A Decision Support Tool to assist demolition contractors in choosing to Reuse, Recycle or Recover building elements

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Abstract

The construction industry is responsible for a high waste production and extraction of natural resources. Therefore, it should shift towards a circular economy, which means that waste should be designed-out and material loops must be closed. Demolition contractors have an important role in this transition, as they should decide what waste management strategy should be executed for building elements. However, little is described in literature about how demolition contractors can evaluate waste management strategies and recent studies overlook the implementation of evaluation methods in the decision-making process of demolition contractors. This research followed a design-science research methodology to develop a Decision Support Tool (DST) which should assist demolition contractors during the decision-making regarding the waste management strategies for all building elements present in a to-be-demolished building. Multiple design cycles were executed consisting out of different activities; problem identification, define objectives, design and development, demonstration, evaluation and communication. The DST uses a Multi-Criteria Decision Methodology to compare three different waste management strategies (i.e., Reuse, Recycle, and Recover) by evaluating four main criteria (i.e., economic costs, environmental gain, technical feasibility and social gain). The output of the DST is (1) a ranking which provides the optimal waste management strategy regarding the four main criteria, and (2) a graphical presentation of the absolute and relative difference between the strategies regarding economic costs and environmental gain. It was observed that the use of the DST will have some implications on the current work process of the demolition contractor. By using the DST, decisions are not longer based on tacit knowledge or only on economic costs, but also on environmental impact, technical feasibility and social impact. Therefore, the DST can assist demolition contractors in the transition towards a circular economy.

Keywords: circular economy, demolition, decision-making, design-science, waste management

1 Introduction

The construction industry should shift from a linear economy towards a circular economy. A reason for this is that the sector produces a huge amount of waste each year. It is responsible for 40% of the total waste production in Europe. A big part of this Construction and Demolition Waste (CDW) is disposed to landfill, which leads to negative environmental impacts such as soil and groundwater pollution (Gálvez-Martos et al., 2018; Llatas, 2011). In addition, the sector consumes 40% of the raw materials worldwide. Continuing this leads to a natural resource depletion (Yilmaz et al., 2019). Therefore, a shift is needed from a 'take-make-use-dispose' economy to a circular economy. This circular economy can be defined as a regenerative system that aims to close material loops and to design out waste (Ellen MacArthur Foundation, 2013).

Demolition contractors have an important role in this transition. These companies should determine what they will do with building elements present in a demolition project. More specific, demolition contractors should determine what waste management strategies they will use for these building elements. Existing waste hierarchy models (e.g., 9R-model) indicate that multiple waste management strategies can be chosen for building elements present in a to-be-demolished building, for instance; Reuse, Remanufacture, Recycling, and Recover (Kirchherr et al., 2017; Zhang et al., 2021). When a building element will be reused, this means that it is used for the same function or purpose by another consumer (e.g. disassembling a kitchen and installing it in another house). With Remanufacture, parts of a building element will be used to produce a new building element with the same function (e.g. using legs of a wooden frame to produce a new frame). When a building element will be recycled, it will be processed to the raw material which is of the same (high) quality or a lower quality (e.g. concrete can be processed to aggregates for new concrete or to debris for road foundation). Lastly, Recover indicates that building elements will be incinerated (energy production) or landfilled (e.g., building elements that are contaminated with asbestos). All different strategies have their own consequences in terms of costs regarding materials, executed labour, energy usage, capital and other externalities such as greenhouse gas (GHG) emissions (Ellen MacArthur Foundation, 2013). For example, disassembling a building element for reuse can result in higher demolition cost than when the element is disposed for landfill. A reason for this is that disassembling a building element (e.g., a kitchen) will take more time than when a crane is used to remove the element and will thus lead to higher costs for removal. However, due to reuse it is prevented that a new building element must be produced, which means that there is an environmental gain compared to recover (of the element itself). This indicates that demolition contractors should actually evaluate the different consequences of several waste management strategies for a building element before choosing and executing one strategy.

During a previous executed field study, in which the researcher executed 300 hours of participant observations during a circular demolition project, it was observed that the demolition contractor did not evaluate the consequences of different waste management strategies for building elements (Hulsbeek & van den Berg, 2022). Indeed, the demolition contractor had to choose during the execution phase of the project what waste management strategy would be used for the different building elements. It was observed that the demolition contractor did not know what building elements could be recovered and for which there was an economic demand. Due to that, building elements of good quality were destructed which means that downcycling occurred, i.e. a reduction of the raw material quality, potential for future uses, and economic value (Chini, 2007). This illustrates that decisions regarding waste management strategies are made ad-hoc during the execution phase without evaluating the consequences of different strategies. By that, inefficient waste management strategies can be chosen by demolition contractors, which lead to, for example, higher economic costs or higher GHG-emissions. There is thus a need to support decisions.

Therefore, the aim of this research is to develop a Decision Support Tool (DST) for demolition contractors to make a more-informed decision regarding the waste management strategies of building elements. By that, demolition contractors could be assisted in the shift towards a circular economy. This article starts with a literature review on the current used evaluation methods and models for similar issues. Thereafter, the design-science research methodology applied in this research is elaborated. Subsequently, the results obtained during the execution of the different design activities are presented. After that, these results are discussed, including the limitations of this research and suggestions for future research. The article ends with a conclusion.

2 Literature review

This literature review first elaborates on the current practice of decision-making for waste management strategies at demolition contractors. Thereafter, it is analysed what tools and methods are already available for similar issues. Subsequently, it is elaborated for which specific issues and users these tools and methods are developed.

2.1 Current practice in demolition

Building demolition is the final stage within the life-cycle of a building. This does not always indicate that the building is in bad condition. Buildings are also demolished as these cannot be used for the desired function or they should be removed to construct new infrastructure (Huuhka & Lahdensivu, 2014). This demolition can be done in various ways. Traditionally, building elements will be destructed and disposed for recycling or landfill. This leads to high amounts of waste (Pun et al., 2006). However, deconstructing buildings is an upcoming demolition activity and will be used more in future. Deconstruction, also called 'reverse-construction', allows to recover building elements for reuse and leads to higher recycling rates as the building can be dismantled part by part (Bertino, et al., 2021). This is needed to shift towards a circular economy. The shift to deconstructing buildings will also impact the project organisation, as other demolition activities must be executed when a building element will be recovered for reuse. But, there are barriers which hamper the reuse of building elements present in buildings, e.g., the high disassembly costs, low disposal costs and the fact that a lot of buildings are not demountable (Hosseini et al., 2015; Durmisevic & Binnemars, 2014). Demolition contractors should analyse what the best waste management strategy is for the building elements by evaluating these kinds of barriers and factors.

However, lots of decisions are made by not evaluating these kinds of factors but are made by using experiences and knowledge (i.e., tacit knowledge). This was observed during the previous executed field study. Tacit knowledge is defined by Nonaka and Takeuchi (1995, p. 8) as "highly personal and hard to formalize, making it difficult to communicate or to share with others. Subjective insights, intuitions, and hunches fall into this category of knowledge". As an example, the project manager argued that they never sold glass wool plates and that it would also not be possible in this project. However, the researcher got it picked up for free and prevented that high disposal costs had to be paid (Hulsbeek & van den Berg, 2022). This indicates that the use of tacit knowledge can lead to inefficient decisions regarding waste management strategies, which means that it is important to create a more-informed decision-making process.

Within literature, it is described that demolition contractors do not make cost estimations for different demolition techniques available. So, a demolition engineer does only make a cost estimation for the selected demolition techniques, which means that other techniques are not compared regarding economic costs (Abdullah, 2003). By that, there is a chance that a demolition contractor does not use the economic optimal demolition technique. During the literature analysis it was found that recent studies focused on the differences between demolition and deconstruction (Coelho & de Brito, 2013; Bertino, et al., 2021), the selection of appropriate demolition techniques (Abdullah, 2003) and the barriers for deconstruction and reuse (Iacovidou & Purnell, 2016; Hosseini et al., 2015). However, little is described in literature about how demolition contractors currently make their decisions regarding waste management strategies and how strategies can be evaluated.

2.2 Methods for evaluating waste management strategies

Regarding the end-of-life decision making for (industrial) products, Vanson et al. (2022) showed that different evaluation methods can be used to facilitate the end-of-life decision-making. These are mathematical models, multi-criteria analyses (MCAs) or cost-benefit analyses. They evaluated also different end-of-life strategies for an EBS-module by modelling generalized coloured stochastic Petri nets. However, they argued that this became complex when you have products with different characteristics. The model was based on variables which influence the decision-making. These were categorized under product health state, the market demand and regeneration processes (which included parameters of different waste management strategies). Alamerew and Brissaud (2019) identified three main evaluation methods for the end-of-life decision making for product recovery: empirical methods, mathematical optimization methods and multi-criteria decision methodologies. With empirical methods, decision-making is based on the experiences gained from previous cases. They argued that mathematical optimization methods are focusing on economic costs only using quantitative factors. Contrarily, Multi-Criteria Decision Methodologies (MCDM) can combine quantitative and qualitative factors, and users can consider their own preferences during the decision-making. In their study, they developed a Product Recovery Multi-Criteria Decision Tool, to assess product end-of-life strategies.

MCAs are used in previous studies with respect to decision-making regarding waste management strategies for complete buildings, products, and demolition techniques. Roussat et al. (2009) used an MCA to compare different waste management strategies during the demolition of complete buildings. By that, they could consider different criteria to determine the most sustainable waste management strategy for complete buildings. Fiore et al. (2020) used an MCA to develop a methodology which could be used by public administration to decide what interventions are most appropriate on school buildings. This was done by considering different evaluation criteria (such as costs, disturbance and environmental impact). In that way, different alternatives were compared, e.g. selective demolition versus traditional demolition. Alamerew et al. (2020) used a MCDM to facilitate the decision-making process for the product-level circularity strategies. They analysed what the best product-level circularity strategy is for products of companies who offer these to clients. The reason that they chose a MCDM was that this evaluation method can be used to solve complex problems and that both qualitative and quantitative factors can be used in the decision-making.

