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Development of an impact assessment tool for demolition

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Development of an impact assessment tool for demolition

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Abstract

Currently in the field of demolition, which generates most of the waste in the construction industry, the treatment of waste largely relies on landfill or degraded recycling, which leads to significant consumption of natural resource and energy and a shortage of landfill site. In order to improve the inefficiency of demolition waste recovery, **“to suggest improvements in the environmental impact of the demolition industry in UK”** was set as the aim of the present research. After the identification of few opportunities for communication between demolishers and constructers in the current social system, a collaboration support system between these two stakeholders called ‘Demolition Project Mapping’ (DPM) system was suggested.

To establish the suggested collaboration system, there were six main stages. As the first step, i) a literature review was undertaken to understand the background of demolition and demolition waste management. Similarly, ii) knowledge acquisition methods were used to collect knowledge from non-literature sources. Based on this collected knowledge, iii) an online-based collaboration system between demolishers and constructers was developed to encourage sustainable waste recovery (e.g. reuse or onsite recycling). In this system, demolishers input building data in BIM to create a project plan in 4D. After prospective project planning is designed and uploaded online, constructers can retrieve information about projects where demolition waste could be utilized in their own project. Since the shortage of detailed information for waste properties (e.g. waste purity and origin) was regarded as a bottleneck for sustainable recovery here, iv) an impact evaluation model of project planning was developed in 4D-CAD software, Blender. Through v) a pilot study with BIM data designed for an actual construction project on the University of Bath campus, the model was tested. Finally, vi) validation of the suggested model and system was conducted by survey methods (e.g. questionnaire and interview to practitioners).

Research findings showed the advantage of the suggested model application in three aspects; i) accurate recreation of project planning in 4D, ii) availability of computational approach and iii) project impact evaluation with multiple factors. For demolishers, project management, waste estimation and onsite safety management could be implemented more efficiently owning to the dynamic planning visualization. In addition to this, the adoption of computational approach in demolition planning enables the application of algorithm and the tracking of target objects in the model. Users can plan successfully with little effort thanks to the automated project simulation and efficiency comparison between different plans with algorithms. For a tracking function, the hazardous objects can be identified and their path recorded on site. Controlled project implementation eliminates the risk of exposure to hazardous waste for onsite workers and waste operators. By evaluating impact using multiple factors, this model, as a decision support tool, allows users to select the most suitable project planning according to the boundary conditions.

On the other hand, for constructers, the application of recovered waste becomes a realistic and convincing option if the waste component properties are accurately estimated by 4D simulation. These bidirectional encouragements of demolition waste recovery for next construction phase are expected to reduce the future environmental impact in the UK. Since the result of a developed social impact model indicates the reduction of the environmental impact by using the suggested collaboration system, it is concluded that the research aim has been theoretically achieved through this research approach.

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Table of Abbreviations

AB	Agent Base
AEM	Applied Element Method
AHP	Analytical Hierarchy Process
AI	Artificial Intelligence
AP	Accredited Professionals
API	Application Programming Interface
AR	Augmented Reality
ASR	Alkali-Silica-Reaction
BA	Building Act
BCA	Building and Construction Authority
BEDEC	
BEE	Built Environment Efficiency
BGE	Blender Game Engine
BIM	Building Information Modelling
BR	Building Regulations
BRE	Building research Establishment
BSI	British Standard Institution
C&D	Construction and Demolition
CDMR	Construction Design and Management Regulations
CEN	Committee European Normalization
CFC	Chlorofluorocarbon
CFD	Computational fluid dynamics
CND	Co-ordination Network on Decommissioning of Nuclear Installations
CNEA	Clean Neighborhoods and Environment Act
CPA	Construction Products Acts
CPCR	Central Plant Cold Recycling
CPD	Construction Products Directive
CPHR	Central Plant Hot Recycling
CPR	Construction Products Regulations
CSH	Code for Sustainable Homes
CWR	Controlled Waste Regulations
D-BOQ	Demolition Bill of Quantities
D&E	Demolition and Excavation
DCR	Duty of Care Regulation
DEFRA	Department for Environment, Food and Rural Affairs

DEM	Discrete Element Method
DPM	Demolition Project Mapping
DRI	Demolition Recovery Index
DSS	Decision Support Systems
DTSS	Demolition Technique Selection System
EA	Environment Act
EA	Energy and Atmosphere
EPA	Environmental Protection Act
EPA	Environmental Protection Agency
EPBD	Energy Performance of Building Directive
EPBR	Energy Performance of Building Regulations
EPM	Environmental Profile Methodology
EPR	Environmental Permitting Regulations
FEM	Finite Element Method
GA	Generic Algorithm
GBCA	Green Building Council of Australia
GBCI	Green Building Certification Institution
GGS	Green Guide to Specification
GIS	Geographic Information System
GSA	General Services Administration
GUI	Graphic User Interface
GUID	Global Unique Identifier
H&S	Health and Safety
HLA	High Level Architecture
HSV	Hue, Saturation and Value
HWD	Hazardous Waste Directive
HWR	Hazardous Waste Regulations
IBEC	Institute for Building Environment and Energy Conservation
ICE	Institution of Civil Engineers
IDE	Institution of Demolition Engineers
IPC	Infrastructure Planning Commission
IPPCD	Integrated Pollution Prevention and Control Directive
LCA	Life Cycle Analysis
LCCM	Life Cycle Cost Minus
LCCO2	Life Cycle CO2
LCSP	Lowell Center for Sustainable Production
LD	Landfill Directive
LR	Landfill Regulations

LR	Load Reduction
LTR	Landfill Tax Regulation
LWR	List of Waste Regulations
MAS	Multi Agent System
MR	Materials Resource
MRE	Materials Resource Efficiency
MSW	Municipal Solid Waste
NBRI	New Build Recovery Index
NIST	National Institution of Standard and Technology
NPSs	National Policy Statements
ONS	Office for National Statistics
PA	Planning Act
PCD	Polycrystalline Diamond
PPCA	Pollution Prevention and Control Act
PPCR	Pollution Prevention and Control Regulations
PSG	Project steering group
RA	Recycled Aggregate
RAP	Reclaimed asphalt pavement
RCBP	Recycled-Content Building Product
RFID	Radio-Frequency Identification
RMCM	Recycled Mineral Construction Materials
SD	System Dynamic
SDA	Sustainable Development Ability
SEPA	Scottish Environment Protection Agency
SIC	Standard Industrial classification
SSBA	Sustainable and Secure Buildings Act
SSBR	Sustainable and Secure Buildings Regulations
SWMP	Site Waste Management Plan
SWMPR	Site Waste Management Plan Regulations
UKAS	United Kingdom Accreditation Service
USGBC	US Green Building Council
VAC	Apparent Construction Volume
VAD	Apparent Demolished Volume
VAE	Apparent Package Waste volume
VBA	Visual Basic for Applications
WBS	Work Breakdown Structure
WEEED	Waste Electrical and Electronic Equipment Directive
WEEER	Waste Electrical and Electronic Equipment Regulations

WFD	Waste Framework Directive
WMLR	Waste Management Licensing Regulations
WR	Waste Regulation
WRAP	Waste and Resources Action Programme
XML	Extensible Mark-up Language
ZEB	Zero Energy Building
ZEH	Zero Energy House

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Chapter1

<Chapter Abstract>

In this chapter, the motivation and the adopted approach in this research are explained as the introduction. After the description of the current circumstance surrounding the demolition and waste treatment industry, the background is interpreted and translated by the author as the steps of hypotheses. Based on this, the aims and objectives of this research are proposed. The adopted research methods are selected for individual objectives. Since the thesis organization is summarised at the last section, readers can comprehend the thesis structure linking with the research context mentioned above.

Chapter1. Introduction

1.1. Background

Impact significance of material use and waste generation on the construction industry

The construction industry which includes the general construction and related activities (including demolition in preparation for new construction) for building and infrastructure has a large impact on the resource flow although the value produced is only around 5- 7 % of GDP in the UK (Rhodes, 2015). The amount of natural resources used by the construction industries is almost the same as the total resources for all other industries in the UK (Office for National Statistics (ONS), 2014). This causes the large amount of waste generation which, in many European countries including the UK, makes up approximately 30% of total waste. This is also attributed to the issue that a considerable amount of waste is disposed of by landfill in construction industry (Dyer, 2012). In the Waste Framework Directive (2008/98/EC), all EU countries had to set goals to fulfil 70% or more recovery of Construction and Demolition (C&D) waste by 2020. In the report from European Commission in 2015, the UK was classified as having a recovery rate of between 50-70% which means the requirement could possibly be achieved within 5 years (by 2020) by intensifying and increasing the recovery and recycling operations (European Commission, 2016). In other words, C&D waste treatment is still necessary for approximately 40% of total waste volume in the UK. As a result, huge consumption of natural resources and energy, and shortage of landfill space are urgent issues to be tackled in the UK as well as many other EU countries.

Demolition process in construction industry and the recent approach to the waste recovery

In the definition of the construction industry in accordance with Divisions 41 to 43 of the UK Standard Industrial Classification of Economic Activities 2007 (SIC, 2007), demolition refers to new construction work which is defined as the conversion process of building use. In terms of waste generation, the demolition phase occupies the largest share (60% in 2006) in the whole life cycle of building (Communities and Local Government, 2007). While the waste generation in the construction phase is predictable according to the construction design ("as-planned" based), the demolition waste after finishing its service life is more complicated due to the large time gap from the material input and the composite material application. Because of the time gap, it is difficult to access the old building design ("as-planned" design), and, even if it is accessible, the repair or refurbishment process makes it more difficult to understand the material application from those designs. Moreover, with the passage of time, some materials approved by law at the time of construction may be identified as hazardous to human health and specific treatment methods may be legally required in demolition, as in the case of asbestos. Due to this scarcity of design information, demolition practitioners tend to mainly use site observation to understand the building information to decide the project planning. Even with the observation by experienced practitioners, hazardous wastes are sometimes unexpectedly found at the implementation phase, which exposes labourers to health risks and causes a huge delay in the process with extra cost for the additional treatment. Due to this difficulty of estimating accurate waste generation, **understanding of waste properties to apply to the next construction** (e.g. reuse or recycle onsite) **is not feasible**. Moreover, the waste recovery is not likely to happen without a financial benefit obtained by selling the waste to salvage companies and demolishers are **not closely connected to constructers to achieve the waste recovery**. Accordingly, offsite treatment including landfill becomes the first option of waste treatment generated in the demolition phase. As a result, **the main treatment methods being used for waste in construction industry are unsustainable**.

1.2. Research justification

Academic approach to improve the conventional demolition practice

Currently researchers tackle the inefficiency of demolition and demolition waste management in practice mainly from three different aspects; i) demolition project analysis, ii) evaluation of the waste generation (at the project level) and iii) strategic suggestions for waste management (at the society level). In the demolition project analysis, due to the heavy dependence on the knowledge and experience of practitioners, a number of researchers have suggested the quantification of the project planning (Fox, 1994; Abdullah,2003). Although previous studies succeeded in generalising demolition project planning from the knowledge of practitioners (Qu, 2010), it did not cover the waste generation part which has been less prioritised in decision making in demolition projects. To compensate for this gap, other researchers have focused on developing methods to estimate the waste generation in demolition projects. Most of them are based on previous data for the generated waste volume. According to the average impact for each target (floor area, building unit, building element) in the specific building types, total waste generation and related cost can be evaluated (Jalali, 2007; Banias et al., 2011).

The best solution is recycling waste from demolition and using it as a resource in construction. However, the composite waste of different materials requires facilities and considerable expense in order to sort the waste for recycling. Therefore, it is not enough to analyse the availability of waste recovery for the next construction in practice. Considering the impact of each treatment method, other researchers aim to evaluate the environmental impact derived from demolition waste management. This approach has two main stakeholders to consider; demolishers and policy makers. While individual waste management is suggested as the optimal treatment from the demolishers' point of view, the influence of waste management policy or decision making for the total impact generation is analysed at the social level (e.g. SMARTWaste (BRE, 2013a) and Demolition Protocol 2008 (ICE, 2008) respectively). Due to the complexity of stakeholders and impact factors, these researches or impact evaluation tools can only focus on one of the four main waste management phases (demolition, treatment, production and construction) or the single connection between phases. Therefore, the individual information about generated waste such as waste purity, generation timing and the site location are not accessible to the individual constructer to consider the recycled waste application in their projects.

Current gap in demolition and research suggestion

Lack of consideration about the relationship between demolishers and constructers, and lack of a method to collect the waste properties (e.g. purity and generation timing) to discuss with constructers are identified by the author as the major drawbacks in the current demolition industry to fulfil the sustainable waste recovery in the UK. To address the former drawback, the relationship between demolishers and constructers, a collaboration support system is suggested in this present research. As a solution to the second drawback, enabling two different types of stakeholders to discuss the possibility of waste recovery at the project planning phase, the author suggests a 4D-CAD impact evaluation model for the detailed waste information. This model is developed to recreate the mix of wastes and its time lapse change to quantitatively evaluate the generated waste purity in simulation.

Accomplishment and academic contribution

The concept of the present research approach is described in Figure 1 with the conventional approach. The present model simulates the demolition process in 4D, and provides quantitative information for each object at each demolition step (Visualisation and **Dynamic evaluation**). Such visual information helps demolition engineers to get a deeper understanding of the process and wastes. Sorting the different mixtures of waste along the time axis, one can obtain information about waste purity which it has never been possible to evaluate using conventional static approaches (**Waste purity evaluation**). In case of a contaminated building, this function helps to minimize the propagation of contaminants and the exposure of workers to them. Such information about demolition waste can be taken into account by constructors so they can recycle it in new construction projects. This enhances the material flow from demolition projects to construction projects.

In addition to this, the **computational approach** in modelling can improve demolition plans to reduce the time, cost and environmental impacts under individual boundary conditions. By adopting algorithms to the machine operation pattern and the setting of demolition order, users can quantitatively compare the suitability of suggested demolition plans. The extension of demolition planning from the experience-based approach to the computational approach enables the application of computational methods in other fields. In the present research, the adoption of the computational approach and the fundamental survey of approach applicability in pilot studies can be regarded as the academic contribution, which allows researchers in the future to apply the innovative computational methods in demolition planning.

In order to quantify the potential reduction of the environmental impact by applying the suggested system to the UK society, the author also proposes a macro level simulation model which involves demolition and construction teams. This model will allow us to construct effective material flow between construction and demolition sites with minimum impact from individual project level to the national scale.

To conclude, the demolition project impact evaluation model developed in 4D-CAD enables the dynamic impact estimation with visualization. In addition to the waste purity data from the simulation, the computational approach enlightens the further innovative approach from other fields. Developing the nation-scale impact estimation model, the impact of the suggested system in the present research can be evaluated to address the effective material flow in the UK at a national level.

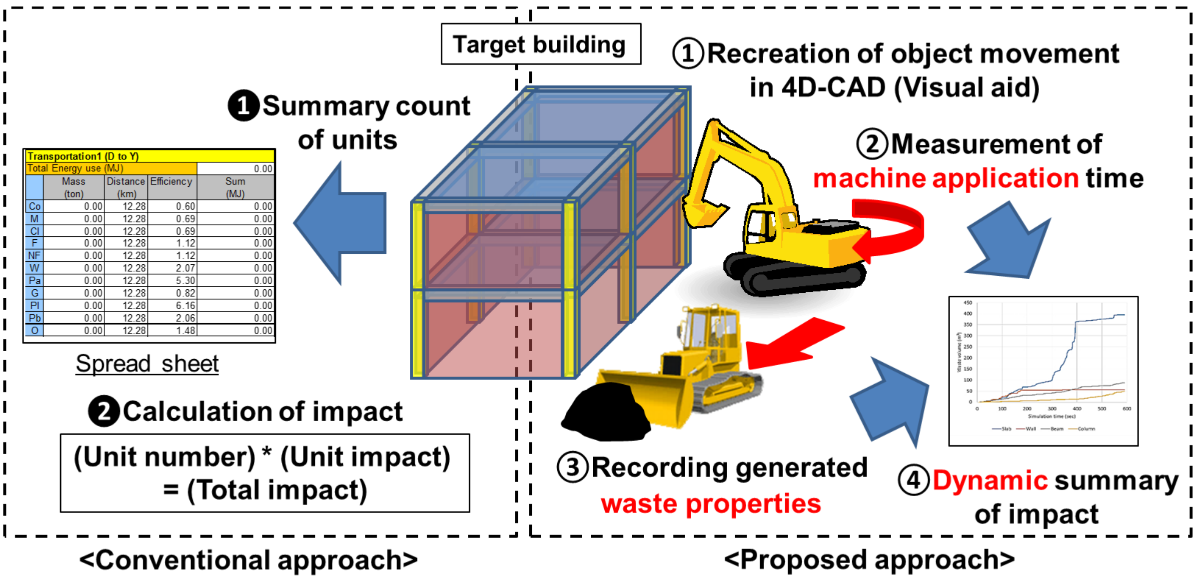


Figure 1 Concept comparison between conventional and present approach

1.3. Hypotheses

The fundamental hypotheses to be validate in this research is explained before mentioning the aims and objectives. The final hypothesis is withdrawn from the four steps of hypotheses as following.

Step1:

- "Current unsustainable situation for demolition waste recovery derives to the scarcity of direct interaction between demolishers (suppliers) and constructers (consumers) at the demolition stage."

Step2:

- "Constructers rarely try to utilise the demolition wastes because of the infeasibility of project planning with uncertain information for generated wastes in demolition."

Step3:

- "Amount, timing and purity for generated waste in demolition are the necessary information to be given for the project planning of waste recovery in construction projects."

Step4:

- "The dynamic simulation of project planning using 4DCAD enables to evaluate above three types of information."

Final hypothesis:

- "The development of a collaboration support system between demolishers and constructers with a 4DCAD simulation tool can contribute to sustainable demolition waste treatment."

In a science field, hypotheses tend to be designed to set as goals to be validated. However, this approach tends to be applied when the truth exists as the answer for these hypotheses. On the other hand, in this research, the final hypothesis can only be validated except the actual application of the suggested system. Therefore, it is alternatively validated by the practitioners' feedbacks on the suggested 4DCAD tool and the collaboration system, which was surveyed through questionnaires and interviews.

1.4. Aims & Objectives

Demolition waste has traditionally been regarded as waste and treated by landfilling or downgrade recycling at best. As a result, there is a huge social demand for the paradigm shift of this waste treatment policy. The aim of this research is,

"to suggest improvements in the environmental impact of the demolition industry in UK"

focusing on the waste recovery for future construction. In order to achieve this aim, the research objectives are;

1. To understand current demolition processes and the material waste flow into new construction project.

2. To suggest a **demolition project mapping (DPM) system** to encourage interaction between demolishers and constructors

3. To develop a **4D-CAD evaluation model** for demolition projects to enable the dynamic simulation of project planning which is the key technology in the DPM system.

