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Development of a knowledge-based tool for waste management of prefabricated steel structure projects

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Highlights

- The process model for material waste management in prefabricated steel structure projects is developed.
- A knowledge-based material waste management tool is developed as a web-based tool.
- The tool integrates three material waste management mechanisms, namely waste estimation, waste monitoring, and waste analyzing.
- A similarity assessment method was used to estimate material waste and monitor material waste management performance of an ongoing project by comparing it with the previous projects.
- The tool is validated by five professionals from three construction companies.

Abstract

Although the construction industry is critical for sustainability goals due to the high amount of waste it generates, its waste management performance is still not at the desired level. One of the main reasons for this can be attributed to the lack of enough knowledge of construction companies on the sources/reasons of waste and amount of waste. The major aim of this study was to develop a knowledge-based tool for capturing, storing, and disseminating waste-related knowledge for prefabricated steel construction projects. The developed tool can be used for waste estimation, monitoring, and minimization of all materials used during different phases of prefabricated steel structure projects based on the data captured from current and previous projects. One advantage of the tool is the integration of all processes of waste management, which have been usually considered independently in previous studies. Moreover, being a knowledge-based tool, it can increase awareness and learning ability of

companies about waste and its management. Finally, although the process model of the tool is generic and can operate in alternative domains, the tool is applicable for only prefabricated steel projects. It is believed that the process model and the tool presented in this paper can be further customized for different project types and considering different company needs.

Keywords: Knowledge-based waste management tool, prefabricated steel structure projects, construction industry, Material waste, Web-based tool.

1. Introduction

The construction industry is one of the most prominent sources of waste generation worldwide since it consumes the utmost portion of natural resources and generates an exorbitant amount of landfill waste (Ajayi et al., 2016; Guerra et al., 2020). Therefore, effective waste management in construction projects is critical to achieving sustainable development goals. However, the construction industry usually manages the waste by dumping it in landfills, which is not an effective method for eliminating the detrimental effects of waste on the environment (Lu et al., 2011; Magdalena Daria Vaverková, 2019). Besides, because of limited landfilling areas, the governments demand landfill tax from the companies. This demand leads to an extra cost burden for the construction companies. According to Osmani (2012), the annual landfill cost for construction companies is approximately £200 million. Therefore, construction companies should move towards different waste management strategies. For instance, waste minimization that aims to reduce the waste generation at source by identifying the root causes and improve the current processes and practices can meet the needs of construction companies. Unfortunately, construction companies are still struggling to achieve this transition due to the construction companies' culture, lack of waste management plans, lack of waste management methods, and lack of waste management tools (Ajayi et al., 2016; Udawatta et al., 2018; Yuan, 2013). It is especially advocated that waste management tools have a critical role in achieving this change (Akinade et al., 2016).

One of the main reasons for waste generation in construction projects is material waste (Formoso et al., 2002). It is estimated that construction material waste accounts for about 30% of the total weight of building materials delivered to a standard construction site (Osmani, 2012). Material wastes lead to 21% to 30% of cost overruns in construction projects (Yu et al., 2013). These overruns lead to loss of profit and competitive advantage for contractors (Arijeloye and Akinradewo, 2016). Material waste is also considered a vital source of low productivity in projects (Bell and Stukhart, 1987). Unfortunately, each year, the amount of material waste in construction projects increases due to the increase in the standard of living, increase in population, and the complexity of design (Saka et al., 2019). Therefore, construction companies should develop strategies and implement tools to minimize material waste in their projects.

Although prefabrication is considered a momentous remedy for minimizing waste in construction (Jaillon et al., 2009; Tam and Hao, 2014), a considerable amount of waste is still generated during prefabrication (Cao et al., 2015). For instance, including most of the construction materials such as concrete, steel reinforcement, formwork, and brick/block (Tam and Hao, 2014), only a 52% reduction in average waste rates is achieved in prefabricated projects (Jaillon et al., 2009). In fact, Lu et al. (2021) determined an overall reduction amount as only 15.38%, which is much less than expected, by evaluating 114 sizeable high-rise building projects in Hong Kong. Consequently, prefabrication is not a magic wand that can eliminate all wastes that emerged in construction projects. In fact, some materials specific to prefabricated construction projects can be more hazardous to the environment than the on-site construction projects because of the chemical composites of these materials (Mirshekarlou et al., 2018). On this account, material waste management is still critical in these projects, even it can be more fundamental than the on-site projects when permanent effects of materials in prefabricated construction on the environment are considered.

Knowledge on waste is critical for managing waste, yet obtaining appropriate data is challenging, as they are scattered across different data sources (Bilal et al., 2017). Besides, most of the existing waste management software consider construction waste as mixed waste. Therefore, waste data is not managed effectively in most of the construction projects (Bilal et al., 2016). Meanwhile, using data and knowledge obtained from past projects is an effective method for confronting problems since the same setbacks seen in one project are likely to re-occur in other projects until an appropriate solution is implemented (Eken et al., 2015). Also, by applying effective knowledge management in waste management, the companies can become innovative organizations that realize the sustainability principles by adopting appropriate measures that represent sustainability objectives (Robinson et al., 2006). However, knowledge management is not at the desired level in the context of sustainability (Martins et al., 2019). Besides, construction companies are criticized because of their low capability of capturing, storing, and disseminating knowledge (Eken et al., 2020; Tan et al., 2007). Also, one problem that construction companies confront in waste management is data efficiency (Hobbs et al., 2011). Akinade et al. (2018) asserted that the construction waste data cannot estimate waste accurately because of the location-specific data and lack of detailed material information. Therefore, detailed material waste information that emerged in different projects should be captured for estimating the waste accurately in forthcoming projects. That being the case, capturing the knowledge related to waste and using this knowledge for mitigating the negative effects of waste and preventing waste generation at the source is crucial in construction projects.

Based on these gaps, this study aims to develop a knowledge-based material waste management tool for prefabricated steel construction projects. This tool can be used for waste assessment, waste monitoring, and waste controlling. The other function of this tool is capturing, storing, and retrieving the waste knowledge, which is crucial for managing waste.

First, findings of a literature review about the existing waste management tools presented in the construction management domain will be provided. This review will appear under the section "Research background and motivation". Later, the research methodology will be explained. Second, a generic process model which integrates the processes of waste management will be elaborated. Then, the development process of a web-based waste management tool based on the proposed generic model will be given. Finally, findings from testing and validation of the tool in terms of functionality and applicability in a case company will be presented, followed by the conclusions.

2. Research background and motivation

There are many efforts for the development of waste management tools in the literature. Akinade et al. (2016) classified these studies under five categories, namely waste management plan templates, waste data collection and audit tools, waste quantification, waste prediction tool, and geographic information system enabled waste tools. Also, they identified 32 waste management tools and evaluated all these tools by using 40 criteria that they proposed. Based on this evaluation, they detected that all these tools are developed for performing specific functions. In other words, although there are studies that focus on waste data collection, most of them do not have any capability to use this data for waste quantification, waste prediction, and waste management performance monitoring. Likewise, others that satisfy the criteria required to perform waste quantification and prediction are not providing solutions for capturing, storing, and recalling the data necessary for waste estimation. Akinade et al. (2018) proposed five limitations that exist in waste management tools. These limitations are (i) the existing tools do not consider the design process, (ii) they have limited interoperability capabilities, (iii) waste data are insufficient, (iv) the responsibilities in the waste tool are not declared clearly, and (v) life cycle waste performance is not assessed appropriately.

In recent years, there have been efforts to use building information modeling (BIM) for waste management. Porwal and Hewage (2012) used BIM for disseminating project information among all design teams. The developed BIM-based tool can be used for performing optimization analyses to minimize reinforcement waste. Cheng and Ma (2013) developed a BIM-based system that can be used for estimating and planning the demolition and renovation waste. Wang et al. (2018) proposed a conceptual framework that integrates the life cycle assessment and BIM for quantifying the carbon emission of building demolition waste. Jayasinghe and Waldmann (2020) developed a BIM-based Web tool with the ability to quantify the waste to disposal amount, reuse amount, and recycling amount based on the developed BIM model. The required data for the system can be extracted from the model, which has recyclability and reusability information for each component. This system provides a material and component bank. Akinade and Oyedele (2019) developed a BIM-based tool for waste prediction in the construction supply chain based on Adaptive Neuro-Fuzzy Interference System, besides the tool-generated waste-related reports throughout the project life cycle. In all these studies, the information should be available and embedded in the BIM model. Thus, their systems capture the required information from the BIM model developed for the project. In other words, information readiness is a crucial prerequisite for implementing these studies (Lu et al., 2017). However, they do not provide any mechanism for satisfying the information readiness and assume that the information has already been inserted into the model at the design stage. Contrarily, there should be systematic approaches to capture and store the accurate waste data to use these systems since, as stated by Cheng and Ma (2013), accurate data is required to apply BIM effectively for waste management. Therefore, the accurate knowledge should be firstly captured and stored in BIM based waste management. Capturing knowledge is not a straightforward process since a significant amount of knowledge that emerged throughout the projects is in tacit form. In other words, this knowledge is vastly rooted in an individual's mind and experiences. Therefore, most of the time, the practitioners are not consciously aware of the existence of this knowledge. Besides, the tacit knowledge should be converted to organizational knowledge in the construction industry to avoid losing this knowledge because of the frequent project and team changes (Mohd Zin and Egbu, 2009). For capturing, storing, and sharing information, tools play critical roles (Argote, 2012). Therefore, different tools for collecting waste data are also developed in the literature. However, none of these tools provide detailed information that considers all aspects (Gupta et al., 2020). To achieve information readiness, there have been some efforts that integrate information systems and BIM. Akinade et al. (2016) proposed a holistic BIM framework that aims to organize waste knowledge at the design stage. In their framework, the data layer, which is one of the important components is used for capturing and sharing the knowledge. This data layer captures the design information according to the five design principles proposed by WRAP (2009). Xu et al. (2019) developed a construction and demolition waste information management system for quantifying and reducing greenhouse gas. However, they only focused on the quantification of greenhouse gas, and they used BIM for storing the waste information of a specific project. Therefore, the developed system does not provide any mechanism for retrieving the knowledge acquired from different projects. Although there are advancements in the applications of digital technologies in recent years, these efforts in waste quantification, control, monitoring, and overall management are not at the desired level (Jin et al., 2019).

There are different methods for collecting waste data from construction projects, such as direct observation, questionnaire survey, sorting and weighing the waste materials on-site, and indirect observation via employees (Lu et al., 2018). Hu et al. (2021) proposed a five-step on-site measurement strategy for construction waste generation. They used the collected data based on this strategy for performing waste estimation using an SVM-based prediction model. In reverse, some researchers tried to provide the required information directly. For instance, Bilal et al. (2017) stated that to perform a waste analysis, the specific material should be available. They developed a repository using a resource description framework and web ontology language to provide this data to the researchers. Similarly, Bilal et al. (2016) proposed a conceptual big data architecture for construction waste analytics, and they claimed that big data technologies are necessary for performing waste analytics since performing these analytics requires large and complex datasets which cannot be handled using traditional technologies. However, because of the costly and disruptive structure of these methods, they are not widely and effectively used in construction projects (Lu et al., 2018). On the other hand, one of the most effective methods for capturing knowledge that emerged in construction projects is live knowledge capture (Eken et al., 2020; Okudan et al., 2021; Tan et al., 2007). By using this method, the tacit knowledge embedded into the mind of the practitioners can be captured. Besides, web-based tools developed for live knowledge capturing are convenient solutions to capture waste knowledge effectively due to the elimination of time and location limitations (Aziz et al., 2006). These tools can facilitate inter-project learning where the knowledge that emerged in different projects can be combined to form a generic organizational memory and enhance organizational learning. The other important feature of the management of waste is the retrieval of the most appropriate knowledge. Therefore, an effective waste management tool should have a mechanism to retrieve the relevant knowledge.

Based on this literature review, the main objective of this research was to develop a knowledge-based waste process model and a tool that can be used for capturing and storing waste-related knowledge in a project and retrieving the required knowledge from previous projects to perform waste estimation, waste monitoring and analysis of waste performance in the prefabricated construction industry.

