Automation in Construction 128 (2021) 103734

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Decision support system in management of concrete demolition waste

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A R T I C L E I N F O

Keywords:
Decision support system
Circular economy
C&D waste
Recycled concrete aggregate

A B S T R A C T

Processes of concrete waste management can be carried out using various technological and organizational systems. Such systems must meet the boundary conditions of a given project involving deconstruction of a building and will differ in terms of waste management costs, environmental impact and nuisance to the surrounding community. Selecting the most advantageous solution, taking into account numerous standards such as sustainable development, requires a multiple-criteria analysis of such variants. The system presented in this work supports the decision-making process in terms of choosing a technological and organizational solution in the field of concrete waste management. It is based on a mathematical simulation model, which produces rating indicators for technological-organizational waste management systems. Based on a synthetic rating indicator, the decision maker is provided with a list of ranked variants to choose from. Moreover, the system analyses qualitative parameters, such as the building site area required and waste management time.

1. Introduction

The construction sector generates almost 35% of the EU's waste, which corresponds to $871 \cdot 10^9$ kg of waste per year to be utilized. In business practice, construction waste is recovered to a great extent. The share of concrete waste in the construction waste mass in EU countries is in the range of 12 - 40% [1]. Next to brick waste (8-54%), concrete represents the largest group of waste to be managed. Moreover, the consumption of concrete is continuously increasing, hence the development of techniques for its management in demolition processes is required. The recovery rate for the construction and demolition waste in the EU in 2016 was 89% [2] (the high recovery rate results from including soil masses in the construction waste). However, the current concept of social-economic development requires a holistic approach to the organisation of waste recovery processes, including an efficiency increase of the existing recovery systems in the three fields of sustainable development [3]. Increasing the effectiveness of activities associated with waste management requires knowledge about the profits and losses as well as limitations related to the organisation of the processes and their multi-criteria analysis.

In business practice, there are three basic systems of concrete waste management (WM) [4,5]:

- **W**aste **R**ecycling on a construction site by **M**obile machinery (WRM),
- **W**aste **R**ecycling on a **S**tationary waste processing site (WRS),
- **W**aste **T**ransferring to business entities for **U**tilization (WTU).

If there are favourable conditions at the construction site, it is possible to organise a mobile recycling line. Waste management in this system involves storing waste on the construction site, transporting machines for recycling, loading rubble into a crusher, crushing the rubble, loading the aggregate onto trucks and transporting the aggregate out of the construction site. The WRM system can be structured in a variety of ways, by means of different types, numbers and capacities of machines, using continuous, rhythmic or other work organization methods.

In the WRS recycling system, waste is stored on the construction site and loaded onto transport vehicles. Next, the waste is transported to an external waste processing site where it is unloaded, subjected to recycling processes, loaded again and transported in the form of aggregate either to the storage site of the company performing the demolition or to the customer. The WRS system can be structured depending on the process organisation, the machinery used for loading and transporting the aggregate (including the number of trucks) and the choice of the rubble crushing service provider.

The WTU system assumes collection of waste in containers and its subsequent removal to a recycling plant (subcontractor service). Such a solution, despite many disadvantages, is applied particularly when there are impurities of concrete rubble, lack of space and time for recovery processes, or in the case of small amounts of waste. This system also

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https://doi.org/10.1016/j.autcon.2021.103734
Received 26 November 2019; Received in revised form 17 April 2021; Accepted 21 April 2021
Available online 6 May 2021

assumes a continuous waste collection manner and hence it does not require any additional space (except for a container) to store waste on site. Furthermore, the system assumes recultivation of the waste disposal landscape in the future (this activity is actually common and affects the environmental indicators of the system). On-site processes related to the WTU system include:

– delivery of a container (by the service provider, i.e. the company collecting the rubble),
– ongoing loading into the waste container, and
– waste collection following a fixed schedule or notifications by the service provider.

The difficulty in selecting the best system variant of waste management from a set of possible solutions stems from the multiplicity of parameters resulting from the individual character of each construction project, such as transport distance, size of the construction site, time of the construction works, age and efficiency of the machines [5]. Randomness of construction processes, which affects the uncertainty of the results of the undertaken actions, is also of substantial significance. It creates many barriers related to the organisation of waste management processes, especially in the area of waste recovery systems (WRS, WRM), which include:

– insufficient knowledge of the organisation of reverse supply chains [6],
– uncertainty about the results of the implementation of reverse logistics (RL) [7,8],
– resistance to changes in the well-established procedures [9],
– lack of resources, including financial ones, to cover initial costs [10–12], and
– poor product quality [11].

Case studies of construction waste management presented in the literature [13–18] confirm interdependence of individual parameters and the results obtained. Limited experience in terms of changing boundary conditions does not help entrepreneurs to eliminate the above-mentioned barriers and makes it impossible to generalise conclusions on the effective waste management solutions.

One way of facilitating complex decision-making processes is to use IT tools. Construction works are susceptible to external factors (environmental, social, economic) as well as internal factors related to the organisation of the investment process, i.e. mechanisation, staff selection, schedule creation [19]. For these reasons, decision support systems are more and more frequently used in the construction sector in the areas of risk management, safety, work contracting, technical conditions assessment and others [20–29]. In construction waste management, the available literature offers decision support tools to search for an optimal location for the production of aggregate from recycled concrete [13,30–32].

There is an obvious necessity to develop computer systems to support decisions in the management of concrete waste, based on multi-parameter models. Reliable information about profits and losses in particular waste management systems would minimise the risk of making a wrong decision. Thus, a barrier related to the risk of implementing even non-standard waste management solutions in engineering practice would be overcome.

Here, the authors propose a decision support system for concrete waste management in construction projects. The article outlines the assumptions (Section 2.1) and the adopted research methods (Section 2.2) as well as describes the subsequent development stages of the Decision Support System (DSS) (Sections 2.3–2.6). Section 3 provides an example of how the DSS could be used in a construction project. Sections 4 and 5 present the discussion and final conclusions, respectively.

2. Methodology

2.1. Assumptions

The three basic waste management systems - WRM, WRS and WTU have been identified based on an analysis of economic processes. Due to a strong dependence of the effectiveness of concrete waste management on work organisation and machinery, a set of implementation variants has been considered within each system (Section 2.3). Each variant, constituting a separate system of concrete waste management, is marked with an appropriate acronym. The decision support system is dedicated to companies specialising in construction demolition works. It is assumed that the contractor has their own processing-storage site, where they can both organise the crushing process and store the waste and recycled aggregate. Moreover, it is assumed that they hold a permit for the generation, collection, transport and processing of waste from group 17 01 01.

