Citation for published version:
Kunieda, Y, Codinhoto, R & Emmitt, S 2019, 'Increasing the efficiency and efficacy of demolition through computerised 4D simulation', *Engineering, Construction and Architectural Management*, vol. 26, no. 10, pp. 2186-2205. https://doi.org/10.1108/ECAM-11-2018-0492

DOI:
10.1108/ECAM-11-2018-0492

Publication date:
2019

Document Version
Peer reviewed version

Increasing the efficiency and efficacy of demolition through computerised 4D simulation

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Abstract

Purpose: to develop a novel tool to support decision-making for enhanced demolition process efficiency and material waste sortability through computerised 4D motion workflow simulation.

Design/methodology/approach: a time-lapse evaluation model was developed to classify and estimate the impact of building demolition processes and material waste recovery. The dynamic assessment of demolition, collision and mechanical impact were measured through computerised 4D motion game and physics engines. Waste recovery and treatment complemented the simulation algorithm. The simulation of the information workflow was tested through case study using two demolition strategies.

Findings: the simulation successfully estimated the efficiency and efficacy of the different demolition strategies. Thus, simulation results can potentially support better decision-making related to the definition of demolition strategies associated with recycling and re-use targets.

Research limitations/implications: the simulation was limited to a simple machine-led demolition strategy. Further research is required to understand the impact of complex machine mechanic movements and processes on complex building fabrics.

Originality/value: Modelling and evaluating the demolition process and its impact on material waste recovery with a time dimension is novel. The comparative analysis of quantitative data allows demolition professionals to find optimal and more sustainable demolition solutions and more efficient and safer implementation on site. It also contributes to a better understanding of the relationship between demolition strategy and waste sortability. This research represents a significant advancement in applied computing for building demolition waste recycling and notably, it improves the quality of information available in the definition of building demolition strategies.

Keywords: Demolition, 4D, simulation, waste management, construction, sortability.

Paper type: Research paper

1 Introduction

It is widely acknowledged in the literature that the volume of resources used in the construction industry worldwide makes the sector one of the largest consumers of raw and processed materials. To a great extent, this is worsened by inefficiencies in the management of construction projects that make the sector responsible for unacceptable amounts of waste being disposed in landfills. Circa 30% of the total waste generated in most European countries are disposed in landfills (Dyer, 2012). In 2014, an estimated 202.8 million tonnes of waste was generated in the UK. Of this, 60% was generated by construction, demolition and excavation (DEFRA, 2016). Demolition itself is responsible for approximately 26% (CRWP, 2009) of the total construction waste (i.e. 31.8 mtpa). Despite these alarming figures, proposed solutions are failing to resolve the problem and currently so much waste is being disposed that landfill spaces are becoming increasingly scarce.

Reportedly, very few initiatives and programmes exist to attenuate construction waste. The UK Site Waste Management Plan (SWMP), the obligatoriness of which was revoked in 2013, is one example of such initiatives. The SWMP placed obligations on both clients and main contractors, requiring stakeholders to propose optimal waste treatments and maintain extensive documentation related to type, origin and destination of all types of construction waste leaving a site (Clean Neighbourhoods and Environment Act, 2005; Environmental Agency, 2013). However, without being mandatory, the use of such programmes has been left to the goodwill of companies and clients seeking compliance with “Duty of Care Regulations” and sustainability credits within methods such as BREEAM and LEED. Whilst these programmes are helpful, waste recovery calculation remains a relatively inaccurate approximation of the reality (Chen and Ma, 2013). For Chen and Ma, key elements of information (such as materials origin and usage) are not considered within the methods, reducing the possibility of establishing optimal means for recovering materials and components. Other challenges also exist. Addis (2006) argues that deciding which demolition strategy is best is often based on the suitability of traditional demolition methods as applied to a group of elements. For example, several elements demolished simultaneously results in comingled waste, making subsequent separation on site more time-consuming with reduced recovery rates than would otherwise have been possible if demolition was done by separate materials. Thus, the limitations of existing methods requires the development of new approaches to improve the efficiency and efficacy of demolition and waste recovery.

Scientific contributions have been piecemeal in spite of the relevance of this problem. Emphasis has been placed more on construction waste within construction and literature reporting solutions that effectively improve demolition waste recovery rates is also rare. A review of literature on demolition waste shows a constant increase in the number of publications since 2000 (Yuan and Shen, 2011). However, most efforts have been placed on the development of waste quantification methods (e.g. Wu et al., 2016; Won et al., 2016, Cheng and Ma, 2013 and Kourmpanis et al., 2008), methods for the re-utilisation and recycling of waste (e.g. Wang et al., 2010; Addis, 2006; Poon et al., 2001) and the use of Building Information Modelling (Liu et al., 2015; Chen and Ma, 2013; Hao et al., 2010). Less common is research addressing waste recovery as a result of building design and demolition strategy decisions (e.g. Banias et al., 2011; Hao et al., 2010; Peng et al., 1997). This article refers to this latter theme and seeks to develop the science that underpins demolition strategy by looking into how demolition can be simulated to support process efficiency and predictive models of waste recovery.

The aim of this research is to improve demolition process efficiency and material waste sortability through computerised 4D motion workflow simulation. For this purpose, a video time-lapse evaluation model was developed to classify and estimate the impact of building demolition processes and material waste recovery. The model has enabled qualitative and visual assessment of mixed demolition impacts and its time-lapse change comprehension. The dynamic assessment of demolition, collision and mechanical impact were also measured through a computerised 4D motion game and physics engines. The demolition evaluation model has demonstrated positive results in spite of being in its experimental phase. Waste recovery and treatment data complemented the simulation algorithm. The simulation information workflow was tested through a case study. Two demolition strategies supported a comparative analysis showing how this approach provides more accurate projections of waste generation and a better understanding of the project plan can be achieved regardless of users' project knowledge.

2 Demolition Sortability in Construction

According to Yuan and Shen (2011) measuring waste generation rates is a theme that still requires significant attention to support the creation of benchmark figures for different waste management systems. It is a paradox to solve, i.e. maintain, sustainability demolition credentials based on slow and inadequate methods and low material recovery rates while seeking a faster demolition rate and rapid site clearance (Poon, 1997). This is certainly the case when tools that can accurately and conveniently estimate the amount of waste from construction, renovation, and demolition projects are lacking (Cheng and Ma, 2013).

In this respect, there have been several attempts to use Building Information Modelling (BIM) to assist the demolition process. For example, Cheng and Ma (2013) created a BIM system that can extract material and volume information through an "as built" BIM model and then integrate the information for detailed waste estimation and planning. The BIM model proposed by them represented an advancement in the design of demolition methods from manual to automated quantification of Demolition and Recycling (D&R). However, it is limited to extracting the information from an as built model and it does not resolve the issue of debris generation caused by the impact of demolition methods against the fabric of the building. Similarly, Akinade et al., (2015) developed a BIM-based building deconstructability score system that assess buildings' deconstruction levels prior to demolition, which has the potential for improving sortability of debris.

In general, demolition waste is comprised of inert (e.g., sand, bricks, and concrete) and non-inert materials (e.g., timber, plastics, glass, and paper) (Yuan 2013) that require sorting after the demolition process occurs. Waste sorting is a process where material can be manually separated out from the mixture (i.e. inert from non-inert, poisonous from safe, etc. (Wang et al., 2010)). The benefits of on-site demolition sorting are numerous: increased reuse and recycling, reduced transportation and disposal costs, reduced landfill use and less pollution (Wang et al., 2010). However, as discussed by Poon et al, (2001), sorting methods are slow and contractors tend to be reluctant with regards to sorting waste on-site, even in the event of a high penalty fee for not doing so.