4. To design a **demolition algorithm** which can minimize demolition machine use. (Validation of the applicability of computational approaches in demolition)

5. To simulate demolition project planning with the developed model and validate the demolition algorithm for planning improvement.

6. To develop a **social demolition impact model** and evaluate the potential reduction of impact from the application of DPM.

7. To validate the suggested models from the feedback of demolition practitioners who belong to the Institution of Demolition Engineers (IDE)*.

6 *IDE was established to advance the science of demolition engineering and it has a long experience to encourage demolition practitioners to exchange their knowledge and expertise (IDE, 2016). As the group of the experienced demolition practitioners, they tend to be chosen for the respondents of validation in conventional demolition researches (Qu, 2010 and Quarmby, 2011).

1.5. Overview of Research methods

The applied research methods to accomplish the above objectives are summarised in

Table 1. In this section, each applied method is briefly explained. The details are described in the corresponding chapters shown in

Table 1.

i) Literature review

Reviewing of related literature has three main purposes; i) understanding the practice of demolition and demolition waste management, ii) identifying the gap between the social demand and current academic approaches in the demolition field and iii) surveying applicable approaches in external fields (mainly construction) to fill the above gap. For understanding the demolition practice, demolition waste and project planning are thoroughly covered including the adopted demolition system and methods. For the academic approaches, conventional demolition research was classified by main focus into three phases; demolition, waste generation and waste management.

The sources of literature were mainly academic books, journals, papers and PhD theses or MSc dissertations. In addition, the act and regulations were consulted to understand the legal requirement in the UK or EU society. In order to study the actual documentation in practice, actual documents of demolition project planning (for the Site Waste Management Plan) were also shared by the collaborating practitioners in the Institution of Demolition Engineers (IDE).

ii) Acquisition of knowledge

This approach aims to collect the qualitative data from the demolition practitioners or the accumulated knowledge in companies. For the first step of research, exploratory methods were applied to understand the industry background. This was regarded as the preliminary step of research method design. It was mainly achieved by attendance at conferences for practitioners or individual discussions with practitioners contacted there. It is worth noting that the validation step using the same knowledge acquisition methods (e.g. interviews or questionnaires) is explained separately in a later section due to the different objectives in this research although those techniques tend to be categorised as knowledge acquisition methods.

iii) System design

In order to encourage demolishers and constructers to discuss the waste application to new construction, a collaboration system is suggested here. This system framework was created from the process-centred methodology of system development. This aimed to represent the concept of system as a set of processes. This methodology tends to be applied when a conceptual design or a model development to extract the waste property information for discussion has been created, before an actual application or pilot study. For validating the system significance, model simulation of the social environmental impact of demolition was alternatively applied in the following section.

iv) Database construction

A database for the impact evaluation model was created in this research. It was originally intended to acquire data from the onsite survey only. However, due to the limited access to demolition sites, the visual resources found on the internet and the reference surveys were applied to compensate the shortage of resource. These data were separated in two types; raw and interpreted. While raw data such as machine properties (e.g. rental fee, speed) could be directly applicable in simulation, data of demolition patterns (e.g. machine movement or demolition order) were created from the interpretation of demolition progress seen in practice. To eliminate subjectivity in the interpretation process, prospective patterns were listed and their efficiency compared in the model developments and the pilot studies in the following chapters.

v) Model development

Rapid prototyping methodology was applied to develop the impact evaluation model for the demolition projects. This approach designs the initial prototype model and iterates the pilot study and improvement process to create a suitable model in which the developer recognizes the superiority of model according to the model ability and usability. The validation step was set at the final prototype to get feedback from the practitioners to identify the gap with social demand before application. In addition, the social impact evaluation model was developed based on the author's model in the previous research. An agent based model using spreadsheet for the impact evaluation was modified to simulate the interaction between demolishers and constructers, which would be encouraged by DPM system application.

vi) Pilot study (alternative of Case study)

For the test of developed models, pilot study method was applied. For the impact evaluation model, the BIM data which was designed for the construction project on the University of Bath campus was adopted for the pilot study. This was because of the limitation of the access to the demolition project information which should have enabled a case study of waste impact evaluation. For the social impact model, the social impact was evaluated with the statistical data of demolition and construction projects and the geographical data of waste treatment facilities in the UK. Due to the lack of actual social impact data, this was also regarded as a pilot study.

vii) Validation

After the development of the demolition impact evaluation model with the rapid prototyping methodology, knowledge acquisition approaches (questionnaires and interviews) were applied to validate the applicability and ability of the developed model. After the presentation of the developed system and model in this research, the respondents from the practitioner's community were asked to evaluate the model from different perspectives. Validation design has two types, questionnaire and interview, to collect general feedback from the demolition industry with closed questions and more in depth responses with open questions respectively.

Table 1 Summary of research methods

	Research objective	Research method	Main chapter
1	Comprehension of current demolition and waste stream	i) Literature Review	***Chapter2**: Literature Review*
		ii) Acquisition of knowledge	***Chapter3-2**: Adopted Method -Acquisition of knowledge-*
2	Creation of a demolition project mapping (DPM) system	iii) System design	***Chapter4**: Method1) Development of DPM system*
3	Development of a 4D-CAD evaluation model for dynamic simulation of project planning	iv) Database construction	***Chapter5**: Method2) Database construction*
		v) Model development (demolition project impact)	***Chapter6**: Method3) Development of project impact evaluation tool*
4	Design of demolition algorithm	v) Model development (Algorithm design)	***Chapter6-2**: Theoretic setting of demolition order*
5	Model simulation of demolition project planning	Model simulation (demolition project impact)	***Chapter8**: Findings1) Pilot study For method3*
		Simulation data analysis	***Chapter11**: Discussion*
6	Development of a social impact evaluation model	v) Model development (social impact)	***Chapter7**: Method4) Development of social impact evaluation tool*
		Model simulation (social impact)	***Chapter9**: Findings2) Pilot study for method4*
		Simulation data analysis	***Chapter11:** Discussion*
7	Validation of developed models	vii) Validation (Questionnaire and interview to practitioners)	***Chapter10**: Validation*

vi) Pilot study*

*As the fifth research method, 'pilot study' was held for both project and social impact model.

1.6. Thesis organization

This thesis consists of twelve chapters which are briefly summarised below.

Chapter1: Introduction

The aims and objective of this research are explained after the description of the background of construction and demolition. This is followed by the methodologies to improve the material recycle processes in demolition and construction.

Chapter2: Literature review

This chapter consists of three main sections to analyse; i) the current demolition practice, ii) academic approaches to demolition and iii) prospective approaches in external fields. In the first section, the literature of the conventional waste treatment, and demolition methods and decision making processes are surveyed to understand the conventional practice of demolition and its waste treatment. After surveying the current approaches in the demolition industry to identify the social gap between practices and demands, advanced approaches in external fields, especially the methods of data application and optimization modelling, are reviewed for the further development of the model in this research. This includes the selection of software to develop the impact evaluation model based on the previous application of software to construction.

Chapter3: Methodology

In order to achieve the aims and objectives through appropriate research design, research methodologies applied in the social science are summarised to justify the adopted methods in the present research. The aim of application and the adequate setting of target are explained to justify the methods used in this research.

Chapter4: Method I Development of DPM system

This chapter introduces a system framework to achieve sustainable demolition in the UK. At first, the required dataset for the DPM system is explained as well as the data flow in the system. Then, the actual online system in the UK for the design and evaluation of demolition projects, SMARTWaste (BRE, 2013a), is described to explain the current structure of an online service to estimate demolition waste generation.

Chapter5: Method II Database creation

Three different types of database set for the demolition impact evaluation are described in detail; demolition strategy, resource property (e.g. machine, recovered waste) and impact. They contain applied patterns of demolition methods, machine properties and waste generation. With the raw data, the simulation program provides the comparative impact results. Data sources are introduced to justify the rationality of application, and the actual values are summarized in the Appendix.

Chapter6: Method III Development of project impact evaluation model

This chapter consists of two parts to explain; i) the development environment of the evaluation model and ii) the data application in the model. Firstly, the main software, Blender, to develop the impact evaluation model in 4D is introduced with the feature of software and application to previous research as an example. After the description of the model framework, each simulation process is explained for users to know how to operate the model with the visual images created by Graphic User Interface (GUI). The applied formula of impact evaluation is also displayed. In the second part, the interpreted data for the machine control and the demolition order are described as algorithms which allow machine models to auto-run in the model simulation. After the summary of each concept, the suggested algorithms are visually displayed. Both types of algorithms are applied to the pilot study in Chapter8 and the prospective machine control pattern and demolition order are compared for the optimization of planning.

Chapter7: Method IV Development of social impact evaluation model

Previous study of the social impact model for demolition waste recovery is firstly explained as the basic framework of the agent-based (AB) model for the social impact estimation. By adding the new stakeholder agents and construction teams, the model is extended to evaluate the total demolition impact in the UK society with new settings of agent algorithms and sensitivity analysis.

Chapter8: Finding I Pilot study for method III (Project impact)

The results of three case studies are summarized to confirm the model applicability. As a preliminary model application, the prototype model is applied to illustrate the model efficiency for demolition impact estimation with BIM data. Then, the suggested algorithms in Chapter 6 are compared to each other to decide the optimal machine operation and demolition order. This is applied to the actual building design with BIM data and the expected impact reduction with this model application is discussed.

Chapter9: Finding II Case study for method IV (Social impact)

System framework is explained to show how the evaluation model is composed by Agent-Based (AB) and System Dynamic (SD) models. Following sections suggest scenarios which determine the rule of each agent behaviours and describe the estimated impact reduction achieved by the application of the DPM system. Here, agents include all of the stakeholders of demolition waste flow so that the change of application rate of DMP system among demolishers and constructors will improve the recycling efficiency and reduce the impact to the society.

Chapter10: Validation

The questionnaires given to the members of the IDE in order to validate the applicability of the whole evaluation model are explained in this chapter. The aims, the target people and the content of questionnaires are firstly summarised. Then, the answers to questions asking about satisfaction with the model are analysed to evaluate how it would be accepted by people in the industry.

Chapter11: Discussion

The results of above the case studies are discussed here. The application to the actual building design is especially discussed in terms of the impact reduction from the comparison of the several types of demolition methods in simulation. The demolition impact is also evaluated with regard to social scale as the model validation. Regarding the limitations of the model, recommendations for future model development are also mentioned at the end of this chapter.

Chapter12: Conclusion

From the discussion about the ability of the whole model in the improvement of demolition waste treatment, the study draws conclusions on the value of the suggested models and systems for demolition practice in the UK society. Based on this conclusion, future prospects for demolition waste treatment are suggested as the recommendation from this research.

Chapter2

<Chapter Abstract>

In this chapter, the literature review approach is summarised to survey three target processes in demolition; i) project planning, ii) implementation and iii) waste management. In order to decide the optimal approach in this research, each survey is separated into three steps by targets; i) industrial background, ii) conventional academic approaches in demolition and iii) applicable academic approaches in other fields. Readers can follow the logical procedure of research approach in this thesis.

Chapter2. Literature review

In many countries, the amount of resources used by the construction industry is a huge share of the total resources used by all industries (e.g. about 50% in the UK (ONS, 2014)). In the construction processes, excess materials are thrown away and structures turn into waste and are discarded after the long service life. This amount is approximately 30 % of the total waste in many countries and the tendency is to largely rely on landfill for disposal of this waste. This causes serious issues in natural resources consumption, energy usage and landfill scarcity. In addition, many researchers (Federle, 1993 cited in Peng et al., 1997; Marxsen, 2001) have pointed out the hazardous effects of leaching and methane emissions of landfilled waste. Thus, effective recovery of material is crucial to achieving a sustainable society. Many researchers (Peng et al., 1997； Hendriks and Pietersen, 2000; Building Research Establishment, 2003) propose a hierarchy concept for the utilization of used materials. Dyer (2012) classifies five layers; reduction, reuse, recycling and composting, energy recovery and disposal, in order of environmental impact. To achieve sustainable waste treatment in the construction industry, waste should be treated at a higher layer. This can only be achieved when both the waste generation and waste application processes are considered. In particular, the waste generation at the demolition phase makes up the largest share of waste, accounting for 60% of the total, in the whole life cycle of a building (Communities and Local Government, 2007), in which the elements of the building end their service life.

In this context, the demolition waste flow in practice, as summarised in Figure 2, is reviewed in this chapter. The vertical axis indicates the process flow from the project planning and demolition to waste management. The horizontal axis corresponds to the development of knowledge from the background and the demand gaps to suggestion from other fields to fill the gaps. Three columns correspond to each chapter from Chapter 2.1. to 2.3.

In the left column of Figure 2, the conventional demolition process is surveyed as the background of the present research. How the practitioners decide on what factors tend to be prioritised at project planning are focused on first. In the second section, the applicable demolition strategies composed of demolition methods are surveyed. What would happen to the waste at each application step is mainly studied here. Then, the generated waste type and each applicable treatment method are reviewed at the end of this column. The current feasibility of each method and the bottleneck for the sustainable recovery should be identified.

As the next step of this literature survey, the conventional approach in each phase of demolition is compared to the demand of the current society to identify the gap between them. For the project planning, some research attempting to propose a project planning system is reviewed to discuss the advantages and shortcoming of the suggestions. In the demolition phase, the foci of the reviewed targets are shifted to the accurate estimation of waste generation in demolition projects. This approach is connected to the suggestion of efficient planning at the waste management phase.

Demolition waste management phase is separated into four steps; demolition, extraction, production and new construction. Then how the research approaches cover these steps and what type of data is applied to design the efficient waste management planning is summarised.

The second column of Figure 2 summarizes the gaps found in the comparison between the background and conventional approaches by listing three gaps; i) lack of consideration about the dynamic feature of demolition at the planning phase, ii) inaccuracy of waste property estimation (waste purity) and iii) ignorance of the direct connection between demolishers and constructers for waste recovery. In the right column of Figure 2, suggestions from research approaches applied in external fields are surveyed in terms of their applicability to our cases, in order to get solutions to fill the above mentioned gaps. For the recreation of demolition dynamism, 4D-CAD application in construction field is used. Based on this, the basic concept for the impact evaluation model and the adopted software is decided to achieve the dynamic evaluation of demolition planning. To reflect the building material as the waste property information, the BIM data application mainly in the construction field is featured. This is also reflected in the developed model which assumes the form of building data input is BIM to evaluate the waste purity from the material information. Finally, the social system modelling approaches in the social science field are studied to develop a social system model covering the relationship between demolishers and constructers. The social impact evaluation model developed in the authors previous work for MSc thesis (Kunieda, 2012), and which is used for the social impact estimation in this research is covered in detail. The further development of the social model will be introduced in Chapter7.

In summary, the review has two directions; demolition progress (with three phases) and review progress (with three steps). Project planning, demolition and waste management are involved in demolition progress, and this starts with the background survey (in Section 2.1.). Following this, the research approaches corresponding to each phase are covered to reveal the current demand gap in the next step (in Section 2.2.). Based on this, at the final reviewing stage, prospective research approaches adopted in external fields are evaluated for their applicability in filling those gaps (in Section 2.3.). The detailed description of system and modelling using those approaches can be seen in the methodology and method chapters (Chapter3 to 7). Since the volume of these chapters are large, most of the details of demolition methods and waste management methods are put in Appendix 2 and 3 respectively. Readers can skip some parts and come back to current chapter when detailed discussion of previous works is required.

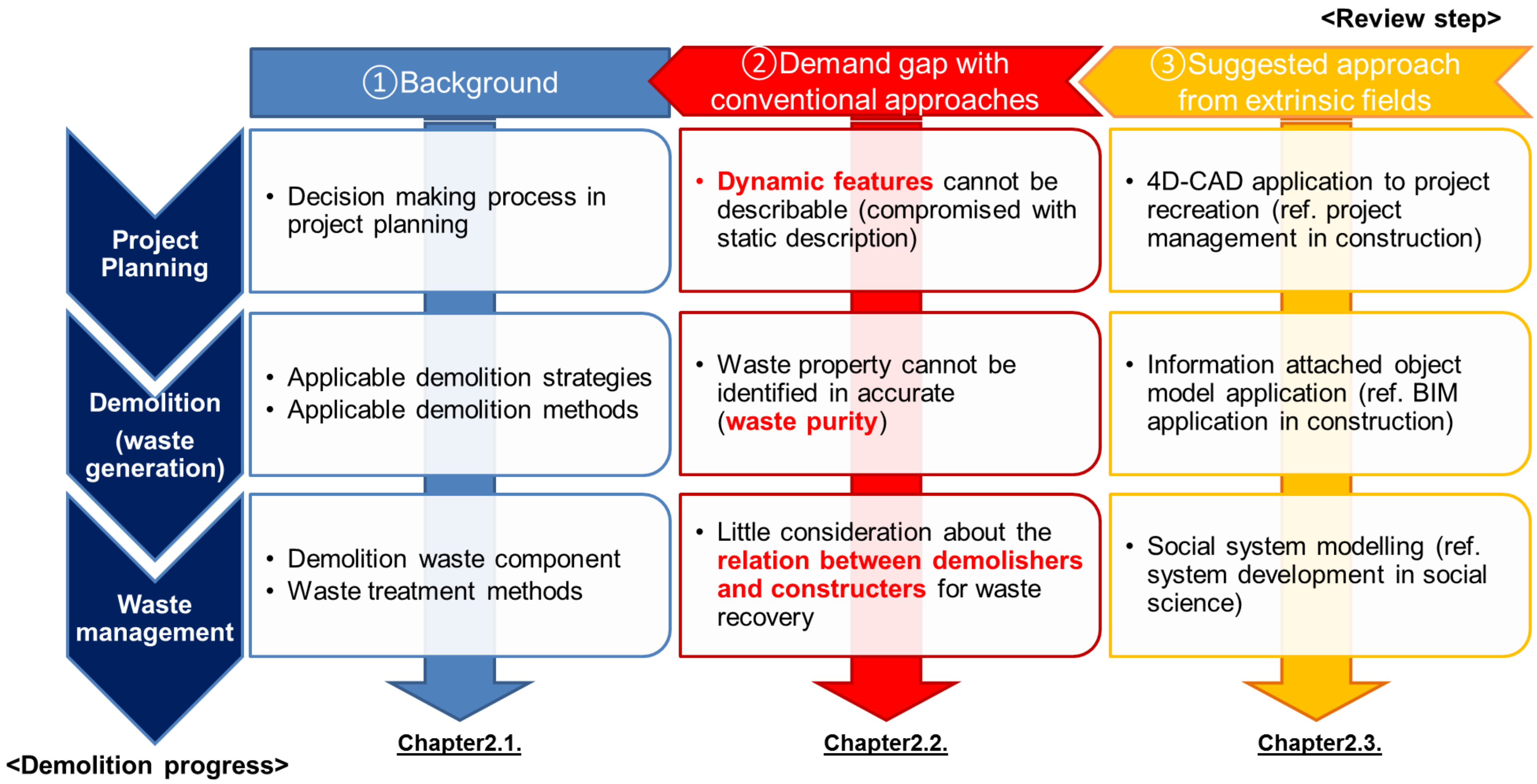


Figure 2 Flow of literature review

2.1. Background Survey

2.1.1. Demolition project planning

The demolition project is basically decided by the client of the demolition and it is committed by the demolition contractors. However, external stakeholders in different phases (reuse and recycling and new construction phases) tend to affect the decision. Therefore, in this section the relationship between stakeholders of the demolition and the way of decision making by the demolition clients and construction clients are explained by referring the book, *"Building with Reclaimed Components and Materials"* written by Addis (2006).