3. Research methodology

Figure 1 shows the steps followed in this study. The interviews and questionnaires were conducted in 2017. In the first step, a need analysis was performed for identifying the required features for an effective waste management system. Thus, expert interviews and questionnaire surveys were conducted for revealing the expectations of the prefabricated construction industry from a waste management system. Based on the need analysis, a knowledge-based system was determined as crucial for performing effective waste management in prefabricated construction projects. Second, a process model was developed which concentrates on three important mechanisms of knowledge-based systems, namely “knowledge capture mechanism”, “knowledge retrieval mechanism”, and “user types and authorization systems" (Eken et al., 2020). It has been understood that the process model should depend on integrating all stages performed throughout waste management according to the findings of the need analysis. Therefore, for each stage, mechanisms were developed and integrated into the process. Then, since the aim of this study is to develop a web-based computer software which can be used for facilitating all stages performed in waste management based on the knowledge captured from the past projects, a software was developed based on the proposed process model. Therefore, the developed software provides a complete waste management system compared with the systems available in the literature. Finally, functions of the developed software were tested and verified by using Black-Box testing methods, then the experts from the industry evaluated the software via interviews and a questionnaire survey.

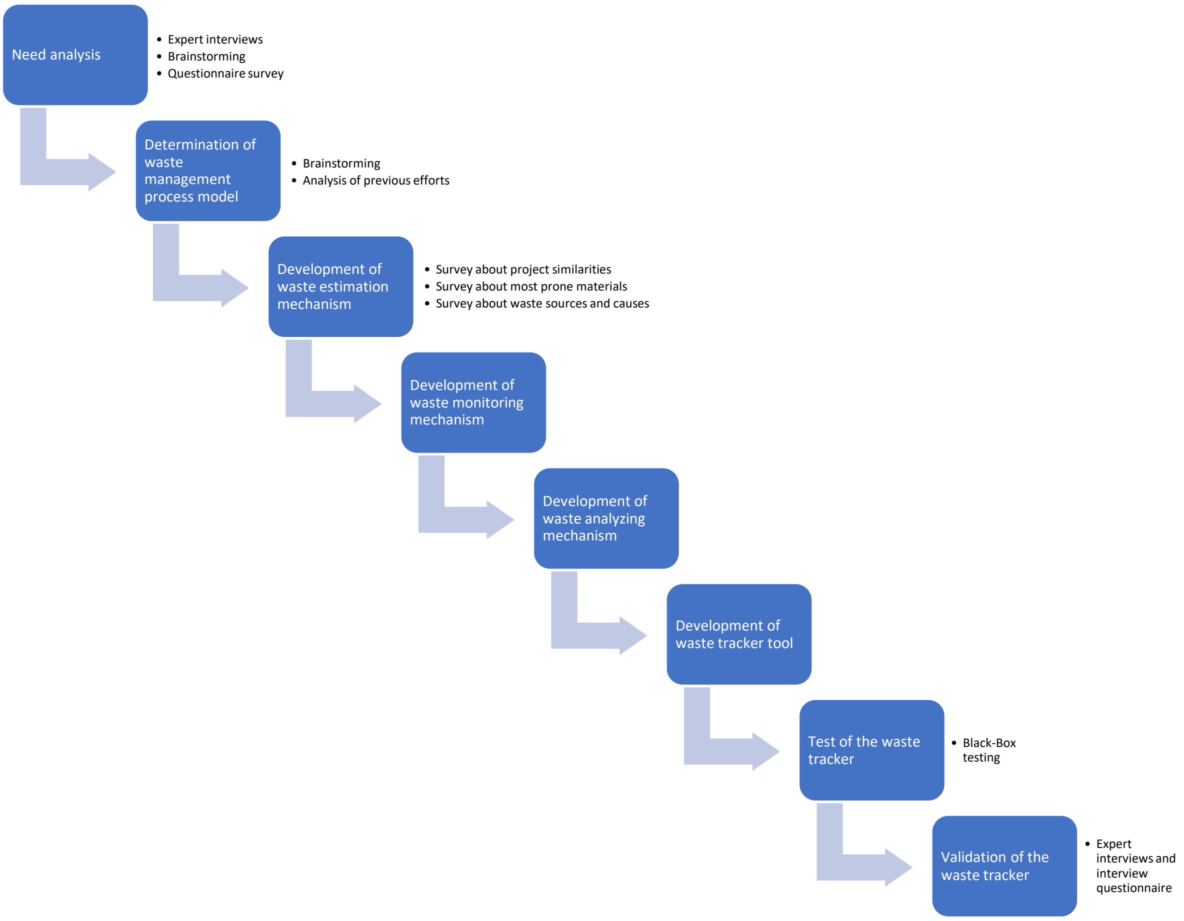


Figure 1: Research Methodology

4. Need Analysis

The need analysis was conducted by following two stages, namely expert interviews, and questionnaire survey. First, to understand the existing practices related to waste management in the prefabricated construction industry, expert interviews were conducted. The interviewees were selected using judgment sampling, since judgement sampling is effective to determine the most informed experts which is critical in investigation of specific subjects. Three criteria were determined to evaluate the competency of the experts for the interviews to eliminate researchers' bias. The first criterion is about the experience level of the participants' companies. According to this criterion, companies should be in the construction sector for over 20 years. Ten companies that are among the largest Turkish steel prefabrication companies and operating in international markets were contacted for this study. Five of them agreed to contribute to this research. Experts were selected from these companies. Second, the experience level of the participants was evaluated. Experts were expected to have at least five years of experience in waste management practices. Finally, all the experts were expected to have managerial roles/administrative positions in their companies. The selected experts were expected to work in different executive positions such as director, project manager, and chief to satisfy the heterogeneity in the sample. Nine experts who meet all these criteria were determined, and expert interviews were conducted with these experts. The profiles and companies of the interviewees are shown in Table 1. All interviews were conducted face to face to avoid any misunderstanding about the questions and provide feedback as soon as possible. In the interviews, seven questions that can provide insights about the waste management practices prefabricated industry were asked. The answers of the respondents to the questions are also shown in Table 2. Besides, the expectations from a waste management tool were asked to each participant using open-ended questions.

Table 1: The profile of the interviewees and their companies

	Firm	Firm size	Firm experience (years)	Experience of the interviewee (years)	Job description
1	B	Large (> 250 employees)	29	9	Project Monitoring and Reporting
2	B	Large (> 250 employees)	29	14	Manager of Construction and Project Management Department
3	A	Large (> 250 employees)	36	12	Lead Planning and Project Control Professional
4	A	Large (> 250 employees)	36	18	Director of Project Management Office
5	C	Medium (50 < employee < 250)	24	21	Senior Project Manager
6	C	Medium (50 < employee < 250)	24	9	Design Group Chief
7	E	Medium (50 < employee < 250)	27	7	Project Manager
8	D	Large (> 250 employees)	43	6	Project Control Engineer
9	D	Large (> 250 employees)	43	13	Design and Technical Office Manager

Table 2: Interview questions and answers

	Questions	Answer	Frequency	Percentage
1	Do you have a waste management plan in your company?	Yes	6	66.67%
		No	3	33.33%
2	Do you have a waste estimation and reporting procedure in your company?	Yes	2	22.22%
		No	7	77.78%
3	What is the focal point of your waste management plan?	Avoidance	0	0%
		Minimization	0	0%
		Recycling	2	33.33%
		Disposal	4	66.67%
4	Which strategy do you usually apply as an on-site waste management strategy?	Avoidance	0	0%
		Minimization	2	22.22%
		Recycling	1	11.11%
		Disposal	6	66.67%
5	Do you apply a waste management concept in the design stage?	Yes	2	22.22%
		No	7	77.78%
6	Do you have a classified lesson learned archive on material waste in previous projects?	Yes	1	11.11%
		No	8	88.89%
7	Does waste management performance assessment apply in your company?	Yes	0	0%
		No	9	100%

In the second stage of the need analysis, a questionnaire survey was conducted to evaluate the deficiencies of the existing waste management practices. This questionnaire comprised two parts. In the first part, questions about the company and the participants were asked. The second part included 18 listed deficiencies extracted from the interviews. These deficiencies were evaluated by the participants based on a 1-5 Likert scale, in which 1 denotes that this deficiency does not exist, 5 denotes that this deficiency exists. The potential participants were selected using random sampling. 11 Turkish companies with national and international experiences in steel structure prefabricated building projects were identified by contacting Turkish Contractors' Association (TMB). 73 questionnaires were sent by email to professionals from these companies. 45 of the questionnaires were returned. The final return rate of 45 valid responses represents 61.64 percent. Table 3 represents the demographic structure of the participants. Table 3 shows that the participants and their companies are well experienced in prefabricated steel structure projects. Also, they have different roles in the organization and backgrounds. Therefore, the sample can be considered heterogeneous and reflect the different opinions about the deficiencies of existing waste management practices.

Table 3: Demographic structure of the participants and their companies

Company size	Micro (<10 employee)	Small (10 < employee < 50)	Medium (50< employee < 250)	Large (> 250 employee		
	0	0	4	7		
Company experience	0-5	5-10	10-15	15-20	20-25	>25
	0	0	0	2	4	5
Job designation of the participant	Project/Construction Manager	Technical Manager	Engineer	Technician	Tech. Supervisor and Inspector	Other
	12	11	13	3	5	1
	Civil/Architectural		Mechanical Engineering		Electrical Engineering	

Field of the participant	28		9			8		
Experience of the respondents	0-3	4-6	7-10	11-13	14-16	17-20	20-25	>25
	3	4	8	9	7	8	5	1

The findings of the questionnaire survey were represented in Table 4, which shows the criticality of deficiencies based on the relative importance index (RII). RII is calculated by using the following equation.

$$RII = \frac{\sum W}{A \times N} \quad (1)$$

Where W is the weight given to each factor by the respondents, A is the highest weight, and N is the total number of respondents.

Table 4: Deficiencies and their RIIs

	Deficiency	RII
1	Low training and education about waste management and control in projects	0.64
2	Low level of usage of integrated design and estimation software (e.g., BIM software)	0.60
3	Lack of analysis of cost impact of material waste in projects	0.58
4	Lack of analysis of actual and nominal waste data in projects	0.56
5	Low personnel designation for implementation of the waste management plan	0.52
6	Low capturing and storing capability of learned lessons about the waste management	0.51
7	Lack of evaluation of waste management performance in projects	0.48
8	Low consideration of environmental and waste management issues in the design stage	0.48
9	Low awareness of project team about estimated waste causes and rates for each material	0.44
10	Low accuracy of methods used for waste source and quantity estimation in projects	0.44
11	Low quality of systematic waste data capturing for direct and indirect waste	0.42
12	Low efficiency of waste management and control plan in projects	0.41
13	Lack of company knowledge about the actual amount of waste and waste causes	0.40
14	Lack of the actual waste data during construction	0.36

15	Lack of documentation of material wastes and waste sources	0.35
16	Inappropriate company policies in material waste avoidance or reduction	0.34
17	Poor material traceability at the construction sites	0.33
18	Lack of awareness of company/ project stakeholders about the waste management	0.31

By evaluating the interviewees and questionnaire survey, the following critical features and tasks proposed for eliminating the deficiencies of the existing practices in the prefabricated construction projects and achieving the expectations of the professionals from a waste management tool were determined:

1. Establishing an integrated waste management system involving waste estimation, reporting, analyzing, and recording.
2. Improving the quality of waste estimations and reducing poor estimations due to personal perceptions by developing a material waste database for previous projects and facilitating the access of the project team to a database.
3. Facilitating systematic waste source estimation to improve proactive waste management by anticipating waste generation sources for the project team and letting them plan for proper waste management procedures.
4. Improving the extent of material waste capturing by establishing a pre-defined procedure and structure for direct and indirect waste reporting.
5. Promoting the common understanding of project participants about material waste by establishing a standard format of waste reporting and waste source identification.
6. Establishing material waste reporting as part of the project progress reporting process to minimize the amount of waste ignorance by project participants.
7. Facilitating the live capturing and monitoring of waste generation by developing a systematic method for waste identification and reporting by project participants.

8. Developing a waste analysis tool to assist the project management team in tracking the waste generation and comparing it with previous projects' performances to improve the efficiency of waste monitoring and controlling processes.
9. Developing a waste data recording system by establishing a classified waste information database for each project based on the different material groups to facilitate preparing waste-related lessons learned documents.