For Wang et al., (2010), the aversion to on-site demolition waste sorting results from a series of factors that makes the business case unfeasible. Firstly, large manpower resources are needed to manually sort materials; secondly the scarcity of a market for recycled materials can lead to storage issues and additional costs; thirdly, waste sortability is a complicated task because of the various factors involved such as the heterogeneity of the debris (different sizes, sometimes with more than one material, etc.); Fourthly, it requires additional management capacity to resolve logistics, health and safety, etc.; furthermore, it can imply the use of site space which may not be available (e.g. storage for equipment and sorted waste containers). In this respect, it is very important to distinguish on-site sorting of construction waste from on-site sorting of demolition waste. The first is characterised by packaging, cut-outs and left overs of materials while the latter refers to debris resulting from the demolition process. Most existing research focuses on the former (e.g. Hao et al., 2010; Wang et al., 2010; and Wang and Yuan, 2008), whereas very little (if anything) exists for the latter, which is the focus of this research.

This research builds on the principle that being able to generate simulations in the demolition planning process can encourage construction teams to utilise demolition waste and hence reduce the necessity of waste treatment. This can benefit the environmental impact of the construction project and also provide budget savings. Without much precedence to draw a path and lessons from, a choice was made to explore the use of parametric design and information modelling to support on-site demolition waste storability, in particular the use of 4D (3D + time) modelling linked to game engines for simulating the physical impact of demolition tools as explained in the following sections.

3 4D use in demolition

The relevance of 4D to assist demolition comes from the support it provides to planning activities and forecasting issues that can be missed in traditional planning. In a nutshell, 4D adds the dimension 'time' to digital objects in a 3D model (which contains geometry and other characteristics of each building component). In general, 4D is used to assist production planning and control through the simulation of sequencing of production processes. Work-Breakdown Structure (WBS) and Critical Path Method (CPM) are the most common techniques used to create a 4D plan (Moon et al., 2013; Wang et al., 2004) and as such, bring the same limitations associated to these methods. Within WBS, the construction process is seen as a sequence of individual activities (e.g. building a wall, first fix, second fix, etc.) with target elements (digital objects such as brick and mortar, plasterboard, etc.) that leads to project completion. Elements are associated to activities and processes to form a three layered structure (process-activity-element) where time is added to elements and organised following a desired sequence of activities. Modifications to the activity plan can be easily updated on the elements model and vice versa. This two-way data reflection between the 3D model and the schedule allows for the application of mathematical algorithms to optimize project plans (Zhou et al., 2015 and Wang et al., 2004) in accordance with critical activities (and constraints) impacting the flow of execution. In addition, other methods such as Line of Balance can be applied to model locational information on a time line. Thus, overlaps and inefficiencies within schedule planning can be identified (Jongeling and Olofsson, 2007). These techniques are also known for the support they provide to improve various aspect of production planning such as health and safety (Benjaoran and Bhokha, 2010), constructability measurement, spatial conflicts, site layout design, sequencing and logistics, cost estimating, resources management, stakeholder communications and collaboration (Mahalingam et al., 2010). The criticism of both techniques centres on the high level of uncertainty related to planning and the low level of accuracy involved in planning activities far in advance of execution.

In practical terms, various lessons can be drawn from 4D research that apply to both construction and demolition. The interpretation of 4D simulation is, in general, based on visualization and testing of a 'plan of attack'[1] strategy. Planning is refined through a trial and error approach. Both aspects also apply to demolition. One of the areas that demolition can benefit is the anticipation of on-site problems, as reflected in the work of Trebbe et al (2015) who raised the issue of accrued costs due unanticipated on-site conflicts and provided detailed practical information related to how practitioners used 4D to assist planning in a major project. We should also consider alternative methods for visualising on-site information, such as Boton et al., (2013) who developed alternative visualisation methods for collaborative 4D that are supported by meta-models adapted to planning and user requirements. Also key are the areas of Health and Safety, highlighted in the work of Zhang et al (2013, 2015), Zhou et al (2013) and Benjaoran and Bhokha (2010), that are focused on safety hazard detection and prevention algorithms and the area of Risk Management, such as the Kang et al (2013) system for visualising risk using Analytic Hierarchy Analysis associated with 4D modelling. Other areas to benefit include on-site workspace planning and logistics. In this respect, Moon et al (2013) and Jongeling et al (2008) propose methodologies to identify clashes between schedule and workspace conflicts. Zanen et al (2013) expanded this concept by looking at additional impacts on traffic and noise levels and Zhou et al (2015) investigated shortest path algorithms that apply to route optimization. Finally, there is research around tracking such as Kim et al., (2013) who analysed on-

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[1] In Lean Construction literature, the term 'plan of attack' refers to the organisation of construction activities according to a series of directives that enables construction flow in spite of constraints.

site visual data with Hue, Saturation and Value (HSV) filters; Turhan et al., (2012) using live 3D laser scanning methods and Wenfa (2008) who applied the radio-frequency identification (RFID) method to identify (according to plan) installed elements. Kim et al., (2017) is of specific importance to this article as it discusses the conversion of volumes of materials obtained from 3D modelling and its conversion into demolition waste volumes. Also is Bilal et al., (2017) who developed a database for building waste analysis which can increase the granularity of information related to materials characteristics that impact on waste sortability. All of which can benefit demolition planning.

From the 4D related research it is evident there are various overlaps between construction and demolition which indicates potential benefits from using this approach in the demolition industry. If expanded to BIM, the overlaps are even greater as presented by Won and Cheng (2017). Although various studies have demonstrated the possibilities of improving demolition and waste recovery, there are other areas, such as the modelling/simulation of machine impact (i.e. numerical impact evaluation) on digital objects (digital demolition), that remain unexplored, further justifying the approach used in this research.

4 Method - Using waterfall for the development of a 4D simulation tool

The steps built into the research design were: First, a literature review to map out the use of software evaluation tools for demolition and packages for 4D CAD modelling. The key decision criteria included advantages within different software packages and an easy to use interface. Second, the defining of a (digital) building type to be demolished in the simulation. The model had to be simple enough to allow initial tests, but robust enough to embed information (i.e. using different materials) for it to be representative. A simple five-storey (Figure 1) building was chosen as having sufficient complexity for the purposes of this research. This decision was informed through a workshop with professionals involved in the demolition of buildings. Third, the dynamic assessment of demolition, collision and mechanical impact had to be measured through computerised 4D motion game and physics engines. For this purpose a tool was developed according to methods currently used in demolition projects in the UK. Finally, the tool interface, usability and applicability as a support to decision-making was assessed by testing it with three demolition practitioners. The work was also presented to UK and Japanese demolition practitioners at two national conferences (see Kunieda, 2016; Kunieda & Kitsukata, 2017).

[INSERT FIGURE 1 HERE]

Figure 1. Axonometric and floor plan views of the 5 storey building studied.

4.1 Requirements

Various attributes were considered in the development of the 4D tool for the simulation of demolition processes. Key requirements included the definition of a software package and the identification of process input and output formats, including the establishment of building physics rules related to different demolition machinery and their impact on digital buildings. These are described below.

4.1.1 Selection of a software package

Various game engines for construction have been explored, in areas such as health and safety (e.g. Guo et al., 2012; Lin et al., 2011), design reviews (e.g. Kumar et al., 2011) and construction education, (Nikolic et al., 2011) showing significant improvements. For Petridis et al. (2010) relevant quality criteria for game engine selection includes: audio-visual and functional fidelity, composability, availability and accessibility, networking, and heterogeneity. Analysis suggests the combination of quality criteria and modules, such as: graphics, physics, collision detection, I/O, sound, AI and network, form the basis for choice of package.