A mathematical programming model was created by Aidonis (2019) to support the decision-making process to select the optimal dismantling technique for buildings which are at their end-of-life. The model had to propose the dismantling technique which is optimal regarding costs and time needed to complete the deconstruction and demolition of buildings. According to Aidonis (2019), the decision-making model should incorporate the environmental impact, however this was not added in this model. It was argued that in future a new model should contain both the environmental and technological issues as well. Bentaha et al. (2020) created a model to select the best disassembly process for products (with the maximum profit), by considering the variability of the products' quality. This model was more applicable for the manufacturing industry. So, there are different evaluation models and methods developed for similar issues, the specific focus of these models is elaborated next.

2.3 Focus of the existing evaluation methods

Models are developed for decision-making regarding waste management strategies for single products, (Vanson et al., 2022; Alamerew et al., 2020). However, these models are not applied on building elements. Alamerew et al. (2020) focused specifically on what the best circular strategy is for products (e.g. storage furniture) and what the consequences are for customers and companies. Moreover, methods and models were developed for decision-making regarding dismantling or disassembly techniques, waste management strategies, and interventions for complete buildings (Fiore et al., 2020; Aidonis, 2019; Roussat et al., 2009; Bentaha, Voisin, & Marangé, 2020). These do thus also not focus on building elements.

The methods and models proposed in literature are developed for different users. Alamerew et al. (2020) created an evaluation method for companies who produce products and provide a service for these products to customers. Fiore et al. (2020) developed an evaluation method which proposed the most appropriate intervention strategies of a complete building for the public administration. For some tools, methods, and models described in literature, there was no specific user identified. As an example, the model of Aidonis (2019) could support decision-makers to choose the optimal dismantling technique for buildings. However, it is not defined who these decision-makers are (e.g., property owners or demolition contractors). Besides that, Akanbi et al. (2018) developed a BIM-based tool that can be used by designers to estimate the salvage performance of a building. This indicates how much of a building can be reused or recycled after a certain lifespan.

Moreover, the developed evaluation methods or models do consider both qualitative and quantitative factors to make decisions regarding waste management strategies, dismantling techniques or intervention strategies. The most common factors used were the product health state, economic costs, environmental impact, social impact, and time (Vanson et al., 2022; Roussat et al., 2009; Fiore et al., 2020; Aidonis, 2019; Bentaha et al., 2020). So, both qualitative and quantitative factors should be considered in the decision-making process for waste management strategies.

Concluding this literature review, it could be said that there are little evaluation models or methods published in recent years which could support (1) demolition contractors during the decision-making process regarding waste management strategies for (2) individual building elements. Moreover, it becomes clear that demolition contractors (3) should evaluate diverse quantitative and qualitative factors during the decision-making regarding waste management strategies. However, little is described about what factors are important to consider during the decision-making as a demolition contractor. Besides that, the studies analysed (4) do focus more on the design of the tools and methods, and are not focusing on the implementation of these in the decision-making process at demolition contractors.

3 Design-science research methodology

The goal of this research was to develop a Decision Support Tool that can support demolition contractors to make more-informed decisions regarding the waste management strategies for building elements. To achieve this goal, a design-science research methodology was followed. During a design-science research, an artifact is developed which could solve a problem within a certain context (Peffers et al., 2007; Mullarkey & Hevner, 2019; Sein et al., 2011; Wieringa, 2014). The design science process model of Peffers et al. (2007) was used to develop the DST. This process model was chosen as all activities belonging to this design cycle could be executed during this research. The process model consists of six different activities that are executed consecutively; problem identification, define objectives, design and development, demonstration, evaluation and communication. The problem identification is executed once, the other steps are executed multiple times by performing iterations over the design cycles. The evaluation results of the demonstration and possible feedback from the communication is used as input for the new design cycle again. In total, three design cycles were fully executed to create a final design of the DST.

The so-called DSRM Process Model of Peffers et al. (2007) was adapted for this research, see Figure 1. This methodology section continues by elaborating how the activities of the three design cycles were executed and how data was collected.

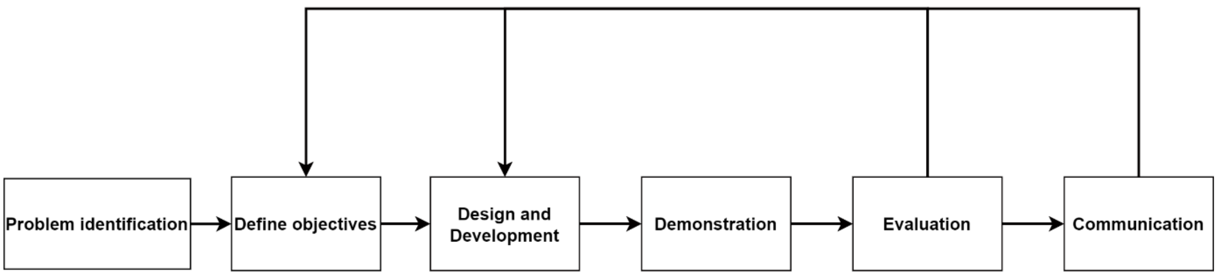

Figure 1 - DSRM process model used in this research (adapted from Peffers et al. (2007))

First design cycle

During the problem identification, the researcher analysed how the demolition contractor currently made its decisions regarding the waste management strategies in practice. The researcher could better understand the problem and knew what should be improved. Moreover, it was observed what factors are considered by the demolition contractor to make a decision. This was done by using three data collection methods: a document analysis, project observations and conducting interviews.

During the document analysis, multiple cost estimations and material inventories of different projects were analysed. The cost estimations were used to determine how these are set up and whether these contained waste management strategies. Material inventories were analysed to determine what information is available about building elements for the demolition contractor. Three projects were visited to observe how decisions were made in practice and what factors do influence these decisions. It was also possible to talk with workers and site managers, to collect more data. One of these projects was in the procurement phase, and the other two projects were already in the execution phase. Specific information of these projects is provided in Appendix A. The observations were noted down in a field diary and pictures were made to collect the data.

The interviews were conducted at 11 persons who had different functions: estimators, planning engineers, site managers, project managers and directors. Specific information about the interviewees can be found in Appendix B. The interviews were semi-structured, which indicates that questions were prepared. However, follow-up questions were asked to obtain more in-depth information. They were conducted physically and online, and had a duration of one hour. After the interviews were transcribed, they were coded. This was done by using the axial coding method (Locke et al., 2022), to relate the individual codes (open codes) of the interviewees to each other (axial codes). This method is illustrated for one interview question in Appendix C.

The second part of the problem identification consisted out of analysing what factors are important to consider during the decision-making according to existing literature. This was done by analysing scientific articles.

The data collected during the problem identification was used in the 'define objectives' phase, as objectives should be derived from the problem identification. An overall objective was divided into so-called system objectives of the DST (Peffers et al., 2007). These requirements had to be prioritized to make a division in their importance, this was done by using the MoSCoW method. This method was chosen as the prioritization can be done together with stakeholders, in this case the demolition contractor (Hudaib et al., 2018). The MoSCoW method is further explained in the result section. Besides that, some requirements had to be made SMART (Specific, Measurable, Achievable, Reasonable and Time-bound) to make sure that these could be processed in the DST. This resulted in a list of requirements which was used to create a first design in the ‘design and development’ phase. During this phase, a (static) conceptual model was made which was transferred into a (dynamic) model in Microsoft Excel.

The ‘demonstration’ of the first design was done by using a focus group which consisted out of four employees of the demolition contractor with different functions (estimator, planning engineer, project manager and director). The list of requirements, including the prioritization and how they were made SMART, was presented and discussed during this focus group. Thereafter, the design was presented including the system boundaries and assumptions made for the first design. Finally, the DST was jointly used to determine what waste management strategy should be chosen for plasterboards.

The feedback given during this demonstration was analysed during the ‘evaluation’ phase. Moreover, an evaluation form (see Appendix D) was used to receive additional feedback from the individuals about the design. The results from this evaluation were used as input for the second design cycle. During the first design cycle, feedback was also received by organizing meetings with the internal and external supervisors of the research. This can be seen as the ‘communication’ phase of the design cycle. However, this feedback was given throughout the whole design cycle and not only at the end of the cycle. The feedback was about the design process in general and contained for instance how requirements should be set-up and how the demonstration of the designs could be executed. This feedback was used throughout the whole design process and is therefore not separately discussed in the result section. The communication was executed in the same way during the second and third cycle and will not be elaborated further.

Second design cycle

The second design cycle started with the ‘define objectives’ activity. The evaluation results were used to analyse what requirements had to be changed and what improvements were needed. When necessary, additional literature was analysed to determine how requirements or aspects of the design could be changed or improved. During the ‘design and development’ phase, the new requirements list and evaluation results regarding the design were used to create a new design.

The 'demonstration' activity was executed by using the Technical Action Research (TAR) method as described by Wieringa (2014). With the TAR method, an artifact can be tested by the end-user to solve a problem in the real-world. By that, the researcher can identify the effects of the designed artifact in practice. This method was used as it is artifact-driven, which means that the focus is on the design of the DST. Other types of action-research are problem-driven (Wieringa, 2014), and are therefore not useful in this research. During this TAR method, the DST was used in practice by six employees of the demolition contractor (three estimators and three project managers). The researcher presented the new design to the employees and after that they had to use the model. The employees had to fill in the DST for five different building elements (plasterboards, ceiling panels, concrete floors, wooden beams and bricks). The researcher observed how the employees were using the model and noted down their comments and recommendations for improvements. Thereafter, the employees filled in another evaluation form (see Appendix E) to receive additional feedback. The results of the TAR and evaluation form were analysed during the 'evaluation' activity.

Third design cycle

This design cycle started with the 'define objectives' activity, in which the evaluation results were used to improve requirements when necessary. Thereafter, a new design was created by using the refined requirements lists and the evaluation results regarding the design. Some suggested improvements given in these evaluation results were not possible to implement in the new design. This was not possible with the available resources during this research. The new design was treated as the final design.