System models have certain limitations, such as the area of the construction site and the time needed for waste management processes. Depending on the construction schedule, two variants are considered:

– Waste management begins after demolition works have been completed, i.e. when the waste input stream intensity (I_{so}) is unlimited. Therefore, it will take the form of the waste management intensity (I_{go}):

$$I_{so} = I_{go} \tag{1.1}$$

– Waste management begins during demolition works. In such a case, the waste input stream into the waste management system is correlated with the efficiency of the demolition works. The model assumes continuity of the waste management processes and the following relation:

$$\overline{I_{so}} \leq \overline{I_{go}}, \tag{1.2}$$

Then, the start time of waste management T_{rgo} is set in the system:

$$T_{rgo} > (T_{zr} - T_{rr}) \bullet \left(1 - \frac{\overline{I_{so}}}{\overline{I_{go}}}\right), \tag{1.3}$$

where T_{rr} and T_{zr} are the start and completion time of the demolition works, respectively.

It is assumed in this model that both rubble and aggregate are stored in the form of piles up to 3500 kg/m^2, in accordance with the storage standards. The minimum area for recycling on the construction site is determined on the basis of the size of the crusher and the size of the aggregate prism zone. The model assumes that the excavator loads rubble from the rubble slope - hence the additional operational area for the excavator is not required.

The organisation of the demolition processes determines the purity of concrete rubble. Therefore, the implementation of the demolition processes in the course of deconstruction with selective waste collection was adopted in the model. The model also assumes that the stream of waste from the demolition processes is rubble cleared of primary reinforcement with the rubble size not exceeding 40 cm. This limitation is based on the operating parameters of the smallest crusher included in the model. The product of recycling is aggregate of 0-63 mm fraction. An analysis of the construction market in Poland shows that this fraction is characterized by the greatest demand and supply. In the construction practice, this wide fraction is sieved and divided into smaller fractions needed. The model assumes a continuous demand for recycled concrete aggregate.

This paper analyses the following technological and organisational solutions of demolition works, which determine the waste stream intensity:

– demolition using pneumatic hammers,
– manual demolition, and
– demolition using hydraulic hammers mounted as part of excavation equipment.

In the study, demolition works are not included in the waste management systems and, therefore, are not assessed. However, it was necessary to include them in the simulator to reflect the concrete waste stream.

2.2. Concept of system development

The aim of this research project was to develop a model to support decision making in the field of concrete waste management. The model ranges from demolition processes to the management of concrete waste by recovery or disposal. However, the demolition processes are not assessed, they are only considered for waste stream modelling. The assessment of WM systems is carried out from the perspective of the contractor, so includes the costs to be incurred, the environmental impact of the implemented operations and the direct social impact (neighbourhood) of the construction site.

Defining systems and identifying their parameters followed observations of waste management processes during demolition works as well as interviews with the supervisors of such works and companies supplying construction machinery and equipment. The data collected in this way allowed us to single out and describe (analytically and logically) elements of the systems (such as waste streams, machines and devices used) and relations between them and their features. Hypotheses and theories available in the literature, our own measurements, including measurements in situ (e.g. of the noise level, works timing), catalogue data and machinery technical data were used to find the character and values of individual parameters (see more in Sections 2.3–2.4). A list of input variables, system elements and modelled processes are summarised in Appendix 1.

The role of the simulator in the system was to provide evaluation indicators (Costpoint, Sociopoint and Ecopoint) for a multi-criteria analysis. The simulator also allows checking the limiting conditions related to the duration of the waste management processes and the construction area required. The values of the economic, social and environmental indicators are passed on to the multi-criteria analysis module, where the systems are evaluated based on the decision-maker's preferences. The results of the analyses are presented via a user interface. The concept of the decision-making system structure proposed by the authors is presented in Fig. 1.

The basic modules of the *OptiC&DWaste* decision-making system are:

– User interface - a module that allows the decision maker to enter the input data necessary to perform a simulation;
– Simulator - a module that simulates the operation of a given system. In this part of the programme, indicators for the evaluation of the systems are calculated;
– Systems evaluation module - a module that performs a multi-criteria analysis of variants and determines the system limitations;
– Explanatory module - a module that presents the results of system evaluations as a ranking list and charts, as well as it provides information about the limitations.

Conceptually, a realisation of the DSS requires:

I A definition and description of concrete waste management systems, including recovery systems, i.e., the specification of system boundaries and limitations, structure and elements (described in Section 2.3).
II A mathematical description of the model parameters (Section 2.4):

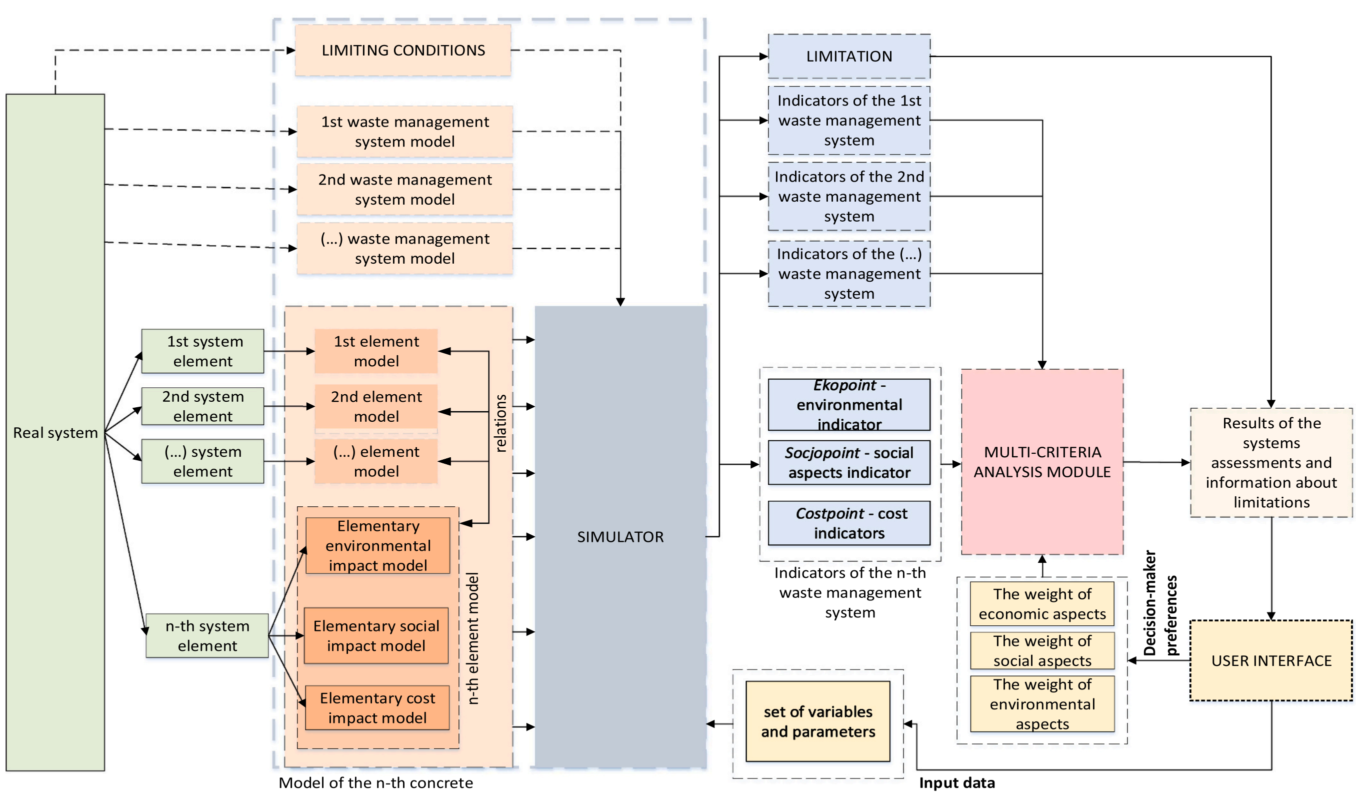


Fig. 1. Scheme of DSS structure.

