Decision-support for selecting demolition waste management strategies

SPECIAL COLLECTION: UNDERSTANDING DEMOLITION

RESEARCH

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ABSTRACT

The construction industry is increasingly challenged to reduce its waste production, resource consumption and energy emissions. Moving towards more circular and sustainable practices therefore seems imperative. Demolition contractors play a vital role in this move as they need to select waste management strategies for distinct obsolete building elements. Previous research has nevertheless overlooked how demolition contractors can gain insights into the consequences of such strategies. This research therefore adopts a design science research methodology to iteratively develop a decision-support tool for selecting demolition waste management strategies. Through collaborating with a pioneering demolition contractor in the Netherlands, in-depth insights into actual decision-making processes were obtained. A tool was subsequently designed that compares and ranks three different waste management strategies (reuse, recycle and recover) by evaluating their impacts in terms of technical feasibility, economic costs, environmental gain and social gain. This tool enables demolition contractors to make more informed waste management decisions and, as such, offers new opportunities to adopt circular and sustainable demolition methods.

PRACTICE RELEVANCE

Demolition contractors are pressured to adopt more circular and sustainable methods. This requires these firms to consider waste management strategies other than traditional energy recovery or landfilling. A new decision-support tool offers demolition firms insights into the consequences of different waste management strategies. This tool compares and ranks reuse, recycle, and recover waste management strategies. The tool was demonstrated and evaluated by a demolition contractor in the Netherlands. It was found that the decision-support tool assists in making more informed waste management decisions through illuminating technical feasibility, economic costs, environmental gains and social gains. A suggested ranking of strategies is provided for distinct obsolete building elements. Implementing the tool will require changes to local project routines.

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1. INTRODUCTION

Waste management decisions taken during demolition works have important consequences that often remain misunderstood. Demolition marks the last phase of a building's life cycle. This traditionally involves the deliberate destruction of a building and its parts. Demolition contractors have relied on heavy equipment and crushing force for such works. Conventional demolition can be cost-effective, but it also brings about various other impacts on its workforce or the environment (Kourmpanis *et al.* 2008). Certain materials hidden in existing buildings, however, can also become attractive alternatives to raw ones (Arora *et al.* 2021; Koutamanis *et al.* 2018). Accordingly, buildings may be dismantled more carefully with the aim instead being to maximise reuse or recycling value during selective demolition (also called deconstruction) (Kibert 2016). Demolition contractors must then decide which elements are to be reused, recycled or otherwise reprocessed. Those waste management decisions would hence demand an understanding and systematic comparison of the associated impacts during demolition works.

More informed waste management decisions are both urgent and important as the construction industry keeps struggling with its significant share in generating waste, consuming resources and using energy. Construction and demolition waste represents the most voluminous waste stream worldwide, with a share of 30–40% of all waste (Cheshire 2016; Li *et al.* 2020). Landfilling of the waste can lead to space problems, particularly in densely populated areas, and may contaminate nearby water bodies (Cooper & Gutowski 2015). The industry also consumes more than half of the total global resources (Iacovidou & Purnell 2016). This puts a strain on the environment, limits equitable use and contributes to resource depletion (Gálvez-Martos *et al.* 2018). The industry finally contributes to climate change as it accounts for over a third of the total global energy usage and associated emissions (Yilmaz *et al.* 2019).

More circular and sustainable demolition practices seem imperative in light of these problems. The dominant 'linear' economic model of take–make–use–dispose is seen as a root cause for the problems (Ellen MacArthur Foundation 2013). Policymakers, business leaders and researchers around the world are therefore calling for an alternative, 'circular' economic model based on regenerating, narrowing, slowing and closing material loops (Çetin *et al.* 2021). The European Commission took a substantial step in this direction by adopting a Circular Economy Action Plan which intends to:

> make sustainable products, services and business models the norm and transform consumption patterns so that no waste is produced.
>
> (European Commission 2020: 3)

The transformative agenda has profound implications for demolition contractors. These firms will need to be able to select waste management strategies appropriate to realising circularity targets.

Previous research has nevertheless been limited in offering demolition contractors tools that support waste management decision-making. Barriers to closed-loop material flows and reverse logistics in construction have been mapped extensively instead (Brandão *et al.* 2021; Mahpour 2018; Park & Tucker 2017; Tingley *et al.* 2017). Relatively few studies focus on the organisational activities of demolition contractors, even though their practices are characterised by 'intensive decision-making' concerning the end-of-life strategies of building elements (Van den Berg *et al.* 2020a: 649). Those different strategies have their own consequences, *e.g.* in terms of costs, labour, energy and other externalities. Demolition contractors may not be fully aware of such consequences as they appear to rely heavily on previous experience for taking waste management decisions (Hulsbeek & Van den Berg 2022). The aim of this research is to iteratively develop a decision-support tool for selecting demolition waste management strategies.

The paper is structured as follows. Next, earlier work on decision-making methods for demolition is reviewed. It then elaborates how a design science research methodology was adopted to create a tool for selecting appropriate waste management strategies. The results from the development (and iterative adjustment) of this tool are presented along the design science research activities. The paper ends with a discussion and conclusion about more informed waste management decision-making within demolition contexts.

2. BACKGROUND

Demolition contractors are increasingly stimulated to select more sustainable end-of-life strategies for processing distinct building elements. Positioning these strategies in a broader regulatory and policymaking context, this literature review explains their differences and elaborates on methodologies to choose any appropriate strategies.

2.1 DEMOLITION WASTE MANAGEMENT STRATEGIES

When a building becomes obsolete, this will result in the end of its service life, generally by demolition. Traditionally, that practice essentially turned assets (entire buildings) into liabilities (demolition debris) (Leigh & Patterson 2006). Some building elements may, however, still have value as there can be various causes for obsolescence. Thomsen & Van der Flier (2011) characterised obsolescence by distinguishing, on the one hand, internal and external factors and, on the other, physical and behavioural factors. Internal factors are related to the building itself and may be physical (such as deterioration over time, caused by ageing, wear or weathering) or behavioural (such as damage by maltreatment, misuse or changes in function). External factors are related to the environment and can also be physical (such as impacts of nearby construction, traffic or pollution) or behavioural (such as migration of tenants, urban blight or loss of market value). These different underlying causes for obsolescence suggest there is potential for alternative, piece-by-piece demolition methods that mine valuable materials and reintroduce them into the market. Such 'unbuilding' practices are increasingly promoted under circular economy agendas because of promising sustainability benefits (Lynch 2022). This 'redefines the concept of death in the built environment' by opening up alternative strategies to process demolition waste (McCarthy & Glekas 2020: 16).