2.1.1.1. Transition of demolition industry

Currently, the demolition project focuses on how to minimise the cost and duration of the machinery equipment application onsite, which also affects the treatment of demolition waste. The focus of waste treatment shifts from simple 'demolition' to 'recovery' and 'disposal', to utilise the resource of a building component. This is also justified from the environmental aspect. for building construction in which the large volume of virgin materials and fossil fuel are consumed. Application of technologies at a waste generation phase, called 'end of pipe', cannot solve this unsustainability. Thus, products must be designed from the life-cycle aspect to concern how to reduce the environmental impact between 'gate to grave' at the production phase. The global movement to relieve the environmental impact also gives some influence on the demolition such as the enacting laws by the local authority or government. Regarding the strict legislations, health and safety onsite are also focused, which is represented by the Health and Safety legislation, the Construction (Design and Management) regulation and the Control of Substances Hazardous to Health (COSHH) regulation in the UK. In response to this, the use of remote controlled machines has altered the human labour and it results in the development of machinery equipment for demolition. However, this movement has reduced the chance to recover the building components without damaging before the whole demolition (Addis, 2006).

2.1.1.2. Decision making for demolition and waste treatment

As shown in Figure 3, there are many stakeholders involved in the demolition and waste treatment. Therefore, here, how to decide the project and the method for each stakeholder are explained to comprehend the framework from multi aspects. It is expected to be reflected on the development of a multi-agent model which is introduced in Chapter7 to recreate the demolition and treatment flow.

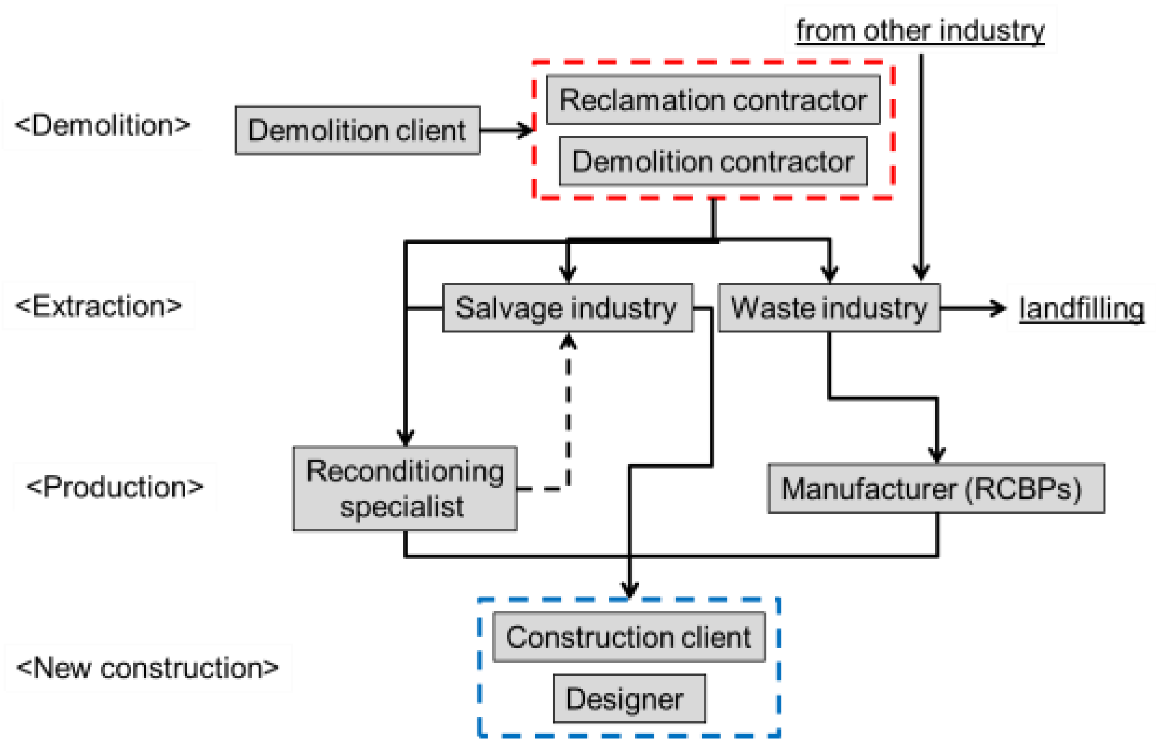


Figure 3 Stakeholders in reuse/recycling flow

(source: Addis, 2006)

Decision of demolition method (demolition clients)

Considering the optimal demolition, decision making is an important process in judging whether an option can be accepted. The choice of a demolition method is decided based on the practitioners' experience, skill and knowledge of the demolition industry. Such decision is made by directors referring to the initial selection suggested by project engineers (Holdsworth, 2008). Many researchers insist that decision making can be attribute to different factors, and they suggest their own factors. As shown in Table 2, Holdsworth (2008) categorized the conventional researchers' factors with his own suggestion. Those are categorized into five parts; financial, time, physical, safety and environment. While Abudayyeh et al., (1998) and Hurley et al.(2001) suggest those factors to explain why some conventional decisions are chosen, only Holdsworth (2008) surveyed the weighing of those factors and reasoned through the questionnaires to the experienced demolition engineers. From the result of questionnaires, Holdsworth (2008) describes the priority of factors for decision making and the possible deciding flow as shown in Figure 4 and Figure 5. From here, the decision making of demolition seems to be controlled by client specification which subjects to the health and safety (H&S) of workers and public. This would be restricted by the physical and environmental aspects, but not by the financial aspect. It is because the demolition contractor will decide the cost after they decide the demolition method which is about 15 to 25% extra fee to the basic cost. Although Holdsworth (2008) insisted there is the financial incentive to choose the low cost demolition method and it may result in the increase of H&S risk, this would happen in the range of acceptable H&S risk and that method can still achieve the client's specification.

Therefore, the major factor in the decision of demolition method seems to include physical and environmental factors, if the financial aspect can be relieved from the concern of all clients for demolition project. It can be fulfilled from the legal approaches such as increasing levies for landfilling and subsidizing recycling, and the movement of construction industry towards a more sustainable approach in the UK by BREEAM and the Green Guide.

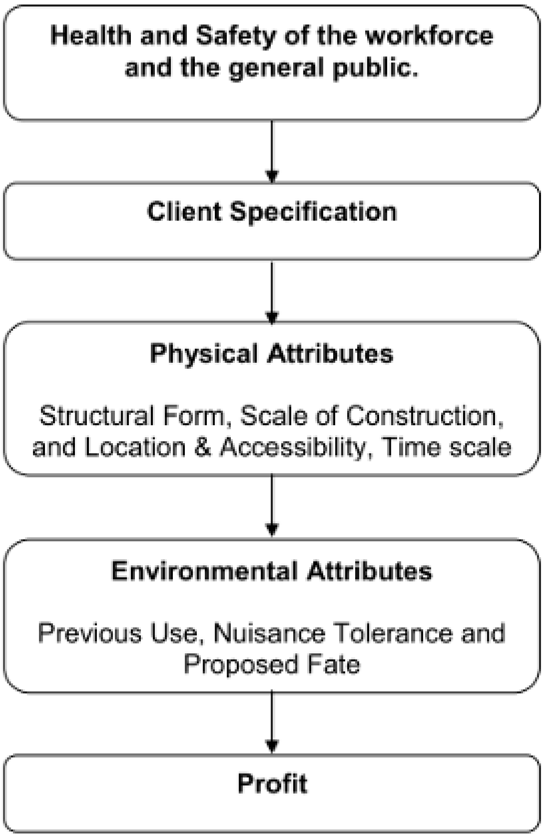


Figure 4 Result of questionnaires for importance ranking of demolition factors

(source:Holdsworth, 2008)

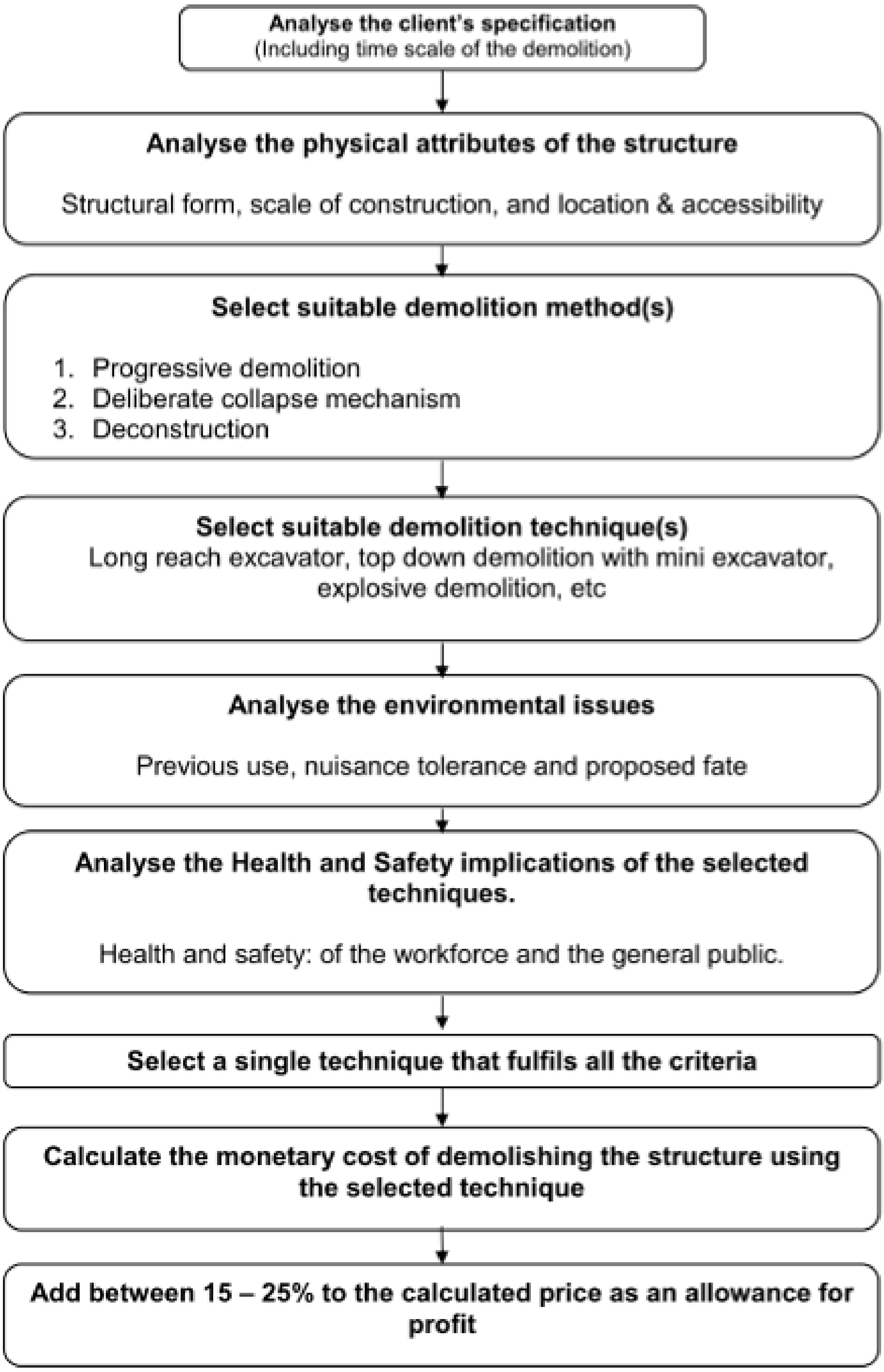


Figure 5 Possible decision flow of the demolition method

(source:Holdsworth, 2008)

Table 2 Suggested key factors for demolition method decision

Abudayyeh et al (1998)		Abdullah (2003)		Hurley et al (2001)		Holdsworth (2008)		
1	Financial considerations	1	Financial considerations	1	Cost	1	Profit for the contractor	Financial
2	Time available	2	Time available	2	Time period	2	Time scale of the demolition	Time
3	Strength and quality of the structure	3	Stability of the structure	3	Structural form of the building	3	Structural form of the building	
4	Shape, size and accessibility	4	Shape and size of the structure	4	Scale of the construction	4	Scale of the construction	
		5	Location and accessability of the structure	5	Location of the building	5	Location and accessibility of the structure	Physical
5	Amount of concrete to be removed	6	Extent of demolition	6	Scope of the demolition	6	Extent of the demolition	
6	Worker and public safety	7	Health & Safety	7	Safety	7	Health & Safety of the workforce	Safety
						8	Health & Safety of the public	
7	Environmental concerns	8	Environmental concerns	8	Previous use of the building	9	Previous use of the structure	
8	Recycling	9	Recycling	9	Proposed fate of the building	10	Proposed fate of the building	
9	Transport and disposal of debris	10	Transport consideration			11	Availability of plant	Environmental
		11	Presence of hazardous material	10	Culture of the demolition contractor			
		12	Structural engineer approval			12	Permitted level of nuisance	
		13	Client specification	11	Permitted level of nuisance	13	Client specification	

(Source: Abudayyeh et al., 1998; Abdullah, 2003 cited in Holdsworth, 2008; Hurley et al., 2001; and Holdsworth, 2008)

Decision of material recovery (construction clients)

Construction clients and their design teams are normally concerned about the function and aesthetic design at the beginning phase of building construction project (Addis, 2006). Following this, materials are specified to apply for each member in terms of technical performance and durability. Then, at the end, a construction method is decided from above factors and the site situation besides construction cost and term. These stakeholders need to concern about the utilization of reuse/recycling material at the design phase as the rise of social awareness to sustainability and the incentive provided by government and the sustainability assessment tools such as BREEAM, LEED and CASBEE. In other words, the building value can be improved by the certification from the third party for the lower risk of necessary repair or reconstruction due to the future severer legislation relating to the sustainability (Addis, 2006).

Three factors are proposed to decide the application of reuse/recycling material to a building construction (Addis, 2006). Firstly, the viability has to be considered from the availability of the source (onsite or salvage yard), easiness of refurbishment and warranty of material properties. Compared to the virgin material, reuse or recycle materials have a huge disadvantage from the dependency of supply on the building demolition. The many factors are vulnerable such as amplitude, timing, distance of source, necessity of storage and transportation. As the other features of reuse/recycling material, it is necessary to be refurbished before the use. The current condition of material at the sorting phase is important to decide the balance between the cost and benefit from the application of the material. In addition, it is more difficult to comprehend the material properties than virgin ones due to the diverse histories of material (e.g. service circumstance, demolition and reconditioning method). The evaluation of material properties including easiness of testing is important here, and the warranty of material by an independent assessment or certification by a third party is necessary for the use of recycled material. This policy that the responsibility of material properties is on the users is very much different from the case with the virgin material whose use is guaranteed by suppliers.

Secondly, clients and design teams consider the environmental benefit respected from two aspects; i) reduction of the natural resource consumption and ii) certification from the sustainability assessment tools. Due to the diversity of the material stream from landfilling to recycling, it can be regarded to reduce the future consumption of virgin materials and the production energy and the land use for landfilling. As a result, the use of these materials or products such as RCBPs reduces the environmental impact of the construction industry. At the same time, this allows meeting the environmental rate criterion set by the sustainability assessment tools mentioned above. The incentive derived from this can exceed the disadvantage of reuse/recycling materials.

As the final factor, the cost and value tend to conflict with the actual application. As mentioned above, the use of reuse/recycling materials requires extra process compared to the virgin materials. Finding the source is the first problem, and if it is decided to recover from not salvage yard but demolished building, a careful demolition is inevitable to recover the materials without the damage so that the demolition process becomes longer and the cost tends to be more expensive. After the procurement of materials, they need to be refurbished to satisfy the requirement at the material property test. During this process, a careful storage is inevitable to prevent the fire and declination of the product properties. Based on these extra necessary spending, the commercial viability is analysed though it is quite difficult to evaluate from the volatile price decided by the scarcity of materials.

As the flow of decision making, clients and design teams start to set the target and degree of reuse/recycling for the use in the construction. Then, the possibility is assessed from above three factors. Finally, the balance between the cost and the environmental benefit is evaluated to decide its feasibility.

Decision making of material recovery (others)

As shown in above sections, there are five other stakeholders for the demolition waste treatment apart from the demolition and construction phases; waste industry, demolition contractor, salvage industry, reconditioning specialist and manufacture of Recycled-Content Building Product (RCBP). For the waste industry, the material stream needs to be altered from disposal to recycling which can produce profits rather than paying the landfill tax. Due to this concept, the waste component is the biggest concern for them rather than the product property or quality. On the other hand, the demolition contractors aim to fulfil the client request in the quickest and cheapest way. Nowadays there is some slight change for a 'cheapest treatment' due to the rise of landfilling tax with the government policy. Accordingly, the demolition contractors need to find the possible ways not to send waste components to the landfilling. This is a trade-off between the additional cost to extract the material and the income from material sales and necessary landfilling cost. Accordingly, they do not salvage materials if there is no prospective buyer, in other words, without a commercial value. This is the completely same idea as the salvage industry. They only salvage the material when they decided it produces a higher value than necessary expense constituted by the waste purchase price, reconditioning, transportation and storage cost (Addis, 2006).

2.1.1.3. Demolition and reuse/recycling process flow

Here, the process flow for the demolition and waste treatment is described from two projects, demolition and construction using demolition materials. In this section, the factors for the decision making process, mentioned above, are highlighted to guide the flow of modelling. Figure 6 describes the process flow of demolition project.

Process flow of demolition project (demolition clients)

As shown in Figure 6, a demolition project consists of five processes; 1) planning for demolition, 2) pre-demolition audit, 3) soft strip, 4) demolition and 5) offsite treatment. In the first process, it has roughly three steps to decide the demolition strategy. At the first step, the building properties are surveyed with drawings and records of building modification. At the second step, the actual condition and small differences from the design are investigated through an onsite survey in which the hazards for the demolition operation is also identified. Then at the third step, the demolition strategy would be decided based on the result of survey concerning the legislation requirements and Health and Safety (H&S) of workers. As the next process, an audit is held before the implementation of demolition. Here, the optimal demolition method is decided through the audit which calculates the benefit to be generated and the extra burden (cost and term) from extraction of reuse/recycling materials. In detail, the quantities of the removal material by soft strip and other building components are comprehended and the above trade-off is calculated to suggest an optimal demolition method (Addis, 2006).