- the efficiency of the systems as well as the waste stream intensity,
- the costs of waste management systems and of machinery operation, the profits from the sale of aggregates and other,
- the environmental impacts of waste management processes, including the selection of indicators for the assessment of environmental impacts and methods of their standardisation and weighing,
- individual environmental indicators for all elementary processes,
- the social impacts, including the selection of indicators representing the social aspect, and the development of methods for their determination.

III A multi-criteria analysis module for the variants (Section 2.5).
IV Simulation modelling of the waste management systems and a simulator (computer program) for the models (Section 2.6).
V Verification and validation of the developed models. The work was carried out with a use of the following methods: data confrontation, extreme conditions test, sensitivity analysis and compatibility tests.
VI Transformation of the simulator into a DSS, further referred to as *OptiC&DWaste* (Section 2.6).

2.3. Description of waste management systems

2.3.1. Waste recycling on a construction site by mobile machinery

A recycling system on a construction site can use a variety of work organisation structures and machines with different capacities. The organisation of work determines the costs of on-site recycling processes as well as their environmental and social impacts. Fig. 2 presents one variant of organization in the WRM system.

This study considered the possibility of implementing the WRM system using four different crushers (Table 1) and four excavators of different capacities (Table 2) combined into a technological process forming a total of 10 variants (K1E1; K2E1-E2; K3E1-E3; K4E1-E4). The technological compatibility of the machines, i.e. the size of the excavator bucket and the size of the loaded basket of a crusher, were taken into account. Each variant is a unique realisation of the recycling system on the construction site and hence evaluated separately.

In the study, it is possible to create and implement a WRM system based on other organisational structures.

2.3.2. Waste recycling on a stationary waste processing site

Another system considered in this study is the WRS system, in which the recycling processes take place on an external waste processing site by means of an independent service. In this system, concrete waste is loaded onto transport vehicles by excavators and transported to an outside waste processing site where it is unloaded and recycled. The aggregate is loaded onto transport vehicles and transported to the storage site of an enterprise, where it is unloaded and sold. In the adopted work organisation structure (Fig. 3), a single truck serves all transport links in the concrete recovery logistics chain. This means that its work cycle involves transporting the waste to a stationary site, unloading the rubble, waiting for the rubble to be crushed, collecting the aggregate, transporting the aggregate to the storage site, where it is unloaded, and returning to the loading operation station at the construction site.

In WRS, different variants were used in terms of the load capacity of machines, the number of transport vehicles (Table 3) and the type of excavator at the operation station (Table 2).

Ultimately, for each excavator, four types of tippers (S1 – S4) were considered in a quantity from 1 to 10. The system assumes that high-capacity machines (E3 and K4) operate on the stationary plant.

Table 1
Types of crushers considered in the system (based on machine catalogues).

Marking	Weight of crusher [kg]	Average technical capacity [10^3 kg/h]	Electric motor power [kW]
K1	1400	10	10.8
K2	2900	17.5	29.6
K3	10,000	40	52.0
K4	27,800	125	168

Table 2
Excavator variants (based on machine catalogues).

Marking	Motor power [kW]	Maximum bucket volume [m^3]
E1	29.6	0.18
E2	72.0	0.40
E3	110.0	1.50
E4	159.0	2.00

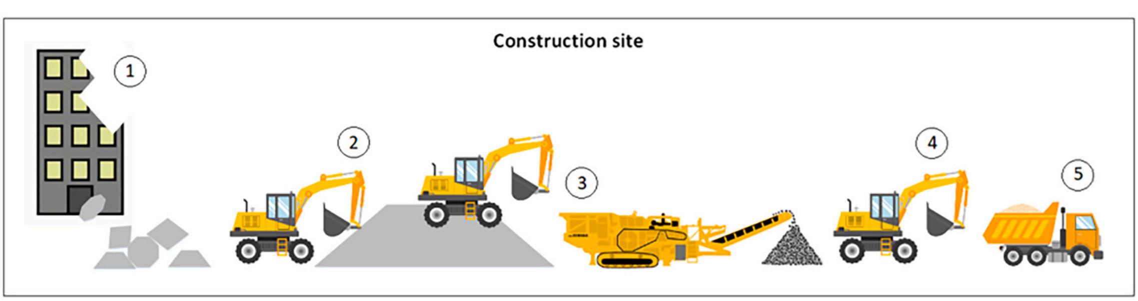
2.3.3. Transporting waste to business entities for utilization

The last system under consideration here, WTU, being also the reference point for the recovery systems WRS and WRM, is a system of transferring waste to business entities and their waste disposal plant. In this system, the contractor must only load the waste into provided containers and the remaining waste management processes are taken care of by the waste recipient. The volume of the container (12 different capacities from 3 m^3 to 25 m^3, with an interval of 2 m^3) and the size of the excavator (E1-E4) are used as variants and in total give 48 variants in the system. The number of containers needed for each variant is calculated from the input data.

2.4. Mathematical modelling

2.4.1. Waste stream

Concrete waste stream can be measured by the amount of waste produced per unit of time, i.e. the efficiency of demolition works. To model the average value of concrete waste stream (Φ_o, m^3/h, the labour



1- deconstruction/demolition of concrete structure, 2 - debris storage, 3 – debris crushing, 4 - aggregates loading, 5 - customer receipt

Fig. 2. Organisation variant in WRM system.

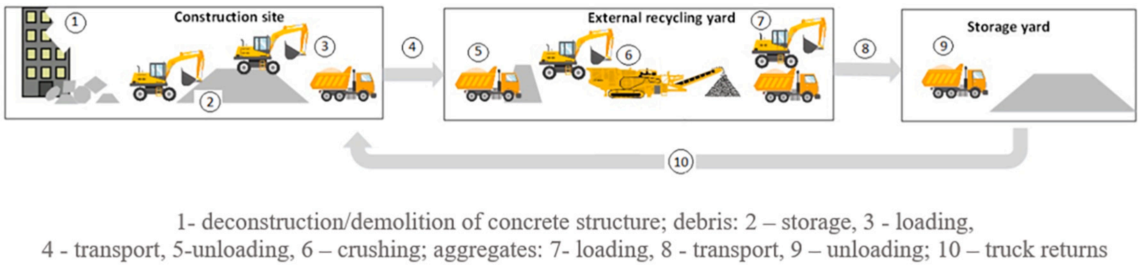


Fig. 3. Scheme of the adopted organisational structure of the WRS system.