Demolition waste management strategies mainly differ to the extent to which the original value of a focal element is preserved (Lansink 2017). Traditional landfilling involves discarding elements without any attempt to recover energy or other value. When an element is recycled instead, it is reprocessed into raw materials for new products. Recycling is a predominant strategy in construction and often seen as good environmental practice (Coelho & De Brito 2013). However, the reprocessed materials are usually of lower quality and thus a great proportion of the initially invested energy is lost (Allwood *et al.* 2011). Recycling therefore often means downcycling. More environmental benefits can be achieved with reuse, during which an element is recirculated and used for a similar function whilst the embodied energy is preserved. Reuse can reduce waste generation and new production (as well as the associated energy). With growing recognition for resource efficiency, these more sustainable demolition waste management strategies are increasingly incentivised by policymakers within Europe and beyond (Ghaffar *et al.* 2020).

2.2 REGULATORY FRAMEWORKS

Regulatory developments encompassing circular economy and sustainability policies are significantly influencing demolition practices. The European Commission embraced the circular economy as: 'a technologically driven and economically profitable vision of continued growth in a resource-scarce world' (Hobson & Lynch 2016: 15). Its Circular Economy Action Plan encompasses an agenda for accelerating the transformational change required by the European Green Deal, a comprehensive set of policy initiatives to achieve climate neutrality in the European Union by 2050 (European Commission 2019). The agenda offers a targeted approach to promote circularity in the management of waste. It builds upon and complements the Waste Framework Directive 2008/98/EC, which declared construction and demolition waste as a priority waste stream because of its vast volume and high resource value (European Commission 2018a). The Directive also established a minimum target of 70% of construction and demolition waste to be prepared for reuse, recycling or other material recovery by 2020. The regulatory framework has, accordingly, promoted the adoption of more sustainable alternatives to conventional mechanical demolition and landfilling across Europe (Moschen-Schimek *et al.* 2023).

The framework was implemented into several guidelines on how to properly handle construction and demolition waste. The assessment of an existing structure before demolition or renovation, called waste audit, is necessary, and in some countries compulsory, to plan for the type and amount of materials that will be demolished (Hurley 2003). The European Union Construction and Demolition Waste Management Protocol offers guidance to that end (European Commission 2018b). It suggests how a desk study and/or field survey can be used to make a materials inventory and to recommend specific strategies for handling of the waste. Several research projects have furthered the assessment with suggestions for identifying reuse and recycling opportunities: Malk & Lauritzen (2021) developed a pre-demolition screening procedure, whereas Smeyers & Mertens (2022) proposed a so-called reclamation audit that complements the pre-demolition audit. These studies draw attention to reuse and recycling opportunities, but do not systematically compare the various impacts of different waste management strategies with each other. Yet material inventories offer a basis to start doing so.

2.3 DEMOLITION WASTE MANAGEMENT DECISION-MAKING METHODS

Several types of methods have been developed to support end-of-life phase decision-making. Vanson *et al.* (2022) distinguish between end-of-life assessments, disassembly assessments and other assessment methods. They showed that mathematical models, multi-criteria analyses (MCAs) and cost–benefit analyses are the most common types of methods within these categories. Alamerew *et al.* (2020), for example, used a multi-criteria decision methodology (MCDM) to facilitate decision-making for product-level circularity strategies. Their methodology focused specifically on what the best circular strategy is for products (*e.g.* storage furniture) and what the consequences are for customers and companies. Fiore *et al.* (2020), likewise, used an MCA to decide what interventions are most appropriate in school buildings. MCAs are also used in studies with respect to decision-making regarding waste management strategies for complete buildings, products or demolition techniques. Roussat *et al.* (2009), for example, used an MCA to compare different waste management strategies during the demolition of complete buildings. Bentaha *et al.* (2020) created a decision tool for the manufacturing industry which can be used to select the best disassembly process for products (with the maximum profit) based on the variability of the products' qualities. Decision-making methods such as these are, however, not suitable to compare waste management strategies at an element (rather than building) level.

Few decision-support tools are available to demolition contractors. Evaluation methods typically consider many qualitative and quantitative factors. Relevant factors in end-of-life evaluations include economic aspects, environmental consequences and social issues (Bentaha *et al.* 2020; Roussat *et al.* 2009). The consequences of waste management strategies can be quite different in these regards. Reuse-oriented demolition practices can, for example, yield environmental benefits, but require more manual labour and costs which may, in turn, be compensated by landfill costs saved and revenues incurred (Leigh & Patterson 2006). Few studies have sought to evaluate multiple such factors altogether from a demolition point of view. Akanbi *et al.* (2018), for example, developed a tool that designers can use to estimate the salvage performance of a building. Alamerew *et al.* (2020) created an evaluation method for companies producing products and providing a service for these products to customers. Fiore *et al.* (2020) developed an evaluation method that proposed the most appropriate intervention strategies of a complete building for public administrations. The decision-making methods are furthermore rarely implemented in actual projects or organisations. Thus, limited knowledge exists on how demolition contractors can be supported in comparing and selecting waste management strategies for distinct building elements.

3. DESIGN SCIENCE RESEARCH METHODOLOGY

This research adopted a design science research methodology to iteratively develop a decision-support tool for selecting waste management strategies during demolition works. Design science research is particularly suitable for developing a certain intervention or artefact to solve a real-world problem within a certain context and obtaining knowledge through the engagement of its users (Hevner 2007; Mullarkey & Hevner 2019; Wieringa 2014). The typical output of a design science study is a field-tested and grounded technological rule. Van Aken (2004: 228) defines a technological rule as:

> a chunk of general knowledge, linking an intervention or artefact with a desired outcome or performance in a certain field of application.