The 'demonstration' activity was executed by testing the DST on a real demolition project of the demolition contractor. A project manager had to use the DST to determine the waste management strategy for a building element within this project. It was tested whether the DST functioned for a real demolition project and the impact of the DST on the current work process was analysed. The specific characteristics of this case project are provided in Appendix A. During the 'evaluation' phase, the results and observations of the test were analysed. These evaluation results contained some suggestions for improvement which could be interesting to execute during future research.

4 Results

The results of the problem identification till the evaluation are described for all design cycles in Paragraph 4.1 till 4.4. A graphical summary of the main results per design activity is provided in Figure 2 below. These results are elaborated in more detail in the upcoming paragraphs.

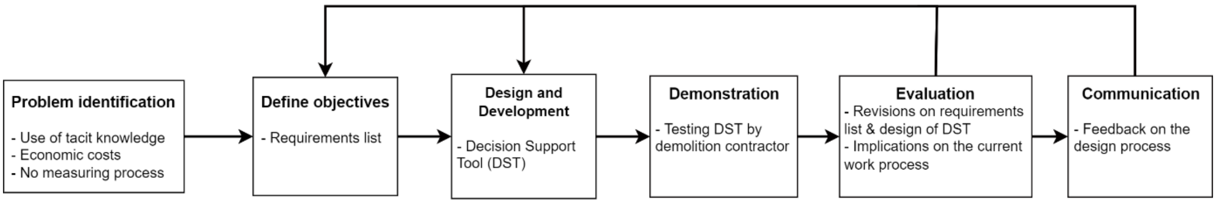

Figure 2 - Graphical summary of main results per design activity

4.1 Problem identification: current decision-making process

The problem identification was the first step of the process model. During this step, it was observed how the demolition contractor does make its decisions in practice (Paragraph 4.1.1). Thereafter, it is analysed what factors are important to consider during the decision-making according to literature (Paragraph 4.1.2).

4.1.1 Decision-making by the demolition contractor in practice

The demolition contractor makes use of different waste hierarchy models (e.g., the Ladder of Lansink or a 10R-model) to make a distinction between waste management strategies. However, it became clear that these models do contain waste management strategies which are not applicable for demolition contractors when it is decided that a building will be demolished. These waste management strategies (i.e., Refuse, Rethink and Reduce) are about preventing or reducing the amount of waste. Moreover, there are waste management strategies which are not often chosen by the demolition contractor. These strategies (i.e., Repair, Refurbish, Remanufacture and Repurpose) focus on improving the quality of building elements, or using building elements for other applications. Making a distinction between different waste management strategies was argued to be important, although it is realized that a higher step in the waste hierarchy is not always financially or environmentally better. For instance, DIR.2 argued that transporting an element over thousand kilometres to refurbish (R5) it, will not be better than remanufacturing (R6) the element in the neighbourhood of the demolition project (in terms of energy usage and CO_2-emission). So, strategies about preventing or reducing waste are not applicable for demolition contractors and strategies about improving the quality of building elements are not often used.

From the analysis of cost estimations and interviews, it was concluded that the decisions regarding waste management strategies are sometimes made during the procurement phase. Cost estimations are made by estimators and project managers when the demolition contractor is invited to make a bid for a client. The current cost estimations contain two separate cost items: one for disassembling building elements and one for the revenues received from the sale of these building elements. However, these are rough estimations. Within cost estimations, no division is made in waste management strategies. The cost estimation of Project 1 contained a product-specific cost items for sawing a concrete floor. Interviewees argued that these are only made for circular demolition projects or when the client requires this. PM.1 argued; "The costs for reusing hollow-core slab floors can completely be calculated by including sawing, removing and finally lifting it of the building". So, during the procurement phase it is not a regular process to determine the waste management strategy for building elements. Most decisions are made after the project is awarded (i.e., during the execution phase), which was also the case at Project 2 and 3.

The demolition contractor uses different data sources to make a decision for a waste management strategy. It was argued that most decisions are based on tacit knowledge of project managers and directors. They have the knowledge about the market demand for building elements and whether a building can be demolished in a certain way (EST.1, PM.1-3, DIR.2). Another data source used is the project documentation which is available for the demolition contractor, i.e., technical drawings, material inventories, asbestos and Chrome6 reports, and pictures. These documents are used to analyse what building elements are present including the amount, the quality, the connections used, and whether the building elements are contaminated. Also, interviewees argued that project visits during the procurement phase are important to see what building elements are present including their quality. Project managers do contact traders during the preparation and execution phases to check the market demand for building elements present. Lastly, employees discuss internally what waste management strategy can be assigned to a building element. So, different data sources are used. However, the tacit knowledge of project managers and directors is currently the most important data source during the decision-making.

The financial factor is the determinative factor for the demolition contractor regarding the choice for a certain waste management strategy. It is determined whether there is a market demand for the building elements, and if a certain waste management strategy is financially feasible. This financial feasibility is about the balance between the costs and possible revenues received of a certain waste management strategy. DIR.1 argued that demolition costs are depending on how a building element is extracted from the building, i.e., as product (e.g., complete wooden frame), semi-finished product (e.g., legs of the wooden frame) or as raw material (e.g., the wood itself). This indicates that each waste management strategy has different costs, and that the financial feasibility also depends on the technical feasibility. Interviewees argued that landfill costs, material handling costs and revenues from selling products and (raw) materials do influence the decision. A change in one of these costs or revenues could lead to the fact that other waste management strategies become more or less financial interesting for the demolition contractor. The demolition contractor also analyses whether it is financial interesting to clean contaminated elements. For instance, at Project 2, iron ceiling panels were cleaned to remove the asbestos (Figure 3). By that, the amount of asbestos-contaminated waste was reduced, and revenues could be received by selling these panels or disposing it as metal-scrap. Lastly, the demolition contractor actively searches for reuse options during the procurement phase in case this is appreciated by the client in terms of a fictive discount (Project 1). So, it can be said that the financial factor is determinative during the decision-making process.

(a) (b)

Figure 3 - (a) ceiling panels with asbestos pollution, (b) cleaned ceilings panels stored at project location (Project 2)

However, sometimes waste management strategies are chosen which lead to extra costs for the demolition contractor. DIR.1-2 argued that they invest in new techniques and methods to become the forerunner in certain processes or to meet the project goals. As an example, they removed an asbestos-glue from hardwood frames, to transport the hardwood to a hub where the frames are remanufactured into new wooden beams. By that, a new process was set up, although this was not financially optimal in the beginning.

The demolition contractor does also consider the technical feasibility during the decision-making. Interviewees argued that it should be technical feasible to extract building elements in such a way that these can be used for a certain waste management strategy. All interviewees argued that the demountability or releasability of a building element is important for the technical feasibility. Also, interviewees argued that the quality and lifespan of elements should be considered before making a decision (EST.1, PM.2,4, PE. 2). In addition, it was mentioned that the accessibility, manageability and transportability of building elements are important factors regarding the technical feasibility (EST.1, PL. 1, DIR. 2, PE. 1). Lastly, the presence of contaminations and the cleanability of the building element are important factors to consider (Project 2 and 3). For instance, it was not possible to disassemble a rail of a wall, as this was connected to an asbestos-polluted floor (see Figure 4). Sometimes, project managers deviate during the execution phase from a previously chosen waste management strategy. Reasons for this are a financial optimization, change in the market demand and a change in the technical feasibility (PM. 1, PE.2, DIR.1).

Figure 4 - Rails cannot be disassembled while maintaining quality as it is connected to an asbestos polluted floor (Project 3)

Moreover, interviewees argued that the environmental impact of different waste management strategies should be considered before a waste management strategy can be chosen. They argued that a measuring process is needed to determine the environmental impact of a certain waste management strategy (EST.1, PE.2, DIR.1-2). For instance, DIR.1 made clear that cleaned bricks can be transported over a long distance as the production of new bricks does also lead to a high environmental impact. Moreover, it was observed that it is important to consider the time spent to remove building elements, whether this can be done safely and if building elements meet with the Building Decree (PM.3, SIM.1, Project 2).

Summarizing, most decisions regarding the waste management strategies are currently made during the preparation and execution phase based on the financial factor. Some decisions are made during the procurement phase, based on tacit knowledge and using some other data sources (e.g., project documentation and project visits). From the perspective of the demolition contractor, it is also important to consider the technical feasibility and environmental impact of different waste management strategies during the decision-making. However, currently the demolition contractor does not use a measuring process to compare different waste management strategies.

4.1.2 Factors influencing decision-making

After analysing literature, it was concluded that there are three main factors which are important to consider during the decision-making regarding waste management strategies. These are the economic, environmental and social factors (Roussat et al., 2009; Fiore et al., 2020; Alamerew & Brissaud, 2019; Vanson et al., (2022); Nadazdi et al., 2022). Moreover, the technical feasibility is important for reuse and deconstruction to occur and is therefore important to consider during the decision-making (Alamerew et al., 2020; Vanson et al., 2022; Durmisevic & Binnemars, 2014).

The economic factor is in literature divided in multiple sub-factors which should be considered during the decision-making. These are the demolition costs, revenues from selling building elements, and landfill costs. Di Maria et al. (2020) and Alamerew et al. (2020) recommended to use Life Cycle Costing (LCC) as an indicator for the economic factor. According to them, this is useful as it can determine the costs over the whole life-cycle of a building element and can thus determine the costs of a waste management strategy. The landfill costs are important to consider as this is influencing the direct reuse of building elements. Currently, these costs are low which makes it financially interesting to dispose building elements (Durmisevic & Binnemars, 2014; Kuehlen, Thompson, & Schultmann, 2014; Hosseini et al., 2015). However, Di Maria et al. (2018) argued that landfill costs and revenues can vary over time, which makes some waste management strategies suddenly more or less financial interesting. So, some economic sub-factors are variable. Ghisellini et al. (2016) argued that there is also a trade-off between these landfill costs and the revenues, as with some strategies (i.e., Reuse) there are no landfill costs as the element is not disposed. Lastly, the market demand is stressed to be important in the decision-making process (Alamerew & Brissaud, 2019; Van den berg et al., 2020).