To complete the demolition as planned, soft-striping and demolition are implemented after the first and second step in Figure 6. The main point is the treatment of redundant services (for electricity, gas) for soft-striping. The suspend of redundant services is necessary to start the demolition, and this is to be fulfilled simultaneously with the removal of other materials. Thus, the marking up and isolation of them are done first, followed by an intrusive survey of the hazardous materials. Then, the first path is set to transport removed interiors such as carpets, curtain, furniture, rubbish, fixtures and fittings to outside. Successively, specialists can treat the hazardous materials such as asbestos. Finally, redundant services and non-structural elements are removed using the second path. It is important to separate the hazardous material from other materials here. After the soft strip, the demolition is implemented basically from a higher place to ground level with concerning the local environment and H&S onsite. The demolition along members allows the effective separation of component materials for each member. The structure properties (e.g. building type, location of service), nature and value of components studied at the previous process improve the separation efficiency. In addition, it is also beneficial to concern about the onsite material flows as there are many geographical and functional constraint on site, especially for partial demolition which needs to maintain the remaining part of building. Consequently, building components are collected as materials or wastes through the demolition, and transported to offsite facilities. While recovery/recycling facilities treat dry and recyclable materials to produce the secondary materials, an offsite sorting facility aims to separate the comingled waste into a single type of materials to recover them from the waste stream to the material stream. Thus, the access to the other offsite facilities is also important which decides the significance of transportation burden (Addis, 2006).

1.Planning for demolition

1.desk study (e.g. check of drawing, building history etc.)
2.completion of decommissioning report
3.onsite survey
4.identification of hazard
5.consideration of legislation requirement
6.concerning H&S arrangement
7.selection of demolition strategy

2. Pre-demolition audit

- introduction of optimal demolition method from construction method
- comprehension of removal materials by soft strip
- comprehension of building component quantities

3. Soft strip

1.survey of existing redundant services
2.survey of hazardous materials
3.setting first pass to remove fixtures and fittings
4.removal of hazardous material
5.isolation of existing redundant services
6.setting second pass to remove all redundant services

4. Demolition

1.roof tile
2.timber (beams)
3.internal plasterboard
4.exterior cladding
5.floors
6.major structural elements
7.footing and foundation

5. Offsite treatment

A. recovery/recycling facility
B. offsite sorting facility

Figure 6 Process flow of demolition project

(source: Addis, 2006)

Process flow of recovery in a construction project (construction clients and design teams)

The process flow of construction project has ten different phases as shown in Figure 7. Phase1 to 7 can be regarded as one group of activities for setting a project program and its fundamental survey. It is the most important aspect of the program setting to specify the degree of reusing/recycling materials/products application. Based on the final goal of the environmental benefit at the first phase, reusing/recycling degree is specified into three different levels of a project; 'project brief', 'design development' and 'materials/products specification'. This specification allows clients and design teams to evaluate the environmental benefits so that the adequate building design can be decided to maximise the benefit. They must possess a deep understanding of the construction codes relating to reuse/recycle, and need to specify the materials/products properties. There are two patterns for property certification. While some guidance (e.g. 'green guide' used in BREEAM) and standard suggest detail specification, the project team can verify by themselves through the performance tests. After the designation of materials/products used for construction, the total cost and program for construction can be decided. Compared to the construction project only using virgin materials, it is better to have some flexibilities in the processes depending on the vulnerability of reuse/recycle materials/products flow. Scarcity, timing and location of source can make the supply cost higher than the expectation and cause a long delay of project from the supply (Addis, 2006).

The procurement of materials/products in the next phase is significantly important. There are three basic sources, from a salvage yard or a demolish building and the use of RCBPs. In specific, when a demolished building is expected as the source, it is pivotal to get information before the project. There are mainly four paths for construction clients to get the demolition information. The architectural salvage firms have some information of a forthcoming demolition for their business. Project management firms also have the information of the future demolitions planned by their clients. As a similar method, major property owners have some demolition plans for their estate as well. In addition, it is possible to ask a local planning authority on the new building plans which tend to be associated with a demolition before. Regardless of these sources, the allocation of responsibility for the procurement must be clear to prevent the trouble for any losses caused in the process. Then, after submissions of the application plans of reuse/recycle materials/products to the local authorities, the actual construction is implemented to embody the above design. During construction, ISO14001 and ISO9001 should be concerned for environmental performance and an effective quality management, respectively (Addis, 2006).

1.Setting of project goal
- setting of goal to be satisfied by whole building

2. Organizing design and construction team
- selection of adequate members to achieve client's requirement (design, cost etc.)

3. Specification of reuse/recycling degree
- specification of the degree of reuse/recycling application at three phases; 'project brief', 'design development' and 'materials/products specification'

4. Design decision
- design decision based on the evaluation of benefit from the application of reuse/recycling materials/products

5. Materials/products specification
- specification of materials/products properties

6. Cost planning
- evaluation of necessary cost for construction project

7. Project program
- decision of project program (e.g. schedule, activity flow etc.)

8. Procurement of materials/products
- sequrement of suitable materials/products source

9. Submission of planning
- submission of reuse/recycling material application to local authorities

10. Project management
- implementation of above planning

Figure 7 Process flow of reuse/recycling at construction project

(source: Addis, 2006)

2.1.1.4. Summary

Demolition should be regarded as not just a simple project to treat a building effectively but a resource for the next construction project. According to this concept, it is more important to concern about the mutual understanding between clients of demolition and the next construction. Specifically, mineral waste components such as concrete, bricks and soil having a large bulk require a large transportation burden for both the landfilling and recycling at other sites. Therefore, the accommodation of those wastes for the next onsite construction as fill and landscaping or recycled aggregate is quite beneficial from the environmental aspects. It is most feasible to encourage construction clients and their designer teams to choose a sustainable design exploiting the demolition wastes especially the wastes generated onsite. There are two approaches to create such situation; from legislative process and from incentive awarded for the environmental benefits. The government and the local authority are setting the severer requirement of the environmental impact and they are also increasing the tax for landfill. In addition, the assessment tools for building environmental impact offer the incentive suggesting ways to enhance sustainability of the building. Though the system and criteria vary among assessment tools, they commonly focus on the utilization of old structures and its reuse/recycle waste at the material procurement phase. Besides this approach, some tools also concern about the sustainability at the demolition phase. Therefore, the assessment tools for building environmental impact will be studied in the next section. This aims to clarify the global attitude for buildings' sustainability and their gap between the attitude and the social requirement.

2.1.2. Demolition (implementation)

2.1.2.1. Demolition strategy

The decision-making process of demolition project for constructions has three phases to consider from multiple angles. In the first phase, the client request is interpreted as project conditions for 'term', 'cost', 'next construction' and 'other designation' (e.g. environmental friendly). Then, in the second phase, the survey of the building describes condition of 'building size and design', 'type of building and elements', 'difference from design' (e.g. deterioration and requirement) and 'existing hazard' (e.g. asbestos). The survey of surrounding also shows the boundary condition of 'site area and configuration' and 'position and type of adjacent building'. In the final phase, the planning condition of 'disposal' and 'new building' defines the project based on the 'relating legislation and control'.

Based on these demolition conditions, the factors can be found to decide the adequate demolition. Kasai (1988a) suggests eight factors as: I) structural type e.g. reinforced concrete, steel and masonry, II) construction scale, III) building location (e.g. urban, suburb and rural), IV) demolition range (e.g. whole or partial), V) construction use (e.g. for specific purposes or not), VI) required safety, VII) required concern for neighbour (e.g. noise, vibration and dust) and VIII) demolition term. Taking account of these factors, they firstly decide the demolition system. Then, the demolition methods applied to certain areas or elements such as column fillings or concrete removal are designated. As the main demolition systems currently applied, 'machine', 'implosion demolition' and 'top-down' systems are included. This is fundamentally classified from applied tools and the demolition policy whether they demolish the structure along columns and beams. On the other hand, the demolition method tends to be applied for a specific purpose, or multiple applications are often used such as combination of drilling and chemical expansive demolition agent. Both demolition systems and methods are introduced in the following sections.

Demolition system

<Machine demolition system>

Compared to the top down demolition, the machine system demolishes the structure regardless of floors. That makes the process faster and due to the demolition process from the outside, the operators can work from relatively safe situations. The method employs a hydraulic crusher which tends to be used in the way shown in Figure 8. It can break even framework and can be applied to help other methods. In addition to this method, a wrecking ball is sometimes used. It uses a steel ball controlled by a crane to break structures with its impact as shown in Figure 9. Vertical drop, swing in line with jib, and slewing jib are included as the main movement in this method. The control of the ball requires an experienced operator not to damage surroundings. The application of this method to the sites in urban areas is rather difficult, due to the same problem. This demolition generates mixed demolition wastes which need to be separated on and off site.

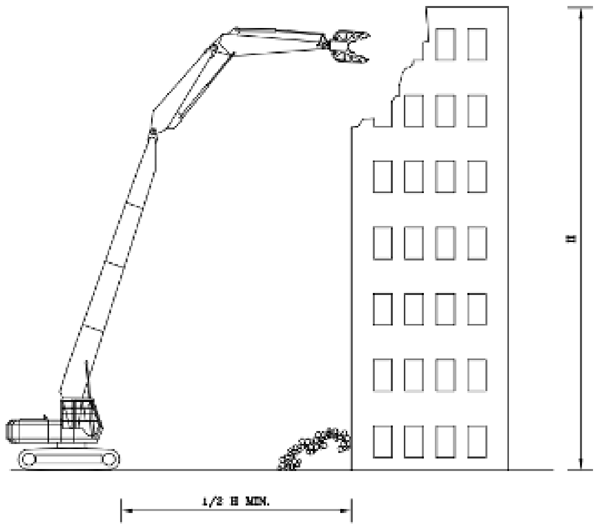


Figure 8 Machine method using hydraulic crusher

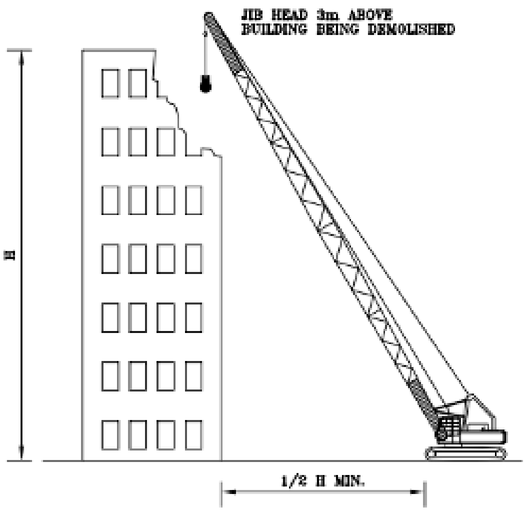


Figure 9 Machine method using wrecking ball

(source: Hong Kong Buildings Department, 2004)

<Implosion demolition system>

Implosion is used in some cases to save time or cost. It uses explosive to demolish structures either partly or completely. It also includes a pre-weakening process such as the cutting out of part of shear walls before implosion. However, this method also needs experienced engineers. Noise, vibration, dust and other nuisances caused by bursting must be carefully controlled not to exceed the site limitation. Although this type of demolition reduces structures to small, manageable size of pieces, it makes the generated demolition waste mixed up and then difficult to segregate for reuse and recycling.

<Top-down demolition system>

The top-down demolition system, as the name suggests, processes a structure being demolished from the top floors to the bottom. Only this system demolishes structures along framework after they breakdown the concrete parts if they have concrete structures. This is also separated into manual and machine demolition. The manual top-down demolition uses jack hammers to break down concrete to reveal the reinforcements and cut it by an oxy-acetylene torch. Then, winches and wires are used to pull down the frame works as shown in Figure 10. On the other hand, the machine demolition system deals with both parts with different attachments as shown in Figure 11. To demolish frameworks, hydraulic crushers and other methods can also be applied. Because of the two phase's demolition, the waste can be separated into concrete, reinforced concrete and other materials. The reinforced concrete can be segregated properly offsite so that a higher segregation can be achieved than other methods, although it takes a longer time and there is a higher risk for labourers working inside.

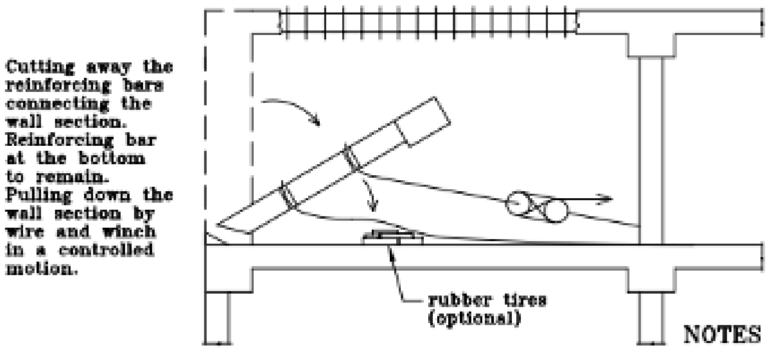


Figure 10 Top-down by manual method

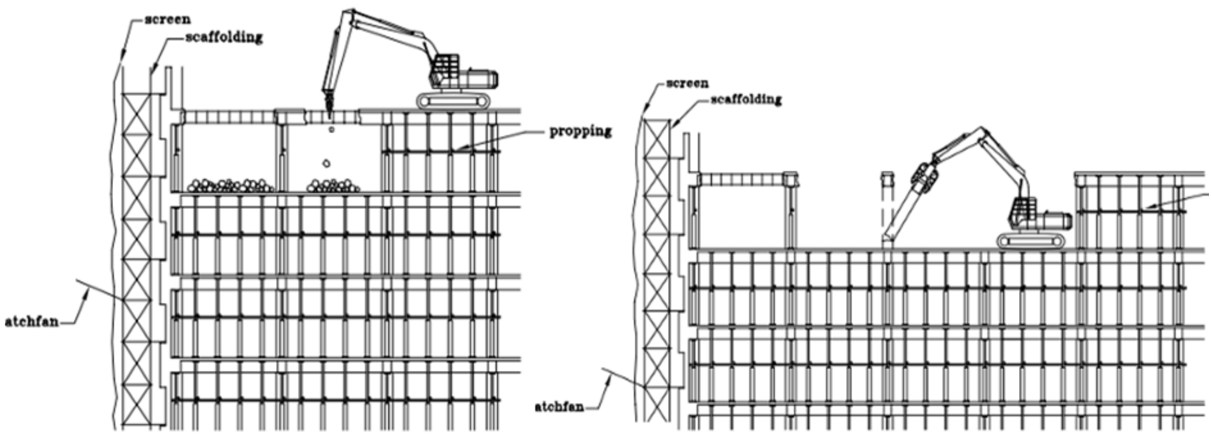


Figure 11 Top-down by machine method

(source: Hong Kong Buildings Department, 2004)

2.1.2.2. Demolition method

Before discussing demolition methods, the structure of demolition system explained in previous section is summarised as Figure 12 which is based on the method description of researches for each demolition methods. While the former two systems demolish the whole structure at once (the left column in Figure 12; whole demolition), the top-down demolition system tries to demolish along elements in which two patterns of demolition flow can be seen (the middle and right column in Figure 12). The difference between two partial demolition patterns are classified by the method types applied for extracting elements; cutting or crushing. For the first pattern, continuous partial demolition with some preparations allows whole demolition. In detail, the construction elements such as wall, beam columns and slabs are dismantled from the upper floor by 'cutting with abrasion and melting' and 'felling' with the support of propping. Otherwise, elements are clashed into concrete and reinforcement by 'hammering', 'bursting with non-explosive' and 'heating', and remaining reinforcement is eventually treated by 'shearing'. Here, 'drilling with abrasion' is also applied as the preparation of 'bursting with non-explosive'. On the other hand, the latter pattern of systems demolishes the whole part with a primitive process. In detail, 'hammering', 'bursting with non-explosive' with 'shearing' are preliminary applied to certain elements. 'Hitting', 'breaking by hydraulic power', 'bursting with explosive' and 'simple machine' (which tend to be used for masonry) are successively applied to demolish the framework effectively. After the large scale of demolition, often a secondary demolition by 'hammering' is required to transport the demolition waste off site. According to the purpose and the concept of the method, demolition methods contemporary applied onsite are summarised in

Table 3are surveyed and summarised in Appendix2 due to the volume of content (about 100pages). This aims not only to understand the feature of demolition methods or their applicability but also to clarify the feature of demolition waste generated during the operation. This is expected to suggest the optimal demolition in terms of sustainability.