Such a technological rule (or solution concept) is 'field-tested' if the intervention or artefact is tested in its intended field of application; it is 'grounded' if the reason why it gives a desired outcome or performance is known (Van Aken 2004; Van Aken & Romme 2009). Design science research therefore aims to develop actionable, prescriptive knowledge that professionals of the discipline can use to design solutions for their field problems (Voordijk 2009).

The research was conducted in collaboration with a demolition contractor in the Netherlands with whom the researchers have an ongoing relationship. The Netherlands has implemented policies to cut primary materials usage by half in 2030 as a first milestone towards realising a fully circular economy by 2050 (Dijksma & Kamp 2016). Since the country implemented a ban on landfilling reusable waste in 1997, the country's construction and demolition waste recycling rates have increased to almost 100% (Zhang *et al.* 2020). Within the country, the selected demolition firm can also be seen as a frontrunner in circular demolition. The firm supports the United Nations' Sustainable Development Goals and works towards those goals by participating in various sustainability innovation projects and initiatives, including reverse logistics hubs (in which people with a distance to the labour market refurbish certain mined materials) and online marketplaces (through which mined materials are offered for sale). The firm was interested in gaining better insights into the impacts of different waste management strategies.

The design science process model of Peffers *et al.* (2007) was followed to develop the decision-support tool. The process model consists of six different activities that were executed iteratively: problem identification, define objectives, design and development, demonstration, evaluation, and communication. Data were collected and analysed during each step (Figure 1).

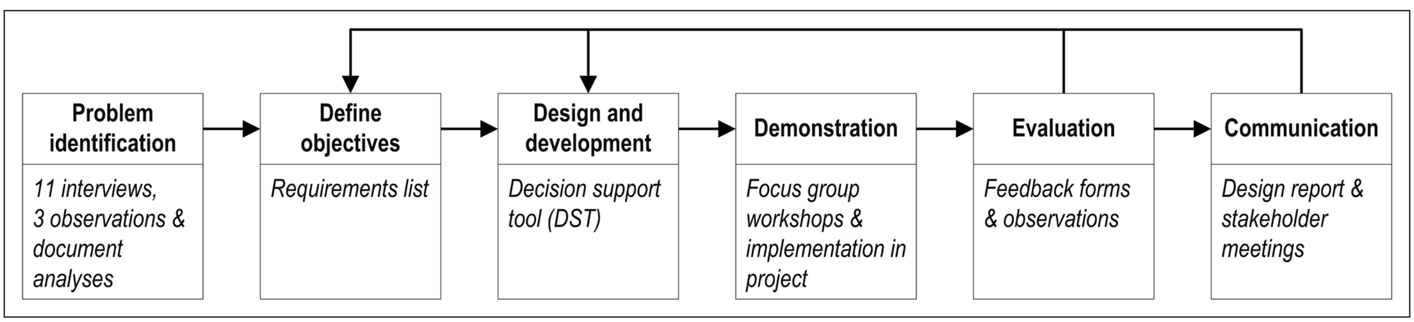

Figure 1: Design science research methodology process model with research and design activities.

Source: Adapted from Peffers *et al.* (2007).

The research started with the *problem identification* activity. Three data collection methods were combined to better understand how the selected demolition contractor makes waste management decisions in practice: document analyses, participant observations and semi-structured interviews. Drawing from several projects, cost estimations, material inventories and other project management documents were collected. Cost estimations offered an insight into explicating waste management strategies; material inventories into the availability of information about recoverable building elements. Participant observations were conducted (Musante & DeWalt 2010) to observe how decisions were made on site. Three different demolition projects in the Netherlands were visited to obtain such in-depth insights: complete demolition of a meat processing factory (procurement phase) and of a university building (execution phase) and partial selective demolition of an office building (execution phase). During these visits, the demolition activities were observed closely to acquire an insider's point of view (Phelps & Horman 2009; Pink *et al.* 2010). Furthermore, semi-structured interviews were conducted with 11 key informants: estimators, planning engineers, site managers, project managers and directors (Table 1). Questions covered both the existing situation (how decisions were made) and a potential future situation (how an artefact could assist). All interviews lasted approximately one hour each and were later transcribed. A literature review finally helped to position the problem within the ongoing scientific debates.

These inputs were used in *defining objectives* for the design artefact. Codes were assigned to meaningful chunks of the interview transcriptions and other data sources, after which these codes were compared with each other to identify relevant themes (Saldaña 2016) for waste management decision-making. Those themes were then turned into a list of (solution-neutral) requirements for the artefact (Peffers *et al.* 2007). These were made specific, measurable, achievable, relevant and time-bounded (SMART) and then prioritised with the MoSCoW method (in must-haves, should-haves, could-haves and won't-haves) together with the practitioners (Hudaib *et al.* 2018). The resulting requirements list was revised during a second and a third design iteration, when a better understanding of the design problem was obtained and users also requested certain changes to the artefact.

Table 1: Background information about the interviewees

ID	FUNCTION	WORK EXPERIENCE (YEARS)	PROJECT SIZE
DIR.1	Director demolition and reverse logistics hub	35	All
DIR.2	Director demolition	17–20	All
EST.1	Estimator	3	Small/medium
PM.1	Project manager	8–10	All
PM.2	Project manager	6	All
PM.3	Project manager	30	All
PM.4	Project manager	7	Big
SIM.1	Site manager	10	Small/medium
SIM.2	Site manager	15–17	All
PE.1	Planning engineer	14	All
PE.2	Planning engineer	5	Large

That artefact, a decision-support tool (DST), was *designed and developed* based on the requirements list. This was initially conceptually represented in a model without any interaction functionalities. During later design iterations, this model was turned into a spreadsheet-based tool that users could fill out and interact with. Several data sources were used as input for the waste management evaluations to that end. For example, unit prices of the focal firm were obtained from the focal firm and environmental impact data from a national database.