The identified features are also compatible with features proposed by Akinade et al. (2018). Therefore, the identified features can be considered reliable, and a tool that satisfies these features can be beneficial for construction companies in waste management.

5. The knowledge-based waste tracker process model

A process model was developed by considering the needs stated above. The presentation of the proposed model is shown in Figure 2. The waste tracker server at the center of the system is a gateway of the system to the database. Therefore, this server is accessible via web browsers, which provide opportunities to access anywhere without setting up extra software for client devices. Akinade et al. (2016) also recommended that a centrally accessible database should be inserted in a waste management system to improve accessibility. In the system, each user has different access abilities to the server. Therefore, each user uses the system based on their authority level. In other words, not all users have full authority to perform all operations in the system. This limitation is also critical for successful waste management since the party commitment is directly related to the well-defined responsibilities (Osmani et al., 2008). On this account, the parties are reluctant to commit to waste management when their responsibilities in waste management are poorly defined.

As shown in Figure 3, the users were divided into three groups. The first group can be called waste data sources qualified enough to enter the knowledge into the system. The prime responsibility of this group is preparing waste reports. In other words, the emerged knowledge related to waste management is captured by the system via these users. While preparing the waste report, they must define the report type, waste quantity, and waste source. These users also can create a material list and waste baseline which can be used in analyzing the waste in the project. The other user group is called waste data users. These users can retrieve the captured knowledge in the system by using queries. Besides, they can review the waste analysis reports from the system. The last group is the system admin group with full authority to control the system and play a critical role in managing the system. “System Admin” handles system maintenance, defining projects, waste baseline creation, and documents reviewing and controlling in the system. The most important duty of the system admin is monitoring the reports to achieve high-quality knowledge in the system. Knowledge quality is considered an essential indicator of an effective knowledge management system (Jennex and Olfman, 2006; Karlinsky-Shichor and Zviran, 2016; Wang and Yang, 2016) since the knowledge in the repository should be relevant, accurate, reliable to encourage the users to use your system. Otherwise, the users will confront with time-consuming and unproductive knowledge searches while using the system. Besides, the quality of data is critical for waste management, especially the accuracy of waste quantification directly depends on the quality of the waste data (Akinade et al., 2016; Cochran et al., 2007). Therefore, all the reports created by the data sources are reviewed by the system admin, and they have the authority to accept or reject the report.

The process model of the developed waste management system is illustrated in

Figure **4**. As shown in Figure 4, the first step of the process is identifying the project, since the material waste-related data is captured under the related projects. In this step, the project scope critical to perform the similarity analysis is defined. After project creation, all stages of knowledge-based waste management are performed, respectively. In other words, the model incorporates waste estimation, waste data collection, and waste analysis. Combining all these stages is critical to ensure data transparency and uniformity in data collection (Akinade et al., 2016). At the end of the process, waste analysis reports used for identifying the waste causes and measuring the waste management performance of the project team are generated.

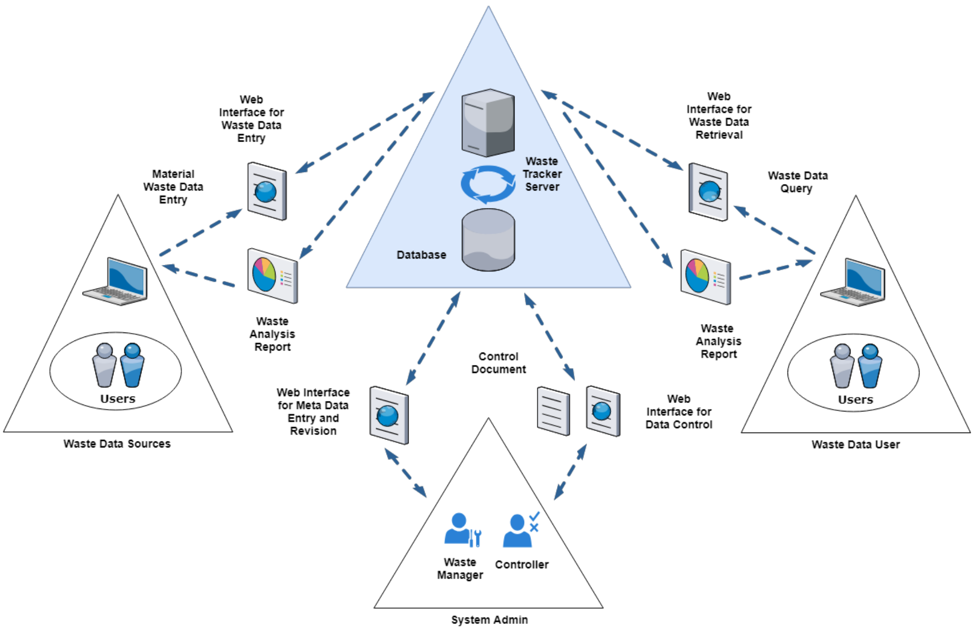


Figure 2: Representation of the proposed structure for lessons learned capture and sharing

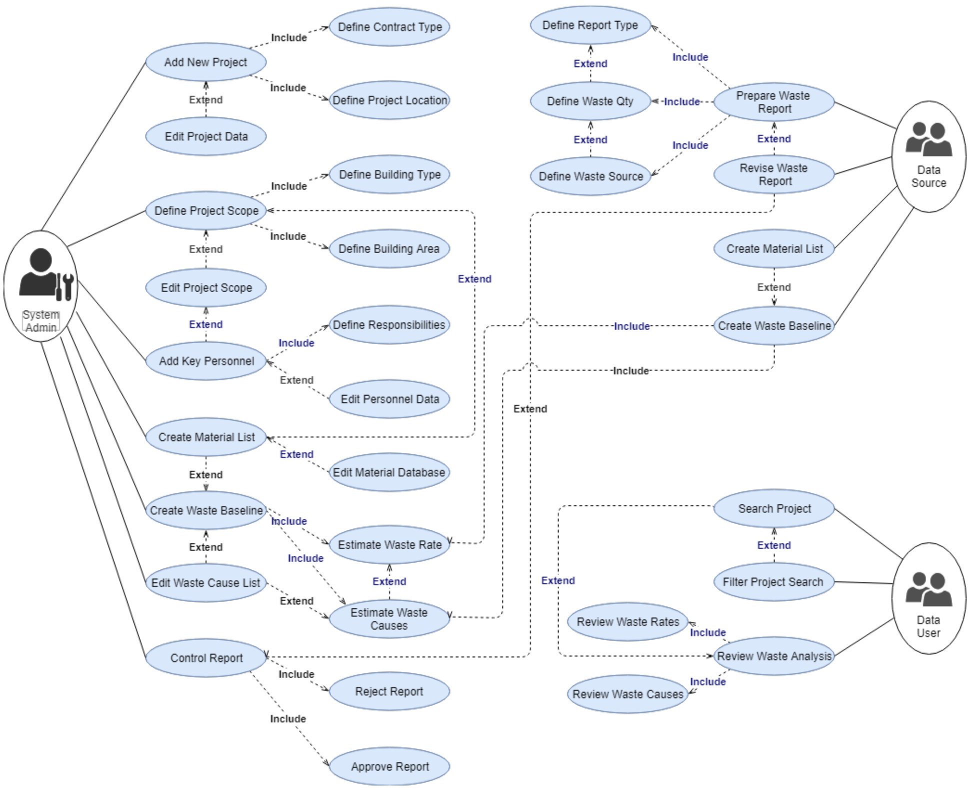


Figure 3: Use case diagram of Waste tracker

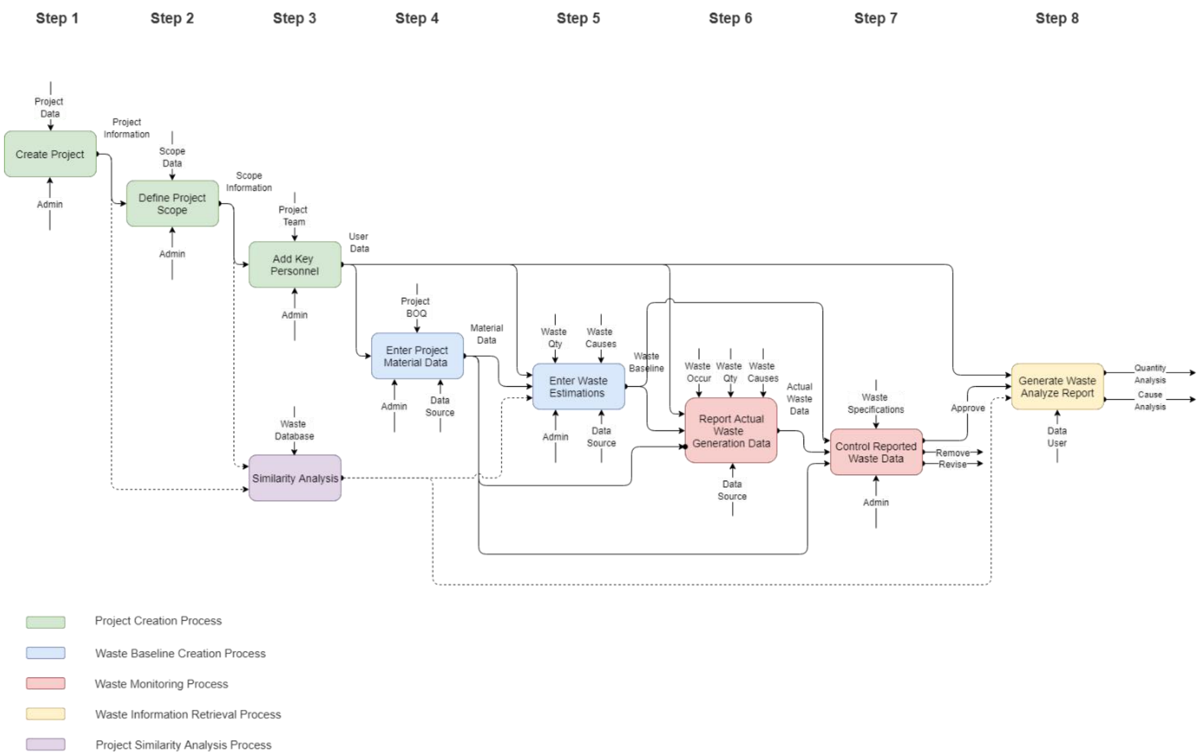


Figure 4: Process model

5.1. Development of waste estimation mechanism

One of the essential steps of waste management is estimating the waste in a project. The workflow shown in Figure 5 represents the process details of estimating the waste in the waste estimation mechanism. According to this workflow, at the end of this mechanism, a waste baseline used for analyzing the waste management performance of the project is created. This waste baseline includes project material data, estimation of waste of these materials, and estimation of the waste causes. The following sections elaborate on how the waste baseline is created.