Table 3
Truck variants (based on machine catalogues).

Vehicle type	Symbol	Load capacity (model) [10^3 kg]
Tipper (from 1 to 10)	S1	Up to 10
	S2	over 10 to 15
	S3	over 15 to 20
	S4	More than 20

intensity of demolition works is used:

$$\Phi_o = W_e = 1N_c, \quad (1.4)$$

where W_e is the operating efficiency of the works, m^3/h, which is determined from the working time standard [h/m^3]). The labour intensity standards for manual and pneumatic demolition works used in this work were adopted from the Catalogue of material expenditures (KNR 4-04 Demolition of buildings and structures).

In case of demolition using hydraulic hammers mounted on excavator equipment, the modelling of the waste stream follows a parametric method of work standardisation, making the efficiency of work dependent on the thickness (x) of the element subjected to demolition. The functional relationship between the technical capacity of the hammer and the thickness of the element is determined by approximation of the data obtained from the hammer manufacturer (Table 4).

The description of the actual system, however, requires the determination of the capacity of the hammers. For this purpose, auxiliary processes and no-load runs of the hammers were identified and measured. The research was conducted by observations of the modernisation works of the furnace building and the tank at the "Saint Gobain" plant in Dąbrowa Górnicza on 21-23 February 2018. The results are as follows:

– the dust settlement time and the hammer touchdown point change (average of idle runs): 36.93% operational working time (t_g),
– the rubble and reinforcement removal time to enable continuation of works (average of the auxiliary processes.): 44.25% t_g.

Table 4
Technical capacity of hydraulic hammers (m^3/h) as a function of element thickness (x cm).

Model	Capacity	Material type	Functional form of technical capacity (in the range 5-140 cm)
X	*Small*	Concrete	$W_{tm}(x)$= 0.0001x^3 - 0.0192x^2 + 0.8379x + 3.1396
		Reinforced concrete	$W_{tm}(x)$ = 8E-05x^3 - 0.0135x^2 + 0.598x + 1.3862
Y	*Medium*	Concrete	$W_{tm}(x)$ = 3E-05x^3 - 0.0118x^2 + 0.9726x + 7.866
		Reinforced concrete	$W_{tm}(x)$= 2E-05x^3 - 0.0069x^2 + 0.5829x + 6.258
Z	*Large*	Concrete	$W_{tm}(x)$= −4E-05x^3 - 0.0015x^2 + 0.8365x + 11.517
		Reinforced concrete	$W_{tm}(x)$= −1E-05x^3 - 0.0032x^2 + 0.5977x + 7.3226

The time of technical and organisational breaks (t_o) and the time for physiological needs (t_f) of the machine operators were adopted from [33].

Construction works are highly sensitive to changing environmental conditions, including atmospheric conditions [19]. Other factors interfering with the construction process are [19,34]: poor organisation of work, human factor, machine failures and more. According to research [35–39], the operational performance of construction works is a random variable with the following distributions (depending on the type of works): beta, triangular, logarithmic-normal, Poisson and others. The triangular distribution was adopted to reflect the variability of the waste stream. The average value of the distribution was taken from labour intensity standards, while its range of variability was dependent on the expected scope of interference in the works (Table 5). This relationship was established based on interviews with experts.

Due to the change in the structure of concrete from solid to aggregate, the waste stream is expressed in mass units [10^3 kg/h], assuming the volume density of concrete recommended by the Eurocode 1 [40] of 2400 kg/m^3, while the bulk density of rubble was assumed, by experience, to follow a uniform distribution in the range of 1700–2000 kg/m^3.

2.4.2. Description of the elements of the waste management systems

Indicators of economic, ecological and social aspects are correlated with the working time of the particular elements of the system (machines), hence, their simulation description is necessary. The capacities of the excavators K1 and K4 were measured during their rubble loading operations. The observations confirmed the logarithmic-normal distribution hypothesis of the working cycle time of the excavators and that the sample was representative. Given the linear relationship between the working cycle time of a machine and the size of the bucket [46], the average value of the working cycle time of the excavators K2 and K3 was determined analytically by interpolation. The results are summarized in Table 6.

One of the parameters affecting the work efficiency of an excavator is the filling ratio of the bucket. Observations were carried out, consisting in a subjective assessment of bucket filling with concrete rubble from demolition. The experiment confirmed the representativeness of the research sample and the normal distribution hypothesis for this variable with an average value of 0.73 (bucket filling ratio).

The time of the crushing process and the no-load run of the crusher depends on the work efficiency of the excavator (which acts as a loader). Thus, the entire work station was modelled based on observations. The auxiliary processes time is the time needed to clean the crusher mouth by removing rebars and other elements blocking the jaws and amounted

Table 5
Variability range of demolition works efficiency.

Range of interference	Low	Medium	High
Range of variability[1]	±19.58% of the expected value	±35.80% of the expected value	±19.58% of the expected value

[1] Arithmetic mean of the answers given by experts (13 respondents).

Table 6
Working cycle time of excavators during loading operations.

Excavator symbol	Average value of the working cycle time of the excavator $\bar{t}$ [s]	Method
K1	11.39	Experimental
K2	13.47	Interpolated
K3	23.87	Interpolated
K4	28.60	Experimental

to 14.4% of the crushing time. The time of technical and organisational breaks and the time for physiological needs of the machine operators was adopted from [33].

The efficiency of the WRS system was found using the mass service theory. In practice, in a modelled system, there are two different operating stations - one for loading and one for crushing. Stationary crushing, however, is characterised by high efficiency, hence it is assumed that no queue is formed at the crushing station. Therefore, the system is considered as an M/M/1 system (according to D. Kendall's classification) with feedback, where the operating station is an excavator on the construction site loading rubble onto hopper trucks. The average speed of transport vehicles was adopted from the characteristics of truck traffic in Poland [41]. The operating time at the stationary site as well as the loading and transport time are the results of a simulation, while the total transport distance is a variable controlled by the decision-maker.

2.4.3. Costs

An analysis of the system operation costs was done by classifying costs by function and inventorying individual operation costs of specific elements. The analysis included an evaluation of the costs of transport and crushers, depreciation (using the linear method), servicing, insurance, technical maintenance, repairs, additional charges (tachograph, road tolls), vehicle tax, fuel, lubricants and oils, tyres, average one-off costs, mark-ups for fixed and changeable costs. The unit costs of excavator operation were taken from the price list [42]. The loss of the excavator working time in the WTU system was calculated as a potential profit of excavator rental. The prices of the external services in the model were based on the author's market research. Approximately, the unit cost of collecting concrete waste for landfilling ($C_{ju}[PLN/Mg]$ equals:

$$C_{ju} = 159.75 \cdot V_k^{-0.583} \tag{1.5}$$

where V_k is the container volume expressed in cubic meters.