The current literature is scarce regarding the application of game engines to demolition. However, works such as Lind and Skavhaug (2012) simulating production processes provide helpful insights. They used the Blender Game Engine (BGE), open source software equipped with a resourceful game engine integrated into a Bullet Physics library. It’s a *flexible and adaptable* package due to an embedded Python interpreter and game engine logic enabling real-time interaction with external control software. Its use is recommended *whenever mechanical parts are exposed to uncontrolled motion*, such as sliding or falling (Lind and Skavhaug, 2012); processes often seen in demolition. *Disadvantages* include a limited bullet physics engine library that doesn’t feature static friction and heavy physics computation, requiring separation of the physics dynamics body from geometry as well as freezing settled geometry (Lind and Skavhaug, 2012). Although BGE outperformed all criteria assessed by Petridis et al. (2010) when compared to paid-for software, *the difference was deemed insignificant* for *accessibility, heterogeneity, physics and collision detection*. It also provides an easy to use graphical interface (El Nimr and Mohamed, 2011). Accordingly, models in BGE can be constrained, colliding with each other under physical laws regardless of collision, body and mesh types (Coumans, 2012).

BGE is also recommended for its *interoperability capabilities*. For example, Pitman and Watts (2011), Gore et al., (2012) and Kulahcioglu et al., (2012) successfully used BGE for building life cycle assessment. BGE’s high interoperability enables 3D-CAD tools, such as Vectorworks and Revit, to import 3D (BIM), 2D geometry and construction data files. In addition, *dynamic simulation* with object control at runtime and physical laws are essential features in demolition simulation which BGE delivers through complex logic design and Python script, as shown in El Nimr and Mohamed (2011). BGE’s rendering also enabled continuous real-time updating of information to reflect user interaction with the system requiring minimal code writing skills for complex interactions.

Combined, these studies show BGE offers advantages that, in turn, enable assessment of the essential multiple criteria required in this research, justifying its adoption for practical application in the simulation of demolition processes.

4.1.2 Data input and database construction

Data collection was supported by demolition practitioners in the UK. First, project documents of two projects were analysed to identify **conventional demolition methods** (i.e. machinery and equipment) and **approaches** (i.e. plan of attack and material triage process) used in practice. **Project data** (e.g. 2D and 3D information) were also gathered in this process. The data was stored in its native format within a database[2] and served as baseline for pilot model application studies. Building design and site information were used for modelling site conditions, while the actual on-site impacts (e.g. cost, waste generation, etc.) were captured in numerical format for comparison with simulation results. Second, onsite visual data (Figure 2) was collected to understand the **physics of conventional demolition systems**. From the repeated pattern in the data, the typical order of demolition in demolition systems were identified and converted into algorithms that were stored in the database. These algorithm patterns were used for planning the demolition strategy in the model application phase. Also, the demolition equipment used in the simulation was restricted to Caterpillar 312D*(STDC4.2ACERT) which is commonly used in practice operation (key parameters also shown in Figure 2 – Left). Thirdly, a literature review was conducted for the identification of a **waste generation estimation model** for traditional and 4D comparison purposes. Finally, survey questionnaires were given to fifteen demolition practitioners for the evaluation of the usability of models. The questionnaire had 15 questions related to: the ability of the model to support decision-making, the fit-for-purpose qualities of the model and the advantage and disadvantages of the model. A 5 point Likert scale was used ranging from ‘poor’ to ‘excellent’. Answers ranged from 3 to 5, in general, with more experienced respondents being less optimistic regarding the use of the model. An additional fifteen interviews were conducted for detailed understanding of the key issues raised by respondents. Key issues raised included: the lack of BIM data for running the simulation and, more importantly, the concern that machine simulation does not include experience of machinery operators and other aspects such as health and safety aspects, which were not included in the tool hitherto. Respondents tended to view the tool as replacing experience rather than an aid to decision-making. However, after further explanation regarding the use of the tool, there was a general agreement that visualization and waste property analysis could significantly support decision-making and help professionals with less experience to identify issues that could occur during demolition.

[INSERT FIGURE 2 HERE]

Figure 2. Visual data machine movement analysis through 3D marker tracker systems

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[2] Within the conceptual development, no systematic database was structured such as SQL.

4.1.3 Output features

Key elements related to the efficiency of the demolition process included: **(1) total volume to be demolished**: measured in m^3, this was calculated automatically according to geometrical information of 3D objects and separated per object type (e.g. beam, column, wall, etc.); (**2) time utilised for demolition:** time information was extracted in seconds from the simulation process; **(3) demolition machinery travelled distance:** this information is extracted automatically from the simulation engine and measured in meters through measuring movements in the X and Y-axis. A limitation of the process is that machines are allowed to stay as long as targets are located within the arm range of the demolition tool and it does not consider the occlusion of targets with other building elements; (**4) after impact waste distribution**: a map of demolition waste distribution is generated throughout the simulation process based on debris element location and type. Each element type was coloured differently to facilitate element identification. Maps are generated on a time-lapse base and updated every 100 seconds of the simulation. Limitations in this process include that of elements being demolished, not by the result of collision with the shovel, but rather by free fall. Moreover, elements are segregated into the set unit grid, rather than a realistic set of different debris size: the basic cube size was set as 0.3*0.3*0.3m^3 for all elements except slabs which were set as 1.0*1.0*0.12m^3.; and **(5) waste rubble purity** (sortability): a map of waste purity was generated based on the location and volume of waste generated for each demolished element displayed in a unit grid of 5x5 meters. A colour grade is used to classify purity in 20% intervals and purity increases as colours get darker. The method used involved converting graph XYZ data into mesh data using Gray Technical XYZ Mesh 4.0 software (GT, 2017) and then exported to Microsoft Excel VBA to generate a 3D graph of purity.

4.2 Concept Design

In this study, BGE was used to develop the evaluation model. The control of objects was set as ‘Sensor’, ‘Controller’ and ‘Actuator’ (Figure 3). Input is received through the ‘Sensor’, combining inputs is done through the ‘Controller’ and manipulating the objects through the ‘Actuator’. Complex control is achieved through Python scripting as ‘Controller’. After logic settings are defined, the dynamic model simulation is executed and saved as a movie file. The values of the impact projection function are exported to external software (i.e. Microsoft Excel) with ‘Logic Bricks’. The outputs include time of collision and the volume of targeted object.

[INSERT FIGURE 3 HERE]

Figure 3. Setting object logic with Logic Bricks in BGE

The system framework with 4D-CAD impact evaluation model proposed in this study is shown in Figure 4. The main processes in this platform are (i) input of project plan by users to Blender, (ii) data retrieval from database, (iii) model simulation by BGE using physics engine and (iv) output of simulation result. Project plan input includes site information and the project plan in 3D CAD format. The 3D five-storey building was originally generated with Vectorworks (2015), was exported to BGE through IFC and used as the digital demolition test case through simple machine demolition methods in the BGE simulation tool devised.

[INSERT FIGURE 4 HERE]

Figure 4. Conceptual platform of 4D-CAD impact evaluation model

The design of the demolition plan is done through the graphic user interface (GUI), where users access the database and refer to the values and demolition patterns available in the GUI panel. Demolition methods are chosen from the pre-defined list of demolition methods including: top-down, external demolition (high reach excavator[3] and steel ball) and explosives. This process is informed by previously executed Site Waste Management Plans (SWMP) that contain project, waste generation and functional data. Designated project details inform the BGE set model and game logics to manoeuvre demolition machines. BGE plus the physics engine returns the demolition impact projection in .xls, blender supported 3D file formats (e.g. 3DS, FBX, DXF, SVG, STL (for 3D printing), VRML and X3D) and 4D time-lapse impact change movie files. The results can be used to inform decision-makers, while the accumulation of simulation data enhances the robustness of the database for future project planning.