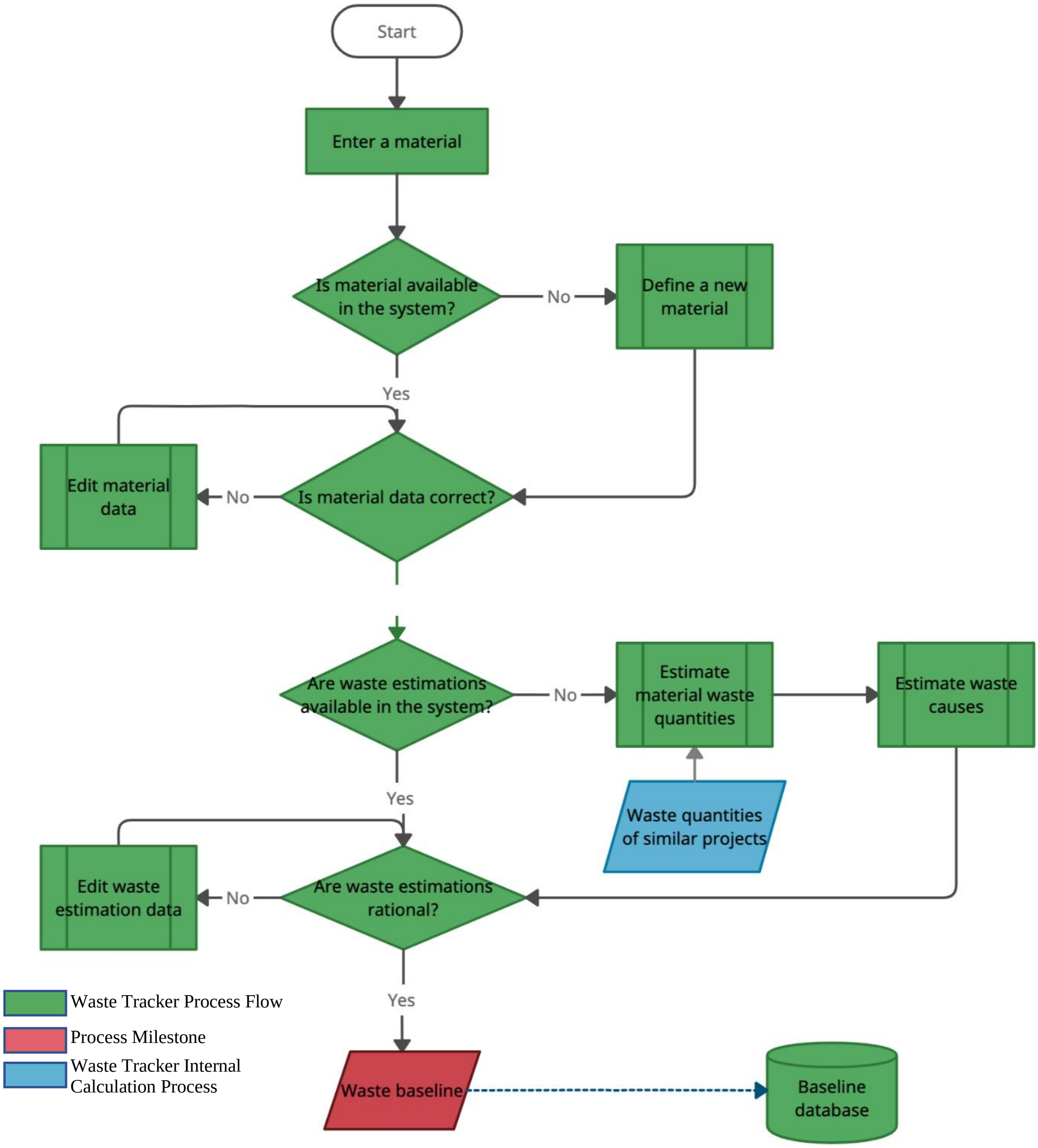


Figure 5: **Flowchart of waste estimation**

5.1.1.Project material data

One component of the waste baseline is the project material data. However, in this system, the materials that have a high potential to create waste in the prefabricated steel structure projects are being evaluated instead of all materials used in these projects since managing an extensive range of materials can entail a complicated and inefficient process. Therefore, a database that comprises the waste-prone materials was prepared by evaluating four prefabricated steel structure projects whose information is provided in

Table 5. These two projects were performed by two Turkish construction companies which have been working in the construction industry for 36 years and 27 years, respectively. In the preparation for the database, the bill of quantities (BOQ) and material purchase lists of the projects were investigated. At the end of the investigation, 47 material groups and 545 materials under these groups were identified initially. Then, these materials were examined by interviewing the 9 professionals who took part in the need analysis. Based on the recommendations of the participants, 5 of the material groups were eliminated because of the low potential of these material groups to create waste. Besides, these material groups were classified under three different categories, namely building, mechanical and electrical materials. The final material list includes 27 building material groups, 9 mechanical materials groups, and 6 electrical material groups. Finally, in this study, 525 material types under these 42 material groups have been entered the system as a default material database.

Table 5: Information about the projects used for extracting the materials

Project	**Company**	**Area (m2)**	**Contract Type**	**Country**
A	1	55,780	Engineering Procurement and Construction (EPC)	Qatar
B	1	41,360	EPC	Kazakhstan
C	2	18,750	Turnkey	Turkey
D	2	26,930	EPC	Turkey

5.1.2. Waste causes

The other important input that should be inserted into the estimation mechanism is the waste causes. To avoid scattered estimations leading to uncategorized reports, the potential waste causes should be identified. Thus, a detailed literature review was conducted to investigate the principal causes of material waste generation. A categorized list of 49 potential waste causes was identified and they were classified under 5 categories by considering Bossink and Brouwers (1996), Polat and Ballard (2004), Adewuyi and Odesola (2015), and Umar et al. (2016). The prepared list was discussed by interviewing nine professionals and some specific waste causes that were not identified in the literature review were added and some causes with the same concepts were merged. Besides, the documents of the four projects were also revised for identifying the waste causes in these projects. At the end of this document review stage, 15 waste causes were identified. By merging all the waste causes extracted from different sources, a list of 46 waste causes under 6 different categories was identified and inserted into the system as default waste causes. All these waste causes and their categories are obtained from Mirshekarlou (2018).

5.1.3. Waste Estimation

Waste rate estimation of each material is another crucial component of the waste baseline since estimating the waste rates can be critical to handle material, reduce waste rate, and improve productivity (Al-Hajj and Hamani, 2011; Gulghane and Khandve, 2015). The waste rate estimation is performed by the user. However, in this study, the waste rate that occurred in the most similar project is provided as a valuable reference to the user since similar projects may result in similar waste rates originating from identical sources. Still, a similarity analysis is required to determine the most similar project. For similarity analysis, the first step is determining the project's attributes that can help to define the similarities between projects since determining the similarity by considering the unrelated attributes can lead to misleading conclusions (Okudan et al., 2021). First, the critical attributes of the projects that affect the emergence of waste should be determined while developing similarity analysis. To determine these attributes, interviews with nine professionals who took part in need analysis were conducted. Based on the insights of the interviewees, five attributes were identified as the essential attributes playing roles in creating the waste. These attributes were project location, client, project area, contract type, and building type, and they were used in similarity analysis.

The weights of these project attributes should be calculated in the next step of developing the similarity analysis. Thus, a questionnaire that comprises two parts was prepared. The first part is related to the general information about the respondents and their company profile. In the second part, the respondents evaluate the effects of project attributes in similarity assessment and use a 5-point Likert scale in which 1 refers to Very Low, and 5 refers to Very High. This questionnaire was distributed among 73 potential participants from selected 11 Turkish companies with high national and international experience according to the data obtained from the Turkish Contractors Association.

Finally, 34 questionnaires from 5 construction companies were obtained, and the return rate of this survey became 46.57%.

Table 6 summarizes the demographic structure of the respondents and their companies. According to this table, all the companies are medium or large. Besides, they are well experienced in prefabricated steel structure projects. The participants have a wide range of positions and backgrounds. Therefore, the sample set is not homogenous, and the sample set reflects the different views of the industry. Finally, the respondents are also well experienced in prefabricated steel structure projects. The sample is determined as proper.

Table 6: Profile of the respondents and their companies took part in the questionnaire survey

Company Size	Micro (# of employee<10)	Small (10<# of employee < 50)	Medium (50<# of employee < 250)	Large (# of employee>250)				
	0 (0%)	0 (0%)	2 (40%)	3 (60%)				
Company experiences in prefabricated steel structure projects	0-15	15-20	20-25	>25				
	0 (0%)	1 (20%)	2 (40%)	2 (40%)				
Positions	Project/Construction Manager	Technical Manager	Engineer	Technician	Tech. Supervisor and inspector	Other		
	12 (27%)	11 (24%)	13 (29%)	3 (7%)	5 (11%)	1 (2%)		
Profession	Civil/Architecture	Mechanical Engineering	Electrical Engineering					
	28 (62%)	9 (20%)	8 (18%)					
Experience of the respondents	0-3	4-6	7-10	11-13	14-16	17-20	20-25	>25
	3 (7%)	4 (9%)	8 (18%)	9 (20%)	7 (16%)	8 (18%)	5 (11%)	1 (2%)

The project similarity is calculated according to the method proposed by Boriah et al. (2008), which is based on matching ratios of project attributes between selected and the existing projects in the company database by identifying the categorical data similarities using the project attributes. First, the weight of each project attribute was determined according to the respective RII.

Where W is the weight given to each factor by the respondents, A is the highest weight, and N is the total number of respondents. Table 7 shows the RII of each attribute, and the weights calculated based on the RII of the project attributes are depicted. In this study, the similarity is assessed based on the similarity between the categories. Therefore, each project attributes category was determined. For instance, the project size was categorized under 5 categories, namely very small, small, medium, large, and extra-large based on the area range of the projects. Although the data user enters the exact value for project size, the system automatically allocates the project size into these five categories based on pre-defined criteria. Similarly, three general building types, namely heavy structural steel, panelized light steel, and containerized, were available as building type attributes. Since four contract types, namely lump sum contract-EPC, lump-sum contract-PC, unit price contract-PC, cost-plus contract, are used in prefabricated steel construction projects, these contract types were used in defining the contract type attribute.

Table 7: Survey results and attribute weights

Attribute	RII	Ratio	Weight in terms of %
Contract type	0.80	0.80 / 3.59 = 0.2226	22.26
Project area	0.79	0.79/3.59 = 0.2209	22.09
Project Location	0.72	0.72/3.59 = 0.1997	22.09
Building Type	0.71	0.71/3.59 = 0.1964	22.09
Client	0.58	0.58/3.59 = 0.1604	22.09
Total	3.59		

The assigned project attributes of a newly created project are compared with the attributes of the other projects in the database for calculating the similarity rates between this project and other projects. When two projects have the same value for one of the project attributes, according to the weight of the project attribute, the similarity rate is increased. For instance, when only location and area are matched for two projects, the similarity rate between these two projects is calculated as 44.35%. The formulas used in calculating between projects A and B are given below.

$$S(A,B) = \sum_{k=1}^{n_k} w_k \times s_k(A_k, B_k) \tag{2}$$

$$s_k(A_k, B_k) = \begin{cases} 100\% & if\ A_k = B_k \\ 0 & otherwise \end{cases} \quad k = 1,2,\dots,n \tag{3}$$

Where $S(A,B)$ is total similarity value, w_k is attribute weight obtained from survey study, $s_k(A_k, B_k)$ is similarity for attribute k, n_k is the maximum number of attributes. According to equation 2, when the project attributes are not matched exactly, the system can be modified by adding additional project attributes to provide flexibility to data sources even though the similarity is determined as zero. In other words, two projects can show similarity in terms of any project attributes, and therefore the data sources should add similarity lower than 100%. For instance, although one project is in Georgia and the other project is in Azerbaijan, due to the similarities between these two countries in terms of culture and bureaucracy, these two projects can confront the same problems in waste management. Therefore, the waste data obtained from this project can be a valuable reference in waste estimation. To avoid losing the precious knowledge gained from this project, the user can add additional project attributes, such as 90% similarity when the project is carried out in Azerbaijan. The process conducted for calculating the similarity rate between projects A and B is also presented in Figure 6.