2.4.4. Environmental impact

The classical LCA method was used to describe the impact of waste management processes on the environment [43–47]. Seven main environmental indicators recommended by a standard dedicated to construction processes were used to assess the following environmental aspects [48]: global warming (GWP), ozone depletion (ODP), soil and water acidification (AP), eutrophication (EP), photochemical ozone formation (POCP), abiotic resource depletion – elements (ADPe), abiotic fossil fuel depletion (ADPf). The characterisation coefficients derived from the CML-IA database [49] were used to calculate the indicator values. Next, the indicators were normalised and weighed in order to obtain a single-point evaluation – Ecopoint (Ep). The authors are convinced that it is necessary to integrate political strategies with economic activities. Thus, the paper adopts a method of standardisation and determines the significance of the environmental indicators based on the EU objectives set for 2020 [50].

Software GaBi [51] was used to carry out an inventory of input and output streams of individual processes and determine the values of the environmental indicators. However, since environmental assessment is not a common practice in the industry, the database dedicated to construction processes is limited. Therefore, to determine the environmental indicators, models of exhaust emissions from combustion engines of construction machinery were also used. The NONROAD model was used for calculations [52] given its easy accessibility, universality of application and method clarity.

One of the main parameters determining fuel consumption and emissions from a diesel combustion engine is the load of the engine during construction works. It is dependent on many variables, especially working conditions. In the simulator designed in this work, the load factor of an excavator engine was modelled as a random variable with an even distribution within the limits of the classification given by Caterpillar for average operating conditions of the excavator, i.e. from 0.38 to 0.56 [53].

The model takes into account environmental impacts related to the fuel supply chain using the *EU-28 Diesel mix at filling station ts* model. In turn, the *EU-28:Construction waste dumping (EN15804 C4) ts* model was applied to determine the environmental indicators related to concrete waste storage. The values of the environmental indicators for recycled aggregate were taken from [54].

2.4.5. Social impact

Currently, the impact of noise on third parties is included in the decision-making system. The authors propose an adaptation of the models of sound waves propagation. The value of the equipment sound pressure level is taken from the catalogue of acoustic power. The distance *r* from the source is a model parameter, measured as the shortest distance between the sound source and the noise protection zone defined in the Regulation of the Minister of Environment of Poland, published on 14 June 2007 [60] on permissible noise levels in the environment. Following Weber-Fechner's theory [55] of the relationship between the physical measure of a stimulus and the response of the senses, sound level (noise intensity) is expressed in decibels (dB), which express the sound pressure up to the threshold of audibility on a logarithmic scale. However, the noise level (dB) determined in this way does not reflect its harmfulness, therefore, the noise indicator is proposed as a multiple of the noise exposure level standard (k_{LAeq}) [56]:

$$k_{L_{Aeq}} = 10^{\left(L_{Aeq,T} - L_{AeqD}\right) \cdot 0.1}, \tag{1.6}$$

where $L_{Aeq,\ T}$ is the acceptable noise exposure level and L_{AeqD} is the calculated noise exposure level, both expressed in dB.

While observing the processes of concrete waste management, a significant problem of dustiness was also observed (Fig. 4). In the authors' own research, only non-standardized dust measurements were carried out using a *Microdust Pro meter*. However, due to a large discrepancy between the results and the observed sensitivity to weather conditions, this part of the studies was considered unrepresentative.

2.5. Multi-criteria analysis module

The spider web method was used to evaluate the variants. In this method, the evaluation result is represented by the surface area of a triangle (P_i) with vertices z_{1i}, z_{2i}, z_{3i} located on the axes of a coordinate system, where each vertex is a weighed measure of the economic (z_{ki}), environmental (z_{ei}) and social criteria (z_{si}).

$$P_i = \sqrt{(z_{ki} \cdot z_{ei})^2 + (z_{ei} \cdot z_{si})^2 + (z_{ki} \cdot z_{si})^2}, \tag{1.7}$$

As the decision-making system is designed to identify the most favourable solution under given conditions within the set of acceptable solutions, the result of the evaluation is a function of the system objective. The evaluation result of a given system is also a measure of its effectiveness. For the assumed quality factor of the system, consistent with the direction of the axis, the function of the target (Z) takes the following form:

$$Z = max(P_1, P_2, \ldots, P_i), \tag{1.8}$$

with all indicators considered as destimulants. A positive cost result is a

Fig. 4. Observed dustiness around the crusher.

cost to bear, a negative cost result is a profit.

2.6. Transformation of model into DSS

Due to the size and complexity of the *OptiC&DWaste* system, its parts have been tested individually and the results have been formulated separately. The system has a regular structure consisting of hierarchically built modules linked to and communicating with each other using strictly defined rules.

The simulator evaluates indicators in accordance with the predefined rules in the computer system, including the simulation processes realised for the input values. It consists of four modules - one dedicated to demolition processes and three corresponding to the systems analysed.

The systems are evaluated using statistical methods, which require a sufficient number of observations carried out in subsequent iterations. The variance of the results depends on the model parameters, and, hence, on a variable number of experiments required for the assumed confidence level. The simulator optimises the number of iterations through a pilot experiment consisting of 35 runs on the input data set and calculates the required number of runs (n) according to formula (1.9):

$$n \geq \frac{t_\alpha^2 \widehat{S}_1^2}{d^2}, \tag{1.9}$$

where t_α is a t-Student distribution parameter for the confidence level $(1-\alpha)$ and (n_0-1) degrees of freedom; $\widehat{S}_1^2$ is a variance from the sample; and d is the assumed permissible error in the estimate of the mean. If the number of runs is insufficient, the set of results is completed in subsequent iterations.

The DSS system was developed according to the structure presented in Fig. 1; the system was programmed in MATLAB Software.

3. Results

We present a tool supporting the decision-making process in a broader context of its application, i.e. requirements and interpretation of outcomes.

A construction project is a set of processes that must be identified, organised, optimised, carried out and controlled in order to increase the efficiency of company's operations. The decision to initiate activities related to the planning and design of waste management processes is preceded by an evaluation if the DSS system is an appropriate tool to solve a task. Since the system requires a preparation of input data on the construction site conditions and its surroundings, specific tasks were assigned to individual participants of the investment process. Typically, the initiation of activities is performed by the project manager who gives instructions to:

- the cost estimator to assess quantitatively and qualitatively the sources of concrete waste using the facility documentation,
- the planner to analyse the construction condition and logistical possibilities of the construction site, and the time constraints for waste management processes,
- the market analyst to examine the market in terms of waste management services and the prices of recycled aggregate.

The collected information constitutes a database for the programme. Next, the programme assesses the effectiveness of waste management systems and specifies the limiting conditions for their implementation. The decision-maker, knowing the limitations of the systems and the limitations of the construction site, chooses the most advantageous solution and makes a proper disposition to the works manager.