4.2.1 Implementation

- Developed Tool Interface and Settings

Figure 5 shows an overview of the GUI developed for this research and different stages of the application while in use as described in the following.

[INSERT FIGURE 5 HERE]

Figure 5. Setting Interface (left) and Process model application (right)

Input site information (i): The site layout and the building model are imported from the existing BIM data file to BGE using the ‘building model import’ field. Preferably, surrounding site data should also be imported as neighbouring conditions can influence decisions regarding line of movement, impact on neighbouring properties and boundaries, amongst others. Whenever possible the CAD file should be merged with GIS so to include location specific data.

Designation of element demolition treatment (ii): Users can modify the input parameters until intended project requirements are fulfilled. The “treatment of elements” field enable users to classify elements according to three groups: ‘preserved’ for processes where demolition machines are

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[3] In this research, only external high reach excavator method was used.

operated to avoid damage to elements; ‘soft-stripped’ for processes where elements, such as doors, windows, pipes, are removed before demolition. Elements that are not striped can be demolished as other structural elements and materials are regarded as impurity of structural waste. And ‘ground’ processes where element includes the path of demolition machines and the site boundary as the movable area in the BGE simulation. Soft stripping costs and labour information are calculated through conventional methods that describe additional impacts at the treatment stage. In addition, the reservation of elements allows the evaluation of partial demolition impact in refurbishment or renovation projects.

Decision of demolition method (iii): The demolition strategy is defined by choosing type and direction of demolition in the ‘Demolition Method’ field. The algorithm for the demolition sequence (order) of composed elements is selected with a basis on previous demolition projects. The ‘set’ button links the algorithm to the element and a number is assigned to the element (except from registered ones). Assigned machines demolish elements sequentially from the smallest number. This process can be altered manually if the algorithm does not reflect the intended plan. The path through all targets is automatically calculated and displayed after numbering. Users can compare several demolition methods to find the optimal solution from this value.

Registration of machines (iv): After setting the demolition sequence, machines in use must be registered at the ‘Demolition machine’ field. From the tab menu, users can choose from a series of suitable demolition machine types. This process is based on default sizes for each body part that can be customised for enhanced accuracy. Once registered, roles are allocated to machines for defining the phase(s) in which they will be applied. The multiple registration and designation of roles enables the simulation of complex project demolition plans. Registration can be modified and cancelled at any point.

Execution (v): The BGE has enough information to simulate the demolition project once the settings of demolition machines is complete. After choosing the output saving location, the simulation can be triggered by using the ‘Run simulation’ button at the ‘Model simulation and export’ field. Once started, model elements are segregated into a unit cube to recreate the destruction of elements by the confliction of demolition parts. Unit cubes are set to start demolition through contact between one another with impact always exceeding element durability. The game logic of machines, defined during registration, enables the monitoring of machine movement and the measurement of waste generation according to changes occurring through the time-lapse simulation. Machines continuously interact with target elements until impact data is generated. The data generated can be exported to other software such as MS Excel before the file is closed. Based on the results, users can modify the plan until intended project requirements are fulfilled.

Estimation of Waste Generation (vi): Solís-Guzmán et al. (2009) waste generation calculation method (the Spanish model) was used to estimate the amount of waste generated from the total building floor area (Equation 1). This follows is recommended by tradition of Cheng and Ma (2013) in the verification of their own BIM-based model for demolition, which used the Spanish model. In this model, the demolition waste volume is calculated as a product of the building total floor area and the coefficients for each element type, derived from 100 building case studies. Accordingly, the waste generation is calculated using the following formula:

$$V_{dem} = Fl \times M \times F_{dem}$$

Equation 1. The Spanish model for quantification and management of construction waste (adapted from Solís-Guzmán et al. (2009))

Where Vdem is demolition waste volume (m3); Fl is the floor area per level (m^2); M is the number of floors and Fdem is demolition waste volume factor (m^3/m^2). The designation of element types follows the element type mapping from the Solis et al model and presented in Cheng and Ma (2013).

4.2.2 Implementation through simulation

Solís-Guzmán et al. (2009) waste generation calculation method was used to estimate the amount of waste generated from the total building floor area (Table.1). The value of *S* in Table1 is the same as the calculation of each element's volume is done according to the floor area. In the simulated pilot, the building is symmetric, thus the floor area is the same for each component. In addition, the total area is calculated by S(single floor area)* N(number of floors).

Table 1. Case study waste generation estimation

[INSERT TABLE 1 HERE]

The five-storey building was set to be demolished by external demolition method comprising of one high reach excavator with a 15m boom and 9m dipper. Main and sub-direction of demolition orders were set as 'South to North' and 'West to East'. Demolition at higher levels is prioritised in line with onsite health and safety practices. The machine logic settings included two patterns of machine behaviour to allow the comparison of:

1. The demolition of targets in sequence within the arm range without changing machine location (scenario1: 'fixed'). The machine arm is long enough to complete demolition without moving its location.
2. The demolition of targets regardless of the distance from the (moveable) machine (scenario2: 'movable').

The differences in impact results caused by machine use were numerically compared through 'transportation distance' and 'total time to complete demolition'. Only the demolition process was assessed in order to simplify the simulation (i.e. waste collection and treatment process were not included). The excavator's transportation distance and waste's treatment volume were measured on a dynamic timescale. Three aspects were considered for waste generation time-lapse change impact:

(i) waste distribution, (ii) total waste generated and (iii) waste purity within the unit area. The demolition of elements were also measured according to the time, location, material type and volume when hitting the 'ground'. Results are presented through a waste distribution map, a purity map and a generation map was drawn to visually express the demolition progress and physical features. All slabs were divided into three sections (south, middle, north).

5 Results and discussion

Simulation results of both scenarios and its comparison with the Spanish model by Solís-Guzmán et al., (2009) are summarised in Table.2. Most of the unit objects that compose the building elements have been recorded as waste objects. There are no significant differences between the two demolition strategies except the computation time in BGE. A total of 96.9% accuracy was achieved, which makes the model ideal for supporting demolition planning. The comparison with method shows significant differences for wall (≅ +51.6%) and column (≅ +300%) volumes This can be attributed to the target building model, which has a frame structure and no partitions and external walls.

Table 2. Simulation results compared to the Vdem model

[INSERT TABLE 2 HERE]

With regards to travelled distance, the comparison of machine impact between scenario 1 -'fixed' and scenario 2 -'movable' as illustrated in Figure 6 (left) shows that the excavator in scenario 1 travelled 60m to demolish the targets whereas in scenario 2 the distance was 2200m. Considering that the interference from other building elements is not included in this simulation, operators can change the location of the excavator. However, results show that it is considerably more efficient to adopt a 'fixed' position for both, distance travelled and demolition efficiency.

[INSERT FIGURE 6 HERE]

Figure 6. Result of machine impact (left) and waste generation (right)

In terms of total time consumption, the fixed treatment strategy uses 20% less time. This result should be interpreted carefully as various assumptions were made concerning the time scale of each demolition process (the accuracy of which can be improved by referring to the actual demolition data, such as machine properties, onsite visual record, etc.). The time for simulation shows consistency in scenarios 1 and 2 (Figure 6 - right and left). Comparing the two scenarios, there are no significant difference in results with the exception of time scale. The different is explained by the use of the same order of demolition for both scenarios and the simplification of the element demolition method that considers a free fall for each element unit (rather than a joint one, which would be the case in a real scenario, thus reducing the time difference between the two scenarios). It is expected that improvements can be achieved if the actual hitting of the target with the shovel can be simulated to recreate a more accurate behaviour of object scattering, which in turn impacts on the machine and target layout relationship.