The artefact was *demonstrated* in various settings. The authors conducted a workshop with a focus group consisting of four employees of the demolition contractor (estimator, planning engineer, project manager and director) during the first design iteration. The design was presented including the system boundaries and assumptions made for the first design. As an initial test case, the tool was used to determine the best waste management strategy for plasterboards. During later design iterations, the Technical Action Research (TAR) method by Wieringa (2014) was followed to test how end-users use the artefact to solve an actual problem. As such, the DST was used by six demolition contractor employees (three estimators and three project managers). They were asked to use the tool for five frequently occurring building elements (plasterboards, ceiling panels, concrete floors, wooden beams and bricks), while their interactions were observed and suggestions for improvement were noted down. The users also filled out additional individual feedback forms. During a third and final design iteration, the tool was implemented in an actual demolition project (of a police office) where the project manager used it to determine the waste management strategy for several building elements.

The DST was *evaluated* by analysing the data collected during these demonstrations. Feedback forms were collected immediately after the practitioners had used the tool. Their feedback was compared with each other. Together with the notes taken during the workshops, this offered more in-depth insight into the local project routines of practitioners' decision-making. Such insights were used to sharpen the requirements list and, subsequently, to further adjust and refine the tool itself. Finally, the knowledge obtained during these design iterations was *communicated* via a design report, frequent meetings between the researchers and practitioners—and this publication.

4. RESULTS

This section presents the findings of the iterative design science research activities that culminated in a decision-support tool for selecting demolition waste management strategies.

4.1 PROBLEM IDENTIFICATION

The demolition contractor makes a distinction between three waste management strategies: reuse, recycling and recovery. Based on the interviews, it appeared that strategies about preventing or reducing waste were not relevant for the demolition contractor. Waste management strategies about improving the quality of building elements are, likewise, rarely applied. Furthermore, it was found that most decisions regarding waste management strategies are made only after a demolition project was awarded (*i.e.* during the execution phase). This was also the case for the university and the office building demolition projects. Cost estimations did not take into account different waste management strategies. 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). Other complementary data sources used are project documentation (*i.e.* technical drawings, material inventories, asbestos and chromium-6 reports, and pictures), project visits and internal discussions.

The financial factor is decisive for the demolition contractor regarding the choice for a certain waste management strategy. The demolition contractor determined whether there is a market demand for the building elements, and if a certain waste management strategy is financially feasible. This financial feasibility takes into account both costs and possible revenues received of a certain waste management strategy. DIR.1 argued that demolition costs are dependent on how a building element is extracted from a building: 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. Interviewees also argued that landfill costs, material handling costs, and revenues from selling products and (raw) materials influence their decision. A change in one of these costs or revenues could lead to the fact that other waste management strategies become more or less financially interesting for the demolition contractor.

The demolition contractor also considers the technical feasibility during the decision-making. Interviewees argued that it should be 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. Interviewees also argued that the quality and lifespan of elements should be considered before making a decision (EST.1, PM.1, DIR.2, PE.2). In addition, it was mentioned that the accessibility, manageability and transportability of building elements are important factors to assess technical possibilities (EST.1, PM.1, DIR.2, PE.1). Lastly, the presence of contaminations and the cleanability of the building element are important factors to consider. Sometimes, project managers deviate during the execution phase from a previously chosen waste management strategy. Reasons are a financial optimisation, change in the market demand or a change in the technical feasibility (PM.1, PE.2, DIR.1).

Moreover, interviewees argued that the environmental impact of different waste management strategies should be considered before a strategy can be chosen. They argued that a measuring method is needed to determine the environmental impact of a certain strategy (EST.1, PE.2, DIR.1–2). For example, DIR.1 argued that cleaned bricks could be transported over considerable distances while having a significantly lower environmental impact compared with producing new bricks. It was also found that it is important to consider the time spent to remove building elements, whether this can be done safely and if building elements still meet Building Decree stipulations (PM.3, SIM.1, Project 2).

These findings largely resonate with the literature on end-of-life decision-making. Generic decision-making factors found in the literature concern mostly economic, environmental and social aspects (Chileshe *et al.* 2018; Di Maria *et al.* 2020; Roussat *et al.* 2009). Other publications also highlight technical factors specific for (selective) demolition contexts, such as the possibilities to access and demount certain elements (Van den Berg *et al.* 2020b; Vandenbroucke 2016). Social factors concern environmental nuisance and job creation possibilities (Alamerew *et al.* 2020), although the demolition contractor did not find the latter aspect relevant with a shortage of labour in the (Dutch) market at the time. Iacovidou & Purnell (2016: 794) nevertheless emphasised that 'taking into account all the multiple aspects (*i.e.* environmental, economic, social and technical)' is essential to understand the full impacts of waste management decisions. Hence, drawing insights from both practice and theory, the identified design problem concerned how these various impacts (beyond mere economics) of reuse, recycling and recovery strategies may be understood better.

4.2 DEFINE OBJECTIVES

The second step was to define the objectives for the DST. Using the findings of the problem identification phase, the main objective became developing a DST which assists demolition contractors in the waste management decision-making process for separate building elements during the procurement and execution phases. This was further elaborated into a list of requirements for the tool. That requirement list was revised twice regarding the contents, prioritisation and how requirements were made SMART. This led to a final requirement list used in the design and development phase.

The final requirements list consists 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 subcategories: (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 prioritised ranging from requirements that must be met for a successful design (M), via requirements that are important but not necessary to consider (S) and requirements that are desired but not necessary (C) to requirements that are not implemented but can be fulfilled later (W).

For each main category and the five subcategories of category 3, an example requirement is given in Table 2. The requirements are derived from the problem identification and originate therefore from practice, the literature or both.

Table 2: Examples of requirements for each category used for the development of the decision-support tool (DST)

Note: [a]For abbreviations, see the main text.

ID	DESCRIPTION	CRITERION	PERFORMANCE	BANDWIDTH	PRIORITY[a]	SOURCE
1	*Process and output of the design*					
1.2	Present waste management strategy ranking based on evaluation criteria	Ranking	Present order	Based on evaluation criteria	M	DIR.1, PE.2, literature
2	*Types of waste management strategies*					
2.1	Waste management strategies relevant for demolition contractor	Strategy	Reuse, recycle and recover	Include all three	M	PM.1–2, PE.2

(Contd.)