The example analysis was carried out for the Institute of National Remembrance building in Lublin. Input data was extracted from the technical documentation of the facility, the land development project and a local reconnaissance (services market, prices at aggregate sales). A summary of the input data is presented in Table 7.

Based on the input data, the software determines the evaluation indicators for all variants. In the case study, the difference between the highest and lowest costs in the waste management process is nearly PLN 239,100 depending on the technological and organizational variant. The highest cost (PLN 155,560) is generated by the system of rubble transfer to economic entities (WPOVK3E1), in which the waste is not subject to recovery processes. The costs in the WPO system decrease with an increase in the volume of the container, while the selection of a waste loading machine on this scale does not significantly affect the costs. In the WRM system for all variants, the income from aggregate sales covers the cost of waste management processes, generating additional profit for the entrepreneur (from PLN 37,542 PLN to almost PLN 83,540 in the WRMK4E3 system). On the other hand, in the WRS system, the trends are not so unambiguous. The system, depending on the number of transport units and the performance of an excavator, generates either financial profits or losses. The highest efficiency of the system is characterized by the WRSK3S4.3 variant (PLN 35,161).

Similar general trends were found in relation to environmental indicators. The least favourable solution from the environmental point of view is the system of waste transfer for utilization (Ep = 0.956). Environmental indicators decrease with the volume of the container due to the efficiency of rubble transport processes. The values of the indicators for the other systems (WRS and WRM) are, on average, an order of magnitude lower (Ep range: 0.0065–0.02). Such a significant difference is caused by high environmental indicators of waste storage in the WTU system and environmental gains from recycling in WRS and WRM.

A different tendency characterizes the systems in terms of social nuisance. Recycling processes on the construction site (WRM) significantly decrease the comfort of residents through noise. Due to the small area of the construction site and close vicinity of nearby buildings (about 30 m from the plot boundary), assuming the continuity of machines operation for eight hours, noise exposure level standard is exceeded for

Table 7
Variables defined for experimental purposes.

Input variables		
Volume of concrete building elements: (walls, ceilings, beams and joists, columns and pillars, foundations, concrete substrates)		According to the bill of quantities (ceilings, beams, columns, walls)
Average thickness of building elements		
Presence of reinforcement in the element	Columns and pillars	
	Walls	
	Foundations	
Expected scope of interference with demolition works		Low
Choice of demolition methods		hydraulic hammer
Choice of hydraulic hammer capacity		medium
Determination of the noise protection zone in the surroundings of the construction site		Zone III
Distance of the construction work station from the areas covered by noise protection		30 m
Transport distance of the crusher from the equipment base		200 km
Transport distance between the stationary recycling site and the construction site		6 km
Transport distance between the stationary recycling site and the storage site of a company		30 km
Transport distance between the company's storage site and the construction site		40 km
Unit cost of stationary crushing service		10.00 PLN/ 10^3 kg
Annual cost of warehouse maintenance		PLN 10,000
Annual turnover of goods in storage		20,000 × 10^3 kg
Unit selling price of aggregates		30.00 PLN/ 10^3 kg
Importance of the economic aspect		60%
Importance of the environmental aspect		20%
Importance of the social aspect		20%

all WRM systems (k_{LAeq} ranges from 5 (WRMK1E1) to 1127 (WRMK4E4)). The lowest value was obtained for system WPOVK25E2 - 1.33. Based on the sustainable evaluation indicators and the weight of criteria reflecting the preferences of the decision maker, the systems have been assessed and ranked from best to worst. To illustrate the operation of the DSS, the evaluation and overview of the indicators for the first 10 systems in the ranking list are presented in Table 8.

A graphic interpretation of the *standardised* evaluation indicators for the ten best solutions is shown in Fig. 5.

As the considered construction site is small in size, it was assumed that the maximum area that can be used as a concrete waste storage site and a recycling site is 350 m^2. This condition is met by the WRMK2E2 system in which the recycling processes take place on the construction site, using a *small* crusher and a *small* excavator. In the ranking list, the system is in the forth position (Table 9). However, it requires extending the project implementation time by 43 working hours, which amounts to nearly 5.5 working days. Nevertheless, it was assumed that the planner would allow such a solution because of the possibility of carrying out parallel works related to the completion of the construction, i.e. clearing the construction site, removing temporary installations, levelling the ground, etc. Thus, variant 4 from the ranking list was finally selected, assuming the performance of crushing processes at the construction site with the use of small-sized equipment. What is more, such a choice reduces the risk of complaints and penalties related to the violation of the noise standards. Limiting factors caused a decrease in the effectiveness of the solutions both financially (by nearly PLN 15000) and environmentally (by 8%) aspects.

Table 8
Results of system evaluation.

No.	System acronym	System evaluation	Evaluation indicators		
			Kp [PLN]	Ep [−]	Sp ($k_{L_{Aeq}}$)
1	WRMK3E2	0.271	−7.29E+04	7.32E-03	4.62E+01
2	WRMK3E1	0.268	−6.98E+04	6,67E-03	4.21E+01
3	WRKM3E3	0.267	−6.94E+04	7.18E-03	5.09E+01
4	WRMK2E2	0.256	−5.79E+04	8.28E-03	2.47E+01
5	WRMK2E1	0.255	−5.65E+04	7.12E-03	2.06E+01
6	WRMK1E1	0.235	−3.75E+04	7.48E-03	4.83E+00
7	WRSE4S3.3	0.231	−3.52E+04	8.35E-03	1.04E+01
8	WRSE3S3.4	0.231	−3.49E+04	9.04E-03	1.04E+01
9	WRSE4S3.4	0.231	−3.48E+04	8.44E-03	1.04E+01
10	WRSE3S3.3	0.231	−3.47E+04	8.96E-03	1.04E+01

4. Discussion

Decision support systems have found wide applications in process controlling, building designing, diagnostics (technical, medical, risk-related) and in planning processes in many fields of life, e.g. banking, industry, commerce [57]. Their usefulness is becoming more and more evident in construction [58,59] with growing projects complexity and market uncertainty, sensitivity of construction works to external conditions as well as issues connected to the organization of investment processes [19].

The DSS presented in this work is a tool facilitating selection of concrete waste management method in construction works. The system compares technological and organizational systems of waste management for specific building site conditions taking into account the technology of demolition works (which determine the waste stream). Two out of the three systems analysed here (WRM, WRS) are elements of reversed supply chains and hence of circular economy, whereas the third system (WTU) constitutes both a reference point and an alternative solution when recycling is impossible (e.g. the material has impurities, it is not possible to conduct mobile recovery, there are no stationary facilities).

Securing waste recycling is now a basic but not the only condition in the modern economy. Waste management processes should be effective environmentally, socially and economically [60]. The building industry has a great potential to alleviate the environmental and socio-economic burdens and from this point of view it is far from optimum. Specifically, the following barriers are worth noticing in this field [11,12,61–64]:

(1) organization problem related to a limited building site area and time-consuming waste management processes (bulky waste),
(2) no awareness of recycling-related benefits,
(3) long life-cycle of products and hence a changing character of waste,

Table. 9
A list of limitations of the first ten systems from the ranking list.