For treatment volume, there is a steady increase up to 400sec in scenario1 and 500sec in scenario 2 that is followed by a small decrease. This is the result of a target shift, from the large slab unit to the small column unit at the end of demolition. The relative reduced efficiency for scenario2 is due to the time-consuming re-location time of machinery. Therefore, the efficiency of demolition method and the time required for each process can be read accurately from the machine impact data in this model simulation.

In relation to waste generation (Figure 6 - right - continuous lines for scenario 1 and dashed lines for scenario 2), the results reflect the plan of attack choice (South to North) and model configuration (i.e. walls on the South and columns on the North). In other words, walls have been demolished at the beginning whereas column waste increases its volume towards the end.

With regards to waste generation time-lapse change, Figure 7 shows the resulting successive waste distribution maps (for scenario 1). Following the South to North approach, walls have been demolished within 200sec and columns in the North started being demolished from 400sec. The maps show the relation between original and final location for each element type (e.g. columns were located longitudinally on both sides of the building - East and West - which falls vertically, thus forming a similar layout on the waste generation map). Attention has to be given to the slab-origin waste distribution. The map is influenced (on the South side) by the effect of higher level slab waste falling over lower slab levels. This is clearly seen on 200sec and 300sec maps that shows no wastes on the middle area. As slabs were divided into south, middle and north sections, it is only after the collapse of all slabs in the south that the slab waste from the middle section start falling to lower levels. The waste slides down to the south and spills from the lowest level to land. Similarly, slab waste start falling on the north side of the north slab (see 500sec map). This graph also reveals that a *sortability* strategy can be aligned with the demolition times (for instance, through the implementation of beginning or end of the working day collection regimes).

[INSERT FIGURE 7 HERE]

Figure 7. Waste distribution map per element category (scenario 1: fixed)]

Information about waste purity is essential for demolition planning, given the importance of waste *sortability* for increased reuse. In this respect, a purity map was produced based on the location and volume of waste generated for each element (Figure 9, Equation 2). Figure 9 shows the results in a unit grid of 5x5m and the volume rate per waste type is plotted on the centre of the grid. The centre part of the building shows a high value of purity, but the value declines as it approaches the location of the columns and beams. The purity level stays at high level because the case building has the same floor design for each level. For more complex building designs, increased purity and sortability will be the result of a waste transportation plan based on waste distribution time-lapse change and on-site features as mentioned above.

[INSERT FIGURE 8 HERE]

Figure 8. Impact conversion flow with waste generation data

$$P_{unit(x,y)} = \frac{\sum Vi\{i|ec_i = ec_{M_{unit(x,y)}}, A_i \in unit(x,y)\}}{\sum V_i\,\{i|A_i \in unit(x,y)\}}$$

where P_{unit}: Purity of collected waste in target unit area.

Equation 2. Purity of collected waste in target unit area

Further analysis of Figure 9 shows that the north waste purity levels reduces after 400sec because of the demolition of the column in the same area. In this case, demolition should be halted temporarily at 400sec and the waste recovered before the remaining building element gets mixed with other types of waste. Even after the whole demolition is complete, waste can be recovered with high purity if extracted locally. The graphs representing different grids (Figure 9 bottom) show that as purity increases as grid size decreases. Although time-consuming, it is feasible to recover waste in small scale by manual labour or by small vehicles in small areas where treatment is critical. In this respect, planning should be considered along with the volume of waste generated so to maintain the onsite work productivity.

[INSERT FIGURE 9 HERE]

Figure 9. Change of waste purity map (scenario 1: fixed)

Other aspects related to sortability mentioned in the literature include barriers to the implementation of rapid site clearance as impacted by heterogeneity of the debris (i.e. different sizes, sometimes with more than one material), additional management capacity to resolve logistics, health and safety, storage, etc. These have not yet been studied in this research, but constitute the next steps of the research.

6 Conclusions and future work

The 4D evaluation method presented in this research can contribute to more effective and efficient demolition projects. From the machine journey and treatment volume, users can simply modify demolition sequences, the number and types of machines to be applied in the projects, while waste generation and classification data is described in a dynamic time-lapse process. Waste recovery strategies and site risk assessment can be informed by the simulation with the additional benefit of a 4D visual aid. With the simultaneous analysis of time and efficiency, users can count on this model as the decision-making supporting tool.

While there is very little relationship between modelled waste generation and waste generated on site, demolition modelling can help direct professionals in the right direction to make informed decisions. The science about waste sortability is still embryonic. While the physics of demolition methods is unknown, we now know that there is a relationship and it is possible to plan demolition based on the level of sortability and reuse that each demolition approach has. This process can be used to inform new policies related to demolition practice.

The relationship model between building types and sortability (which is also related to building size and complexity in terms of sub-systems) in this research is still developing. In this respect, practice will have to wait for a well-established science to emerge and a series of equations to be developed. However, the system presented in this research can provide a practical classification for building demolition strategies from ‘highly inefficient’ to ‘much improved’.

Our results show that by sorting the different mixtures of waste along the time axis, one can obtain a level of information about waste purity that has never been possible to evaluate using conventional static approaches (e.g. waste purity evaluation). In the case of a contaminated building, this function can potentially help to minimize the propagation of contaminants and the exposure of workers to them, thus also improving the health and safety of workers. Information about demolition waste can be taken into account by constructors so they can better recycle materials in new construction projects. In turn, this enhances the material flow from demolition projects to construction projects, helping to contribute to a circular economy.

The way forward for further research relates to better data accuracy. In order to recreate an accurate demolition behaviour, simulation accuracy and rationality need to become more robust. For example, the collision for each part of elements must be decided from the comparison between the material strength and the collision impact, instead of a grid. For the rationality of the demolition process, more scenarios of actual data of demolition implementation needs to be developed and incorporated within the tool so that the development of demolition plans is more realistic and accurate. Furthermore, machine efficiency can only be assessed through BGE simulation time consumption. This should be converted to on-site implementation time with the actual data of machine movement (e.g. running and tuning speed, bloom movement, etc.) so that the machine use can be evaluated by cost, CO2 emissions and other impact factors. This would require comprehensive data collection from construction sites to establish an accurate information base. Increase model accuracy will lead to increased predictability of demolition results. Moreover, it also enables a better and more accurate understanding of different demolition strategies and its efficiency, thus unlocking potential improvements within the demolition planning process.

In spite of the limitations, modelling and evaluating the demolition process and its impact on material waste recovery with a time dimension is novel. The comparative analysis of quantitative data allows demolition professionals to find optimal, sustainable demolition solutions and more efficient and safer implementation on site. It also contributes to a better understanding of the relationship between demolition strategy and waste sortability. In this respect, the research represents a significant advancement in applied computing for building demolition waste recycling and notably improves the quality of information available in the definition of building demolition strategies.

7 Limitations

Various limitations were identified during the development of this research including: a) BIM data is needed from inception to recreate the demolition project planning and it might not be available for existing projects; b) The destruction of objects was restricted to the collision between machine and elements, thus excluding element to element collision during fall and impacting on debris' granularity accuracy; c) Machines were operated automatically, thus not including factors such as operator's experience in critical situations such as those related to health and safety within the site; d) Size validation has not been investigated and it is the next step for the research. At this stage, the validation was restricted to 4D simulation recreating acceptable waste comingle and debris' granularity; and e) The evaluation of the demolition processes was limited to time and needs to be expanded to other criteria such as health and safety, cost and labour behaviour.