ID	DESCRIPTION	CRITERION	PERFORMANCE	BANDWIDTH	PRIORITY[a]	SOURCE
3	*Factors influencing decision-making*					
3.1.3	Evaluate accessibility of building element	Accessibility level (three-point scale)	Assess level	Accessible, extra movement needed, inaccessible	M	EST.1, SIM.1, literature
3.2.1	Evaluate removal costs	Euros	Estimate	Include man-hours, machinery and equipment	M	All interviewees, literature
3.3.1	Evaluate environmental impact	Environmental Cost Indicator (ECI)	Evaluate	Use Dutch Environmental Database (NMD)	M	EST.1, PE.2, DIR.1–2, literature
3.4.2	Evaluate environmental nuisance	Nuisance level (three-point scale)	Assess level	Low, normal, high	M	Literature
3.5.1	Evaluate Building Decree compliance	Compliance (yes/no)	Evaluate	Complies, does not comply	S	All interviewees
4	*Usability*					
4.2	Use information commonly available to estimator and project manager	Information availability	Available	Material inventories, project visits, asbestos/ chromium-6 reports and drawings	M	Observations, document analysis

4.3 DESIGN AND DEVELOPMENT

The design of the tool is based on the requirements list. The final DST consists of a spreadsheet, linked to several data sources, that guides a user in systematically evaluating distinct building elements in terms of technical feasibility, economic costs, environmental gains and social gains. Based on the evaluations, a ranking of waste management strategies is suggested (reuse, recycle or recover). This ranking uniquely takes into account the relative importance of key evaluation criteria, as provided by the user, which may differ per project.

The final design of the DST uses an MCDM evaluation method called the analytical hierarchy process (AHP) method. This method enables the user to determine the weights between criteria by using pairwise comparison (Melese *et al.* 2020). The four main criteria evaluated in this MCDM are divided into subcriteria, which were (together with the main criteria) derived from the requirements list made during the 'define objectives' activity. Based on the demonstration of the requirement list and designs, it became clear that some revisions were needed on the requirements and subcriteria used regarding content, prioritisation and how these were made SMART. For an overview of the final criteria used including their characteristics (*i.e.* direction of preferences, and the scale and unit of measurements), see Table 3.

The following design principles are incorporated into this DST. First, the tool determines the impacts of the three waste management strategies that are most relevant to demolition contractors: reuse (use for a similar function), recycling (reprocessing as raw materials for new elements) and recovery (incinerating/producing energy or landfilling). Second, transport activities, including their impacts, are left outside the scope of the tool and are therefore not considered during the decision-making. Third, the environmental impacts of the different waste management strategies are calculated using data extracted from the Dutch Environmental Database (NMD), a database with shadow costs per material (commonly used for life cycle analyses). Fourth, the DST focuses on activities necessary to remove building elements till the temporary storage of these elements at the project site, including costs and revenues. Fifth, all subcriteria of the technical feasibility are considered equally important to evaluate technical feasibility. Finally, precepts are determined for the waste management strategies: reuse assumes disassembly using simple tools and small machinery; recycling assumes material destruction and separating using simple tools and small machinery; and recovery assumes destruction using large machinery without separation of materials.

The DST offers its users insights into the different impacts of the three waste management strategies, culminating in a suggested ranking (Figure 2). It can be used through, first, conducting a pairwise comparison between the different evaluation criteria to determine their weights (relative to each other). To that end, the tool requests users to systematically indicate how important one criterion is compared with another one. This results in a so-called 'priority vector' in which each main evaluation criterion has a certain weight (to be used for determining a final ranking). Second, users select a building element (such as a door or a beam) for which they want to choose a waste management strategy. Before the various impacts per strategy are determined, it is first checked whether that building element is 'clean' (unharmful or 'restorable' to such a state) and if there is a market 'demand' for the element. The user provides such input (yes/no) using dropdown menus in the tool. If any of the answers is 'no', then 'recover' remains the only waste management strategy; otherwise the user is guided to the third step: an evaluation model. The user then needs to provide information about the focal building element by filling out certain cells in the spreadsheet. This involves evaluating, estimating or assessing each of the criteria in Table 3, which are subsequently given a score. For instance, the user assesses the 'demountability' of the focal element in terms of the type of connections used (Vandenbroucke 2016): 'irreversible' (score = 1), 'semi-reversible' (2) or 'reversible' (3). Separate databases (with in-company cost data and generic shadow costs of the NMD) were thereby created to evaluate both economic costs and environmental gains. Finally, when all required information is entered into the tool, the impacts are calculated per main criterion, ranked per strategy in a 'normalised matrix' and multiplied with the earlier 'priority vector'. These scores can also be visualised in bar charts. Summing them per strategy, ultimately, results in the final output: a ranking of waste management strategies for the selected building element (Figure 3).

Table 3: Overview of the final criteria and their characteristics

MAIN CRITERIA	DIRECTION OF PREFERENCES	SCALE AND UNIT	SUBCRITERIA
Technical feasibility	Maximisation	Qualitative (scores)	Demountability, manageability, accessibility, separability, technical quality, transportability, time spent
Economic costs	Minimisation	Quantitative (euros)	Removal costs, cleaning costs, direct revenues, indirect revenues, material handling costs and landfill costs
Environmental gain	Maximisation	Quantitative (Environmental Cost Indicator—ECI)	Impact due to (prevention) production, impact due to recycling raw materials in new products, impact due to waste processing
Social gain	Maximisation	Qualitative (scores)	Prevented environmental nuisance

4.4 DEMONSTRATION

The final DST was tested during an actual demolition project, after in-company workshops with earlier versions. This section elaborates on this demonstration. A project manager with cost estimation responsibilities (PM.1) tested the final DST during a project that had already been awarded to the demolition contractor. The demolition contractor still had to determine appropriate waste management strategies for the elements present in these buildings though.