The environmental impact of waste management strategies is according to literature important to consider during the decision-making. It is argued that a Life Cycle Assessment (LCA) can be used to determine the environmental impact of building elements over their entire life-cycle (Di Maria et al., 2018; Sobotka & Sagan, 2021; Alamerew et al., 2020). The environmental impact of a certain waste management strategy can then be expressed in for instance the Global Warming Potential (GWP). Another method was used by Morris (2016), in which the environmental impact of different waste management strategies for wood were compared. The environmental impact was calculated as one monetary value, by monetizing the different environmental impacts (e.g., climate change and acidification) of a waste management strategy.

The social factor is the third main factor which is (theoretically) important to include in the decision-making process. Examples of social factors are the quality of life of residents, safety and the chance on job-creation. However, according to researchers this factor is hard to quantify (Yu et al., 2022; Alamerew et al., 2020). Therefore, recent studies used qualitative factors to consider the social factor during the decision-making process (Alamerew & Brissaud, 2019; Nadazdi et al., 2022; Roussat et al., 2009).

Lastly, the technical feasibility is in literature described as another important factor for the decision-making besides the three main factors. The technical factors which are used in previous studies to consider the technical feasibility during the decision-making process are: demountability, manageability, presence of hazardous materials, separate ability, accessibility, transportability, speed of removal, technical quality, and lifespan (Iacovidou & Purnell, 2016; Kuehlen et al., 2014; Durmisevic & Binnemars, 2014; van den Berg et al., 2020; Kamp, 2021; Alamerew et al., 2020; Vandenbroucke, 2016).

4.2 Define objectives

The second step was to define the objectives for the DST. The results of the problem identification were used as input for this phase. The output of this activity, a requirements list, is used in the design and development phase.

The overall objective was *to develop a DST which should assist demolition contractors in the procurement and execution phases during the decision-making process regarding waste management strategies for building elements.* This overall objective was divided in requirements which resulted in a requirements list. During the design cycles, the requirement list was two times revised regarding the content, prioritization and how requirements were made SMART. This led to a final requirement list.

The final requirements list consists out of four main categories: (1) process and output of the design, (2) type of waste management strategies, (3) factors influencing decision-making and (4) usability. Requirements of category 3 were again divided in five sub-categories: (3.1) technical feasibility, (3.2) economic costs, (3.3) environmental impact, (3.4) social impact, and (3.5) law and regulation. All requirements were prioritized by using the MoSCoW method. This method makes a distinction in four types of requirements; Must-have (M), Should-have (S), Could-have (C), Won't-have (W). Must-have requirements must be met to have a successful design, Should-have requirements are important for the user but are not necessary for the functioning of the design, Could-have requirements are desired but not necessary to consider in the design, and lastly Won't-have requirements are not implemented in the current design but can later on be fulfilled (Hudaib et al., 2018). For each main category and the five sub-categories of category 3, an example requirement is given in Table 1. The requirements are derived from the problem identification and originate therefore from practice, theory or a combination of these two. The source of the requirements is therefore given. The complete requirement list can be found in the attached report.

Table 1 - Example of requirements for each category used for the development of the DST

Req. ID	Content	Priority	Source	SMART
1.2	A measuring process of different factors or criteria is needed to make a verifiable choice. This means that different factors or criteria must be processed in the model.	M	Combination (DIR.1, PE.2)	-
2.1	The model should make a distinction in waste management strategies from the viewpoint that a building is demolished.	M	Practice (PM.1-2, PE.2)	-
3.1.3	The model can measure the accessibility of building elements, by using three accessibility categories of (Durmisevic et al., 2001).	M	Combination (EST. 1, SIM.1)	Accessibility of building elements can be divided in three categories: - Good accessible - Accessible with extra movement - Not accessible
3.2.1	The model can process the removal costs for building elements.	M	Combination (all interviewees)	Removal costs in euros, consisting of: - Cost due to man-hours - Machine and equipment costs
3.3.1	The model can measure the environmental impact due to the production or waste processing of building elements.	M	Combination (EST.1, PE.2, DIR.1-2)	This can be expressed by using: - LCA - Environmental Cost Indicator (ECI) - Environmental effects (e.g. kg CO_2)
3.4.2	The model can measure the influence on the quality of life of the residents due to the demolition activities, by scoring this influence from high to low.	M	Theory	Influence on the quality of life can be measured by using a score from high to low environmental nuisance. A distinction is made in: - High environmental nuisance - Normal environmental nuisance - Low environmental nuisance
3.5.1	The DST can determine whether building elements do satisfy with the requirements of the Building Decree.	S	Practice (all interviewees)	Determine whether products satisfy with Bouwbesluit 2012. Make a distinction in: - Does satisfy - Does not satisfy
4.2	The model can be used with the information available for an estimator and project manager. This are material inventories, observations from the project visits, asbestos/Chrome6 reports and drawings.	M	Practice (observations/ document analysis)	-

4.3 Design and development

The DST was developed during this phase of the design process. The final design was created by using the final requirements lists and using the evaluation results which were received during the demonstration of the different designs. The output of this phase was a final design of the DST which was tested during the demonstration phase. As said, assumptions and boundaries were needed to demarcate the design, these are elaborated in Paragraph 4.3.1. The final design, presented in Paragraph 4.3.2, consists of two parts: a preliminary stage model and the evaluation model.

4.3.1 Boundaries of the DST

The boundaries and assumptions made are shortly described in this paragraph. First, it was decided to compare three waste management strategies with each other in the DST: Reuse, Recycle and Recover. These strategies are currently the most common strategies during a demolition project. Strategies like Refuse, Rethink and Reduce are not included as the DST is designed from the viewpoint that a building is demolished. Besides that, strategies such as Remanufacture and Repair are not considered as these are not common during the demolition and these are hard to distinguish. Also, the strategy Recycle is not sub-divided in high- and low-quality recycling as it is still difficult to make a clear distinction between these types. Second, transport is not included in the DST and therefore all activities, consequences and impacts due to transport will not be considered during the decision-making.

Third, the environmental impact of the waste management strategies is determined by using the Environmental Cost Indicator (ECI). This ECI is one monetary value calculated by using 11 different environmental impacts and can be retrieved from an online database called NMD (Nationale Milieu Database, 2022). For each strategy (Reuse, Recycle and Recover) assumptions are made about which life-cycle phases are considered to determine the environmental impact. For Reuse, the ECI from the production of a building element is used (Module A1-A3 of the LCA). There is an environmental profit as it is prevented that new building elements must be produced. Regarding Recycle, the ECI is used which results from the multiplication of the ECI from the production of a building element with the recycle percentage of that building element. This is the percentage of which a building element consists out of recycled raw materials. There is an environmental profit as it is prevented that new elements are produced by only using natural resources. For Recover, the ECI is used resulting from the production of a building element and from the waste processing (Module D4 of the LCA). So, there are environmental costs as new products should be produced and waste is processed.

Fourth, the demolition process which is considered in the DST is the process of removing the building elements till the temporary storage of these elements at the project site. However, the economic costs or revenues due to the disposal or sale of building elements are considered. Fifth, it is assumed that all sub-criteria of the technical feasibility will have an equal importance in the final evaluation. Finally, for each strategy a precept is determined which should be considered when using the DST. For reuse, the precept is that building elements are disassembled (by hand) by using hand equipment and small machines. The precept for Recycle is that building elements are demolished and separated by using hand equipment and small machines. Lastly, the precept for Recover is that building elements are demolished by using big machines without separating the building elements.

4.3.2 Final design of the DST

The final design of the DST is built by using the MCDM evaluation method as central mechanism. The type of MCDM used is the Analytical Hierarchy Process (AHP) method, as the user can determine easily the weights between criteria by using pairwise-comparison (Kasperczyk & Knickel, n.d.; Melese et al., 2020). The four main criteria evaluated in this MCDM are: economic costs, environmental gain, technical feasibility and social gain. These are divided in sub-criteria, which were (together with the main criteria) derived from the requirements list made during the 'define objectives' phase. From the demonstration of the requirement list and designs it became clear that some revisions were needed on the requirements and sub-criteria used regarding content, prioritization and how these were made SMART. An overview of the final criteria used including their characteristics (i.e., direction of preferences, and the scale and unit of measurements) is provided in Table 2.

Table 2 - Overview of main criteria used in the final design of the DST

Main criteria	Direction of preferences	Scale and unit	Sub-criteria
Technical feasibility	Maximization	Qualitative by scores	Demountability, manageability, accessibility, separability, technical quality, transportability, time spent
Economic costs	Minimization	Quantitative by Euros	Removal costs, cleaning costs, direct revenues, indirect revenues, material handling costs and landfill costs
Environmental gain	Maximization	Quantitative by ECI	Impact due to (prevention) production, impact due to recycling raw materials in new products, impact due to waste processing
Social gain	Maximization	Qualitative by scores	Environment hindrance

The first step when using the DST is to conduct the pairwise-comparison, to determine the weight of each main-criterion. This should be done by a director or project manager by filling in the columns 'more important' and 'intensity' for each combination of the main criteria given in Figure 5. The project specific selection-criteria set by the client could be used for this pairwise-comparison. After filling in these columns, automatically a pairwise-comparison matrix and normalized priority matrix are made. This results finally in a priority vector, in which each main criterion has a specific weight.