8 Acknowledgments

The research presented in this paper was sponsored by the Honjo International Scholarship Foundation, Japan. The authors acknowledge their support.

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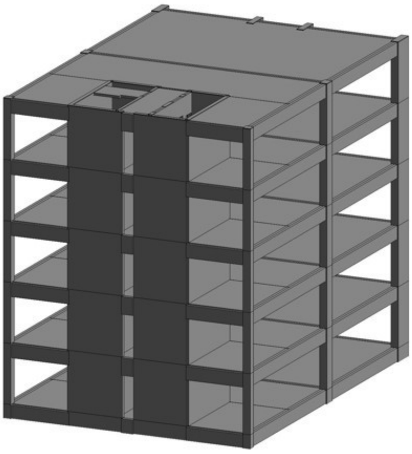
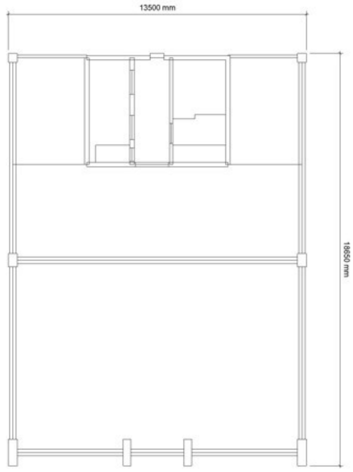
Figure 1



Axonometric View



Typical Floor Plan

Figure 2

Model: Caterpillar 312D*(STDC4.2ACERT)		
Fuel efficiency*	9.5L/h	
Average bucket volume	5.3m^3	
Engine power	72kW/94hp	
Machine weight	12900 kg	
Total weight*	13690 kg	
Body length	3490mm	
Body width	2490mm	
Body height	2760mm	
Boom	15000mm	
Dipper	9000mm	
Shovel length	532mm	
Shovel width	1200mm	
Shovel height	1065mm	
		Modified
Travel speed	5.6 km/h	10km/h
Swing speed	12.4rpm	20rpm

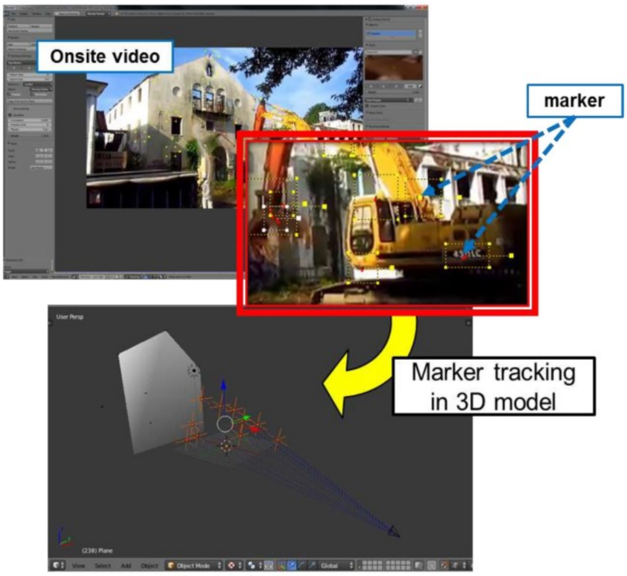


Figure 3

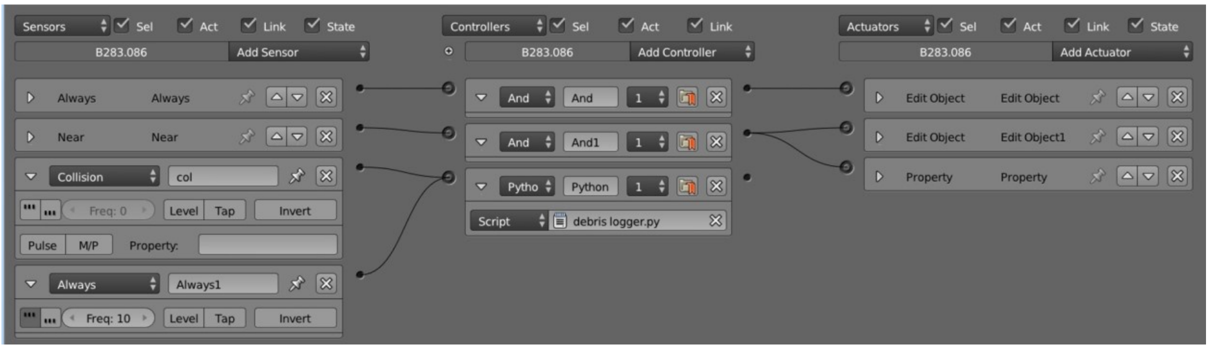


Figure 4

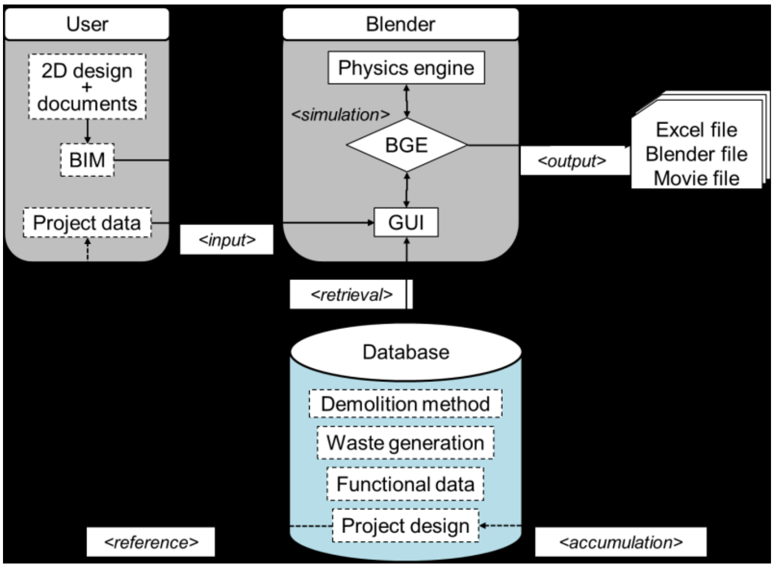
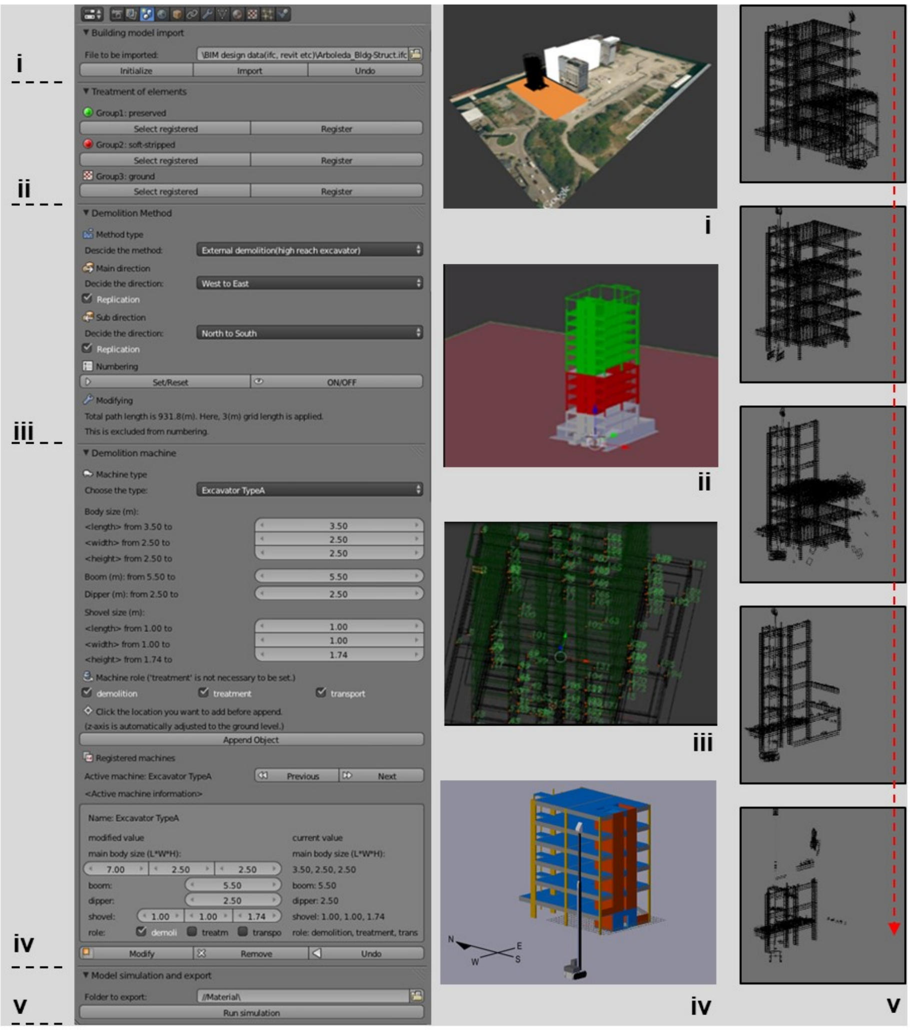