The project manager used the DST for this situation. First, he analysed the tender guideline of the project to analyse what the selection criteria were for the particular project during the procurement phase. He 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. Therefore, he conducted the pairwise comparison in the spreadsheet. The result of this pairwise comparison was that the weights of the technical feasibility, economic costs, environmental gain and social gain were 0.09, 0.27, 0.60 and 0.04, respectively. The project manager then analysed the material inventory of the demolition project.

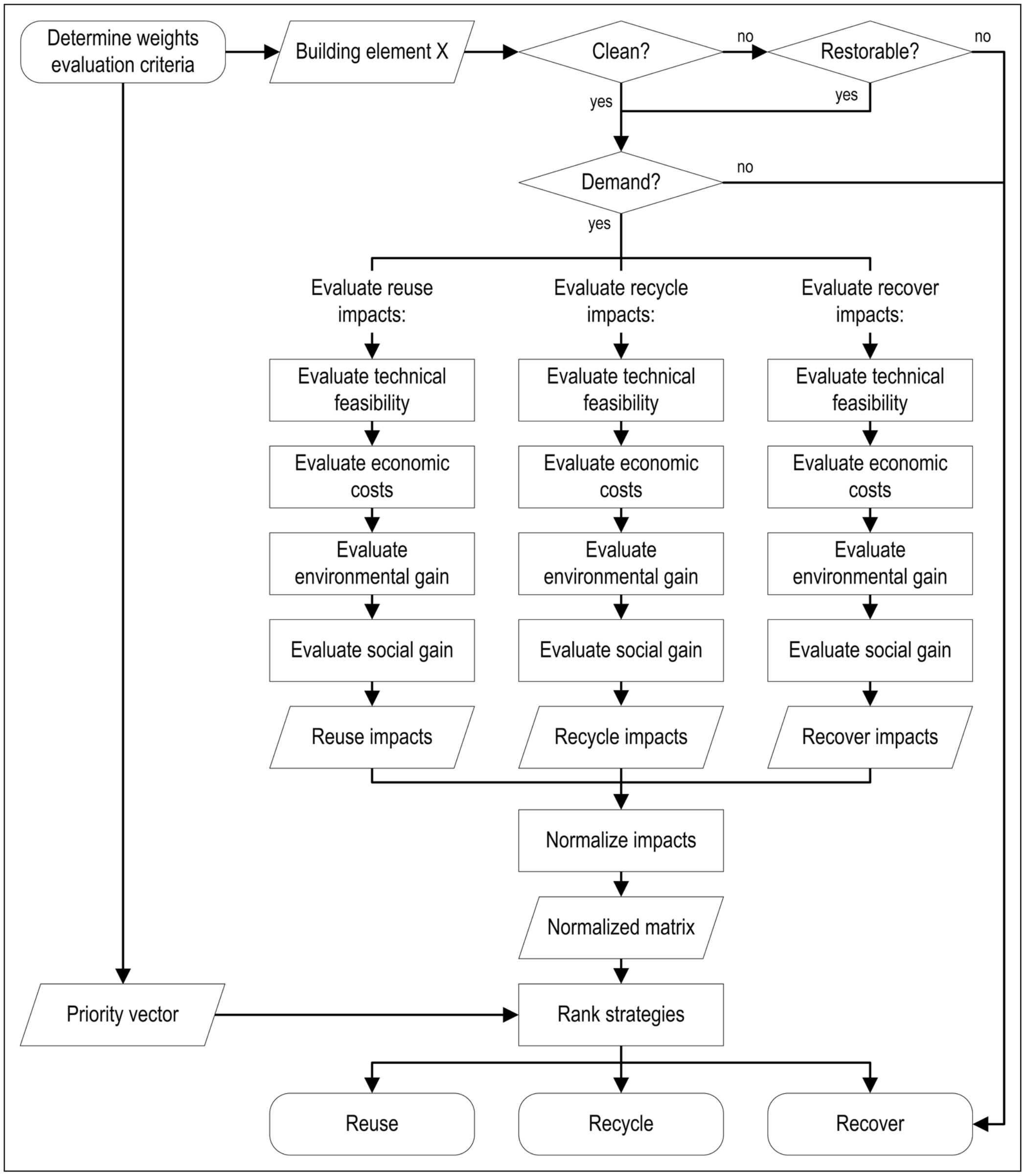

Figure 2: Flowchart of waste management decision-support tool design.

Plasterboards (20 tons) were selected as building elements for which the DST was tested. The preliminary conditions were satisfied for these elements (*i.e.* clean material with market demand), and thus the project manager was guided to the evaluation model of the DST.

Within the evaluation model, the project manager used dropdown menus to choose plasterboards and filled out the amount in m^2. The project manager had to convert the amount of 20 tons to m^2. He assumed that the walls contained double plasterboards and used a ratio of 50 kg/m^2. He worked with an amount of 400 m^2, accordingly. The project manager then noted that both economic costs and environmental impact were completed automatically, and that he only had to fill in the subcriteria for the technical feasibility and social gain for each waste management strategy. Thereafter, he analysed the ranking and supporting bar charts and concluded that reuse (with a final score of 0.42) was the best waste management strategy. Recycle and recover had a final score of 0.30 and 0.27, respectively. The project manager interpreted that reuse would be best, as this strategy had a high environmental gain compared with the other two strategies. This environmental gain also had the highest weight compared with the other main criteria. The project manager, consequently, argued that this outcome would be realistic for the demolition project. However, he also disputed the unit prices used to evaluate the economic costs and changed the direct revenues in order to check whether this would impact the final ranking of waste management strategies.