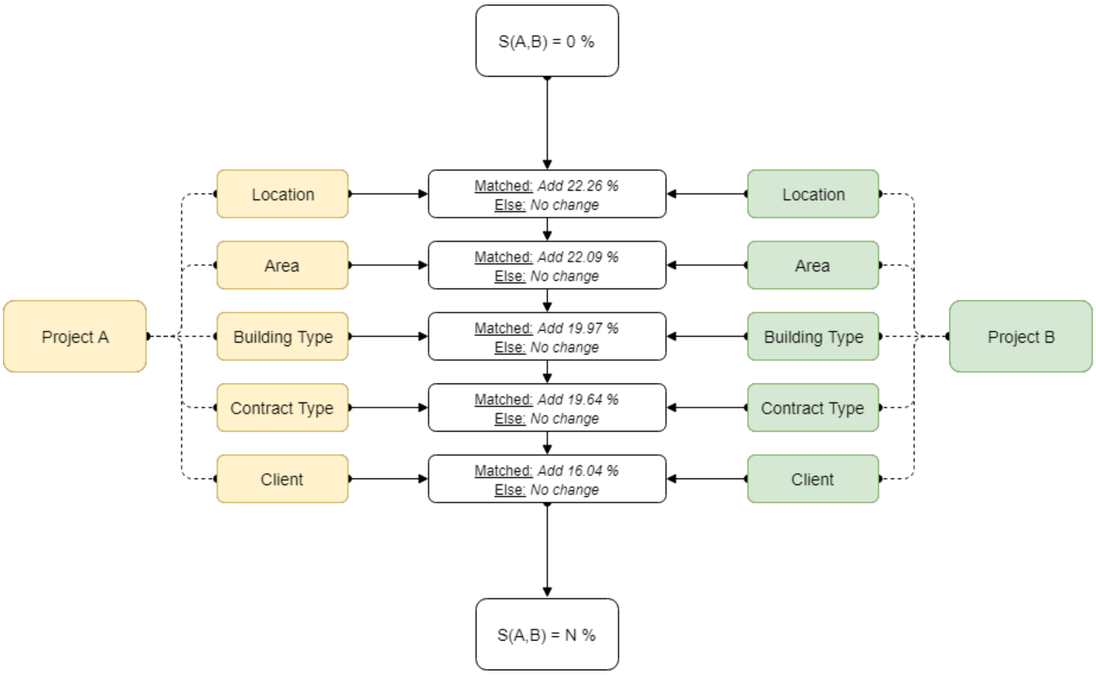


Figure 6: Project similarity calculation procedure

After identifying the most similar project based on the similarity rates, an expectation waste rate was calculated by using the following formula for each material group.

$$\mathrm{WRA}_{\mathrm{i}_{\mathrm{sp}}} = \frac{\sum_{\mathrm{j}=1}^{\mathrm{n}} \sum_{\mathrm{k}=1}^{\mathrm{m}} \mathrm{AWQ}_{\mathrm{j},\mathrm{k}_{\mathrm{sp}}}}{\sum_{\mathrm{j}=1}^{\mathrm{n}} \sum_{\mathrm{k}=1}^{\mathrm{m}} \mathrm{EQ}_{\mathrm{j},\mathrm{k}_{\mathrm{sp}}}} \tag{4}$$

Where i is a material group, j is a material in the material group (i), k is a location in a similar project, n is the number of materials of the material group in the similar project, m is the number of locations in a similar project, $EQ_{j,k_{sp}}$ is the estimated quantity of material (j) in location (k) of similar project, $AWQ_{j,k_{sp}}$ is the actual waste quantity of material (j) in location (k) of similar project.

5.2. Waste monitoring mechanism

Monitoring the waste stage is also crucial as it enables the users to determine the actual waste generation throughout the project. This stage is also critical for capturing waste data throughout the project. In the proposed system, two steps, namely "waste reporting" and "controlling the reports" were proposed, as shown in Figure 7. According to the proposed process model, waste reporting is defined as a part of the project progress reporting process to avert lateral processes and extra works within the organization. Therefore, a new reporting mechanism, which leads to dramatic structural changes in the existing organizational structure, is not required to perform waste reporting. Besides, the project progress reports are mainly prepared at daily intervals. Hence, merging the waste reporting process with the daily progress report system will enhance the timely reporting of waste generation and facilitate the early identification of waste generation.

To standardize waste reporting, a standard form of reporting and recording system is necessary for a waste management system. Thus, the scattered data inputs are minimized, and the direct information flow is satisfied in the system. The minimization and satisfaction will lead to the enhancement in the quality and quantity of waste data capturing. In addition, the standardization in waste management can lead to a common perception about waste sources within the company. The primary sources of waste generation in prefabricated construction projects are investigated through the literature review and expert interviews elaborated above. Based on the findings of this research, two types of waste, namely direct and indirect waste, were determined. Direct material wastes emerge because of two sources, namely “damage or lost” and “construction errors”. Similarly, indirect wastes originate from the result of “material substitution” and “excessive use of material”.

As stated above, the accuracy of the knowledge captured in a knowledge-based system is crucial for achieving the effectiveness of this system. Therefore, all reports submitted to the system should be controlled to ensure the appropriateness of the reports. When the reports do not satisfy the pre-determined quality criteria, they are sent back to the data sources for revision. This process is repeated until the reports appease all the conditions.

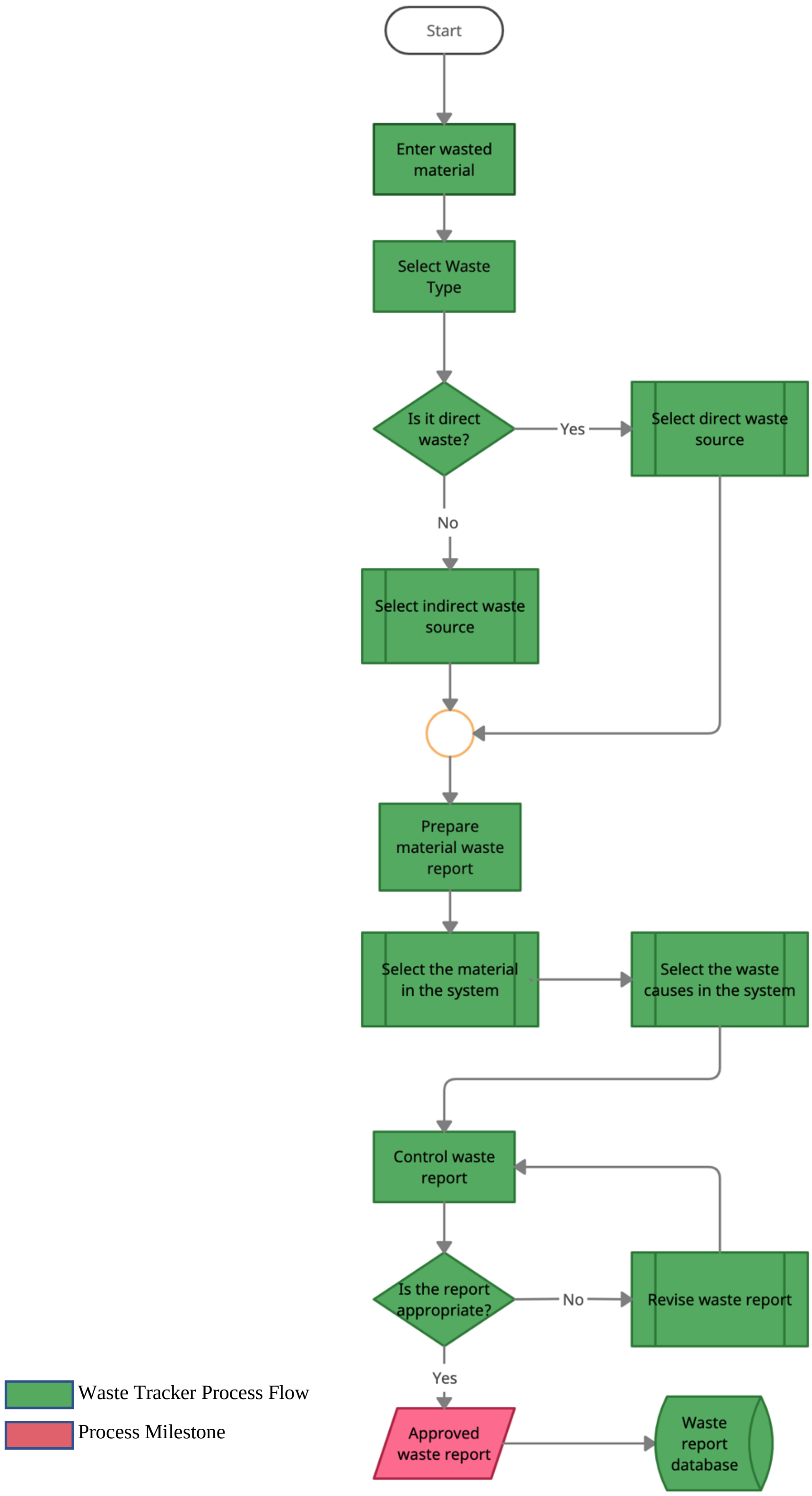
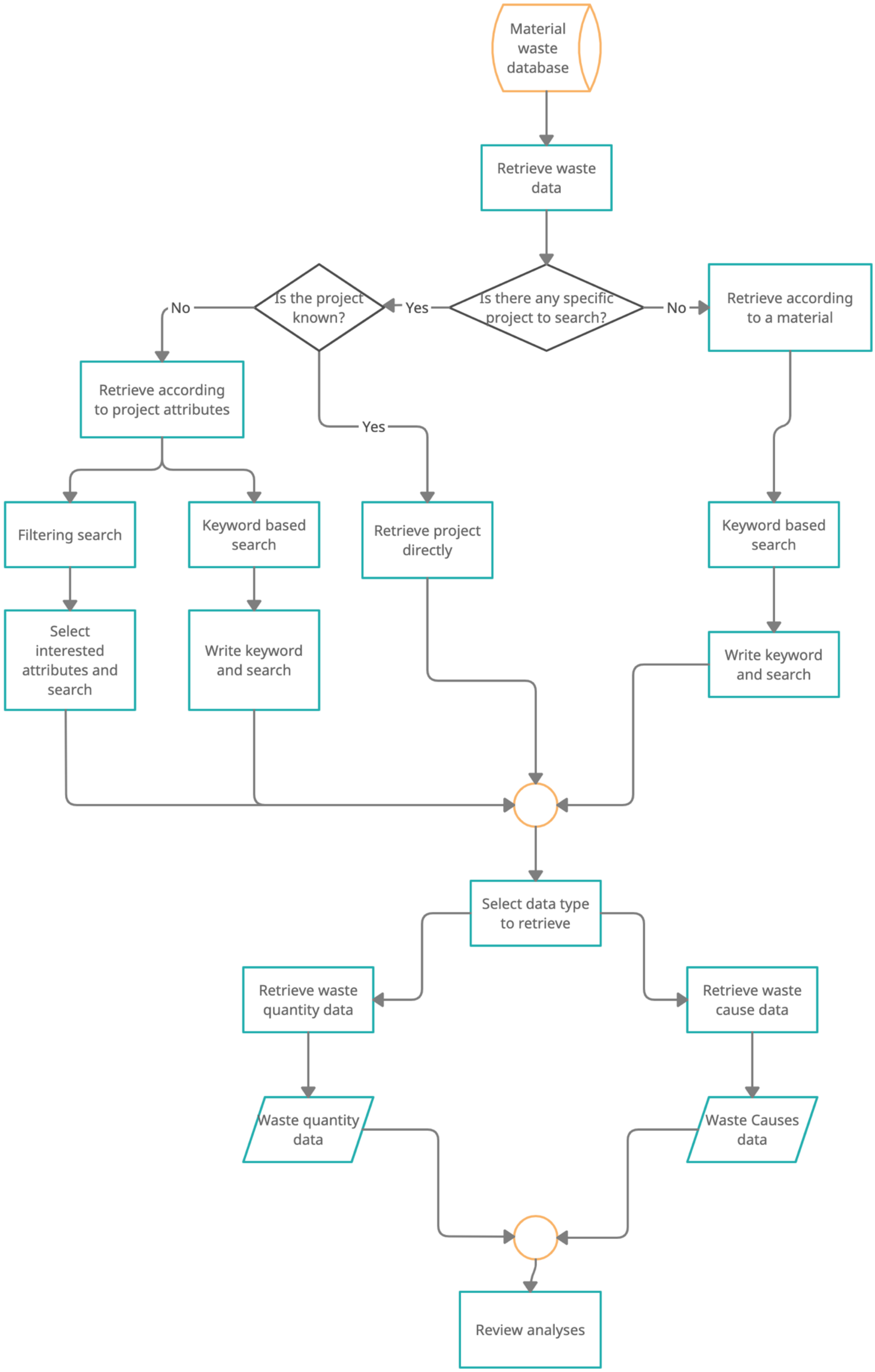


Figure 7: Flowchart for the waste monitoring mechanism

5.3. Waste analyzing mechanism

Since one aim of this study is to integrate all stages in waste management, it should also analyze waste management throughout the project. Figure 8 shows the general structure used to analyze waste management by retrieving the waste knowledge from past projects. According to the flow, first, the user must select the project or material group. There are two options for selecting the project. If the project is known exactly, the user can select the project directly from the drop-down menu that shows all the projects stored in the database. Alternatively, the user can search the project by using two searching options: filter search and keyword search. Considering, the user has flexibility in finding the project in different ways. Filter search uses two project attributes, namely project status and project contract type. These two inputs can be selected by using the drop-down menu that calls the default values from the database. Therefore, the user does not have to memorize the attributes to recall the project. Besides, this option eliminates the potential empty search results after the misspelling of the project attributes. The other option is keyword searching. Keywords for Project ID, project name, and project location can be used for searching. The search can be narrowed down by using more than one search field. For example, the user can search the "continued" projects which are constructed by using the "Lump sum-EPC" contract type. At the end of the search, the search engine displays all projects which satisfy these two attributes. The user can select one project among the displayed projects and access the waste analysis results according to the material groups. For searching the material group, keyword searching is the only option. Then, two types of waste analyses, namely "Waste quantity analysis" and "Waste causes analysis" can be performed.