Figure 5



▼ Building model import

File to be imported: \BIM design data(ifc, revit etc)\Arboleda_Bldg-Struct.ifc

▼ Treatment of elements

● Group1: preserved

● Group2: soft-stripped

▨ Group3: ground

▼ Demolition Method

Method type

Descide the method: External demolition(high reach excavator)

Main direction

Decide the direction: West to East

☑ Replication

Sub direction

Decide the direction: North to South

☑ Replication

Numbering

Modifying

Total path length is 931.8(m). Here, 3(m) grid length is applied.

This is excluded from numbering.

▼ Demolition machine

Machine type

Choose the type: Excavator TypeA

Body size (m):

<length> from 3.50 to 3.50

<width> from 2.50 to 2.50

<height> from 2.50 to 2.50

Boom (m): from 5.50 to 5.50

Dipper (m): from 2.50 to 2.50

Shovel size (m):

<length> from 1.00 to 1.00

<width> from 1.00 to 1.00

<height> from 1.74 to 1.74

Machine role ('treatment' is not necessary to be set.)

☑ demolition ☑ treatment ☑ transport

Click the location you want to add before append.

(z-axis is automatically adjusted to the ground level.)

Registered machines

Active machine: Excavator TypeA

<Active machine information>

Name: Excavator TypeA

modified value		current value
main body size (L*W*H):		main body size (L*W*H):
	7.00 2.50 2.50	3.50, 2.50, 2.50
boom:	5.50	boom: 5.50
dipper:	2.50	dipper: 2.50
shovel:	1.00 1.00 1.74	shovel: 1.00, 1.00, 1.74
role:	☑ demoli ☐ treatm ☐ transpo	role: demolition, treatment, trans