To be filled in by the demolition contractor: Columns "More important" and "Intensity"

*** In column "More important" you can choose "A", "B" or "AB"**
*** In column "Intensity" you can choose 1, 3, 5, 7, 9**
*** In case of AB --> choose intensity 1**

Criteria		More important	Intensity
A	**B**		
Technical Feasibility	Economic costs	B	7
Technical Feasibility	Environmental gain	B	7
Technical Feasibility	Social gain	B	3
Economic costs	Environmental gain	A	3
Economic costs	Social gain	A	7
Environmental gain	Social gain	A	7

Figure 5- Pairwise-comparison (AHP method) to determine weights between criteria

Table 2 indicates that there are no sub-criteria about polluted building elements, whether these can be cleaned and if there is a market demand identified. This is added in the first part of the model: the preliminary stage model, see Figure 6. This preliminary stage model is derived from the conceptual model given in Appendix G. Building elements should be added by the estimators or project managers and the first question should be answered with 'yes' or 'no'. The next question will then automatically pop-up. When building elements are polluted (e.g., glass wool plates with asbestos residues) and cannot be cleaned, they should be disposed. This means that Recover is the only strategy (given in red). In addition, Recover is also the only possible strategy if there is no market demand for the building element or the raw material of which the building element exists. If Recover appears after answering a question, the user should not further evaluate that building element. In case building elements are not polluted or can be cleaned, and there is also a market demand, the end user will be directed to the second part of the design: the evaluation model. This is depicted in green in Figure 6.

ID	Buillding elemer	Type of materia	Question Nr. 1	An	Question Nr. 2	An	Question Nr. 3	An	Question Nr. 4
1.1	Plasterboard	Gypsum	Is the building element polluted (for instance with asbestos or Chrome6)?	Yes	Can the building element be cleaned while maintaining qualtiy and can it verifiably be released?	Yes	Is there a market demand for the building element or raw material of which the building elements consists?	Yes	Determine the optimal strategy for the building element or raw material by using the next sheet: "3. Evaluation model."
1.2	Dropped ceiling	Glass wool	Is the building element polluted (for instance with asbestos or Chrome6)?	Yes	Can the building element be cleaned while maintaining qualtiy and can it verifiably be released?	No	Suggested strategy: Recover		

Figure 6 - Final design of the preliminary stage model (filled in for ceilings and plasterboards)

The evaluation model presented in Figure 7 provides the overview of the three strategies that will be compared. This part of the DST is also derived from the conceptual model in Appendix G. During the use of the DST, the estimator or project manager should keep in mind the precept of each strategy. The users should choose the building element from the list for which they want to compare the waste management strategies. Next, they should fill in the quantity of the building element (in the unit which pops-up automatically). Thereafter, the user must fill in the sub-criteria of the technical feasibility and social gain. This is done by choosing for each sub-criterion the right choice option using the dropdown function in the cell below the name of the sub-criterion. The score for the sub-criterion will automatically pop-up. These scores vary from 1 to 3, where the higher the score the better the sub-criterion scores. For instance, at the sub-criterion 'demountability' the user can choose between; 'reversible connection', 'semi-reversible connection' or 'irreversible connection'. An explanation of each sub-criterion including the way how these will be scored is provided in Appendix F.

Choose building element	Amount (kg or m2)	Unit
Plasterboard	400	m2

Strategy	Criterion							
Reuse (Precept: building elements are disassesmbled by using hand equipment and small machines	Technical feasibility	Demountability	Accesibility	Manageability	Separability	Transportability	Technical quality	Time spent (% longer than Recover)
		Irreversible connection	Good accesible	Manageable	Separatable	Transportable	Good	100%
		1	3	3	3	3	3	0
	Economic costs	Removal costs	Cleaning costs	Direct revenues	Indirect revenues			
		9760	0	-3200	-1600			
	Environmental gain	Environmental impact due to preventing the production of new building element						
		187,00						
	Social gain	Degree of environmental nuisance						
		Low environmental nuisance						
		3						
Recyle (Precept: building elements are demolished and separated by using hand equipment and small machines	Technical feasibility	Release ability	Accesibility	Manageability	Separability	Transportability	Technical quality	Time spent (% longer than Recover)
		Releasable	Good accesible	Manageable	Separatable	Transportable	Good	50%
		3	3	3	3	3	3	1,5
	Economic costs	Removal Costs	Cleaning costs	Direct revenues	Indirect revenues	Material handling costs		
		6528	0	0	-1260	340		
	Environmental gain	Environmental impact due to use af recycled raw materials in production of new building elements						
		18,700						
	Social gain	Degree of environmental nuisance						
		Normal environmental nuisance						
		2						
Recover (Precept: building elements are demolished by using big machines without seperating the building elements and raw materials)	Technical feasibility	Release ability	Accesibility	Manageability	Separability	Transportability	Technical quality	Time spent
		Releasable	Good accesible	Manageable	Not separatable	Transportable	Good	
		3	3	3	1	3	3	3
	Economic costs	Removal costs	Landfill costs					
		2048	1600					
	Environmental gain	Environmental impact due to production of new building elements			Environmental impact of waste processing			
		-187,00			-5,97			
	Social gain	Degree of environmental nuisance						
		High environmental nuisance						
		1						

Figure 7 - Final design of the evaluation model (filled in for 400 m² plasterboard)

The economic costs and environmental gain are automatically filled in by using the self-made databases in the DST of these two main criteria. These databases were made to increase the usability of the DST. After all data is filled in for all waste management strategies, a final score for each waste management strategy is calculated automatically. First, the total score of each main criterion per strategy is calculated. For the technical feasibility, the average is calculated of all scores of the sub-criteria. For the economic costs and environmental gain, the total score is calculated by summing all values of the sub-criteria. Thereafter, the total scores of the main criteria are transferred to preference scores using the direction of preferences in Table 2. Next, a normalized matrix is made using these preference scores. This matrix is multiplied with the priority vector (i.e. the weights of each main criterion), which leads to a final score for each main criterion per strategy. Summing all final scores of the main criteria per strategy leads to a final score per waste management strategy. These final scores are transferred into a ranking. The waste management strategy with the highest score or with rank 1, is the optimal strategy regarding the four main criteria used. Figure 8 provides an overview of this calculation.

Calculation of final score per strategy

Step 1: Comparison matrix (Total scores per strategy on each main criterion)

	Technical feasibility	Economic costs (Euro)	Environmental gain (Euro)	Social gain
Reuse	2,3	4960	187	3,0
Recycle	2,8	5608	19	2,0
Recover	2,7	3648	-193	1,0
Sum	8	14216	13	6

Step 2: Transfer to preference scores

	Technical feasibility	Economic costs	Environmental gain	Social gain
Reuse	1	2	3	3
Recycle	3	1	2	2
Recover	2	3	1	1
Sum	6	6	6	6

Step 3: Normalized matrix (using matrix of step 2)

	Technical feasibility	Economic costs	Environmental gain	Social gain	Average
Reuse	0,17	0,33	0,50	0,50	0,38
Recycle	0,50	0,17	0,33	0,33	0,33
Recover	0,33	0,50	0,17	0,17	0,29
				Control --> Sum	1,00

Priority Vector

Technical feasibility	0,09
Economic costs	0,27
Environmental gain	0,60
Social gain	0,04
Sum	1,00

Step 4: Results of mulitplication between normalized materix and priority vector

See below final score and ranking for the three strategies

	Technical feasibility	Economic costs	Environmental gain	Social gain	Final score	Ranking
Reuse	0,02	0,09	0,30	0,02	0,42	1
Recycle	0,05	0,05	0,20	0,01	0,30	2
Recover	0,03	0,14	0,10	0,01	0,27	3
				Control--> Sum	1,00	

Figure 8 - Calculation of final score per waste management strategy for 400 m^2 plasterboard (the ranking is provided at the right bottom)

This ranking provides an overview of what strategy is optimal for a single building element regarding the four main criteria used. However, when scores of two strategies are close to each other it is interesting to compare these strategies. Therefore, two additional graphical diagrams are provided as output of the DST (Figure 9 and 10). These show respectively the absolute and relative difference between the three strategies regarding the economic costs and environmental gain. The legend of Figure 9 contains 'environmental gain or loss' as Recover does have a negative environmental impact (i.e., loss). For plasterboards, Figure 10 indicates that Reuse has 12% less costs than Recycle, and Reuse has 900% more environmental gain than Recycle. These results are for 400 m^2, however these are calculated by using unit prices for economic costs which were based on 100 m^2. Therefore, these results could be disputable which is further elaborated in the 'Evaluation' paragraph. During the second and third demonstration, it was suggested to calculate these unit prices differently. However, this was not possible to include in the final design. Therefore, this and other suggestions for improvement that were not possible to implement are suggested for future research. This DST can be used for each building element of a building, however the databases should then be filled by the demolition contractor.

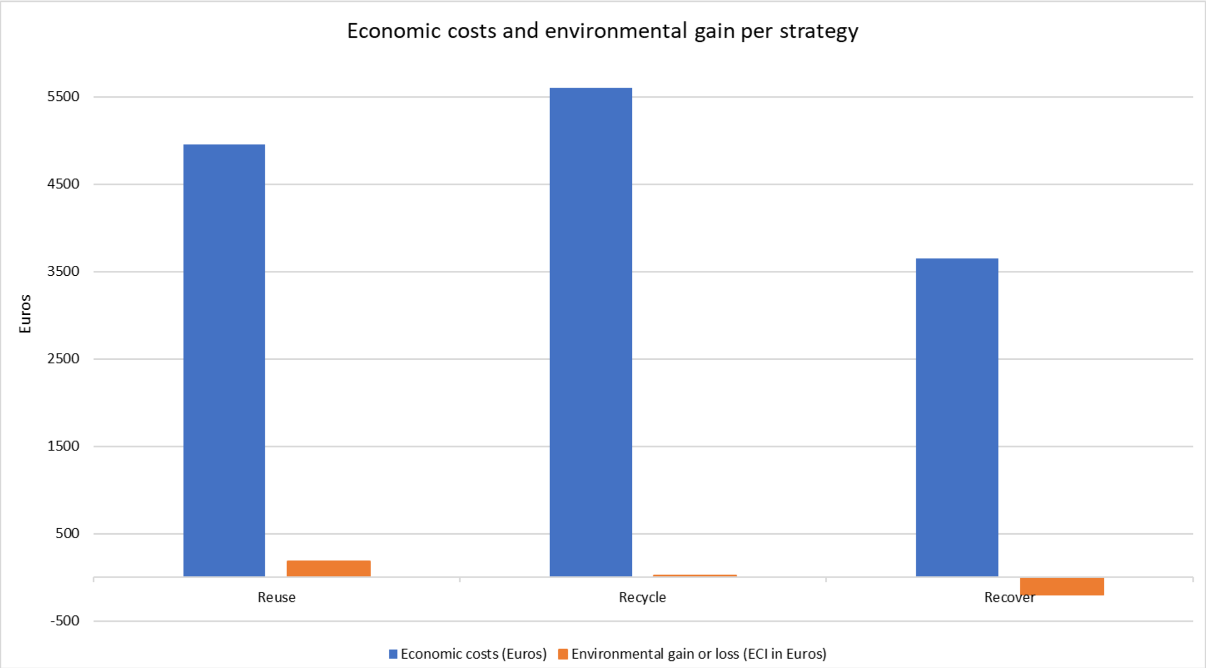

Figure 9 - Absolute difference between three waste management strategies regarding economic costs and environmental gain or loss (for 400 m² plasterboards)