Material waste database
Retrieve waste data
Is there any specific project to search?
Yes
No
Is the project known?
Retrieve according to a material
No
Yes
Retrieve according to project attributes
Filtering search
Keyword based search
Retrieve project directly
Keyword based search
Select interested attributes and search
Write keyword and search
Write keyword and search
Select data type to retrieve
Retrieve waste quantity data
Retrieve waste cause data
Waste quantity data
Waste Causes data
Review analyses

Figure 8: Flowchart for the waste analysis mechanism

In waste quantity analysis, the waste quantities and waste rates are calculated. First, the estimated waste rate of each material is assigned directly according to the estimated waste rate of the respective material group. In other words, all materials placed in the same material group have the same waste rate. Also, the waste quantity of each material is calculated by using formula 5. The actual waste rate of each material in the current project is calculated using formula 6. Finally, the total waste quantity of each material is calculated according to the results submitted throughout the project.

$$WQ_{j_{c.p.}} = \sum_{k=1}^{m} WR_{i_{c.p.}} * EQ_{j,k_{c.p.}} \tag{5}$$

$$AWR_{j_{c.p.}}(\%) = \frac{\sum_{k=1}^{m} AWQ_{k_{c.p.}}}{\sum_{k=1}^{m} EQ_{j,k_{c.p.}}} \tag{6}$$

Where m is the number of locations in the current project, $WQ_{j_{c.p.}}$ is the estimated waste quantity of material (j) in the current project, $WR_{i_{c.p.}}$ is the estimated waste rate of the material group (i) in the current project, $EQ_{j,k_{c.p.}}$ is estimated quantity of material (j) in location (k) of the current project, $AWR_{i_{c.p.}}(\%)$ is the verified waste rate of material (j) in the current project, $AWQ_{k_{c.p.}}$ is the actual waste rate of material (j) in location (k) of the current project.

Comparing the values of estimated and actual waste rates demonstrates the variation between planned and actual waste quantities in the project; if the actual waste rate for any material is above the estimated (planned) value, the project team will know the deviation from waste baseline for that type of material and by investigating the causes of waste generation will be able to take preventive actions as soon as possible.

Also, the minimum and maximum waste rates of the materials in the portfolio are calculated by using the following formulas.

$$WR_{j_{p.min}}(\%) = \min_{p}(\bigcup AWR_j) \tag{7}$$

$$WR_{j_{p.max}}(\%) = \max_{p}(\bigcup AWR_j) \tag{8}$$

Where $WR_{j_{p.min}}$ is the minimum waste rate of material (j) in the portfolio, $WR_{j_{p.min}}$ is the maximum waste rate of material (j) in the portfolio, AWR_j is the waste rate of material (j) in the portfolio. Besides, the projects with the lowest waste rate and highest waste rate are displayed as outputs of the analysis. Finally, the waste rate of each material in a similar project is also provided by modifying the formulas 5 and 6 by changing the current project with a similar project.

The second analysis provided by the system is related to the waste causes. This analysis provides information about the waste generation causes which have been estimated at the waste estimation mechanism and reported in the waste monitoring mechanism. In this analysis, the waste causes are generated for each material group instead of each material. Besides, the frequency of each cause is calculated according to the waste reports generated for each material in the material group obtained throughout the project. In this way, the user can identify the most critical waste causes for each material group in the project. Besides, the impact of each cause in the form of waste rate is displayed in the report, and the most impactful waste causes are open to scrutiny. These outputs can be used for revealing the efficiency of waste source management efforts. The user can decide about the required effort allocations to the elimination of these causes. Finally, the performance of the waste management in the current project can be compared with the performance of the waste management in the most similar projects in terms of frequency and impact of waste causes.

6. Waste Tracker

Waste Tracker is a web-based application, and all the information captured and generated is stored in a SQL (structured query language) database. The tool is developed using PHP language; therefore, the developed tool is compatible with all web browsers and mobile devices. Besides, there is no requirement for installing extra software in the client device to use the tool properly. The prototype of the tool is accessible via "https://www.wastetracker.online/". The tool functions can be divided into four major categories, "administrative settings", "waste estimation", "waste monitoring" and "waste analyses".

6.1. Administrative settings

The tool is flexible enough for modifying many prominent settings. System admin can change project scope by defining building types and building areas, adjust user roles by defining responsibilities and editing personnel data, improve the material database by adding new materials, revise waste cause list, and change weights of the project attributes used in similarity calculation according to the project requirements. Material lists and waste causes obtained in the previous steps were integrated into the system. However, diverse materials and waste causes can emerge in a project. Therefore, these materials and waste causes should be added to the tool. This tool allows the integration of these materials and waste causes into existing lists through the editing area. Similarly, the default values of the similarity weights can be modified using the project similarity coefficient screen.

Since the knowledge is valuable for the company, all information in the system should be secured. Therefore, access to the system is restricted, and the users can access the system only by using the identified usernames and passwords assigned to these usernames by system administration. Each user has unique privileges in terms of allowed actions and accessibility to screens. Therefore, according to their roles, they can access various functions of the system. For instance, waste users can only search projects and review waste analysis of the project. The other modules related to administrative settings - waste estimation and waste monitoring - are not available in their systems. System admins have the primary role in the system, can access all functions, and control the other users' actions. They can review all the inputs provided by the data source and demand revisions from them to achieve a standard for the quality of information stored by the system. The "project creation" task was also assigned to the system admin.

In the project creation, the system admin can define the project, scope metadata, and allocate the key personnel to the project and assign responsibilities to each key personnel. While defining the project, "Project Name", "Client Name", "Project Location", "Contract Type" and "Start and Finish Dates" must be entered into the system. These are critical to perform project similarity analyses and search a project. In defining the scope of the project, the project types are considered in the first step. Scope of work in prefabricated construction projects usually comprises two general fields including building and infrastructure packages. Some projects comprise both, and some contain only a superstructure package. Therefore, any material waste management process and application should cover waste generation in both fields. When scope data of building is defined, the data related to "Building Name", "Building Type", "Building Category", "Building Quantity", "Number of Stories", and "Unit Area" should be defined. The scope of work should also be defined to the system using the infrastructure scope interface. This interface includes data related to “Package Name”, “Package Category”, “Quantity” and “Measurement Unit”. “Contract Type” and “Building Type” are pre-defined to avoid possible mismatches due to different wording or word mistakes. Finally, the key personnel and their responsibilities should be defined. In this field, along with their general identities and contact details, job titles of the users in the project or company organizational structure can be identified. Six job titles are considered in this system, and these titles are assigned to three user roles, as shown in the Table 8. However, the system allows the system admin to change the authorities of the job titles according to the company and project needs.

Table 8: Job title and their user roles

Job Title	User roles		
	System Admin	Waste Data Source	Waste Data User
Manager	X	X	X
Deputy Manager		X	X
Technical Personnel		X	X
Designer/Estimator		X	X
Document Controller	X		
Non-technical Personnel			X

6.2. Waste estimation

Waste estimation is the responsibility of the data sources. However, all the estimations are reviewed and revised by the system admin. The first step of waste estimation is the determination of the materials used in the project. While developing the waste estimation mechanism, a material list has been prepared. Based on this list, the data source can add materials to the project database with the quantity of the material obtained from the BOQ of the project, the revision number of BQO, and the location where the material will be used. Therefore, the same material can be allocated to the different locations of the project. Second, the data sources need to estimate the waste causes, and yet they estimate the causes for each material group instead of each material due to the high number of materials consumed in a project to simplify the estimation process. Otherwise, this process could be time-consuming and complicated. Figure 9 shows the interface used for assigning the waste causes to material groups. As seen in this figure, a list of material groups is retrieved automatically according to the materials allocated to this project previously. Finally, the data sources also estimate a waste rate for each material group instead of each material. Besides, the estimated waste rate of each material group is assigned automatically as the waste rate of all materials placed in this material group. There are two options for the user to estimate the waste rates. First, they can make estimations directly by considering the project. Second, they can make estimations according to the actual waste rates of material groups in the most similar project. As seen Figure 9, the most similar project, and the waste rates of each material group in this project are depicted in the interface.

At the end of this process, the waste baseline is created. This baseline provides a benchmark for comparing the actual waste data, captured by waste reports during the project life cycle, and waste rates and causes estimated in the waste estimation stage. The measuring waste data with the previous waste performances in completed projects in the company portfolio enables live monitoring of waste management performance in the current project. Therefore, real-time analysis of waste performance will assist decision-makers in taking on-time and efficient preventive actions for waste control.

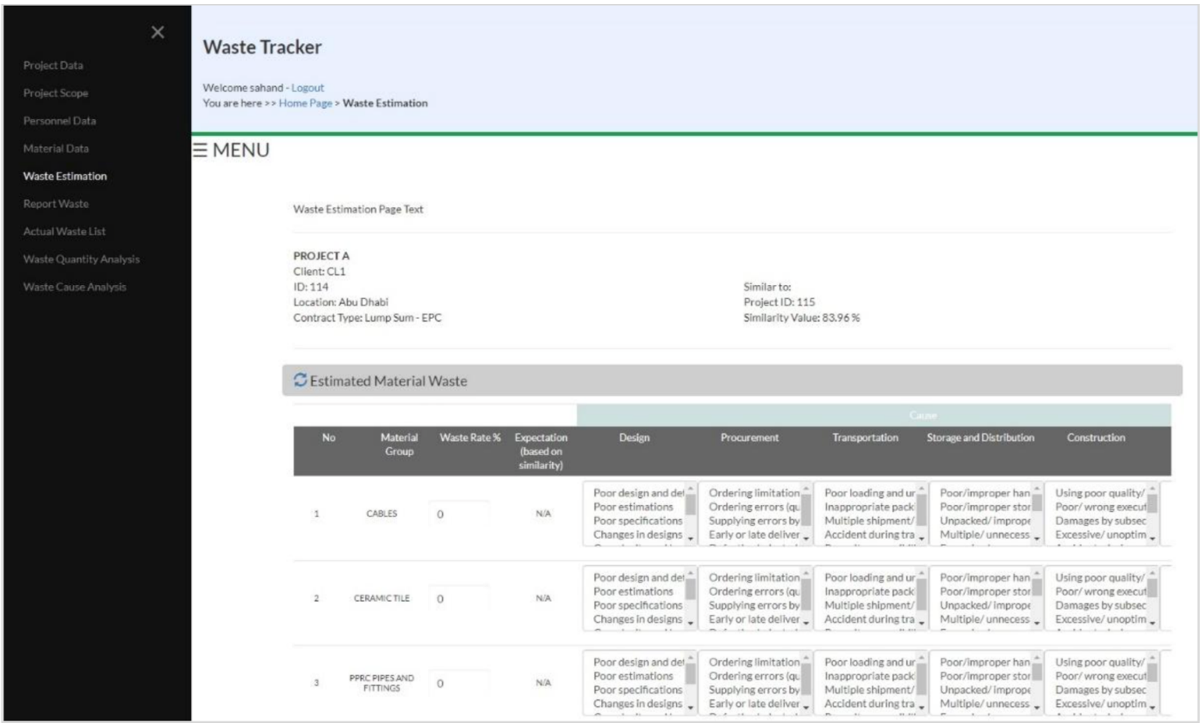


Figure 9: Waste estimation screen

6.3. Waste monitoring

In waste monitoring, four types of reports, namely “Damage/lost report”, “Material substitution report”, “Excessive material usage report” and “Error report”, are available. First, the report type should be selected, since a standard form is provided for different waste sources. After choosing the report type, it is necessary to locate the waste generation according to the project scope data. Identifying the location factor of the waste case will assist the project management team in the exact identification of waste generation causes. The locational factor for prefabricated construction projects in “Waste Tracker” is considered as the building number. For infrastructure packages, it is considered as the package name. Then, the material should be selected from the drop-down menu, which shows the complete list of material for the related location. Finally, the data sources need to identify the waste causes and wasted quantity, as shown in Figure 10. Each report is assigned by a unique number. The user can appoint a new number to the report or attach the current report to an existing one as a supplementary document. This report is submitted, and the system admin controls the submitted report. The system admin can accept or reject the report. When the system admin declines the report, the data sources are informed automatically by the system, and the sources can revise the report and resubmit for control. When it is accepted, this report is stored in the project database.