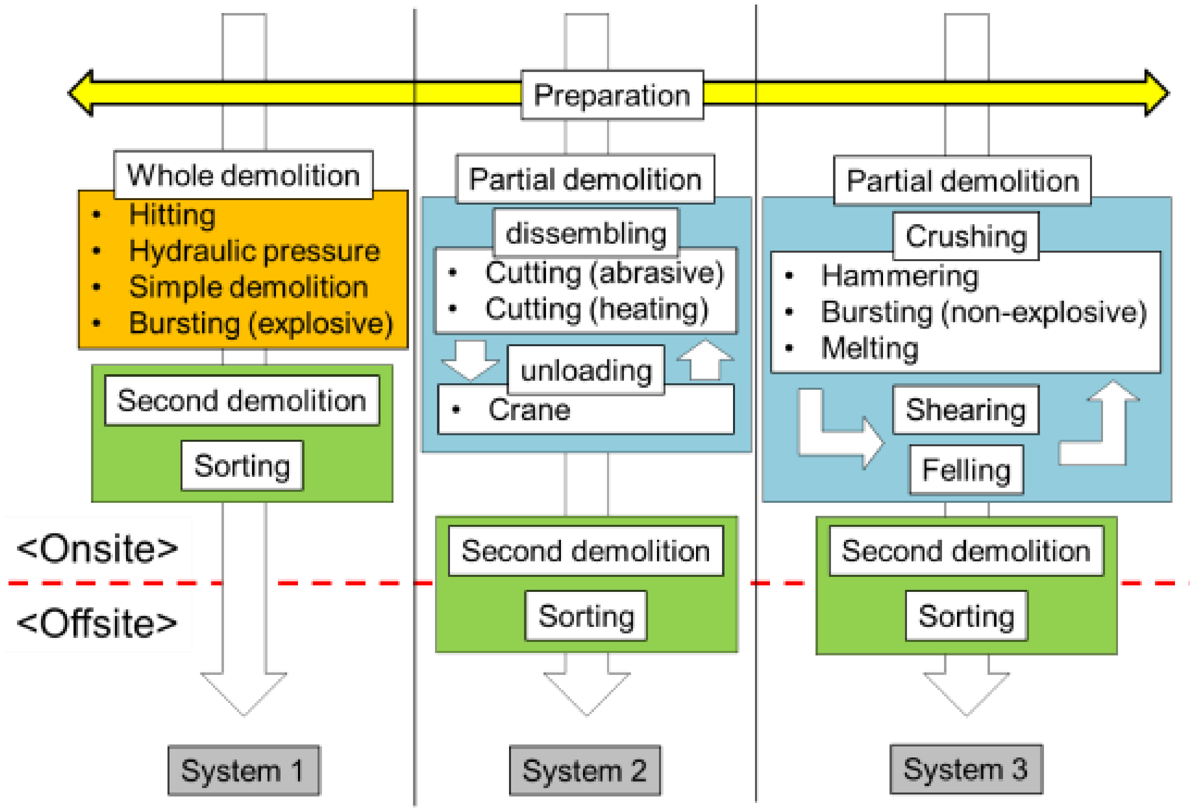


Figure 12 Main demolition systems and component methods

Table 3 List of conventional demolition method in practice

Preparation method	
Drilling	Hand hammer drill
	Large size hammer drill
	Diamond boring machine
Partial demolition method	
Crushing	
Hammering	Hand hammer
	Large size hammer
Bursting with non-explosive	Bursting with wedges (static)
	Chemical expensive agent (static)
	Water and gas power (dynamic)
	CARDOX (dynamic)
Heating	Electric current heating
	Induction current heating
	Microwave heating
Dismantling method	
Cutting with abrasion	Diamond disc cutter
	Diamond wire saw
	Water jet
Cutting with melting	Thermic lance
	Fuel oil flame
	Laser beam
	Plasma
Shearing	Hand shears
	Hydraulic large size shears
Felling	
Whole demolition method	
Hitting	
Breaking by hydraulic pressure	
Simple machine demolition	
Bursting with explosive	

According to the literature survey of demolition method (summarised in Appendix2), the influence on site and the recyclability are depicted below with the general application detail for each demolition method. This can be visualized as Table 4 referring the conventional reports (Kasai, 1988a and Enami et. al, 1988), and the applicable elements for each demolition method are also shown in Table 5.

<onsite influence of demolition method>

First of all, it is clear that the demolition methods using the hitting impact such as 'drilling with abrasion', 'hammering' and 'hitting' have a large impact in terms of noise, vibration and dust while having a high demolition efficiency. In specific, a handy method needs to concern about the impact to the labours as well. On the other hand, the use of the diamond blade such as the diamond boring, disc cutter and wire saw shows less impact on the vicinity of the demolition site. Though in the table the noise level is evaluated as quite high, many journal papers claim low noise on operation. This is also justified from the fact that these tools have been applied to the partial demolition which requires the low influence on the existing structure. The drawback is the waste water treatment due to the generation of the high cutting temperature and the consumption of diamond. It also makes this method relatively costly. On the other hands, the laser cutting has the similar cutting features without a water supply. Moreover, the high cutting temperature stabilises the cut material and its dust. This is very beneficial to treat the members containing asbestos with less diffusion.

The crushing methods except 'hammering' show less vicinity impact during the operation, regarding the reinforced concrete demolition. The non-explosive bursting has the demolition mechanism with internal tensile stress so that the members can be demolished using small energy without a large impact after some preparation process of drilling and cutting. The same advantage can be found in the heating method which uses the thermal degradation of concrete and the bonding between components to remove the covering concrete. Though the target area of demolition is just a few centimetre surface layer of reinforcement, it is especially useful to remove the surface of reinforcement or contaminated concrete.

<waste recyclability of demolition method>Waste recyclability of each method can be discussed from three demolition systems shown in Figure 12. At First, the whole demolition is the major demolition system. Since the purity of recovered wastes decides the recyclability, the elimination of impurity is important in the preparation phase and the sorting after the second demolition phase. However, as mentioned before, the sorting efficiency after the whole demolition naturally becomes lower than with other systems. Secondly, the continuous cutting system dissembles the structures into member pieces with a crane. The systemised demolition flow results in the high recycling efficiency with a fixed recycling process. It also gives demolisher the option of the onsite or offsite waste treatment location. The combination of crushing, shearing (cutting is applicable) and felling

can be categorised as the final type of demolition system. Crushing tends to be applied in the destruction project to support the dissembling process with shearing and felling. Since crushing aims to remove the covering concrete, concrete is a large share of the debris component. In addition, crushing without hitting removes the concrete in large pieces. Thus, it is relatively easy to extract only concrete from the whole demolition waste. The dissembled members can be treated in the similar manner of the second type of demolition system. As a result, the demolishers can achieve a high demolition efficiency thanks to a flexible choice for the second demolition system.

In summary, the evaluation of demolition methods needs to be examined from two aspects. Firstly, the individual demolition properties, have to be compared with other systems for the same demolition site. It includes the vicinity impact caused by the operation and the demolition efficiency. Secondly, the contribution of demolition strategies to the waste recovery is to be focused in the evaluation process. It includes the combination with other demolition methods for different phases and the demolition properties of the whole system. In other words, a certain demolition method prospected to be applied to the demolition system with less vicinity and environmental impact is more feasible than others. Otherwise, the approach to establish the system having fewer impacts are more desirable for the optimization of the demolition project in terms of the environmental aspect.

It can be also discussed from the view of actual compatibility and changeability of the multi methods with a single but multi-function machine. Although every single method is explained above as an individual step, some of them can be shifted relatively smoothly to the other methods due to the changeability of its machine equipment. For instance, the self-propelled machine introduced in the section of the shearing method is advertised its applicability for other purposes with different attachments (e.g. hammering, grappling, pulverizing etc.). This allows the demolisher to utilize the single machine for multiple purposes so that the demolition term and cost can be saved. In addition, Quarmby (2011) insists the importance that it can reduce the number of labours with respect to the demolition process. Thus, it can be concluded that it is quite pivotal to collect the information from the demolishers working at the actual operation site through interviews and questionnaires.

Table 4 Features of demolition method

Demolition methods	Type of breaking	I*	II**	III***	IV****		VI*****		VII	VIII			
		Construction type	Size of target	Urban applicability	Partial demolition	Whole demolition	safety to environment	safety to worker	Noize	Vibration	Heat/fire/water /dust/fume /projection		Speed
Hand hammer drill	Abrasion (boring)	Rc/C/M	-	H	○	×	4	5	5	2	5(dust)	-	2
Large size hammer drill	Abrasion (boring)	Rc/C/M	-	M	○	×	4	3	5	3	5(dust)	-	2
Diamond boring	Abrasion (boring)	Rc/C/M	L	H	○	∆	0	1	2	0	2(water)	-	5
Hand hammer	Hammering	Rc/C/M	S	H	○	-	3	5	4	1	3(dust)	-	5
Large size hammer	Hammering	Rc/C/M	S	H	○	○	4	3	5	4	4(dust)	-	3
Burster with wedge	bursting (non-explosive)	C/M	L	H	○	∆	2	1	2	0	2(dust)	-	4
Chemical expansive demolition agent	bursting (non-explosive)	C/M	L	H	○	∆	2	2	2	0	2(dust)	-	5
CARDOX	bursting (non-explosive)	Rc/C/M	L	L	∆	○	4	4	4	3	4(dust)	4(Pro-)	2
Electric heating of rebar	Heating	Rc	L	H	○	×	2	2	2	1	3(heat)	-	5
Microwave	Heating	Rc/C/M	S	-	○	×	4	4	3	0	1(heat)	-	4
Diamond disc cutter	Abrasion (Cutting)	Rc/C/M	L	H	○	∆	3	3	4	1	3(water)	-	5
Diamond wire saw	Abrasion (Cutting)	Rc/C/M	L	H	○	∆	3	3	4	2	3(water)	-	5
Abrasive water jet	Abrasion (Cutting)	Rc/C/M	L	M	○	∆	4	4	4	1	4(water)	3(Pro-)	2
Thermic lance	Melting (cutting)	Rc/C/M	L	H	○	-	2	3	1	0	4(fume)	4(fire)	5
Flue oil flame	Melting (cutting)	Rc/C/M	L	L	○	∆	4	4	5	0	3(fume)	5(fire)	4
Large size shears	Shearing	S	-	H	-	-	1	3	2	2	-	-	1
Felling	Felling	Rc/C/M	L	M	×	○	5	4	4	5	5(dust)	5(Pro-)	1
Steel ball	Hitting	Rc/C/M	M	L	×	○	5	5	4	5	5(dust)	4(Pro-)	1
Hydraulic breaker	Breaking by hydrauric pressure	Rc/C/M	S	H	○	○	1	3	2	2	3(dust)	3(Pro-)	3
Mild explosives	bursting (explosive)	Rc/C/M	M	L	∆	○	5	3	4	4	5(dust)	5(Pro-)	1
Explosives	bursting (explosive)	Rc/C/M	M	L	∆	○	5	3	5	5	5(dust)	5(Pro-)	1

*Rc, C, M and S imply reinfoced concrete, plain concrete, masonry and steel, repectively.
**S, M and L imply small, middle and large, repectively.
***L, M and H imply low, middle and high, repectively.
****×, ∆ and ○ imply not applicable, applicable, widely applicable, respectively.
*****As number increase, it means less favourable.

(source: Kasai, 1988a)

Table 5 Applicability of demolition method to elements*

Demolition methods	Applicability to members					
	Slab	Wall	Beam	Column	Foundation	Pile
Hand hammer drill	○	○	○	○	○	○
Large size hammer drill	○	○	○	○	○	○
Diamond boring	○	○	○	○	○	○
Hand hammer	○	○	○	○	△	△
Large size hammer	○	○	○	○	○	○
Burster with wedge	△	△	△	△	○	△
Chemical expansive demolition agent	△	△	△	△	○	△
CARDOX	△	△	○	○	○	△
Electric heating of rebar	○	○	○	○	△	-
Microwave	○	○	○	○	○	-
Diamond disc cutter	○	○	○	○	-	-
Diamond wire saw	△	△	○	○	○	-
Abrasive water jet	○	○	○	○	○	-
Thermic lance	○	○	○	○	-	-
Flue oil flame	○	○	○	○	△	-
Large size shears	-	-	-	-	-	-
Felling	×	○	○	○	×	-
Steel ball	○	○	○	○	×	-
Hydraulic breaker	○	○	○	○	△	-
Mild explosives	△	△	○	○	○	○
Explosives	△	△	○	○	○	○

*×,△, and ○ imply not applicable, applicable and widely applicable, respectively.

(source: Kasai, 1988a and Enami et. al, 1988)

2.1.3. Demolition waste management

2.1.3.1. Construction and Demolition (C&D) waste generation

The wastes produced during the construction and demolition processes are defined as construction waste and demolition waste respectively. The global total amount is calculated from the amount and share of municipal solid waste (MSW). The result is approximately 1.42billion metric tons which contains 0.50billion metric tons of carbon in total (Marxsen, 2001, cited in Peng et al., 1997). Marxsen describes the correlation between the MSW generation rate per person and GDP per capita for OECD countries as shown in Figure 13. Since C&D waste corresponds to about 70% of MSW, it is expected to have a correlation with economic growth. However, Dyer (2012) insists the low correlation between economic growth and C&D waste generation, and explains that it only implies a large economic activity allows a larger opportunity to produce waste. He compares the economic value share of the construction industry and its share of waste production, as seen in Figure 14, and points out the unsustainable situation of the construction industry in many countries. Sweden is regarded as an exception and it is explained by the strict regulation and social awareness of sustainability (Dyer, 2012). Tam (2009) also introduces Japan as a country having a low share of C&D waste. He attributes the obstruction of implementation of recycling to the lack of a national scale waste treatment approach, information regarding waste and penalties for landfill disposal. In other words, well-designed regulation and thorough data of C&D waste allow government to cope with the large increase of waste production resulted from the economic development.

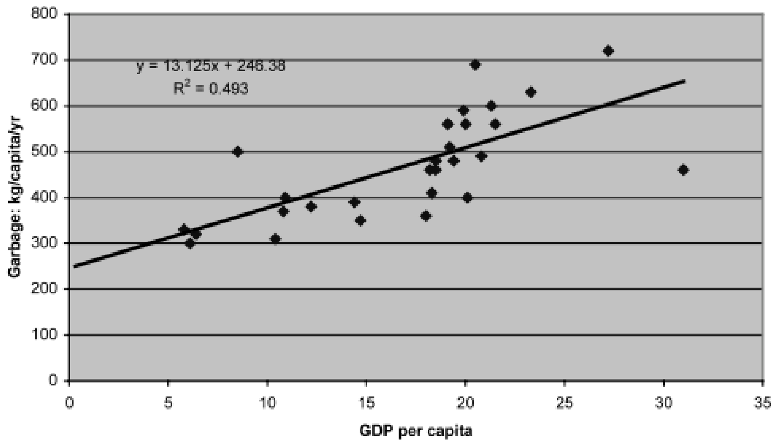


Figure 13 Garbage per capita versus GDP per capita

(source: Marxsen, 2001, cited in Peng et al., 1997)

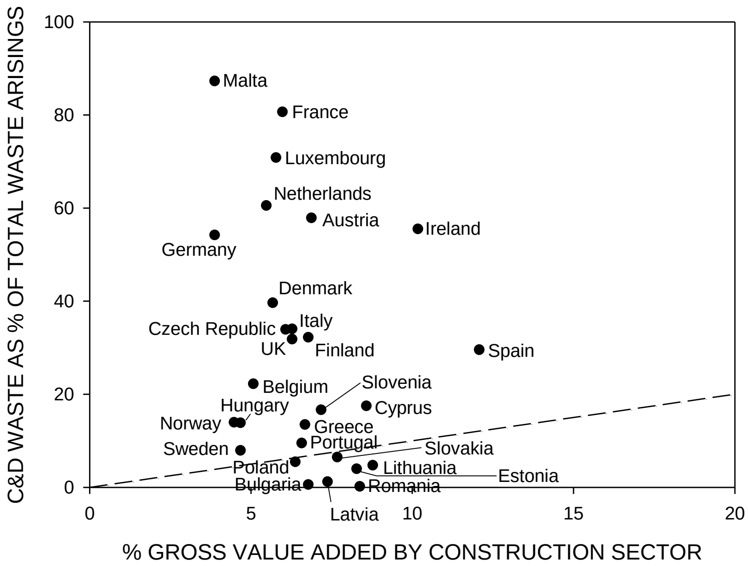


Figure 14 C&D waste share of total waste vs gross share of construction sector

(source: Eurostat statistics database, 2010, cited in Dyer, 2012)

Construction wastes are produced as a sub-product in two construction processes; accidental and predictable processes. The accidental process is caused by the poor management of materials or elements. On the other hand, the predictable waste is the waste that is generated through necessary processes for construction, such as offcuts. Poon (2007) explains that waste from trimming processes on site becomes about 1/10 of the whole construction waste, and this can be reduced by the standardised design, early stage design fixing and the use of fabricated elements. However, according to the questionnaires of Osmani et al. (2008), architects attribute the generation of construction waste to poor work or misunderstandings of the contractors on site. The tight regulation of the design process and education are required to enlighten them. In addition, since a framework also has a huge share, a slim design for temporary work and the use of metal framework are regarded as more sustainable compared to timber ones (Poon, 2007).

On the other hand, the amount of demolition waste is significantly larger compared to the construction waste. This is simply because the structures finishing their service life are all demolished and they are distinguished as demolition waste. Therefore, this component is naturally more complex than construction waste cut from simple elements and utilization becomes more difficult as a result. However, the highly valuable material such as copper has enough benefit to justify extraction from the complex waste (Dyer, 2012).

2.1.3.2. Waste compoent

The components are divided into two main groups by whether it is inert or 'non-inert'. While inert components include soil, earth, slurry, rock and concrete, 'non-inert' components are composed of metal, wood, plastics and wrapping waste. The components of waste from the recycling process are shown in Figure 15. This shows the entire flow of the process which is divided into three major operations; concrete and asphalt fragmentation, disassemble of mixed C&D and wood processing (Peng et al., 1997). The demolition waste is classified into three components; metal, organic and mineral. The metal waste is constituted mostly by ferrous metals, copper, lead, aluminium and zinc constitute. The organic waste includes plastic, paper and timber. Mineral waste is mostly crushed rock regarded as aggregate regardless of its size with the exception of glass and gypsum.

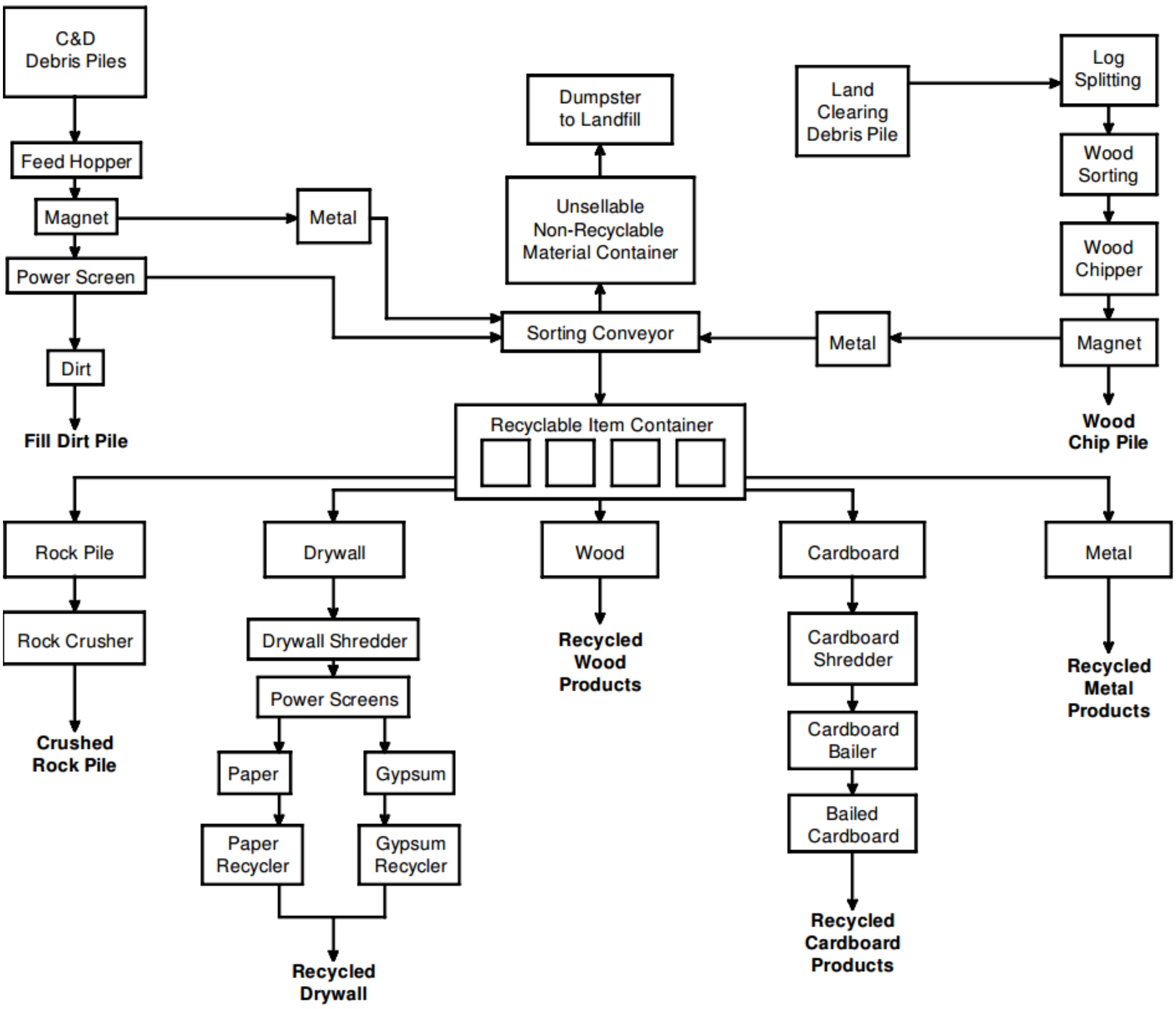


Figure 15 C&D waste process flow diagram

(source: Peng et al., 1997)

As explained in the previous chapter, for the sustainable utilization of the C&D waste, understanding of conventional treatments and new technologies are crucial to suggest the optimal method. Thus, *"The reclaimed and recycled construction materials handbook"* (Coventry et al., 1999) is mainly referred to acknowledge the traditional method followed by new researches to discuss the optimization of waste utilization. The whole waste component types are summarised as Table 6. It explains the main stream of waste management and possible contaminants which degrade waste quality. Due to the volume of content, the reviews of each component are summarised in Appendix3.