System	Start time of waste management processes[1]	Extension of works [working-hours]	Required storage + technological yard [m^2]
WRMK3E2	68	0	522
WRMK3E1	66	0	507
WRKM3E3	68	0	522
WRMK2E2	**0**	**43**	**255**
WRMK2E1	0	43	255
WRMK1E1	0	192	577
WRSE4S3.3	50	0	318
WRSE3S3.4	71	0	456
WRSE4S3.4	72	0	460
WRSE3S3.3	49	0	316

[1] 0 - starting time (working hour) of the demolition of concrete elements

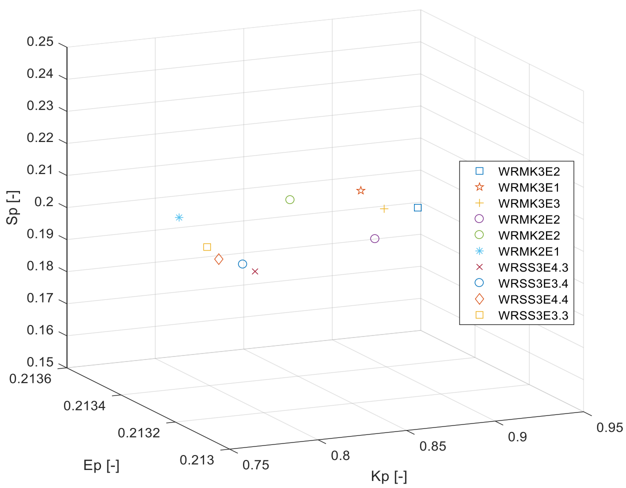


Fig. 5. A diagram of standardised evaluation indicators of ten best solutions-When selecting a system, the decision-maker cannot base their choice merely on the results of the evaluation, but should also take into account the limiting conditions defined by the planner. Therefore, the system provides information about the limitations of the variants analysed (Table 9).

(4) misadaptation of existing objects to deconstruction.

The decision-making support system presented in this article (called OptiC&Dwaste) provides unambiguous information on the costs of waste management in a selected system and can have a positive influence on the environment and the vicinity of a building site through noise reduction (indicators for the decision-maker). Moreover, the system informs about the construction site needed and prolongation of the building process as a result of the time of waste management. This information may be used to eliminate barriers in effective implementation of waste management methods (barriers 1 and 2).

There are four factors that contribute to effective CDWM, namely CDW stakeholders'attitudes, CDW project life cycle, CDWM from sustainability perspective,and CDWM tools [65]. Such tools were classified into three main groups [60]:

– IT-based tools in CDWM including building information modelling (BIM), global positioning system (GPS), geographic information system (GIS), radio frequency identification (RFID), and big data (BD);
– CDWM approaches including lean principle, zero waste management approach, circular economy, green rating system, and site waste management plan;
– CDWM technologies including industrialised building system (IBS) and modularization.

OptiC&Dwaste fits in group one, but it is not yet a comprehensive tool. The currently developed DSS aims at providing information about the selected (simple but common in practice) concrete waste management systems. It is possible to expand waste management scenarios with more advanced concrete aggregate recycling systems to guarantee higher product quality e.g., like that presented in [66]. The developed methodology can also be used to assess the management systems for other construction waste. For more comprehensive applications and to simplify the data acquisition process, the system should be complemented with technologies such as BIM (in terms of waste quantities), BD of stationary plants and their geographical location (GIS).

Due to the complexity and multi-parametric nature of the evaluation indicators, the models have been simplified. Parameters that are not mentioned and not fully discussed in the paper, such as operator skills, fuel quality, age of machines, wind direction and others, also influence the assessment results. They are now included indirectly (e.g., through the engine load index) or generalized through the use of average values (e.g., machine age). It is possible to add these parameters more explicitly in further stages of this project. The selection of the parameters to be developed will be based on a sensitivity analysis of the assessment indicators.

Since *OptiC&DWaste* assesses the waste management systems in three dimensions of sustainability in a qualitative way, it offers a substantial improvement in terms of the social aspects. In the current form of the system, the noise indicator has been included in the ranking of the solutions without imposing any restrictive conditions. However, exceeding the noise level entails a potential additional cost in the form of financial penalties, which should be considered in further work. According to the evaluation of social impacts [67], dustiness should be taken into account. Nevertheless, the own on site tests did not give accurate results. The literature [68–70] reports the levels of dustiness mainly for construction works and to a limited extent concerns concrete waste management processes. Moreover, the literature results show discrepancies and the measurements were related to different dust fractions (total dust/respirable dust). Therefore it was not possible to supplement the model on this basis.

OptiC&DWaste provides evaluation of the results of simulation experiments and currently the user obtains a one-point rating of an average value. In further stages of software development, statistical results should be made accessible to the user, which will enable them to analyse the risk associated with the decision-making process.

The last evaluation indicator concerns the weights of the criteria. Currently, in the system, the decision-maker has a possibility to set their weights. However, due to Client's inappropriate attitude towards construction and demolition waste management by prioritizing profit instead of waste [71], some limitations could be introduced, e.g. in line with the standards of sustainable construction and demolition waste management. This would contribute to increasing the sustainable efficiency of concrete demolition waste management.

5. Summary

Concrete has been used in construction for centuries, but yet it is a source of large amounts of waste. Effective waste management presents a problem when it comes to costs and environmental protection. Waste management can be handled through various technological and organizational methods, using machinery and equipment of different specifications under given building conditions. It complicates the decision-making process and motivates a need for a computer system (DSS) that could help in such decisions holistically.

In our research, three most common and rational types of technological and organizational waste management systems were identified and implemented in the DSS system proposed here. The system offers control over specific parameters of a given construction site and allows one to choose the best variant of works organization and machinery selection.

The analysis of the case study presented in this work shows that construction site conditions may exclude the possibility of implementing certain recovery logistics systems although that may decrease the effectiveness of solutions. The improvement of social indicators and the minimisation of logistic restrictions connected with the development of a storage-recycling site within the construction can be ensured by using smaller-size construction machines available on the market.

Restrictive conditions can also be stimulated to some extent by changing the intensity of the waste stream, i.e. changing the technology of demolition works. Given the observed significant interdependence of recovery logistics systems and waste streams, especially in the area of restrictive conditions, the system can be extended to include demolition processes and their comprehensive evaluation.

Declaration of Competing Interest

None.

Appendix 1. List of input/output variables, system elements and modelled processes

Table 1
Input/ output variables of the system.