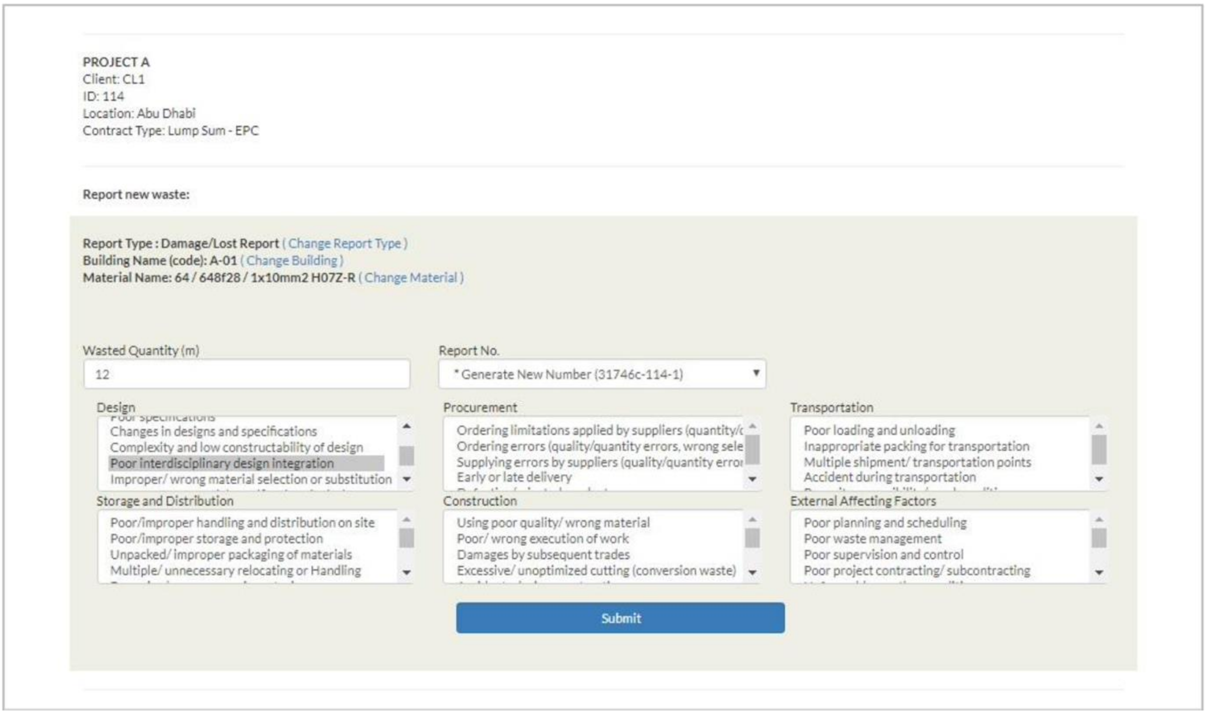
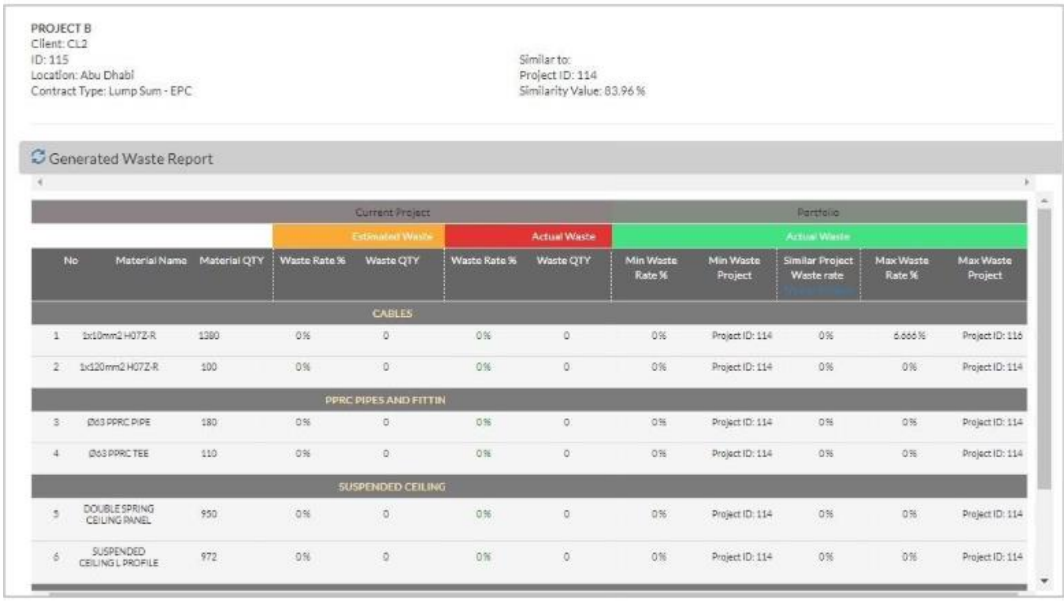


Figure 10: Waste report screen

6.4. Waste analysis

To perform the waste analysis, the project or material group can be selected using the search options. Then, two reports have been generated, namely “Waste quantity analysis” and “Waste causes analysis”. As an example, the output of waste quantity analysis is shown in Figure 11. In the waste quantity report, the estimated values of each material in the current project obtained at the waste estimation mechanism and the actual waste values of each material in the current project obtained at the waste monitoring mechanism are exhibited. Besides, the minimum and maximum waste rate for each material in the portfolio and the waste rate of each material in the most similar project can be seen in the output. Using the provided information, the user can evaluate the current project waste management performance in controlling the quantity of waste by comparing this performance with previous projects in the portfolio and the most similar project.



PROJECT B
Client: CL2
ID: 115
Location: Abu Dhabi
Contract Type: Lump Sum - EPC

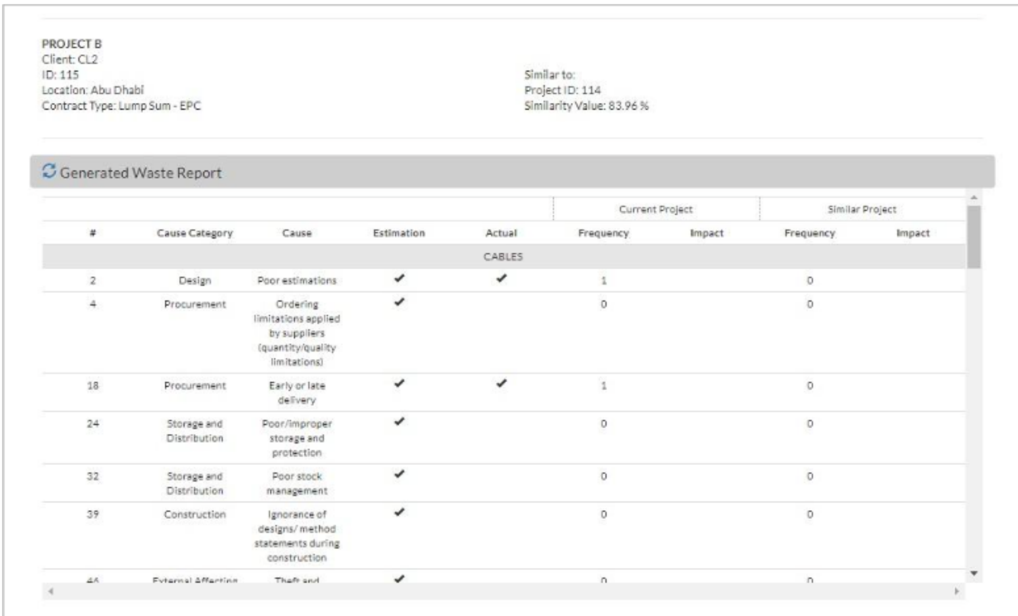
Similar to:
Project ID: 114
Similarity Value: 83.96 %

Generated Waste Report

			Current Project				Portfolio				
			Estimated Waste		Actual Waste		Actual Waste				
No	Material Name	Material QTY	Waste Rate %	Waste QTY	Waste Rate %	Waste QTY	Min Waste Rate %	Min Waste Project	Similar Project Waste rate	Max Waste Rate %	Max Waste Project
CABLES											
1	1x10mm2 H07Z-R	1380	0%	0	0%	0	0%	Project ID: 114	0%	6.666 %	Project ID: 116
2	1x120mm2 H07Z-R	100	0%	0	0%	0	0%	Project ID: 114	0%	0%	Project ID: 114
PPRC PIPES AND FITTIN											
3	Ø63 PPRC PIPE	180	0%	0	0%	0	0%	Project ID: 114	0%	0%	Project ID: 114
4	Ø63 PPRC TEE	110	0%	0	0%	0	0%	Project ID: 114	0%	0%	Project ID: 114
SUSPENDED CEILING											
5	DOUBLE SPRING CEILING PANEL	950	0%	0	0%	0	0%	Project ID: 114	0%	0%	Project ID: 114
6	SUSPENDED CEILING L PROFILE	972	0%	0	0%	0	0%	Project ID: 114	0%	0%	Project ID: 114

Figure 11: Waste quantity analysis screen

The waste causes analysis provides an output, which is shown in Figure 12 as an example. This output grants a list of estimated and actual waste causes for each material group. Besides, the frequency and impact of the waste causes can be seen in the current project and the most similar project. Based on this report, the root waste causes and their severeness for each material group can be revealed. Besides, by comparing the estimated and actual waste causes, the effectiveness of preventive actions to eliminate the waste causes can be assessed. Finally, the results of waste quality and quantity analysis can be exported to Excel for further analysis and visualization of results.



PROJECT B
Client: CL2
ID: 115
Location: Abu Dhabi
Contract Type: Lump Sum - EPC

Similar to:
Project ID: 114
Similarity Value: 83.96 %

Generated Waste Report

					Current Project		Similar Project	
#	Cause Category	Cause	Estimation	Actual	Frequency	Impact	Frequency	Impact
CABLES								
2	Design	Poor estimations	✔	✔	1		0	
4	Procurement	Ordering limitations applied by suppliers (quantity/quality limitations)	✔		0		0	
18	Procurement	Early or late delivery	✔	✔	1		0	
24	Storage and Distribution	Poor/improper storage and protection	✔		0		0	
32	Storage and Distribution	Poor stock management	✔		0		0	
39	Construction	Ignorance of designs/ method statements during construction	✔		0		0	

Figure 12: Waste causes analysis screen

7. Testing and validation of the tool

Testing and validation of the tool were carried out with a two-step procedure, as shown in Figure 1. Initially, the research team tested the functionality of the tool using black-box testing methods. This method of software testing examines the functionality of an application without considering the coding details and internal structure of the software. For performing the black box testing, a portfolio that comprises four projects with project and scope data was prepared by the researchers. Besides, for each project, materials, location of the materials, and quantities of the materials were prepared. Also, other information, such as the waste rate of each material group, the actual waste quantities of each material for each location of the projects were determined for each project one by one. Finally, all information was entered into the system. Finally, a hypothetical project was created by assigning all project attributes for checking project creation and waste estimation mechanism. In waste estimation, the similarity function was also tested if it can retrieve the most similar project. Some miscalculations were observed in similarity analysis because of the wrong categorization of project size. Therefore, the required amendments were performed. This project was stimulated by inserting estimated waste rates for each material group and submitting reports. Based on this simulation, the waste quantity and waste cause analyses were performed, and the reports of these analyses were generated. These reports were examined and compared with the reports obtained by manual calculations. Minor bugs were identified due to some coding problems in waste cause frequency calculations, and all identified bugs were fixed. Five professionals from three different prefabricated construction companies had been invited to hold for the validation process of the developed tool. All the companies have over 20 years of experience in the prefabrication industry. Besides, employing over 250 employees, all these companies are large. Table 9 shows detailed information about the participants. All the participants are well experienced and have deep knowledge about waste management because of their job designation.