Table 6 Recovery methods for waste components

Applicable recovery type	Reuse	Recycle	Downgrade recycle	Others	Contaminant/ Degrade factor
Metal waste					
Steel	✓	✓			Less contaminated
Non-ferrous metals		✓(Zinc)			Less contaminated
Organic waste					
Plastic	✓(pipe)	✓		✓(energy)	Different type of plastics
Paper		✓			Bacteria
Timber	✓	✓	✓(chip, fibre)	✓(energy)	Asbestos, pigment
Mineral waste					
Road pavement	✓(asphalt)	✓			Old bitumen
Soil and excavation soil		✓(RA)	✓(filling)		
Brick	✓	✓	✓(cement)		
Concrete		✓(RA)	✓(roadbed)		Cement paste
Glass	✓		✓ (fibre, RA, glass cullet)		
Gypsum		✓	✓ (soil stabilizer)		

The application highlighted with yellow is not the main stream.

To summarise the appendix content, the waste component of C&D waste can be separated into two types (impurity and rubble type) according to the result of sorting. If C&D waste is not sorted, it can be regarded as rubble type waste with impurity. Thus, most of the non-rubble type regarded as rubble's impurity have different recovery methods from rubbles for both before and after demolition. According to the established recovery path, non-rubble type is mainly separated into three categories as Figure 16. Firstly, reuse is the major feasible choice for some component materials such as brick, glass and non-ferrous metal used for the product members. It requires a careful sorting before the total demolition but it can be sold at a high price depending on the construction demand. However, there is no efficient method to recover the waste from rubbles after the demolition. Although many methods have been suggested to utilise this type of waste for concrete aggregate, recycled concrete shows lower performance, or the treatment cost input for the refinement cannot compete with a virgin aggregate. As the second type, the recycling is established to recover the waste during the reuse process. This is mainly because the purity of that component significantly affects the quality of recycled product such as paper and plasterboard. In addition, plastic recycling also needs to clarify the origin of material or its history so that the share of recycled material increases against the virgin material to achieve required properties. Compared to the above two categories, there are some components such as steel and timber, which have several effective recovery methods. As steel has many advantages for recycling (high value, easiness of sorting and recovery of property), it is still beneficial to recycle the waste after the demolition. Timber also shows the good recyclability from the several forms of material such as wood chip and wood fibre. Therefore, the waste can be utilized even from the recovery after demolition.

On the other hand, the rubbles degraded by above impurity type materials are regarded as category 4 here in Figure 16, which contains road pavements, soil and excavation spoils and concretes. As they have a large quantity in common, the application within the same site as the waste generation site has been mainly studied to reduce the transportation burden. In specific for a road pavement, due to the characteristic of asphalt, it is possible to achieve a close-loop system. In contrast to the other rubble components, the application of waste concrete onsite becomes a down-cycling for concrete, and it would be sent to a landfill in the next demolition phase. Thus, it has several recycling methods to use for concrete aggregate. However, some degree of impurity hinders those choices due to the requirement of applicable recycle aggregate set by British Standard Institution (BSI) (2006) as shown in Table 7.

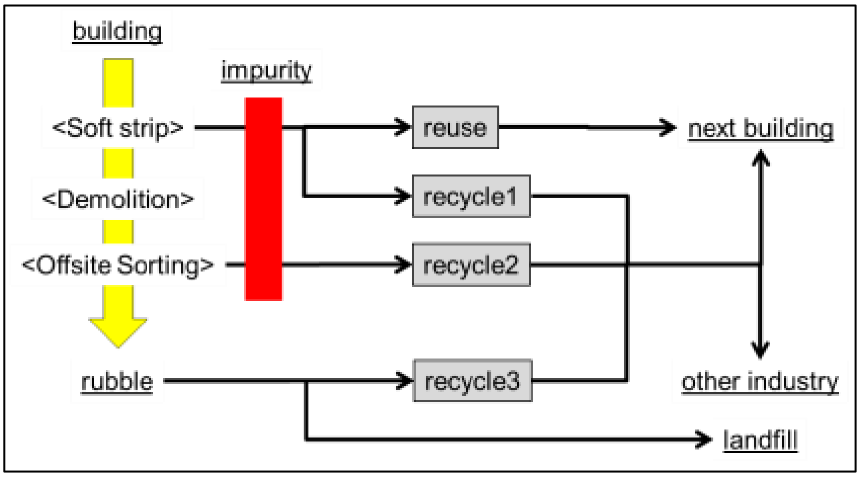
In conclusion, there are mainly four types of demolition waste components according to the main treatment path as shown in Figure 16. It is commonly desirable for impurity types to be sorted before the demolition. As a result, it can maintain a high quality of reuse/recycling product, and concrete can be recycled to a higher grade of next concrete. However, it usually happens that a sufficient sorting cannot be applied due to the limitation of demolition project or the client desire. Thus, it is necessary to evaluate prospective benefits for each recovery in different paths. The comparison of benefits decides an optimal recovery method and moreover, it can suggest an optimal degree of sorting with demolition and sorting data.

Table 7 Requirements for coarse RCA and coarse RA

Type of aggregate	Requirement A)					
	Maximum masonry content	Maximum fines	Maximum lightweight material B)	Maximum asphalt	Maximum other foreign material e.g. glass, plastics, metals	Maximum acid-soluble sulfate (SO_3)
RCA A), C)	5	5	0.5	5.0	1.0	1.0
RA	100	3	1.0	10.0	1.0	— D)

A) Where the material to be used is obtained by crushing hardened concrete of known composition that has not been in use, e.g. surplus precast units or returned fresh concrete, and not contaminated during storage and processing, the only requirements are those for grading and maximum fines.
B) Material with a density less than 1 000 kg/m^3.
C) The provisions for coarse RCA may be applied to mixtures of natural coarse aggregates blended with the listed constituents.
D) The appropriate limit and test method needs to be determined on a case-by-case basis (see Note 6 to **4.3**).

(Source: British Standard Institution (BSI) (2006))



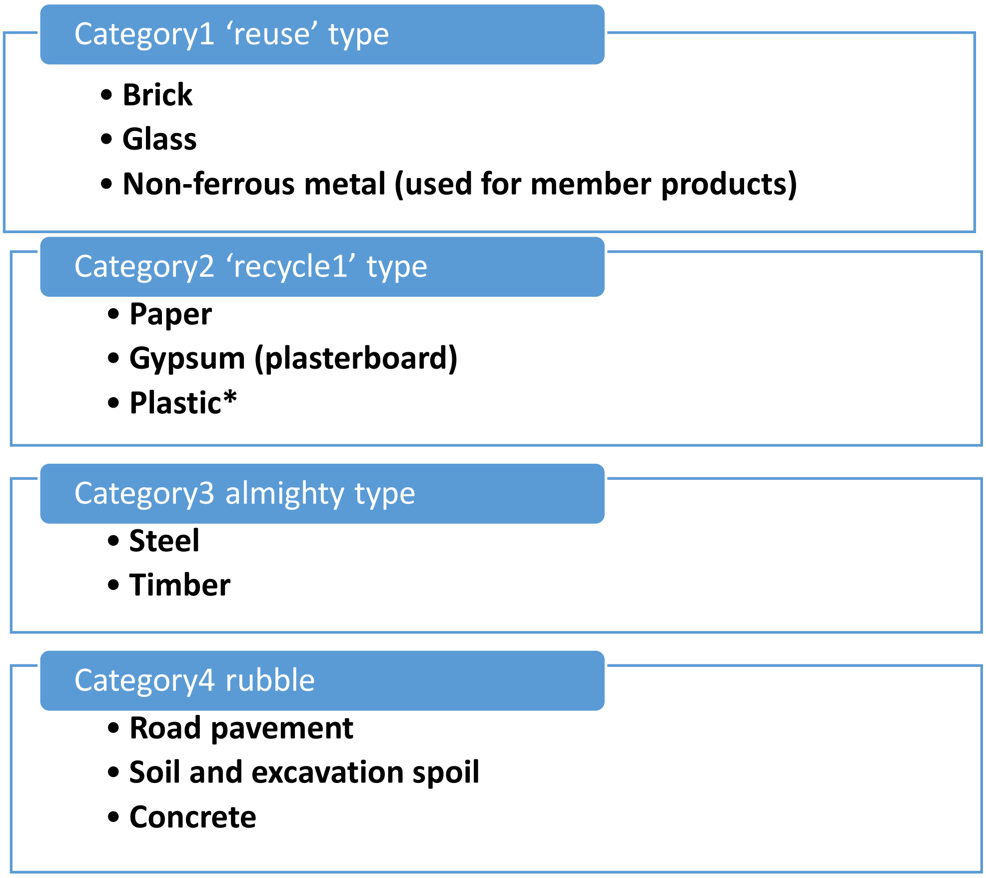


Figure 16 Recovery path and category of waste component

2.2. Review of conventional approach to demolition

2.2.1. Approach to the project planning

The research approaches related to the demolition project planning can be categorised into two major types after the systemization of the decision making procedure; i) identification of the priority of decision making and ii) system suggestion to cope with the social demand. Since the researches classified into the former approach is corresponding to the researches referred in Chapter 2.1.1.2., the approach for the system suggestion is reviewed in this section. Compared to the publication of academic journals or papers, this type of structural approach can be found in PhD thesis in which researchers can spend at least three years for one research topic. Accordingly, the related theses were searched using the Ethos, an e-theses online service which records most of the doctoral theses from 136 universities or corresponding institutions in the UK (British Library, 2016). This approach is justified by the aim of this research which focuses on the UK society. As a result, five theses were sorted as related by searching the database with the keyword, 'demolition industry'. The research contents of those theses are summarised in Table 8 to clarify the approach to the demolition project planning. It should be noted that these researches will be also referred in Chapter3 when author choose the research methods and the new project planning framework in demolition.

As the common sense of all the authors, the current demolition practice has largely relied on the practitioners' knowledge and experiences. The motivation of above researches comes from the threat of losing the knowledge before inherited to next practitioners, or the desire of additional factors for previous planning framework (by knowledge-based). For example, Fox (1994) points out the fact that most of the demolition knowledge are only stored into the practitioners individually and rarely shared or stored into database as knowledge for theoretical work. Accordingly, knowledge is acquired from experienced practitioners, in his research, and converted in knowledge-information to reason the strategy as the logic structure of processes. This approach is applied to both working and safety planning in his suggested model. Thanks to this developed user interface, the users can estimate the required work or treatment in planning process just by answering to the questions in the model. Similar to his idea, Abdullah (2003, P2) says, "The largest and most useful part of this knowledge resides in the minds of expert demolition engineers and is difficult to access and is lost when the engineer retires or dies." In his research, the demolition techniques are evaluated with their cost based on the conventional practice data. If users choose preferable conditions and factors in the project planning, the most appropriate technique will be suggested. Therefore, users are not required any demolition knowledge or experience for project planning but the stored conventional knowledge is internally applied to provide suggestions.

Fletcher (2001) suggests to add the life cycle impact, which have hardly been considered in practice, to the decision factors for demolition project planning. For the precast concrete building, less impact is expected from the reconstruction with disassembly if repeated two to four times, though the initial impact is larger than conventional composite building. Quarmby (2011) attempts to connect the onsite safety and the manual process in soft-stripping. The risk of labour input to demolition structures is suggested to investigate before concluding the planning for sustainable advantage. Those factors to be considers are mapped by Qu (2010) from the process reasoning based on the practitioners' knowledge as shown in Figure 17. He classifies the stored conventional knowledge data as standard logical data into eight main requirements of process. By considering the inter-relationships among them, the whole required information is connected to the central system in which demolition planning is eventually decided. By decomposing the standard process into tasks and tasks into a set of ontologies (containing the demolition processes, capabilities, applications, technics artefacts, and documents), the whole data to be applied to project planning is explained by logical mapping of demolition process. As shown in this structure, demolition project planning contains several requirements to be complied and relevant data needs to be collected to compare different planning. This is the reason for the diversity in research targets as seen in the second to fourth row in Table 8. Due to the limited resources (e.g. time, budget), researchers trim few key requirements to validate the importance at deep level in case studies or validation with practitioners. Considering the logic structures indicated by Qu (2010), the project planning would be more convincing if more factors and their inter-relationships are taken into account. Accordingly, **the research approach which allows users to obtain data for multiple factors are necessary to advance the project planning more persuasive.**

For the achievements given by five references seen in the fifth row of Table 8, the **knowledge acquisition and its compilation** to suggested models are identified in common. Even the qualitative factors such as the users' priority for project planning are converted to the quantitative factors. This is connected to the other achievements, **the establishment of logic process flow** which enables to recreate the whole demolition planning as the continuous group of individual processes. The compiled data at first achievement can be applied to estimate the result impact for each planning. Based on the estimated impact, the most appropriate planning can be suggested to support the user decision. The reasoning of process must be achieved based on the logical interpretation of the acquired-knowledge and structures. As Abdullah (2003) applies the rapid prototyping methodology to update the suggested system, **iteration of testing** is the efficient method to analyse the rationality of suggested system as well as the **validation by practitioners**.

As the limitations of previous approaches, the **application of conventional data** can be pointed out in common. Although it is the simplest approach to estimate the impact with structured process flow, there are two disadvantages; i) incapability to reflect individual project characteristics and ii) necessity of updating for data or process structures. Firstly, the model with the database averaged over many previous cases cannot be described with average value. For example, the treatment cost of steel column should be different for the applicable machines or the local labour cost. Similar to this, the stored data or process structures need to be update if the conventional values are applied.

The cost of steel bar should not be the same as 1980's and the new demolition method such as laser beam cutting cannot be covered without updating. Therefore, **an impact analysis method, which depends more on the input data which is project specific rather than conventional database, is required to analyse the individual process of accuracy.** However, the intensive load of data input for users is listed as the other limitation. For the research of Fox (1994) and Abdullah (2003), both developed tools request users to input the quantity of each element type and scale for the whole composite elements. Even for the system suggestion, creation of new estimation framework with programming or spreadsheet is infeasible for the practical application. **Current manual input should be replaced by computational approach to minimise the users' burden**. Although this requires the fundamental system improvement in data input process, this direction is the same as the above researches to use IT or ICT for the system establishment.

Thirdly, the impact evaluation limited only refers to the final impact value. Similar as the above project characteristic, the model system cannot consider the impact generation at the middle of progress. In fact, Qu (2010) shows the availability of process level discussion with Gantt chart in his approach as the user-defined process planning. The actual application of time schedule for the impact analysis should be the great source for the planners to comprehend the total productivity at target phases. Based on this, t**he impact analysis should be extended to address along time axis to evaluate the project impact in progress and it allows the decomposition of project productivity at target phases.**

To sum up, the project planning requires the shift from the current practitioners' knowledge-based approach to prevent the loss of knowledge stored by individual practitioners and to allow the logical planning. This can be solved by the compilation of practitioners' knowledge and the establishment of the logical structure of demolition processes. The main issues in current approaches can be summarised into three major aspects; i) difficulty of project analysis with multiple factors, ii) necessity to apply conventional average data, and iii) limited evaluation of project impact for the final impact value. Firstly, despite of the complexity of planning requirements and the limitation of research resource, the **research approach to obtain data for multiple factors** are suggested for comprehensive analysis and make the project planning more persuasive. In addition, **the impact evaluation with project specific data (which should be given by users input) is recommended to adopt the project characteristic.** Due to the intensive work load for the required data input, the computational input is also recommended. At the end, **the impact evaluation along the time frame is suggested to be added** to allow the project impact analysis in progress. This is expected to enable planners to analyse the project productivity at target phases so that the problematic processes can be easily identified.

In order to achieve above requirements, a 4D-CAD modelling approach which is utilised in construction industry, will be reviewed in Chapter2.3.1.