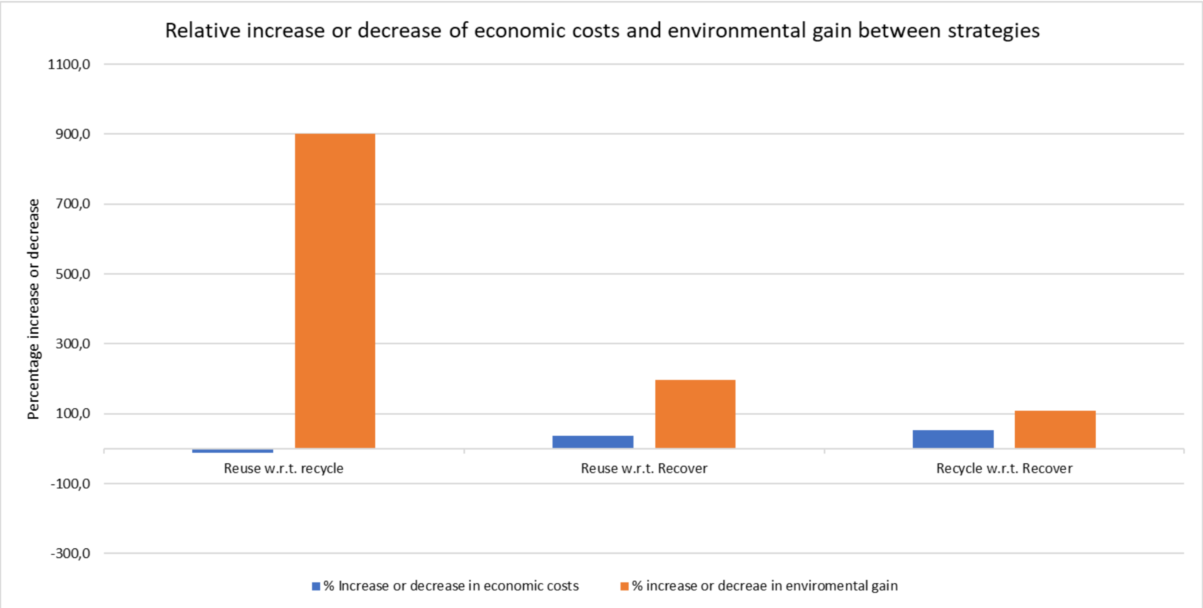

Figure 10 - Relative difference between waste management strategies regarding economic costs and environmental gain (for 400 m² plasterboards)

4.4 Demonstration

The next activity within the design process was the demonstration of the designs. Figure 2 indicates that the designs created in the 'design and development' phase were used as input for this activity. The output of this phase is feedback on the designs which is analysed in the next phase, i.e., the evaluation. The demonstrations of the first and second design cycle led to feedback (regarding the requirements, sub-criteria used, usability and output of the DST) which was considered during the design process to create the final design. How these demonstrations were executed is elaborated in the research methodology. The final design was tested by a project manager during the demonstration of the third design cycle. This paragraph will focus on this last demonstration by elaborating how the DST was used by the project manager in the decision-making process.

The project manager tested the final design on a real demolition project to determine the waste management strategy for a building element. This project manager (PM.1 in Appendix B) does also make cost estimations for demolition projects besides his tasks as project manager. For this demonstration, it was chosen to test the DST on a demolition project (see Appendix A) which was already awarded to the demolition contractor. However, the waste management strategies for the building elements present in these buildings had still to be determined by the demolition contractor. Therefore, this demolition project was chosen as case project.

The Excel file, in which the DST was designed, was opened by the project manager on the laptop of the researcher, however it could also be opened on his own laptop. First, the project manager analysed the tender guideline of the project to analyse what the selection criteria were for this project during the procurement phase. It was found that a fictive discount was received for sustainability in this project. This fictive discount was used together with the final contract price of the demolition project to determine the weights between the main criteria by executing the pairwise-comparison. The result of this pairwise comparison was that the weights of the technical feasibility, economic costs, environmental gain and social gain were respectively 0.09, 0.27, 0.60 and 0.04. Then, the project manager analysed the material inventory of the demolition project and plasterboards were chosen as the building element for which the DST was tested. The amount of these plasterboards was not available in this material inventory, therefore the project manager assumed an amount of 20 tonnes. After filling in the preliminary stage model, the project manager was directed to the evaluation model.

Within the evaluation model, the project manger used the dropdown-menu to choose plasterboards and had to fill in the amount in squared metres. Therefore, the project manager had to convert the amount of 20 tonnes to squared meters. It was assumed that there were walls which contained double plasterboards and thus he used a ratio of 50 kg/m2. By that, the project manager filled in an amount of 400 m^2. The project manager observed that the economic costs and environmental impact were already filled in, and that he only had to fill in the sub-criteria for the technical feasibility and social gain for each waste management strategy. Thereafter, the project manager analysed the ranking and graphs, and concluded that Reuse (with a final score of 0.42) was the optimal waste management strategy regarding the four main criteria. Recycle and Recover had a final score of 0.30 and 0.27, respectively. The project manager understood that Reuse would be optimal, as this strategy had a high environmental gain compared to the other two strategies. This environmental gain had the highest weight compared to the other main criteria and therefore the project manager argued that this outcome could be realistic for this demolition project.

However, the unit prices for the economic costs used were disputable according to the project manager. This was also observed during the demonstration in the second design cycle and will be further elaborated in the evaluation paragraph. Finally, the project manager changed the unit prices of the direct revenues to check whether another strategy would become optimal. This led to some interesting results which are elaborated in the next paragraph.

4.5 Evaluation

During the evaluation phase, the results of the demonstrations of the designs were analysed. This yields the same for the results of the evaluation forms used in the first and second design cycle (Appendix D and E). The evaluation results were used during both the ‘define objectives’ and ‘design and development’ phases to adapt the requirements list and design (see Figure 2).

During and after the demonstration of the final design, the project manager argued that the DST was now more user friendly. From the demonstrations in the first and second design cycles it was concluded that the usability had to be increased by designing the pairwise comparison in a different way and by creating databases for the economic costs and environmental gain to reduce the time needed to fill in the DST. Besides that, a guideline had to be developed to instruct new users. The project manager argued that determining the weights between the main criteria by executing the pairwise comparison was now understandable and easy to execute. Moreover, it became clear that the selection criteria (or fictive discounts) of a project can be used to execute this pairwise comparison. The use of the DST to determine the waste management strategy for a building element, in this case for plasterboards, was not very time consuming according to the project manager. Filling in the preliminary stage model, evaluation model and analysing the results for plasterboards was done in five minutes. The project manager argued that the speed will increase when the use of the DST will become a routine. Besides this, it was concluded that the DST can improve the current decision-making process, as it was argued that it can be used to make a reliable and well-considered decision.

As said in previous paragraph, the project manager agreed with the outcome of the DST that Reuse would be the optimal strategy for the plasterboards, although the project manager argued that it is currently still a barrier to receive the right direct revenues for second-hand materials. The unit prices of the economic costs were now based on one quantity (i.e., 100 m^2). Therefore, it was argued during both the second and third demonstration that the results are disputable. During the second demonstration it was suggested to determine these unit prices based on data of previous executed projects. The project manager suggested the same, however he also suggested to create unit prices for different project sizes (i.e., small, medium and large). By that, unit prices are available for different quantities of building elements. This can be seen as an implication of the DST on the current work process. Data regarding the economic costs of recent projects should be analysed by employees of the demolition contractor to determine these unit prices and to update these unit prices constantly. Moreover, recalculations should be made of recent executed demolition projects to create this cost data. In addition, the unit prices should be discussed and approved by the directors, project managers and estimators.

Another implication on the work process of the demolition contractor is that the weights between the main criteria should be determined by the directors and project manager during the procurement and execution phase. The project manager argued that directors and project managers have knowledge about how to register for a project. The selection criteria and possible other data within the project specific tender guidelines can be used to execute this pairwise comparison. This task should thus be added within the decision-making process. Moreover, the estimators and project managers must know what elements are present in a building during the procurement phase by analysing material inventories or visiting projects. Therefore, this data should be retrieved before the DST can be used.

Besides these implications, it was found during the demonstration of the final design that the final scores between the strategies did not change anymore from a certain unit price onwards. This was identified after changing the unit prices of the direct revenues for Reuse. The reason for this is that the total economic costs per strategy are transferred to preference scores (step 2 in Figure 8). The project manager became interested what direct revenue was minimally needed to make Reuse more interesting than for example Recycle. It was argued that this could be analysed during future research.

5 Discussion

During this design-science research, a Decision Support Tool (DST) was developed that can support demolition contractors during the decision-making process of waste management strategies for building elements. The DSRM Process Model of Peffers et al. (2007) was used to develop the DST by executing multiple iterations over the tasks belonging to the design cycles. Within this chapter, the research contributions, limitations, and suggestions for future research will be discussed.

5.1 Research contributions

From the literature review, it became clear that little is known about how demolition contractor make decisions in practice regarding waste management strategies and what factors are important for a demolition contractor to consider during this decision-making. In addition, recent developed evaluation methods regarding the decision-making for waste management strategies do often overlook the demolition contractor. It was also observed that within recent studies the focus is more on the design of evaluation methods than on the implementation of these methods in the decision-making process of the end-user, in this case a demolition contractor.

