32]

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 … 1/9) of the above weights can be used when necessary.

When all of the pairwise comparisons are made, the priority vectors (eigenvectors) can be calculated as follows: each element of the matrix is divided by its column total and then the priority vector can be obtained by finding the row averages. After that, the consistency of comparison is determined by using the eigenvalue (λmax) to calculate the consistency index (CI), CI = (λmax – n)/(n – 1). After that, the consistency ratio (CR) can be calculated by dividing CR with the appropriate value of the random index (RI), which is listed in Table 3. If CR does not exceed 0.10, it is acceptable, but if it is more than that, the judgment matrix is inconsistent and should be reviewed and improved [32,33].

Table 3. Random index (RI) values [34]

Size of matrix (n)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Random consistency	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.58

Data were collected from seven interviews made during spring 2012. All of the interviewees worked at the managerial level in different construction companies (see Table 4). To obtain an inclusive overview of construction's wastes, interviewees were selected from different kinds of construction companies.

Table 4. Information of interviewees

Title	**Trade**	**Size of business 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

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+

4. Waste priority in construction

4.1 Waste priority number

The results of the WPN analysis are presented in Table 5. Values of waste types are the averages of interviewees' answers. Communication and documentation, peoples' unused potential, defects, making the wrong product or service, and unnecessary movements are ranked the most important waste types.

Table 5. Results of the WPN analysis

Waste type	WPN	Impact	Frequency	Perceptivity
Communication and documentation	**328**	8.0	7.0	5.9
Peoples' 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
Inventories	**45**	4.3	6.2	1.7
Other (weather conditions, theft, vandalism)	**30**	4.7	4.8	1.3

Communication and documentation waste was the most important waste type. The interviewees described that type of waste as a basic reason for other wastes. Its impact was clearly highest, frequency third highest, and perceptivity second most difficult. The second most important waste type was peoples' unused potential which perceptivity was clearly the highest. In addition, the results showed a high frequency of unnecessary movement of both workers and material, but only a moderate impact of this type of waste made it less important than other wastes addressed above.

Often waste types are prioritised by impact and frequency. If ranked in this way, communication and documentation would remain at the top, but defects, overproduction, making-do, and overloading would all increase their importance. With respect to WPN, these waste types are in the middle of the rankings. This is caused by a low perceptivity value. In these circumstances, evaluation of perceptivity brings a new dimension to waste prioritisation. It is also a very important factor in the waste elimination process.

In the total averages, the average perceptivity (4.3) was lower than the averages of impact (6.2) and frequency (6.0). Perceptivity of wastes, therefore, is seen to be relatively easy. It could be that the interviewees knew about lean and were aware of large quantities of waste in construction.

There was no clear correlation in the interviewees' results. For example, in every result the most important waste type was different. This probably is a result of the interviewees' different activity fields. For example, design and construction have different situations with respect to safety, inventory, etc.

4.2 Pairwise comparison

Figure 2 presents the prioritisation of wastes made by pairwise comparison and shows the average of interviewees' answers. Presented values are relative weights and indicate the relation to other wastes. The most important wastes were making the wrong product or service, communication and documentation, overproduction, and defects.