Table 8 Conventional researches focusing on the project planning in demolition

	Fox, 1994	Fletcher, 2001	Abdullah, 2003	Qu, 2010	Quarmby, 2011
Research title	Knowledge-based systems for the demolition industry	Developing disassembly strategies for buildings to reduce the lifetime environmental impacts with systems approach	Intelligent selection of demolition techniques	Demolish-IT: the development of a process management tool for the demolition industry	Safe, healthy and sustainable demolition
Research aim	Validation of the advantage of **IT approach** to demolition industry by establishing the rule-based work estimation system based on practitioners' knowledge	Validation of the reduction potential of lifetime environmental impact with **appropriate disassembly strategies**	Development of a decision support system for demolition engineers to select the most **appropriate demolition technic** for target structure	Development of a **demolition process management system using ICT*** to encourage the integration of stakeholders	Identification of the significance and key factors for the **sustainability development in demolition** sector
Research target	cost, element volume, demolition system	life cycle impact (e.g. cost, embodied CO_2)	user preference in planning factors, cost	all requirement information of demolition process (e.g. H&S, cost, hazard removal)	sustainability with soft-stripping, onsite safety
Research methods for planning	Selection of applied demolition methods from modelled practitioners' knowledge, and estimation of required work for that	Comparison of lifecycle impact between conventional demolition, reuse and recycling (from construction planning)	Comparison of cost efficiency of demolition systems for quantified users' preference	Mapping of demolition process with IT tool in which practitioners' knowledge is investigated its rationality	Consideration of the project planning according to the process risks analysed from the accident data
Achievements	•Compilation and application of practitioners' knowledge in model •Quantification of demolition impact (cost, time, labours, waste volume)	•Comparison of demolition system from the total sustainability impact from the first construction to next construction (this approach is close to the LCA)	•Quantification of users' preference for target project •Cost comparison with different demolition systems with single input	•Comprehensive structuring of demolition process and required information •Creation of required process structure which can be decomposed into ontology information	•Comprehensive summary of current demolition industry practice and stakeholders' attitude in terms of sustainability and safety
Limitations	•Application of conventional unit impact data •Intensive human input •Necessity of updating the reasoning rules and their hierarchy	•Application of conventional unit impact data •Estimation in total	•Application of conventional unit impact data to each system (applied machines or methods cannot be identified the difference) •Intensive human input	•Necessity of process definition by users •Intensive human input (too intense to validate in case studies)	•No actual model or tool are developed to reflect the found relation between sustainability and safety impact with manual handling activities for soft strip

***Intelligent Communication Technology**

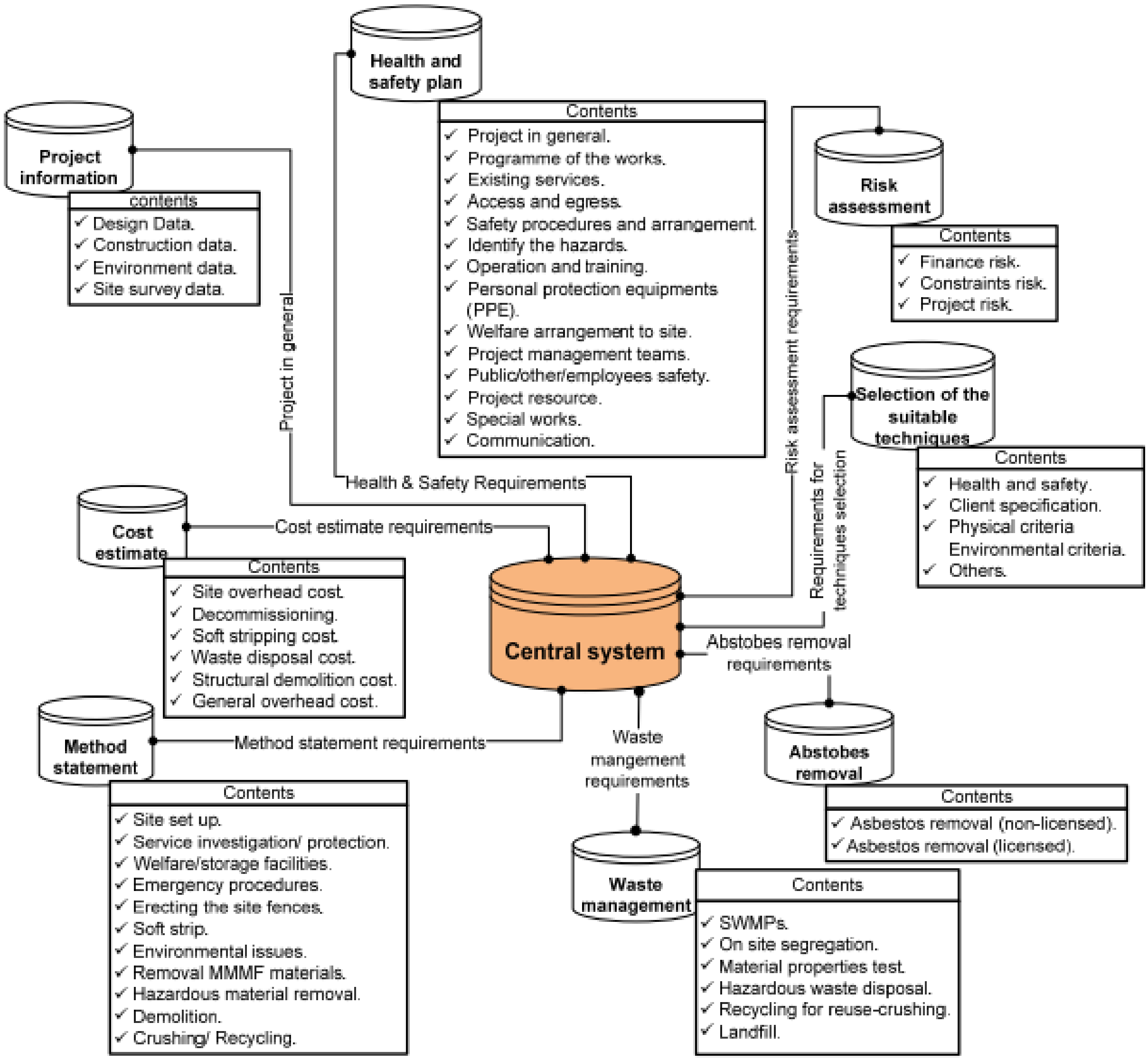


Figure 17 Requirement framework of demolition process in Qu (2010)'s research

2.2.2. Approach to the demolition implementation

Cheng and Ma (2013) categorise the conventional researches which suggest models to estimate the construction waste generation into six types of models according to the type of data source; (i) construction area, (ii) building component, (iii) regional material stock data, (iv) construction quantity data, (v) onsite physical layout and (vi) user input for accounting tool.

i. Constructed area base

According to the proportion of the floor area and the generated waste of conventional construction database, it calculates the coefficient value to estimate the waste generation (e.g. 0.5 ton/m^2 for concrete waste generation). While the study of Poon et al. (2001) can only assess the total volume of construction waste, Jalali (2007)'s model can calculate the volume of each material type separately. This requires the continuous update of a database to make the outcome accurate.

ii. Building component base

Similar to the previous model type, Jalali (2007) uses the conventional construction database to assume the waste amount from a unit building component such as 1m^2 of floor. It requires detail spread sheet which is labour-intensive to implement.

iii. Regional material stock data base

Cochran and Townsend (2010) studied the dynamics of collection and flow of construction materials in the US from the average material consumption data, the average service life, demolition waste proportion and new construction materials used in the US. This model type largely depends on the quality of industrial surveys.

iv. Construction quantity data base

Solis-Guzman et al. (2009) use the data of 100 dwelling case studies for construction and demolition to comprehend the volume change of building with Apparent Construction Volume (VAC), Apparent Demolished Volume (VAD), Apparent Wreckage Waste Volume (VAR), and Apparent Package Waste Volume (VAE). The proportion allows them to calculate the prospective waste generation at the construction and demolition phases. Llatas (2011) did a similar study by measuring material quantities and using existing budget documentations for 20 dwellings. It gave the data of packaging waste volume and demolition rate for each project. However, those targets are low rise buildings and it may not be reliable if this is applied to the high-rise buildings.

v. Onsite physical layout base

Lau et al. (2008) tries to calculate the generation volume of construction waste according to the physical layout of debris piles. This approach is simple and straight forward, but the outcome is too rough to suggest a detailed waste plan.

vi. Accounting tool base

By using the database of accounting tools such as SMARTWaste, the waste generation of each categorized type is suggested through the data collection at the construction phase. The good record onsite allows the accurate evaluation of applicable waste for the next construction projects. Even though BEDEC (2010, cited in Cheng and Ma, 2013) made the similar database, it is not applicable to other sites due to its less quantitative methodologies.

Although there are some differences in how to exploit conventional data, above models aim to estimate the amount (volume or mass) of waste generation from the building volumes and the average proportion of components. To make it accurate, sample data for detail correspondence such as ‘Building component base model’ is necessary. From this point of view, BRE database including input data of SMARTWaste Plan seems to be the most suitable to utilize.

Similar method is also applied in the prediction of demolition waste generation. Banias et al. (2011) suggest a web-based decision support system called DeconRCM. Based on the conventional demolition data in Greece, it allows calculating waste generation of 21 components according to the four building types. As its advantages against previous models, this model can evaluate the total waste management cost from the site location. It includes the cost for the demolition process and the CDW separation, container rent and income from the recyclable waste. The suggestion from this model has already been adjusted to accord to legislation requirements such as the minimum recycling rate. Since it is possible to choose the recycling rate onsite with ‘Environmental Sensitivity Bar’, budget with different assumption rate of recycling can be compared.

Compared to this model, Cheng and Ma (2013) suggest the application of Building Information Modelling (BIM) to predict a demolition waste generation. While the aforementioned models need to use the average generation rate assuming the demolition will be achieved as the previous manner, BIM-based system allows the element level demolition design. As a result, the demolition team can design its demolition plan from the disposal changing fee with the types of waste component and the necessary number of pick-up trucks. In addition, authors imply the future possibilities of model to include the recycling effect and extend its application to a construction project with solid data. According to the future of BIM in construction field such as the application of laser scanning technology of building, it seems prospective to include old building demolitions. The data of each component is expected to identify the recycle waste properties so that the application to a new construction under legislation would be smooth. This data establishment can help the comprehension of a material flow in the whole country or even worldwide. The possibility of BIM model should not be objected by the lack of data as the authors of this paper insist.

Klang et al.(2003) insist the importance of evaluating the demolition project from social, environmental and economic aspects simultaneously. This is based on the concept of sustainable production advocated at United Nations Conference in 1992, whose framework was developed at the Lowell Center for Sustainable Production (LCSP), University of Massachusetts Lowell (Veleva and Ellenbecker, 2001). LCSP suggests the indicators to evaluate the production sustainability from social, environmental and economic aspects at five continuous steps. As the system step goes up, the indicators become more sophisticated for a sustainable production. Veleva and Ellenbecker (2001) point out different characteristics of indicators; some are common for all production facilities and others are applicable to certain facilities, regardless of their importance. They set 22 ‘core indicators’ for a sustainable production with empirical survey in six factors, and define other specific indicators as ‘supplemental indicators’. Based on this, Klang et al. (2003) suggest own indicators for a demolition waste recovery which describes the impact from above three aspects, and applied them to the main waste recoveries for brick, steel and sanitary porcelain. Besides qualitative aspects for the workers’ satisfaction is involved in indicators, an eco-efficiency indicator is set here to describe the energy saving per labours input. Though these assessments deepen the understanding of certain relations between two different aspects, it seems difficult to analyse the project thoroughly. As the possible method to easily compare different projects with multiple indicators, weighting for each factor is a typical way to get numerical results as is performed in evaluation tools such as BREEAM and Eco-point evaluation, which are standardized by the panels of selected experts.

To summarise, two different types of research approaches to the demolition implementation are found through the literature review. While the one type aims to evaluate the waste generation with accuracy, the other type focuses on the comprehensive impact evaluation (in which sustainability is the main motivation) with multiple criteria for both quantitative and qualitative ones. The former approach is simpler to give the information of waste generation volume which is valuable for practitioners to calculate the treatment cost and burden and for policy makers or researchers to analyse the waste management in society level. The issue is all researchers regard wastes as homogeneous in terms of the waste component through the process. Although most of the researches refer the previous practice or survey data, no one concerns about the definition of waste component properties. For instance, even in the Solis-Guzman et al. (2009)'s study, 100 actual buildings were measured with the volume of demolition waste to decide the conversion value for future estimation. However, they only concern about the volume of waste to be recovered. Therefore, the element type of waste origin is the only identifiable information as the waste property. This must be derived from the current practice of waste treatment which mainly relies on sorting and landfilling. Considering the paradigm shift to the sustainable approach (reuse or recycle), the purity and the origin of waste are quite important source for next application. **The method which allows stakeholders to identify the waste information for both purity and origin needs to be suggested to enhance the sustainable recovery.** It should be also mentioned that the differential of impacts from different demolition methods is not considered in those suggestions. This also justifies the application of 4D-CAD which users can dynamically evaluate the demolition impact based on the project planning.

For the latter approach from the sustainability aspect, the demolition impact is not only considered from environmental but economic and social aspect. This is quite useful for policy makers to compare the feasibility of planning policy for the whole society. However, two issues are identified from this approach. Firstly, certain quality and volume of waste information is required to maintain the enough accuracy for discussion. Sicne the data type and quality to be collected for one activity or process is increasing, the burden of data collection would be drastically increased. Moreover, the applied data does not have versatility even though the concept has. As Klang et al. (2003) point out, although the identification of key indicators of each impact can speed up or minimise the data collection process, those indicators may not be important in other cases due to the uniqueness of demolition projects (e.g. site location, limitation of resources). Accordingly, **multiple types of (environmental, economic and social) information for demolition impact need to be extracted with regarding the project uniqueness to discuss the suitability of project planning.**

In order to achieve the above two highlighted gaps, the application of **Building Information Modelling (BIM)** approach to the evaluation model is considered as the new approach. The multiple information attached to object models in BIM must be beneficial for identifying the waste origin. In addition, waste purity can be calculated if the origin of each waste component is identified from the object material data in BIM. This is also applicable to other factors to evaluate for considering the project feasibility. Since the project can be analysed by own building design model, the uniqueness of project is completely recreated at the same time. The conventional approach with BIM in construction industry will be reviewed in Chapter2.3.2 later.

2.2.3. Approach to the waste management

In this study, it is the final aim to suggest a simulation model which allows people to estimate the impacts from C&D waste management. Then, the optimal management strategy can be decided with their weighting according to the conditions and policy of decision makers. A simulation model can be developed from three approaches; i) modification of the conventional models (sometimes integrating several models), ii) creation of a new type of model based on the drawbacks of previous studies and iii) transplantation of the conventional models from different fields.

Firstly, the conventional approaches are studied for the optimal C&D waste treatment such as the suggestion of tools and models. The gap to be covered and the adoptable part of approaches are expected to be discovered. Therefore, the model should be designed from the beginning or developed based on the previous models to fill the gap. Otherwise, transplanting the successful model from other fields such as social science and economic fields should be considered. Accordingly, the conventional approaches to suggest the optimal management strategy for C&D waste are discussed in this chapter. As the main approaches, suggestions of user tools to evaluate the implementation of waste management, and developments of a simulation model are involved to evaluate the waste management.

There are some tools which suggest the sustainable onsite waste management through the production of the Site Waste Management Plan (SWMP) which is compulsory in England. SMARTWaste Plan and Demolition Protocol 2008 developed by BRE and ICE, respectively, are explained below as the effective approaches being applied in the actual projects. In addition to this, the papers suggesting the optimization models for the waste management are classified by their targets and used model types. The application of each model may give a hint for future models to be developed or to show the possibility of model application from other fields.

2.2.3.1. Waste management tools

SMARTWaste Plan

As explained in the previous chapter, SMARTWaste Plan is the tool developed by BRE to help the manager of demolition projects to produce SWMP and measure the waste generations. Strictly speaking, this tool does not explicitly suggest the optimal waste management strategy but it offers the evaluation data from the details of a project so that the project design team can choose an option of the most sustainable and feasible among possible plans.

As shown in Figure 18, a SMARTWaste Plan consists of five process steps; registration, preparation, SWMP implementation, reviewing and data recording. Here, the most important part is forecasting the prospective waste generation with the calculation tool at the SWMP preparation step. This is evaluated based on the previous demolition project data which is followed by the data recording scheme of the SMARTWaste Plan. Besides the total waste generation from project type, bespoke indicators allow users to evaluate the prospective rate of the waste recycling, reusing and landfilling according to the region and the project type (BRE, 2013a). Referring to this result, project teams can comprehend the average waste generation and decide how to manage them or how to improve the rate of sustainable treatments such as reusing and recycling. As the great advantage of SMARTWaste application, project team can forecast the waste generation at the planning phase and compare that value with the actual value of waste generation at the implementation phase. The energy and water consumption and the procurement of certified timber on a project can also be monitored with an add-on tool called smartER developed by BRE. If additional data is collected at the implementation phase, people can evaluate the waste management strategy from multiple aspects. Moreover, a new add-on tool is developed to make the SMARTWaste tool possible to calculate the carbon emission and economic impact of waste (BRE, 2011).

In summary, the features of SMARTWaste create a positive spiral for C&D waste management. As it helps users to produce SWMP which is compulsory in England, increasing number of people attempt to apply this tool to their projects. Then, the data collected in the recording process enriches the BRE data base. As a result, the following users can get more concrete data specific for their region and project type. It improves the whole C&D waste management, and it is also easy to introduce new parameters as the former example for energy, water consumptions in the data enrichment system. On the other hand, it must be noted that this tool only offers an expected waste generation and relevant properties based on the average of conventional projects so far. Though this is quite helpful to set the baseline as the case for BREEAM (in chapter Waste1, Construction waste management), it is not suitable to accurately evaluate the waste management strategy. Because the site circumstance and building design differ a lot in each project and there are many possible combinations of the demolition methods, it cannot suggest the optimal waste strategy including the demolition process. Even with such limitation, the BRE data base seems to be the current best possible choice to predict the demolition impact. The changeability with other BRE tools and standards is also an advantage for the practical suggestion of models.