During the problem identification of this research, it was observed that the demolition contractor makes few decisions regarding waste management strategies for building elements during the procurement phase. When decisions are made in this phase, they are mostly based on tacit knowledge of project managers and directors. Most decisions are made during the execution phase based on economic costs. It was found from both practice and literature that four factors are important to consider during the decision-making process, i.e., the economic costs, environmental impact, technical feasibility and social impact. These were together with other requirements added in a requirement list. It was argued that a measuring process was needed during the decision-making process of the demolition contractor, to determine what waste management strategy should be chosen for a building element.

Therefore, a DST was developed to create a more-informed decision-making process for demolition contractors. This DST is specifically developed to assist estimators and project managers during the procurement and execution phases of a demolition project, to make a well-considered decision regarding the waste management strategies for building elements. The final developed DST was, in contrast to other recent studies, implemented in the decision-making process of the demolition contractor by testing the DST for plasterboards in a demolition project. From this demonstration, it became clear that using the DST will improve the current decision-making process of the demolition contractor, as the user can make a reliable and well-considered decision for a certain waste management strategy (i.e. Reuse, Recycle or Recover). Additionally, it was observed that the implementation of the DST will lead to some implications on the current work process: project managers and directors should determine the weights between the main criteria, end-users should know during the procurement phase what building elements are present, and the unit prices of the economic costs should be calculated and constantly updated using data of previous executed projects.

Referring to the research gap, the DST is a contribution in the research field of decision-making regarding waste management strategies, as this tested DST is developed for demolition contractors and building elements.

5.2 Limitations and suggestions for future research

This research had to be executed within a limited time period. Therefore, assumptions were made and boundaries had to be set to demarcate the design. By that, only three waste management strategies (i.e. Reuse, Recycle and Recover) were considered in the DST. However, it could be interesting to also include strategies regarding the prevention and reduction of waste (e.g. Rethink) or improving the quality of building elements (e.g. Remanufacture). These strategies are upcoming and new business-models can be created for strategies like Remanufacture (Nussholz & Milios, 2017; Schroeder et al., 2018).

From the demonstration, it was concluded that the unit prices of the economic costs should be calculated differently. The unit prices used were based on one specific quantity of the building elements, which makes them not appropriate for other quantities. It was not possible to calculate new unit prices after the third design cycle. Therefore, it suggested to research how data of previous executed projects can be used to determine accurate unit prices. Makovšek (2014) identified that using historical data of project costs and price movements on the market improves the cost estimation of new projects. Therefore, it is interesting to analyse how these unit-prices can be kept updated as economic costs are variable.

Another limitation was that the environmental impact only focused on certain life-cycle phases of a building element (i.e., the impact due to production and waste processing). Therefore it is suggested to consider also other life-cycle phases to determine the environmental impact of a strategy. This can for instance be done by including the transport of building elements to their new destination and the emission of machines and equipment during the demolition activities. For instance, Wang et al. (2018)

determined the carbon emission over the life-cycle of demolition waste by incorporating the emission of machines and equipment used. Using a complete LCA to calculate the environmental impact of the different strategies would be more accurate than using an ECI of some life-cycle phases. This was also suggested in literature (Di Maria et al., 2018; Sobotka & Sagan, 2021).

Moreover, the DST is not used for all building elements in one demolition project, as a full implementation was not possible within the available time period. Therefore, it is suggested to implement the DST in multiple projects during both the procurement and execution phases, to determine the functionality of the DST when strategies should be determined for all building elements in a project. Besides that, it is interesting to do future research regarding what direct revenue should minimally be received for a building element to make Reuse more interesting than other strategies when using the DST.

Lastly, the research was executed at one demolition contractor which can influence the research results. Therefore, the DST could be tested by other demolition contractors to determine its functionality and implications on their decision-making process.

6 Conclusion

A design-science methodology was used to develop a DST that can assist demolition contractors to make a more-informed decision regarding the waste management strategies for building elements present in a to-be-demolished building. This DST can be used during both the procurement and execution phases to make a well-considered decision. It was found that within the procurement phase decisions are based on tacit knowledge, and that during the execution phase most decisions must still be made. These were mostly based on economic costs. During this research it was observed from both practice and literature, that four factors (i.e., economic costs, environmental impact, technical feasibility and social impact) are important to evaluate as a demolition contractor before choosing a certain waste management strategy for a building element.

The DST is developed to compare three waste management strategies (i.e., Reuse, Recycle and Recover) by using a MCDM evaluation method. By evaluating four main criteria (i.e., economic costs, environmental gain, technical feasibility and social gain) for each waste management strategy, a ranking of the three strategies is provided which indicates what strategy is optimal regarding these criteria. Besides that, the absolute and relative difference between strategies is graphically presented regarding the economic costs and environmental gain. The DST can be used in both the procurement and execution phases, although it is desired to use it in the procurement phase as then the chosen strategies can be considered during the cost estimation. The implementation of the DST will lead to implications on the current work process of demolition contractors as for instance material inventories should be made and economic costs of previous project should be analysed.

Using the DST would lead to a more-informed decision-making process which implies that decisions are not longer made using tacit knowledge or based on only economic costs, but are also based on the environmental impact, technical feasibility and social impact. Therefore, the DST can assist demolition contractors in the transition towards a circular economy.

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8 Appendix

Appendix A - Information of the projects visited

Table 3 - Information project 1

Project number	Project 1
Status project	Procurement phase (second project visit)
Type of project	Total demolition
Type of building	Meat processing factory including offices
Date of project visit	09-02-2022
Under guidance of	Estimator 1

Table 4 - Information project 2

Project number	Project 2
Status project	Execution phase
Type of project	Total demolition
Type of building	University building including laboratories (3 floors)
Date of project visit	Multiple times during research period
Under guidance of	Project manager 1 & Site manager 2

Table 5 - Information project 3

Project number	Project 3
Status project	Execution phase
Type of project	Renovation demolition
Type of building	Big office building (6 floors)
Date of project visit	21-03-2022
Under guidance of	Project manager 4

Table 6 - Information case project for demonstration third design cycle

Project number	Project 4
Status project	Awarded to demolition contractor, in preparation for execution
Type of project	Total demolition (1650 m^2 Gross Floor Area)
Type of building	Old police office including houses

Appendix B - Information of the interviewees

Table 7 - Information about interviewed directors, estimators and project managers

ID	Function	Number of years experiences with calculating and/or executing traditional demolition projects.	Number of years experiences with calculating and/or executing circular demolition projects	Working for type of projects (small/medium/big)
DIR.1	Director demolition & residue centre	35	35	All
DIR.2	Director demolition	17-20	15	All
EST.1	Estimator	3	0.5	Small/medium
PM.1	Project manager	8-10	5	All
PM.2	Project manager	6	10	All
PM.3	Project manager	30	30	All
PM.4	Project manager	7	7	Big

Table 8 - Information about interviewed site managers

ID	Function	Number of years experiences with executing traditional demolition projects.	Number of years experiences with calculating and/or executing circular demolition projects	Working for type of projects (small/medium/big)
SIM.1	Site manager	10	0	Small/medium
SIM.2	Site manager	15-17	5	All

Table 9 - Information about interviewed planning engineers

ID	Function	Number of years experiences with preparing traditional demolition projects.	Number of years experiences with preparing circular demolition projects	Working for type of projects (small/medium/big)
PE.1	Planning Engineer	14	3	All
PE.2	Planning Engineer	5	5	Big

Appendix C – Illustration of the axial coding method

Which project documentation and other data sources do you currently use when you have to choose a waste management strategy for a product or element?		**Open coding**	**Axial Coding**
CAL. 1	Drawings (if available), material inventory and observations during project visits. The project managers do also have some experience. From experience they know what is in the building and what the consequences are when you demolish it in a certain way. You can disassemble it how it is constructed, but you can also cut/saw the elements out of the building. So internal discussions are taking place with colleagues about what could possibly be done with the materials.	- Drawings, material inventories - Observation during project visits - Experience of project managers - Internal meeting with colleagues	Knowledge and experiences Project documentation: - Drawings - Asbestos/Chrome 6 reports - Pictures - Material inventories - Material passports Observations from project visits Pre-offer to traders Internal meeting with employees (tender team)
PL. 1	Partly on experience and partly on pre-offering to the traders. But that is again difficult, because those traders talk with other demolition contractors as well. Because then the competitor can also come up with ideas that come from us. You want to distinguish yourself from the others, so you do not want to involve the traders too early in the calculation phase, you actually do that after the award phase. **Follow-up question:** Do you also consult with colleagues? Yes, we usually make a calculation in which we look what the costs are when we demolish it traditionally. Thereafter we determine the costs when we for instance saw the concrete floor and sell the plates. We compare these costs and look what is economic most interesting. This is mostly in consultation with project managers and directors. An estimator just does what he is asked to do, he just has to calculate the work. Usually the initiative comes from the project managers or directors. They have more knowledge about the market demand.	- Experience - Pre-offer to traders, not too early due to competition - Internal meeting with estimator, project managers and directors - Project managers and directors have knowledge about market - Economic interest	
PL. 2	Asbestos/chrome6 reports, material inventories, observations from project visits, drawings. **Follow up question:** Do you also consult with colleagues? With big project, it is normal that you consult with each other about how/what we are going to do. How do you want to subscribe? With those concrete plates, for example, you look at how much that will cost us and what the revenues are. Moreover, you analyse how much fictive discount you can receive. Then you make a decision. You make those kinds of decisions together with the tender team (the people involved in the tendering phase). Together you can come to new ideas. By that you	- Asbestos/chrome6 reports, materials inventories, observations from project visits, drawings. - Internal discussion tender team - Fictive discount client is important	