▼ Model simulation and export

Folder to export: //Material\

Figure 6

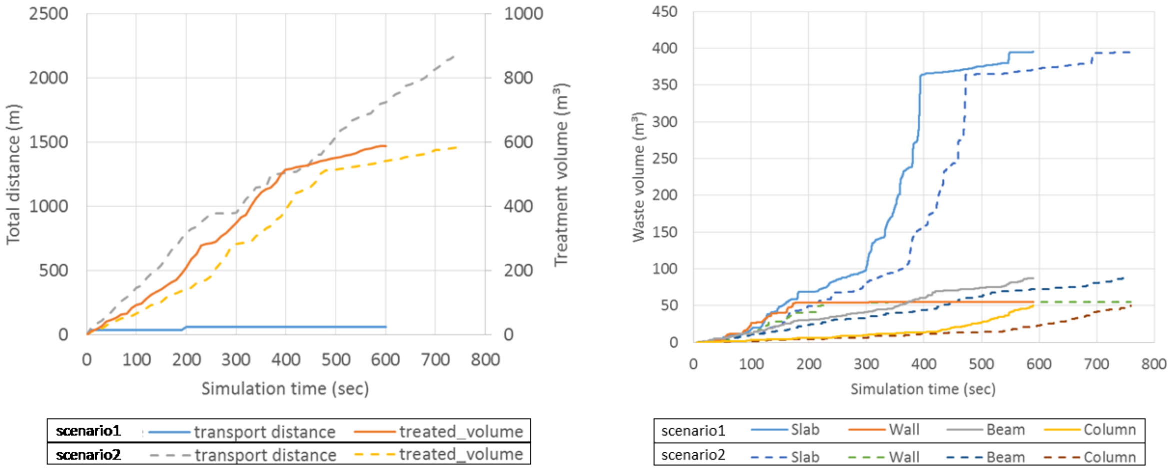


Figure 7

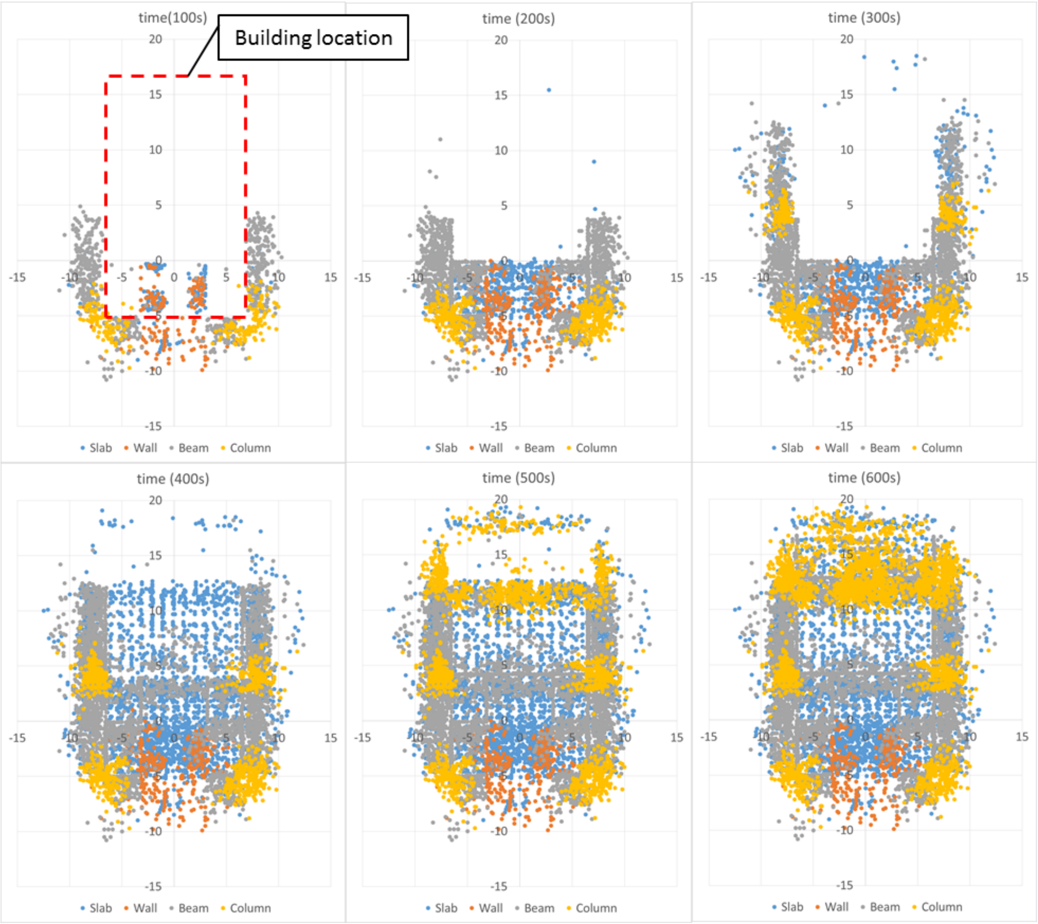


Figure 8

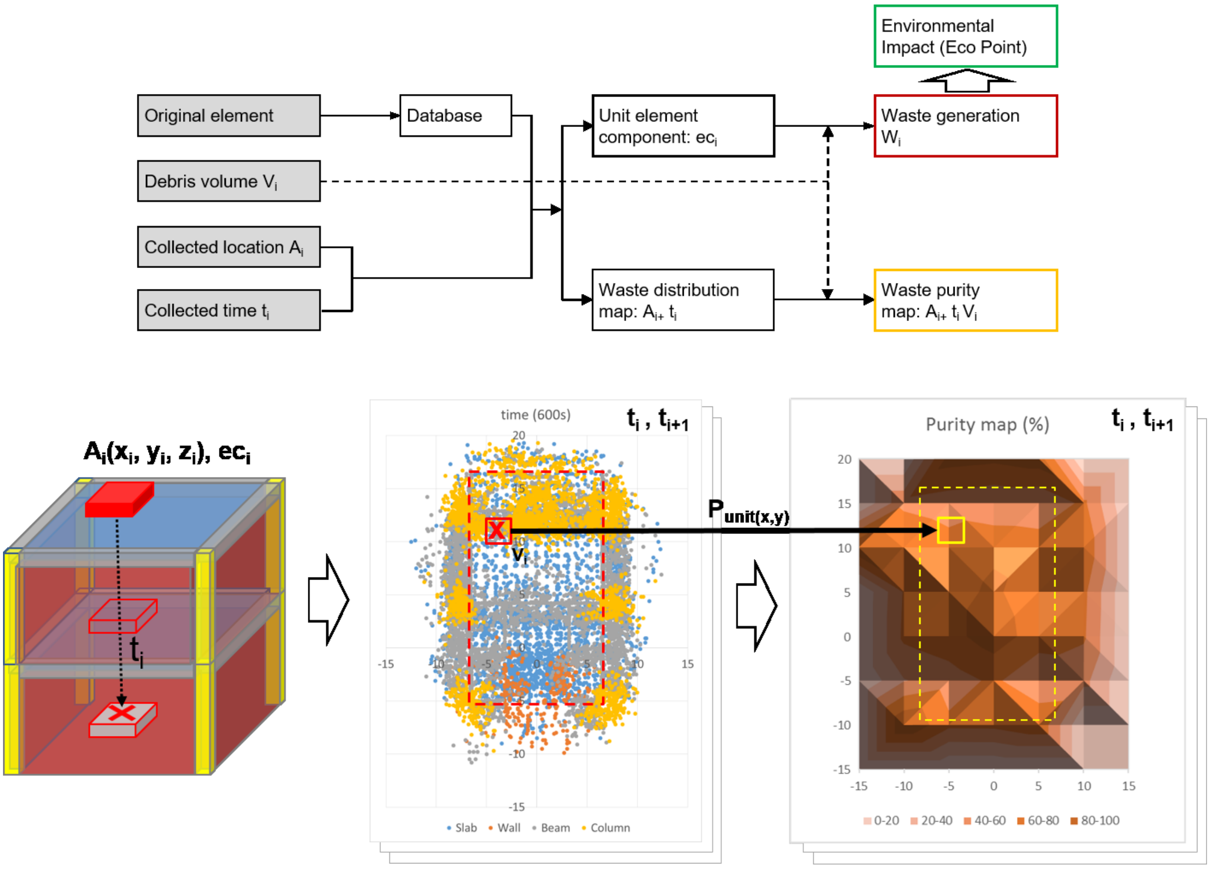


Figure 9

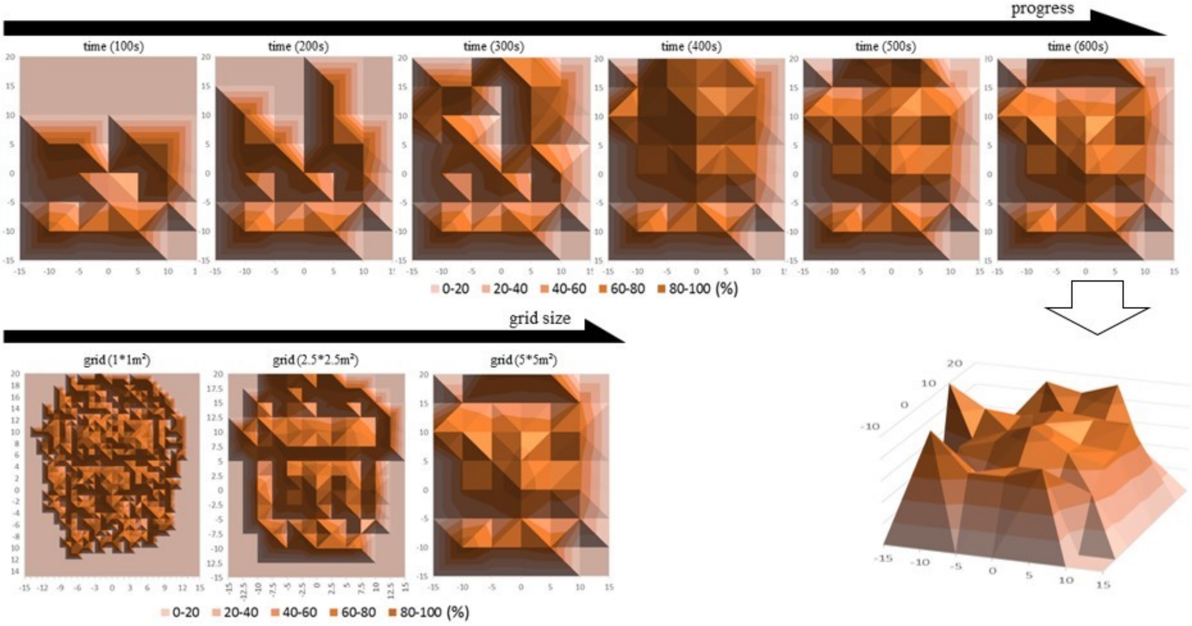


Table 1

Element Type	S(m^2)	N	Total (m^2)	Demolition waste Volume factor (Fdem) (m^3/m^2)	Total demolition waste volume (m^3)
Slab + beam	234	5	1170	0.4340	507.8
Walls	234	5	1170	0.1200	140.4
Reinforcement + Column	234	5	1170	0.1300	152.1
				Total	800.3

Table 2

Scenario	Time	Number of Objects		Accuracy	Waste Volume (m^3)					Total
		Measured	Total	(%)	Slab(1)	Beam(2)	(1+2)	Wall	Column	
1	590.4	11185	11547	96.9	352.6	87.1	439.7	92.6	50.1	582.4
2	759.0	11185	11547	96.6	352.0	87.0	439.0	92.6	50.0	581.5
					Vdem		507.8	140.4	152.1	800.3