Abbrev.	Input variable	
V	Volume of concrete building elements (walls, ceilings, beams and joists, columns and pillars, foundations, concrete substrates)	
x	Average thickness of building elements	
reinforc	Presence of the reinforcement in the element	
Interfer.	Expected scope of interference of demolition works	
met_dec	Demolition methods	
Work_nr	Number of workforce	
W_hammer	Hydraulic hammer performance	
Surr_noice	Determination of the noise protection zone in the surroundings of the construction site	
L_1	Distance of the construction work station from the areas covered by noise protection	
L_2	Transport distance of the crusher from the equipment base	
L_3	Transport distance between the stationary recycling site and the construction site	
L_4	Transport distance between the stationary recycling site and the storage site of a company	
L_5	Transport distance between the company's storage site and the construction site	
K_1	Unit cost of stationary crushing service	
K_2	Annual cost of warehouse maintenance	
K_ann	Annual turnover of goods in storage	
C_j	Unit selling price of aggregates	
W_1	Preferences of the decision-maker	economic aspect
W_2		environmental aspect
W_3		social aspect
Output variables		
T_start	Starting time of waste management processes	
extent	Extension time of construction works	
need_area	Required storage + technological yard	
Total_score	Score values of each variants	

Table 2
Elements and their parameters (attributes).

Element/abbrev.	Parameter	Add. inform.[1]
Excavator [E1,…,E4]	– motor power – engine class – deterioration factor – transient adjustment factor (TAF) – zero-hour, steady-state emission factor – age factor (fraction of median life expended) – excavator bucket volume – unit operation costs – average fuel consumption – in-use adjusted brake-specific fuel consumption – sound power level	The machine parameters were provided by manufacturers. E:The lack of suitable ready-made models requires the implementation of multiparametric analytical emission models, thus additional parameters were included. C: Unit costs were calculated based on the analysis of average fixed and variable market costs. S: Sound parameter was provided by the manufacturer.
Tipper [S1,…,S4]	– payload, – load factor, – unit values of EI indicators of transportation processes (per tkm) for a specified parameter (engine class, road type and share, kind of fuel and its consumption, etc.) – unit transportation cost (per tkm).	E: Due to the availability, a readymade multi-parametric EI models of transportation processes were used. C: Average unit transport costs were used,based on industry quarterly cost reports. S: For safety purposes, the truck engines must be switched off when loading. The noise of tipper engines was not taken into account due to the short-term effect on the construction site surroundings.
Crusher [K1,…,K4]	– technical performance – motor power – unit operating costs – dimensions of the machine outline – hopper size – average unit fuel consumption – engine class – deterioration factor – transient adjustment factor (TAF) – zero-hour, steady-state emission factor – age factor (fraction of median life expended) – sound power level	The machine parameters were provided by manufacturers. E: The lack of suitable ready-made models requires the implementation of multiparametric analytical emission models, hence additional parameters were included. C: Unit costs were calculated based on the analysis of average fixed and variable market costs. S: Sound parameter was provide by the manufacturer.
Container for waste Cont (V)	– container capacity (V) – container surface area	E: The container has not been considered as a carrier of negative EI at the use stage, no additional impact from other life cycle module of the container was

(*continued on next page*)

Table 2 (*continued*)

Element/abbrev.	Parameter	Add. inform.[1]
	– unit cost of waste collection service	included. C: Functional relationships between the volume and cost of waste collection services were determined on the basis of market research (Section 2.4.3). S: The container has no built-in noise source.
Fuel 'diesel'	– unit values of environmental indicators of fuel supply chain – default fuel sulfur weight percent – episodic fuel sulfur weight percent – density of ON – unit price	E: For EI indicator the multi-parametric environmental impact models were applied (Section 2.4.4). C:Unit price was assumed based on the market analyses. S: not applicable.
Aggregate 'agg'	– density – bulk density – normal distribution parameters of sales prices – demand (assumed continuous) – Unit values of environmental category indicators for recycled aggregates	E: Assumed positive impact of RA on the environment (profits). C: The distribution parameters of the prices were determined based on the market analyses. S: not applicable.
Concrete rubble	– density – uniform distribution parameters of the bulk density	
Recycling technology yard 'RCA tech. yard'	– type of crusher – unit costs of the crushing service – service availability (assumed continuous)	E: The highest capacity crusher was assumed (K4). C: dependents on input data. S: due to the limitation of the scope of the impact assessment to the construction site surroundings, no additional impact assessment was performed.
Storage yard	– Annual cost of warehouse maintenance – Annual turnover of goods in storage – Unit selling price of aggregates	E: no additional impacts were taken into account. C: dependents on input data. S: due to the limitation of the scope of the impact assessment to the construction site surroundings, no additional impact assessment was performed.
Landfill	– EI indicators for the landfill process – waste disposal unit cost – LCA module parameters	E: model used: EU-28:Construction waste dumping (EN15804 C4) ts. C: dependents on input data. S: due to the limitation of the scope of the impact assessment to the construction site surroundings, no additional impact assessment was performed.
Additional module		
LCA module	– characterisation factor of EI indicator – weighting of environmental indicators	

[1] Additional information about E- environmental; S- social; C-economic aspects.

Table 3
Processes and their parameters (attributes).

Processes/abbrev.	List of parameter	Add. inform.
Waste stream	- volume of concrete building elements (walls, ceilings, beams and joists, columns and pillars, foundations, concrete substrates) - average thickness of building elements - presence of reinforcement in the element - expected scope of interference of demolition works - demolition methods - number of workforce - hydraulic hammer performance - average labor intensity standard and the range of its variability (parameters of triangular distribution) - rubble parameters set	Model was used to determine the amount of generated waste per time unit as input data in the simulation model. Not subjected to evaluation.
Loading	- excavator parameters set - rubble parameters set - filling factor of bucket (normal distribution parameters) - operating cycle time (parameters of the log-normal distribution) - working time utilisation rate - engine load factor - characterisation and normalization factor for environmental indicator - aggregate parameters set - fuel parameter set - LCA module parameters	Model was used to reflect the loading of tipper, crusher, container and debris handling.
Transportation process	– number of tipper – tipper parameter set – excavator parameter set – transport distance – average transport speed (regarding the share of roads types) – fuel parameter set – aggregate parameters set/ rubble parameters set – LCA module parameters	Queuing systems (M/M/1) were used in the model. The model used for both rubble and aggregate transport.
Crushing	– crusher parameter set – excavator parameter set	The system assumes constant operation of the crusher, the variability of the intensity of the process results from the diversification of the excavator efficiency.

(*continued on next page*)

Table 3 (*continued*)

Processes/abbrev.	List of parameter	Add. inform.
	– distance of the technological site from areas subject to noise protection – engine load factors – fuel parameter set – set of loading parameters – rubble parameters set – LCA module parameters	
Containerised waste collection	– container parameters set – rubble parameters set – tipper parameter set – average transport distance of waste to landfill – Waste streams parameter – landfill parameters – LCA module parameters	The ongoing collection of containers was assumed.
Stationary crushing	- RCA tech. yard - set of parameters of the crushing process - aggregate/rubble parameters set - LCA module parameters	

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