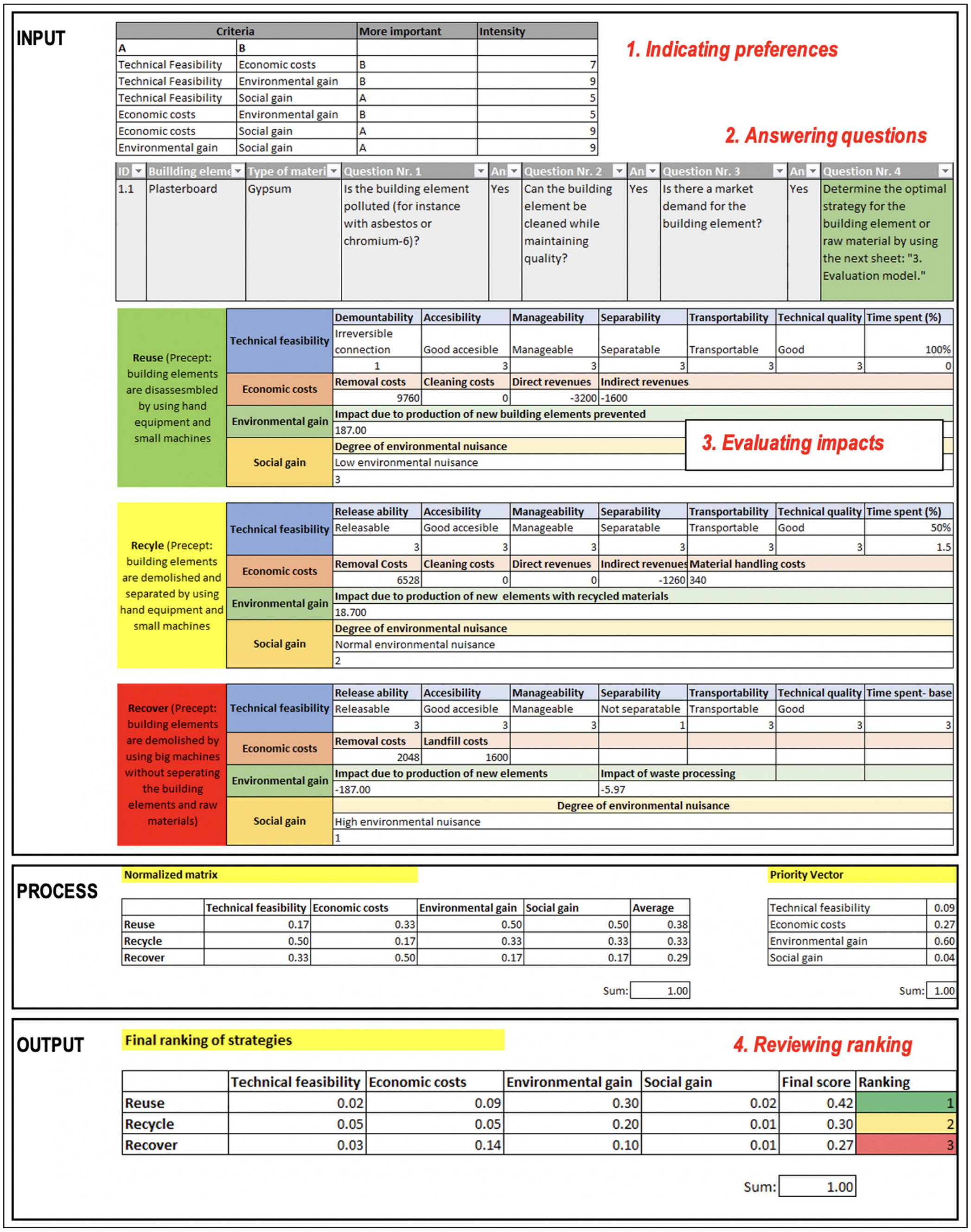

Figure 3: Overview of (spreadsheet-based) decision-support tool with Input (prioritisation preferences, eligibility questions and element characteristics), Process (impact evaluations linked to databases) and Output (suggested strategy ranking).

4.5 EVALUATION

The insights of the demonstrations were analysed during the evaluation activity. During and after the demonstration of the final design, the project manager argued that the DST was user-friendly. He stated 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 plasterboards, was not very time-consuming, according to the project manager. Filling in the preliminary questions and analysing the results for plasterboards was done within five minutes. The project manager argued that the speed would increase when the use of the DST becomes a routine. Besides this, it was found that the DST can improve the current decision-making process, as the project manager argued that it can be used to make a more reliable and better informed decision.

The project manager agreed with the outcome of the DST that reuse would be the best strategy for the plasterboards. He thereby commented that it is still difficult to actually receive the (estimated) direct revenues for second-hand materials. The unit prices of the economic costs were based on one quantity (*i.e.* 100 m^2). Therefore, during both the second and third demonstrations it was argued that the results were disputable. It was suggested to determine these unit prices based on data of previous projects. The project manager commented the same, but also suggested to create unit prices for different project sizes (*i.e.* small, medium and large). Unit prices can then be varied accordingly.

It was also noted that the DST can be used for any element of a building if the corresponding databases (with cost and environmental impact data) are available to the demolition contractor. Thus, this has implications for implementing the DST in local project routines. Data regarding the economic costs of recent projects should be analysed by employees of the demolition contractor. Unit prices can be determined and updated accordingly. Moreover, calculations must be made of recently executed demolition projects to validate these cost data. Directors, project managers and estimators may also need to discuss and approve the final set of unit prices.

Another implication is that the weights between the main criteria need to be determined by the directors and project managers 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 a pairwise comparison. This task could thus be added to the existing decision-making process. Moreover, estimators and project managers need to know what elements are available in a building during the procurement phase by analysing material inventories or visiting projects. Therefore, these data must be retrieved before the DST can be used meaningfully.

Finally, it was found 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. It can be explained by the normalising step, after ranking the strategies per impact. The project manager used the DST in a new way: to determine what direct revenue was minimally needed to make sure that reuse scored highest among all three strategies.

5. DISCUSSION

This design science research study created decision-support for selecting demolition waste management strategies. An artefact (DST) was developed iteratively in response to more informed decision-making needs of a pioneering demolition contractor located in the Netherlands. The artefact offers insights into the economic, environmental, social and technical impacts of possible reuse, recycling and recovery strategies. Demolition practitioners can use it to determine the most appropriate end-of-life strategy for distinct building elements. The presented solution concept can be used by other (de)construction professionals to design similar solutions for their local field problems. This section discusses the insights gained during the creation of that solution concept as contributions for research and practice. It also acknowledges limitations and derives suggestions for future research.