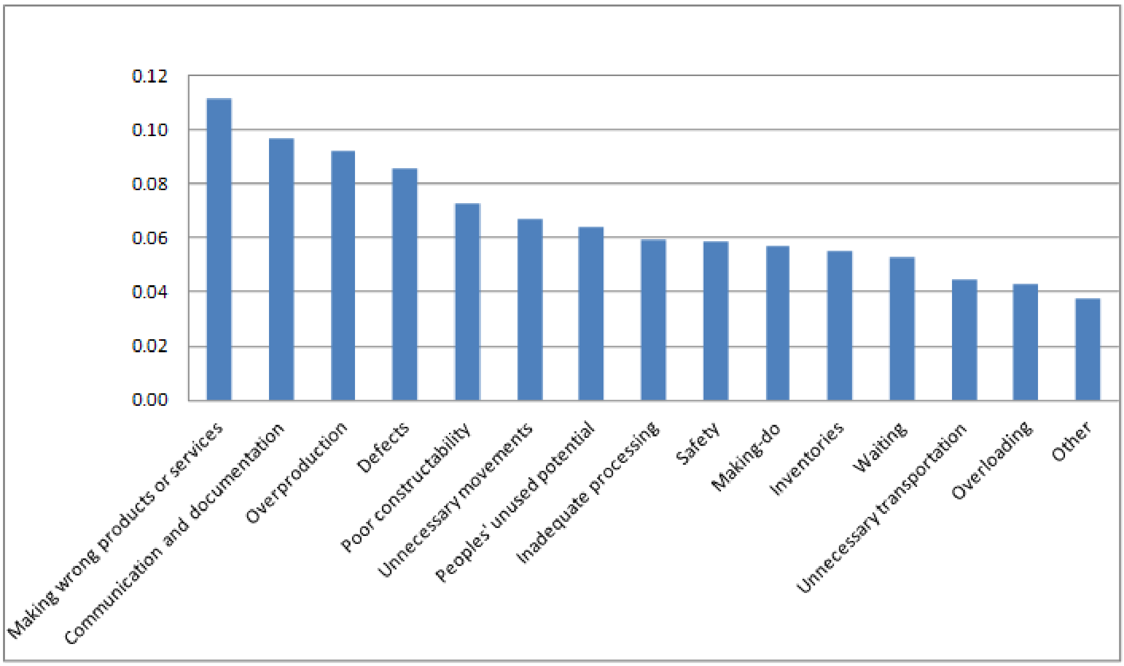

Figure 2. Results of pairwise comparison

There was no clear correlation in the results with the WPN analysis. Communication and documentation, making the wrong product or service, and defects rated highest with both methods. Overproduction and peoples' unused potential had the greatest difference in the top-ranked waste types. Overproduction was third highest in the pairwise comparison but ranked only tenth in the WPN analysis. Peoples' unused potential was second highest in the WPN analysis but seventh in the pairwise comparison.

Notably, the results of the pairwise comparison correlated more with the impact of the WPN analysis than the WPN itself. The pairwise comparison was made after the WPN analysis, and it is possible that its results affected the pairwise comparison. Interviewees' responses had no correlations with each other in the pairwise comparison or in the WPN analysis, which is probably due to the interviewees' different activity fields and different perceptions of waste.

5. Discussion

There is obviously a significant amount of non-physical waste in the construction industry. Often waste identification and elimination concentrate on physical waste like wasted or deteriorated materials or some of Ohno's seven waste types. The results show that concentrating on eliminating these seven waste types is not sufficient because the top five results included only two of those waste types. This study highlights that intangible wastes, such as communication and documentation and peoples' unused potential, need to be taken into consideration.

Interviewees noted that communication and documentation were defective. Communication was mentioned as also being a basic cause of other wastes. The construction industry is fragmented, and increasing collaboration could improve communication. One interviewee said that communication and documentation are ´no one's possession´ and therefore are not controlled.

Identifying waste is the most critical part in the waste elimination process because waste that is not seen cannot be eliminated. According to the WPN analysis, waste perception was considered to be easier than difficult (average 4.3). For example, the averages of impact and frequency were 6.2 and 6.0, respectively. Evaluation of perceptivity is challenging because it is relative and depends on the assessor. Therefore, independent and reliable data about perceptivity are difficult to obtain compared to measuring an impact or frequency using time or a monetary value.

The CR values of pairwise comparison, which measure the consistency of results, were over 0.10 in every interviewee's responses. Therefore, results of pairwise comparisons must be critically evaluated. If CR exceeds 0.10, it means answers are inconsistent. Saaty [32] noted that reviews and improvement are needed to improve consistency between answers if CR exceeds 0.10.

6. Conclusion

The construction industry suffers from a large amount of waste. Lean thinking provides an opportunity to reduce waste and improve productivity. This study concentrates on waste elimination and prioritisation in the construction industry. It also provides useful information in waste identification and elimination. Waste elimination is a process that includes acknowledging, identifying and prioritising waste, defining its root cause, and eliminating it. Waste elimination should not be an isolated technique but an inherent activity in daily operations.

In this study, a classification with definitions for 15 waste types, that were regarded central for construction, was made. In addition, a prioritisation was made for these waste types by applying FMEA to calculate WPN for each as well as by pairwise comparison. Results show that the most important waste type is communication and documentation, which stands out with both prioritisation methods. The study also highlights other intangible but important wastes, such as people's unused potential, that should be paid even more attention to than traditional waste types.

This research has some limitations. The sample was small and inconsistencies were registered in the results from pairwise comparison. Future research should include a more extensive collection of data and iterations to achieve consistency. Interviewees in this study worked at the managerial level, so a comparative survey could be made using workman and masters. Also, a study of communication and documentation problems and their reasons would be valuable.

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