Table 9: Participants of the testing and validation process

Participant ID	Company ID	Experience	Job Designation
1	B	9	Project Monitoring and Reporting Responsible
2	B	14	Manager of Construction and Project Management Department
3	A	12	Lead Planning and Project Control Professional
4	A	18	Director of Project Management Office
5	C	21	Senior Project Manager

Before using the developed tool, all participants had been informed about the proposed process of waste management using “waste tracker”. After giving the related information, all specific functions and processes of the waste tracker were explained by performing all waste management stages using a hypothetical project which had been used in black-box testing. Then, each participant was asked to enter one project data and create a pre-defined project scenario in the tool.

The strengths and weaknesses of the waste tracker proposed by the participants are listed:

- Participant 1 states that the most critical barrier to implementing effective waste management in construction companies is the lack of systematic data gathering. In most projects, the information flow from the construction site is deficient due to the emergence of extra reporting works. Therefore, he states that the proposed process and tool will enhance data capturing from construction sites by enforcing them to report the material waste data as part of the project progress report. Similarly, Participant 2 and Participant 5 appreciate the data-gathering abilities of the waste tracker. Participant 5 particularly declares that the systematic and pre-defined data capturing capacity of the tool can improve the knowledge flow within the company.
- Participant 2 proposes that manual data entering in the tool can be time-consuming and lead to inadequate data sharing from construction sites. Therefore, he suggests that the developed tool should be integrated with enterprise resource planning applications. Similarly, Participants 3 and 5 propose that the existing document control applications in the market and the developed tool should cooperate. Besides, Participant 4 suggests that the reporting module of the tool

should be simplified by increasing visualization so that the project participants can understand and use this module more easily. Participant 5 also suggests that the existing reporting module should be improved to produce knowledge from past projects for each material group. Otherwise, this module can inhibit the usage of the tool.

- Although all participants favored the web-based structure of the tool, Participant 5 recommends a standalone version of the waste tracker that can synchronize while connecting to the internet. It can benefit the prefabricated project in remote locations because of the poor internet connection.
- Participant 3 suggests that the unavailability of waste estimation records and actual waste rates is a crucial barrier for effective waste management in prefabricated construction projects. Using a waste tracker, companies can access this information without difficulty. Similarly, Participant 5 declares that this tool eliminates the loss of experience gained in past projects that can be considered one of the major causes of failures in waste management. Also, Participant 4 states that the upper management can become more aware of the importance of waste in their projects as they can easily access the material waste data and material waste reduction performance indexes.
- Participant 1 criticizes material entering the process in waste estimating since it can lead to an enormous workload due to a substantial number of materials used in prefabricated projects. Similarly, Participant 2 finds the material data entering process as time-consuming. Participant 3 offers a spreadsheet input option that can transfer the BOQ files to the system, and it can appear in the system for entering material data. Similarly, Participant 4 suggests that this tool can be developed as an add-on for spreadsheet software to simplify the waste estimation process, especially for design groups.

After the discussions, each participant has evaluated the tool on the Likert scale seen in Table 10. While “1” on the Likert scale denotes strongly disagree, “7” states strongly agree. Based on the responses of the participants, a positive impression can be observed. Considering their general opinion about “Waste Tracker”, the participants evaluated the application as a completely beneficial tool for establishing efficient waste management in construction companies.

Table 10: Participants responses to interview questions

Expression	Participant					Avg.
	1	2	3	4	5	
Searching and filtering mechanism is properly developed and useful.	5	4	6	6	5	5.20
Project data entering process is suitable and user-friendly.	7	6	6	7	7	6.60
Project data are adequate and comprehensive for project analysis and data retrieval.	6	6	6	5	6	5.80
Scope data entering process is suitable and user-friendly.	7	6	5	6	6	6.00
Scope data is adequate and comprehensive for project analysis and data retrieval.	6	7	5	7	6	6.20
Material data entering process is suitable and user-friendly.	4	4	5	5	5	4.60
Material groups and data are comprehensive and flexible for waste management.	5	6	7	6	7	6.20
Waste estimation process is suitable and user-friendly.	4	5	5	6	6	5.20
Waste estimation data are adequate and flexible for waste management.	6	7	6	7	7	6.60
Similarity calculation attributes are logical and useful.	6	6	5	6	6	5.80
The produced waste quantity information is adequate and useful for efficient waste management.	6	7	6	5	6	6.00
The produced waste cause analyzing information is adequate and beneficial for efficient waste management.	6	6	7	5	6	6.00
In general, the "Waste Tracker" is useful and may have positive effects on waste management in construction companies.	6	7	6	6	6	6.20
Overall evaluation	5.69	5.92	5.77	5.92	6.08	5.88

Results show that the developed tool is appreciated by the participants and found useful to eliminate problems in managing material waste in prefabricated construction projects. The participants also warned about the required cultural change to implement this process and the necessity of new roles for performing the tool effectively. It is believed that these barriers can be eliminated by training, encouraging the employees, and developing an appropriate organizational structure.

8. Implications for research and practice

This study shows that a knowledge-based tool integrating all the steps of waste management can be useful for waste management of prefabricated steel construction projects as it offers several implications for capturing the waste data collaboratively, managing the knowledge on waste, performing integrated waste management tasks, and integration with BIM.

8.1. Implications for capturing waste data

Akinade et al. (2018) argued that one limitation of the existing waste management tools is insufficient construction and demolition data. Without sufficient data, waste management cannot be performed at the desired level. First, the companies cannot estimate the waste accurately (Bilal et al., 2016). Whereas waste estimation is crucial for effective waste management according to the practitioners (Cheng and Ma, 2013), since the designers cannot optimize their designs and the construction companies cannot manage the waste in their projects without accurate waste estimation. Also, the other waste management processes, namely monitoring and analyzing the waste, require the waste data. The waste tracker will assist all parties in capturing the data. However, capturing waste data is not a simple task for construction companies, and most companies confront aforementioned difficulties while collecting this data using traditional data collection methods. On the other hand, since this tool uses a live knowledge capture approach, companies can eliminate these difficulties. Besides, the reliability of the data captured in this tool is satisfied, since all data entered into the system is verified by the high-level users. Consequently, with the waste tracker, the parties can provide reliable waste knowledge collaboratively while performing their activities on the project.

8.2. Implications for managing waste

Although the criticality of knowledge management in the context of sustainability is emphasized in the literature, the implementation level is not at the desired level (Martins et al., 2019). Therefore, knowledge-based tools are critical to achieving the benefits that emerged due to the efficient application of knowledge management. However, one gap in waste management is the lack of a knowledge-based waste management tool that captures, stores, and retrieves the data. The waste tracker can be an excellent solution for this gap. Besides, it provides a framework for exchanging the emerged waste knowledge between the parties; therefore, the parties can generate more creative solutions while performing waste management (Lopes et al., 2017). Finally, the other critical issue Akinade et al. (2018) mentions is that unclear responsibilities in waste management can be eliminated by this tool, since in this tool, each user has strict roles, and these roles are assigned to each user at the beginning of the project. Therefore, each user knows their responsibilities and authorities in the system which prevents all potential waste management conflicts.

8.3. Implications for integrated waste management

Waste management comprises different processes, namely waste estimation, waste monitoring, and waste analyses. Although all these processes are interrelated, most of the studies consider all these processes separately. In other words, different tools are used to perform these waste management processes, which leads to compatibility problems and extra efforts to insert the previously obtained outcomes as incomes to the next process. Therefore, companies struggle to apply these tools effectively. However, the waste tracker integrates all these processes that eliminate these problems. The tool encourages the companies to apply a waste management tool critical for more sustainable construction projects. Besides, another issue related to existing tools is life cycle waste assessment. Most waste management tools focus on specific project stages instead of the entire life cycle of the project (Akinade et al., 2018), whereas the projects generate not only waste at the construction stage but also throughout its life. However, the proposed framework can be used throughout the entire project life cycle. Therefore, this tool has great potential to perform life cycle waste assessment.

8.4. Implications considering BIM

In recent years, BIM has been widely integrated into sustainability. However, to apply BIM, first, the information should be available (Lu et al., 2017). Otherwise, all these tools do not provide any reliable outcomes. In other words, the effectiveness of all these tools depends on the information embedded in the BIM model. This study suggests a framework that can be used for providing reliable and sufficient knowledge. Therefore, the BIM models become more reliable and efficient for waste management. Also, integration of the proposed tool and BIM can automate inserting the reliable waste data into the BIM model which increases the efficiency and reliability of the BIM-based waste management tools. Finally, the framework used in the development of this tool can be adjusted according to the requirements of different construction project types. Thus, new knowledge-based tools can be developed based on the proposed framework.

9. Conclusions

The primary aim of this study is to develop a knowledge-based process model and a tool that can be used for integrating all stages conducted in material waste management in prefabricated steel construction projects. Research findings reveal that the existing waste management practices often ignore the storage of lessons learned in projects, and waste management is conducted according to the personal experiences of project team members since storing all knowledge that emerged in a project can be difficult and time-consuming. A knowledge-based tool for capturing and storing wase-related knowledge is needed to improve the waste management process. On the other hand, the quality of the captured knowledge is critical, therefore this tool should be centralized and have an approval mechanism for checking the quality of the knowledge to be entered into the tool. Thus, a web-based tool that authorizes the user based on their roles can be used for monitoring and controlling the data entries. A web-based system can improve the transfer of knowledge between projects and lead to a decrease in the cost due to the “reinvention of the wheel” for waste management practices. Consequently, in this study, a web-based knowledge-based tool was developed based on the proposed process model, namely the knowledge-based waste tracker process model, based on the material list developed for prefabricated steel construction projects and lists of waste causes determined in collaboration with domain experts. A novel similarity assessment method was also developed to foster learning about waste from previous projects.

The tool integrates all stages, namely waste estimation, waste monitoring, and waste analysis. Therefore, it can be used for estimation, tracking, and analysis of waste and assessment of the waste management performance by comparing the actual and the estimated level of waste. Integrating these stages is critical to perform waste management effectively since the success of these stages depends on each other. For instance, making accurate estimations requires a comprehensive corporate memory that comprises waste-related knowledge from former projects. This corporate memory can be formed by monitoring the projects. Similarly, analyzing the performance of waste management in a project can be performed only by estimating the waste rates and measuring the actual waste rates.

On the other hand, the tool has some limitations, as indicated by the experts. First, as this tool is a prototype, data security is not a priority in this study. Therefore, the companies which will apply the system should make improvements in data security. To achieve data security, advanced firewall technologies, such as SecureSphere Database Firewall (Cherry, 2013) can be used as well as blockchain technology for secure data transfer. Second, this system has no capability of inter-operating with different commercial software which can be used for capturing knowledge automatically. Especially, the materials and their attributes, such as quantities, locations, and units, should be imported from Excel to increase the usability of the proposed tool. Integrating the tool with existing enterprise resource planning applications in the market can facilitate the data entry process. Similarly, the interoperability between this system and BIM can eliminate many time-consuming processes. The other important limitation of this tool is that the data about the cost of waste material is not integrated into the system due to lack of data and the inability/unwillingness of participants to provide cost information. Therefore, the cost of the material waste could not be quantified in this study. However, integrating the "Waste Tracker" with cost control applications of companies may enable the analysis of the cost impact of the material waste in projects.

This study can also be improved in further studies. First, the sample of the study can be changed. For instance, the professionals from the newly established companies applying the green approaches in their activities can be used instead of the professionals from the experienced companies. They can provide different perspectives and additional insights since these companies have different procedures and perspectives in waste management compared to traditional companies. Therefore, new frameworks which can be more effective in these companies shall be developed. In this study, the method proposed by Boriah et al. (2008) was adopted for identifying the most similar projects. There are alternative similarity assessment methods, such as case-based reasoning and natural language processing, to retrieve the most similar cases, which could have been used during tool development and can be used in further studies. The project attributes used for similarity assessment can apply for different project types, however, the weights can be adjusted by the potential users if necessary. Moreover, in this study, three building types confronted widely in prefabricated steel structure projects were considered, which can also be customized if needed. Although this tool was developed considering the prefabricated steel construction projects, the proposed framework and the knowledge-based approach can be used for the development of similar tools for different companies and project types. Finally, the absence of a stand-alone and synchronized version of the tool, which can eliminate problems due to poor web access in remote construction sites can be listed as a limitation that can be considered in forthcoming studies.

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