5.1 OPPORTUNITIES FOR DECISION-SUPPORT

Redefining demolition is essential to reduce its negative sustainability impacts on cities and societies. Buildings are often being demolished even before the end of their technical life-span, resulting in loss of embodied energy and other natural resource value (Hopkinson *et al.* 2019). Mitigation of construction and demolition waste has, accordingly, become a priority for most environmental programmes around the world (Gálvez-Martos *et al.* 2018). Reinvigorated by circular economy agendas, research into alternative demolition methods has started to redefine conventional demolition practice with new perspectives on treating buildings as material banks (Debacker & Manshoven 2016), waste as 'a [resource] state in a never-ending transformation' (Andersson & Buser 2022: 488), and unbuilding as circular practice to reclaim such resources

(Lynch 2022). Yet, where previous research has been limited in suggesting new ways for demolition contractors to comprehend more fully the impacts of various end-of-life strategies, the current research offers such decision-support.

The development of the DST contributed new insights that correspond with each of the design science activities. The selected demolition firm made most of the waste management decisions, perhaps sursprinly, only during the execution of a project (rather than during procurement). This warranted a need to better understand the impacts of decisions at a building element level. Previous research has only characterised this decision-making as an information-intensive process (Van den Berg *et al.* 2020a). The current research adds what factors demolition contractors consider important during this process: technical feasibility, economic costs, environmental gains and social gains. The newly developed DST shows how these factors (other than mere costs) can be evaluated, weighed and ranked in a systematic manner. Earlier studies, instead, tended to overlook demolition contractors as potential users of decision-making methods or only focused on the final design of such methods. The use of the DST was demonstrated during both workshops and project works. This confirmed that such a tool can be useful to determine appropriate waste management strategies for distinct elements. It also opened up another potential use: assessing the minimal direct revenues necessary to choose for reuse. These insights from across the entire design science cycle suggest how tools can be created to meet local needs for more informed demolition waste management decision-making.

New opportunities for implementing and upscaling this study's solution concept are also foreseen. Demolition contractors interested in adopting more sustainable demolition methods can use the proposed tool to understand more fully the impacts of waste management strategies beyond the norm. Although the additional time and cost involved in using the DST appeared relatively small, the tool can have most potential when used for those elements that are commonly found in any building. Implementing the tool also brought changes to the focal demolition contractor's working process to the fore: project managers and directors need to determine the weights between main criteria, end-users should know more precisely what elements are present in a building, and unit prices of the economic costs need to be calculated using recent data of previous executed projects. Other demolition contractors may expect similar changes when they would like to implement the tool in their contexts. Further adoption also prerequires more accurate information about existing building conditions, yet such information is often lacking (Tingley *et al.* 2017). This represents both a constraint and a (business) opportunity, as the European Commission also emphasises in policies targeting the 'twin' green and digital transition (Bianchini *et al.* 2023). Gathering, interpreting and communicating information relevant for more informed waste management decision-making will help to scale up this study's solution concept and promote more sustainable demolition.

5.2 LIMITATIONS AND FUTURE RESEARCH

This research has several limitations, which can suggest future research directions. Most importantly, the DST has been studied within one specific environment only. The DST represents, in line with the tenets of design science (Hevner *et al.* 2004; Mullarkey & Hevner 2019), an instantiated example of a tool to select demolition waste management strategies. This particular tool was motivated by the specific needs of one demolition contractor. Other firms may have slightly different needs, which could motivate certain changes to the tool. Different needs may also originate from the external environment. That is, sustainability ambitions and goals of a client, the regulatory framework and other factors in the environment can strongly influence the waste management strategies adopted by demolition contractors. A client could, for example, select a demolition contractor based on reuse or recycling targets during the procurement process launched before demolition. The DST is, however, limited in taking such constraints into account. It may thus be necessary to adapt the tool for use in other settings. This may involve adding a feedback loop to check whether suggested waste management decisions at the element level are in line with targets for the overall project. More research, embedded in other settings, is thus needed to further substantiate the findings.

Other limitations relate to the design of the tool. First, the unit prices used were limited to one specific quantity of the building elements. The prices appeared not directly transferable to other quantities as well. Future research can look into new ways of using data of previously executed projects for more accurately estimating unit prices. Makovšek (2014), for instance, demonstrated that historical cost and market price movements data can improve cost estimations. It would be interesting to analyse how these unit prices can be kept up to date as economic costs vary constantly. Second, the environmental impacts focused on the impacts associated with production and waste processing only. Using a complete life cycle analysis to calculate the environmental impact of the different strategies would be more accurate. Therefore, it is suggested to include other life cycle phases as well, *e.g.* by including the transport of building elements to their new destination and the emissions of machinery (Wang *et al.* 2018). Finally, the tool focuses on three types of waste management strategies. Given that other waste management strategies—such as refuse, reduce or refurbish—may be more relevant in other (cultural) settings and can potentially have wider impacts, it is recommended to study how such other strategies can be included to further push the boundaries of sustainability and waste management in demolition writ large.

6. CONCLUSIONS

This research provided decision-support for selecting demolition waste management strategies. It was found that many waste management decisions in the Netherlands were made only after the procurement phase, during the execution, and that these traditionally rely heavily on tacit knowledge. Strategies were most often based on economic costs only, but three other factors were identified that are deemed relevant as well: technical feasibility, environmental gains and social gains. Depending on the specific project ambitions, demolition contractors need insights about these impacts to choose appropriate waste management strategies. Consequently, a tool was developed that uses a multi-criteria decision methodology (MCDM) to compare and rank three strategies (*i.e.* reuse, recycle and recover). Users of this tool can systematically evaluate these strategies. The final ranking reflects their priorities (based on a pairwise comparison). The proposed solution can be used during both procurement and execution phases, although earlier usages can yield more benefits for project planning. Actual implementations nevertheless require changes to project routines, particularly regarding deriving accurate unit prices for meaningful evaluations. Understanding the various consequences of waste management strategies can, accordingly, help to choose more circular and sustainable demolition methods.

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COMPETING INTERESTS

The authors have no competing interests to declare.

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