	can make the difference. You have to make this difference at the front of the project. But to do that you need knowledge and skills and experience; how do you do that, which sale channels and is it realistic. We regularly do a tender that you already know that a storage hall can be sold, then you already use different costs than when you will demolish it.	- Costs vs revenues - Knowledge and experience	
PL. 3	Sometimes you have a project where you get 1000 drawings, I'm not going to look through all of them. I usually look at the cross-sections. Furthermore, it is what you see visually, that you think I can find someone for that. Then you have to inform the traders, which is difficult. When we see certain interesting building elements, then we discuss what we will do with them in terms of costs/revenues.	- Drawings - Knowledge and experience - Internal meetings	
PL. 4	You can use the asbestos and chrome 6 inventory reports to make a decision, there you can see which elements are contaminated. Then you determine if it can be cleaned, then you make the choice. We do discuss internally whether something is possible for some elements. That happens also during the calculation phase.	- Asbestos/chrome 6 reports - Cleanability - Internal discussion employees	
DIR. 1	Drawings, project visits, pictures Internal meeting tender team	- Drawings, pictures - Project visits - Internal meeting tender team	
DIR. 2	Data provided by the client, observations from project visits and pictures. Moreover, also the knowledge and experience that you have. In addition, the database of the traders we have. This allows us to look at which traders we can, for example, bring the doors to and what revenue we can get for this. That will come in future, which is now often still based on your own feeling.	- Project documentation - Project visits - Knowledge and experience - Database traders	
WVB. 1	It is also just what is asked, because if the client does not appreciate reuse, then we will think about how we can get as much revenue as possible. Construction drawings are being viewed. But I think that if it is only really required of us from the client, then I think we will work with it more intensively than we would do it ourselves. Because for us, the economic costs are more important than circularity. And that should actually be different, because that circular should bring us more revenues. Because, for example, throwing away a door costs money, but if you can use them somewhere else, they deliver maybe something. Otherwise you don't have to deposit them. That awareness is growing, it has been there for more than a few years. Because how much effort are you going to put into that entire circularity? What weighs more heavily at a given moment, the hours you are working on it or the deposit costs?	- Type of tender - Drawing - Economic costs are still most important	

	This has to be considered in the calculation phase, but then you have to set-up a whole strategy where you will go internally with your waste flows, where do you store it, can it be put in a container, have you already sold it in advance? You have to use the most convenient tactic for yourself so that you reuse it and make sure that it results in high revenues.		
WVB. 2	Drawings, pictures, material passports, inventories and project visits. **Follow-up question →** Do you internally discuss with employees? Yes, that happens, but should be better. Somebody should take the lead and work fully on this. Now, everybody does a bit besides their main tasks. Or there should be a platform that you know what materials are available and where they need certain materials. Information exchange is not enough currently.	- Drawings, pictures, material passports, inventories, project visits - Internal meetings, however, to little information exchange.	
UIT. 1	That's experience. For example, good heavy doors, which cost a lot to deposit, and at the same time you just know that it is quality. You know that there is a demand for that. You call your traders and say I have 50 hardwood doors, plus the dimensions. They will then give you a price. Sometimes they want to pick it up for free, then that's fine too. You do try to make money out of it most of the time. Sometimes, you also discuss with colleagues about whether they have a buyer for some materials. But often you have to use your common sense.	- Knowledge and experience - Contact with traders - Internal meeting	
UIT. 2	I walk through the building myself to see what it's in it. I also let a few traders walk through the building, and they actually determine for me what can be reused. They know what can be put back in the market. Now something is being offered on a marketplace and then you have discussions about 1 or 2 doors. It must be marketed as pieces (10/100 pieces) and not 1 door. There was 1 double door on it, then I had to measure it, how is it fixed, what glass is in it, what material, etc. I will do it, but it can't be the intention. If that is reuse for me, then they have to give us 3 years to demolish a building.	- Project visits - Traders who visit the project - Reuse should be of big batches, not 1 or 2 pieces.	

Appendix D - Evaluation form of the 1st design cycle

	Totally disagree	Disagree	Neutral	Agree	Totally agree
	1	2	3	4	5
About the content and output of the model					
The DST contain all relevant (sub) criteria to choose an optimal waste management strategy for the demolition contractor					
The sub-criteria are made SMART in the right way					
By using this DST, the choice for a certain waste management strategy is verifiable and traceable					
The DST can be used for all different types of building elements present in a to be demolished building					
By using these (sub) criteria within the Multi-Criteria analysis, a reliable and well-considered decision can be made.					
The output what the DST provides is what I expected					
Usability					
The sub-criteria are understandable for the users of the DST					
The DST is easy to use for persons who make cost-estimations and who have to make decision regarding waste management strategies					
Filling in this DST for one building element does not cost too much time for the user					
The DST can be filled in with the current available data sources and knowledge of the users					
Open questions					
Which factors or criteria could be added, as these are also important during the decision-making for an optimal strategy?					
Which factors or criteria could be removed, as these are less important during the decision-making for an optimal strategy?					
How can the output of the DST also be presented, besides giving the ranking of the three strategies (e.g. the optimal strategy)?					
Additional comments or questions					

Appendix E - Evaluation form of the 2^{nd} design cycle

	Totally disagree	Disagree	Neutral	Agree	Totally agree
	1	**2**	**3**	**4**	**5**
About the content and output of the model					
The DST contain all relevant (sub) criteria to choose an optimal waste management strategy for the demolition contractor					
The sub-criteria are made SMART in the right way					
By using these (sub) criteria within the Multi-Criteria analysis, a reliable and well-considered decision can be made.					
The output what the DST provides is what I expected					
Usability					
The DST gives the end-user the right support during the decision-making process regarding the waste management strategies					
Determining the weights between the four main criteria is user-friendly					
The sub-criteria (including how these are made SMART) are understandable for the users of the DST					
Filling in the DST for one building element (with the use of the databases for economic costs and environmental gain) does not cost to much time for the end-users.					
The DST can be filled in with the current available data sources and knowledge of the users					
Additional comments or questions					

Appendix F - Sub-criteria used in the final design

ID	Main and sub-criteria	Description	SMART
A	**Technical feasibility**		
A.1	Demountability or releasability	The demountability of building elements indicates how well building elements can be disassembled. The releasability indicates how well the building element can be released from another building element. Demountability is linked to Reuse, as building elements must be disassembled to reuse them. Releasability is linked to Recycle and Recover, as this is about demolishing building elements by hand and machines. During this activity it is important whether buildings elements are releasable.	The demountability is divided in three categories of the connection type used (Vandenbroucke, 2016): - Reversible (3) - Semi-Reversible (2) - Irreversible (1) The relesability is divided in the same way: - Releasable (3) - Semi-releasable (2) - Not releasable (1)
A.2	Manageability	The manageability of the building element indicates how easy an element or the material of the element can be transported by hand or machine through a building. Without damaging the element itself or other products present in the building.	The manageability is dived in three categories of (Vandenbroucke, 2016): - Manageable (1) - Semi-Manageable (2) - Not manageable (3)
A.3	Accessibility	The accessibility indicates how easy the connections or building element can be reached by a person or machine, without damaging other building elements.	The Accessibility is dived in three categories of (Durmisevic et al., 2001): - Good accessible (3) - Accessible after extra operation (2) - Not-accessible (1)
A.4	Separability	The separability indicates whether building elements or the material of which it exists can be separated from other elements or materials.	The separability is dived in: - Separatable (3) - Not separatable (1)
A.5	Transportability	The transportability indicates whether the building element can be transported in a safe way within the maximum limited dimensions and weight of freight traffic.	The transportability is divided in two categories: - Transportable (3) - Not transportable (1)
A.6	Technical quality	The technical quality of the building element or the material of which it consists indicates what the current quality of the element or material is.	The technical quality can be determined by using categories for the condition measurement of the NEN 2767: - Condition 1: Good (3) - Condition 2: Reasonable - Condition 3: Bad (1)

A.8	Duration	The duration indicates how much time will be spend when executing the waste management strategy for a building element. It is assumed that Recover is always the fastest strategy. Therefore, it is the duration of Reuse and Recyle with respect to Recover.	The extra time needed for Reuse and Recycle w.r.t. Recover is measured by a percentage: - 0% extra duration - 25% extra duration - 50% extra duration - 75% extra duration - 100% extra duration - 200% extra duration
B	**Economic costs**		
B.1	Removal costs	This are the costs which are made due to the removal of the building element out of the building (manually or by machine) till the temporary storage of the element or putting it into a container.	Costs in Euros
B.2	Cleaning costs	This are the costs made for removing the polluted particles from a building element, including the release cost of the laboratory.	Costs in Euros
B.3	Direct revenues	Direct revenues are the revenues received by directly selling a building element or the material of which an element exists. These are only applicable for Reuse and Recycle	Costs in Euros
B.4	Indirect revenues	Indirect revenues are the revenues which are received due to the fact that the demolition contractor prevents to dispose an element. These are only applicable for Reuse and Recycle	Costs in Euros
B.5	Material handling costs	This are the costs which must be paid by the demolition contractor when it disposes building element or materials products to a material recycling company. These costs vary per material type. These are only applicable for Recycle.	Costs in Euros
B.6	Disposal costs	The disposal costs are the costs that a demolition contractor has to pay when it disposes building elements to a waste processing firm. These costs vary per type of waste stream. These costs are only applicable for Recover	Costs in Euros

C	**Environmental gain**		
C.1	Environmental gain	The environmental gain is the environmental impact of a certain waste management strategy using the Environmental Cost Indicator. When there are environmental costs, this value will be negative. For each waste management strategy, an assumption is made which phase of the life-cycle is considered. See Table 2.	Reuse: ECI of production Recycle: ECI of production * recycle percentage Recover: ECI due to production and waste processing
D	**Social gain**		
D.2	Rate of environmental nuisance	The rate of environmental nuisance indicates how much environmental nuisance the residents, traffic, flora and faunae experiences due to the demolition activities belonging to the different waste management strategies	The environmental nuisance is measured by a score. Three choice options can be chosen: - Low environmental nuisance (3) - Normal environmental nuisance (2) - High environmental nuisance (1)

Appendix G – Conceptual model of the final design