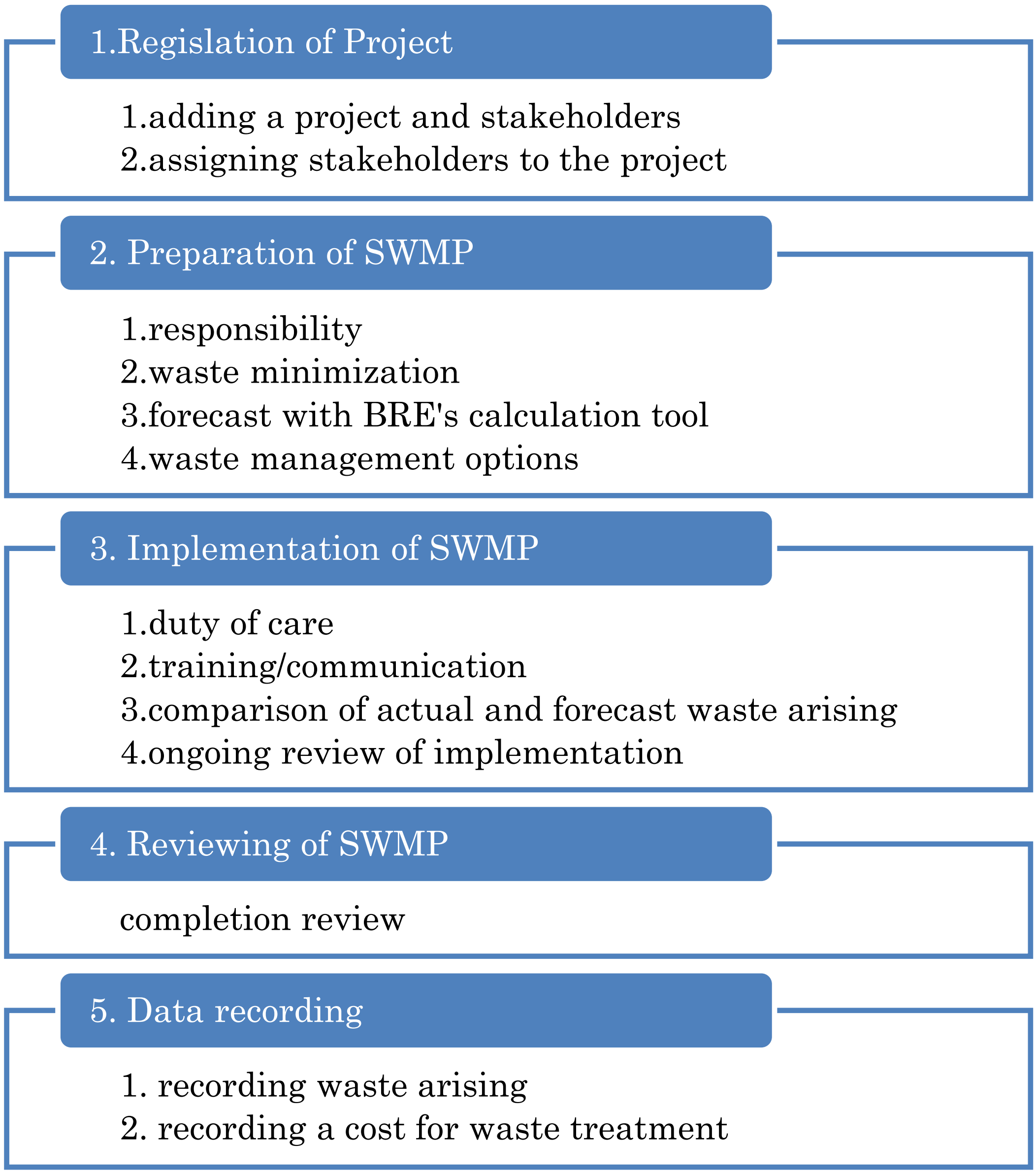


Figure 18 Abstract of SMARTWaste procedure flow

(source: BRE, 2010)

Demolition Protocol 2008

This was suggested by the Institution of Civil Engineers (ICE) which has been funded from the landfill tax and ICE's research fund, following the Demolition Protocol 2003 scheme. Compared to the 2003 version which tried to describe the mechanisms of driving demand and supply of recovered materials, this aims to encourage policy-makers and client teams to treat recovered materials in a high waste hierarchy. In other words, it aims to improve Materials Resource Efficiency (MRE) by considering the waste resource applicability even in earlier phases. Thus, it offers a tool which allows the production of SWMP and the calculation of the prospective waste emission with three coefficients (explained below) as shown in Figure 19 (ICE, 2008).

Compared to the flow of SMARTWaste Plan, the uniqueness of this protocol is three particular coefficients to describe MRE in project; Deconstruction/Demolition Recovery Index (DRI), Demolition Bill of Quantities (D-BOQ) and New Build Recovery Index(NBRI). DRI shows the percentage of material and elements to be reused and recycled. D-BOQ estimates the prospective generation quantity of each waste component at the pre-demolition phase, which is used to describe DRI from the comparison with original building mass. NBRI shows the percentage of materials and elements to be used to the new construction at the same site. While SMARTWaste Plan gives the prospective waste generation from its data set, this protocol asks project teams to calculate the above coefficients to set the target MRE at the audit process. Through the recording of the waste treatment onsite, the actual and prospective values are compared in the review phase to know how far achieved. It makes higher awareness to MRE shared in the project team members and other stakeholders such as contractors and subcontractors. However, as this tool is not internet-based, there is no system to collect data using the protocol as SMARTWaste tool does. As a result, users cannot access the baseline or average value to refer for their own project design.

In addition to the evaluation of waste generation for each component, this also aims to assess the saving of CO_2 emission from the haulage movement. Though this is not sufficient, additionally considering energy consumption and CO_2 emission during the demolition process can describe the total result of project so that the optimal waste management including demolition process can be suggested.

1.Basic data imput

adding data of project and stakeholders

2. Project design

1.waste minimization
2.SWMP planning
3.feasibility assessment

3. Audit of resource recovery

1.refurbishment and reclamation audit (with NBRI)
2.deconstruction audit (with DRI)
3.predemolition audit (with D-BOQ)
4.audit for CO_2 emission saving

4. Design decision

1.design for deconstruction
2.desing assessment for recycle content
3.waste management option

5. Implementation

1.duty of care
2.monitoring
3.comparison of actual and forecast waste
4.ongoing review for cost saving

6. Review

1.completion review
2.waste reduction review

7. Data recording

recording of waste arising and rate of recovery

Figure 19 Abstract of Demolition Protocol 2008 procedure flow

(source: ICE, 2008)

2.2.3.2. Models for waste management

Models for the waste management can be categorised from two aspects, the methods and the targets. As shown in the previous section, Chapter2.2.2., the methods with different types of model were compared to analyse the advantages and disadvantages of each approach. On the other hand, targets mean the process for which models are designed. As mentioned in the previous chapters, there are mainly four phases for waste stream; i) demolition, ii) treatment (recovery or disposal), iii) production and iv) construction. The treatments of the demolition waste to be recycled in generated from the demolition to the next construction are discussed for each phase. Even if they treat the same target, the adopted treatment is diverse with the applied type of model according to the author's view point. Comparing different types in a conventional study, they analyse pros and cons of each type. With both two reviews, the gap of research at C&D waste management is investigated and its adequate model type to be applied are suggested at the end of this section. It is noted that the approaches introduced in Chapter 2.2.2. are also able to be regarded as the target approach focussing on the demolition implementation phase. Therefore, the following three phases of waste generation in the waste management process are reviewed here.

Target of waste management

Following the demolition phase approach introduced in Chapter2.2.2., some researches focus on the impact from sorting and controlling of waste stream as the treatment phase. Hao et al. (2007, 2008) suggest two decision support tools for a construction waste management with a System Dynamics (SD) methodology. They try to comprehend the relating factors for the waste treatment in terms of the disposal volume and treatment cost. For the first study, they try to evaluate the impact of C&D waste disposal on the scarcity of landfilling space shared with Municipal Solid Waste (MSW). In this study, 'waste management experience', 'environmental consciousness', 'site ratio impact', and 'landfill charges' are included as the main factors for the generation of C&D waste. While the qualitative factors are adopted into the first model, the second study takes account of the quantitative factors. The interaction between onsite sorting and the cost for waste treatment shows the optimal onsite waste management scheme based on the price differences between sorting facility and landfill. They find model simulation model simulation is efficient to support and educate stakeholders, and the onsite waste sorting for the reduction of total waste management cost. Moreover, the authors insist the suitability of the SD model application to comprehend the waste management system having complex interactions among relating factors.

For the production phase, researches can be separated into three types which consider the adoption of waste from demolition sites and the supply to new construction sites and both. As the first type, Banias et al. (2011) suggest a methodological framework for the optimal decision making for the alternative C&D waste treatment facilities. This applies ELECTRE III technique to suggest the optimal location for them with multiple criteria; local acceptance, financial viability and environmental quality. In detail, from the seven possible site choices for the new unit construction in Greek, it gives the ranking of suitable locations through the comparison of the criteria satisfaction in each site. This model is very comprehensive approach using both qualiative and quantitive criterion to evaluate the suitability of facility locations. It is, however, not capable to decide the optimal location without enough suggestions. On the other hand, for the second type, Knoeri et al. (2011) try to clarify the reason of a low appllication rate of Recycled Mineral Construction Materials (RMCM). This study consists of two types of description for a decision making flow of material designation with the behavioural data and questionnaire results of stakeholders. The application of Analytical Hierarchy Process (AHP) to the questionnaire results allows knowing the decision factor and the influence of other stakeholders. Similar to this, as the third type, Noguchi et al. (2007) suggest the application of Geographic Information System (GIS) to Multi Agent System (MAS) model simulation called EcoMA to establish the resource circulation model and evaluate the generation of waste and its application to the new constructions. This model includes the whole stakeholder in the construction industry to recreate the resource stream for both virgin and recovered materials. The impact of waste management system is evaluated by the simulation of model with GIS data.

For the construction phase, in addition to the aforementioned simple prediction studies of the construction waste, there are some studies aiming to comprehend the interactions of the waste management factors to improve the methods for the project sustainability. Yuan et al. (2012) suggest a decision support tool for C&D waste reduction, and the key factors for the waste reduction are described through the development of a System Dynamic (SD) simulation model for a waste treatment platform. It involves quantitative, qualitative and dependent variables to describe the following factors; ‘design change’, ‘investment in C&D waste management’, ‘government regulation’, ‘site space for performing waste management’, ‘low-waste construction technology’, and ‘waste management culture within an organization’. They compare simulation results under four scenarios; i) base scenario, ii) scenario 1: to know how an increase of the landfilling charge can contribute to C&D waste reduction, iii) scenario 2: to know whether the increase of investment on waste management influences the efficiency of C&D waste reduction and iv) scenario 3: to know whether the improvement of accordance with the waste management regulations can reduce the waste generation. They confirm the reduction of waste generation with the scenarios ii), iii) and iv), respectively. Compared to this, Shen et al. (2004) develop the Sustainable Development Ability (SDA) model using a SD to evaluate the sustainability of building lifecycle which is separated into five stages; inception, construction, commission, operation, and demolition. The initial values of social, environmental and economic impact for each stage are set by the interview with project clients. The sustainability development from construction project is evaluated with these initial settings. With different weighting of social, environmental and economic impacts for project sustainability, the change of Sustainable Development Ability (SDA) in the life cycle is described to discuss the project feasibility and necessary impact modification.

In summary, the conventional studies cover the whole waste stream for each phase(i) demolition, ii) treatment (recovery or disposal), iii) production and iv) construction phase). Most of the models suggested in those works are designed only to cover the single phase or single relation between two phases. It derives from the complexity of the waste management with the large number of factors and stakeholders and their multiple interactions. As a result**, the authors are required to compromise their models with three points: i) to refine target aspect or phase, ii) to apply conventional average values and iii) to presume qualitative impact.** Therefore, many latest studies focus on three parts to improve the model quality; the convincible setting of boundary conditions, the enhancement of empirical data for specific conditions and the description of qualitative factors as variables of quantitative factors, respectively. To prevent this situation, the social modelling methods which can cover the whole process of demolition management without above limitations should be applied to evaluate the significance of the environmental impact reduction with the system change of waste management. Since there was **no paper which considers the direct connection between demolishers and constructers** but only via offsite facilities, the social impact evaluation model applied in this research needs to extend the material flow between them.

2.3. Review of prospective approaches to demolition in external fields

2.3.1. 4D-CAD application for the recreation of project dynamism

As the basis of the demolition modelling, individual processes are to be followed to estimate the cost, duration, waste and impacts in the time frame of the projects. If a 4D-CAD, produced for construction by linking the 3D model and the schedule of the project plan, is developed for the demolition projects, it should have a huge advantage on the project planning compared to the conventional project management using the 2D designs and a Gantt chart. It comprises of three phases; i) production, ii) comprehension and improvement and iii) comparison.

2.3.1.1. Production

The project plan model is produced by the site installation of each 3D model objects according to the generalized schedule information. Jongeling and Olofsson (2007) suggest the application of the Line of Balance method as the location-based schedule planning which simply visualises the spatial property in a schedule planning and identifies the inefficiency and the issues of plans. As the other method, a Work Breakdown Structure (WBS) is applied by many researchers (Moon et al., 2013, Ma et al., 2014 and Wang et al., 2004). In WBS, templates of corresponding elements to each activity are used to reconstruct a project planning into a tree structure. As a result, the install timing of elements is returned from the order of activities in the project plan. Because of the link between the activity and the elements, the modification of the activity plan can be easily reflected to the elements model and vice versa. With these two-way data reflections between the 3D model and schedule, Wang et al. (2004) and Zhou et al. (2015) apply mathematic algorithms to automatically modify dynamic planning in terms of the resource management and the site layout.

2.3.1.2. Comprehension and improvement

The purposes of comprehension are mainly separated into two types; the visualization for the whole stakeholders' understanding and the plan analysis for the project planners. As an example of visualization, Boton et al. (2013) refer to the result of stakeholders' interview for identifying the priority of visualised information to share in the project. Trebbe et al. (2015) apply a 4D CAD to the construction site with frequent installation of prefabricated elements in order to minimize the project loss from the conjunction of different stakeholders. On the other hand for the plan analysis, this is the process to identify the issues of planning and lead to the modification process. It mainly focuses on the safety monitoring and the overlap of activities. BIM or rule-based algorithm tends to be applied to the safety monitoring for the automatic hazard identification. Zhang et al. (2013, 2015) suggest the 'table-based safety rule transition' algorithm using BIM data. Referring to OSHA's fall protection rules, the horizontal element boundaries in high place are identified by BIM and put the countermeasure tools (e.g. guardrail and cover). Similar to this, Benjaoran and Bhokha (2010) apply 'rule-based' algorithm to automatically identify the hazard and modify the construction plan. It asks if the proper countermeasure is applied to the whole objects on the progress of construction. However, the authors mention the necessity of high enough accuracy of the 4D modelling and the formulation of suitable rules every time. As one of the solutions for this idea, Zhou et al. (2013) apply both rule-based algorithm at planning and actual site monitoring to enhance the onsite safety. For the quantification of risk, Kang et al. (2013) uses an Analytic Hierarchy Process (AHP) for the result of questionnaires to the stakeholders. In addition to the risk assessment with AHP and WBS methods, they also adopt Generic Algorithm (GA) to suggest the optimal planning in terms of the working conjunction as the improvement process. For the overlap of activities, plans can be improved through the quantitative evaluation for spatial and temporal overlap as Moon et al. (2013) set the workplace for each element according to the related activities. Similar to this, Jongeling et al. (2008) focuses the reduction of workability from the adjacent workspace and the interaction of temporally structures (e.g. scaffolding, shuttering etc.), and adopt the evaluation of those values in the 4D-CAD model. As the other analysis, Zanen et al. (2013) attempt to analyse the project impact on the adjacent environment for the highway construction planning with 4D-CAD. Impacts on traffic and construction noise evaluated by the other software are linked to the construction process and visualised as the construction impact. Following the above analysis, construction project planners can improve their plans referring to the 4D-CAD model as the decision support tool. Alternatively, a theoretical optimization for planning is achievable with mathematic algorithms such as the shortest path algorithm and Genetic Algorithm (GA) which Zhou et al. (2015) apply to the route optimizations and Kang et al. (2013) for the workplace conjunctions respectively.

2.3.1.3. Comparison

Process tracking is achieved from the comparison between the as-planned and as-build 4D-CAD models. As mentioned in the BIM application, a visual analysis and the other geographical tracking support tools are frequently applied to comprehend the as-build information on site. In order to compare the as-planned 4D-CAD to as-build or after modification, Kim et al. (2013) analyse the onsite visual data with the Hue, Saturation and Value (HSV) colour space and the image mask filtering, Wenfa (2008) apply the radio-frequency identification (RFID) method to the structural steel components and Turkan et al. (2012) use the 3D laser scanning method to identify the installed elements. In particular, Turkan et al. (2012) show the improved accuracy of process projection from the updated 4D-CAD model in their case studies.

2.3.2. BIM application for the enhancement of waste property information

The Building Information Model (BIM) is the modelling of building to attach continuous, computable and coordinated information from the object level. Compared to the previous 3D-CAD application which describes a 3D model view as graphical data, the semantic information in BIM describes the relation between objects and sets the geometric and functional properties for the whole life cycle (Ding et al., 2014). Accordingly, in terms of the object geometry, the change of design is automatically taken into account from correlativity with the surrounding objects by the parametric design. Farr et al. (2014) suggest customisable curtain wall design application as the system unit using this feature. Moreover, as the data repository BIM application extends the project planning to three different directions in construction; i) data accessibility, ii) function and iii) application phase. BIM Working Party (2011), with the BS555 Roadmap, mentions about the necessity of application of BIM to the UK construction projects due to 'the reduction of whole life cost, risk, carbon and the timely delivery of buildings and infrastructure projects' and justifies the obligation of BIM use in the public projects since 2016 at the maturity of Level 2 which attaches data with separate discipline BIM tools in the 3D environment. Similar to this, many countries make BIM data delivery mandatory. In particular compliance of building design to construction regulations is automatically checked with BIM-based system such as the CORNET in Singapore and the SMARTcodes in the United States (Choi et al., 2014).

2.3.2.1. Data accessibility

Because of the exchangeability and interoperability of information, stakeholders can easily access data and feedback. Due to the better communication among stakeholders, the errors caused by communication problems are minimized which results in the reduction of onsite human risk and increased productivity. Referring the feedback from all stakeholders also makes the project plan more robust. Succar (2009) explain that the BIM competence is attributed to the competence at each level; individual, organization and team. They define the competence derived from an individual's ability to produce outcome and the team performance as the synergy of that competence. This is why the whole stakeholders should be allowed to access BIM data and commit their role for BIM application.

2.3.2.2. Function

The ontology approach using the semantic BIM data is another reason for the versatile ability of the BIM application. For instance, as explained above, spatial and temporal object data can be utilised at the implementation phase as the scheduling information. A semantic data which describes when, where, how and what objects to treat is regarded as the rule codes. Choi et al. (2014) develop a self-checking flowchart for the evacuation designing with which users can identify properly design exit routes. Similarly, Motamedi et al. (2014) apply a fault tree analysis to the sematic data in BIM to comprehend the failure relating objects in the facility management. A building information software, Autodesk Revit (Revit), also tends to be used to extend the function due to the good interoperability with other software and easy application of scheduling data. Kota et al. (2014) develop an add-in for Revit to extract required dataset for daylight simulation tools, Radiance and DAYSIM. Wong and Kuan (2014) insist the advantage of BIM to utilize green rating systems such as LEED in the US and BEAM Plus in Hong Kong. In their studies, the scheduling function of Revit is extended to automatically evaluate the satisfaction of BEAM Plus requirements from the construction design. As another way to use external software, rule codes can be converted into an extensible mark-up language (XML) file which describes the data definition in BIM as a set of rules in text format. For the better data transaction with other software, Mignard and Nicolle (2014) succeed to synthesise BIM and GIS data file which describes the building and surrounding geometry for the city design modelling. For the comprehension of on-time thermal property, Ham and Golparvar-Fard (2013) adopt XML file type to interoperate 2D thermal images and BIM data in the external model. Lee et al. (2014) develop the automatic selection tool for working items. A semantic reasoning system for item choice is achieved by the mutual conversion of the XML data with BIM files.

2.3.2.3. Application phase

Whole life cycle information extends the applicability of BIM data for "from cradle to grave" style. At the design phase, a life cycle analysis such as the building quality evaluation can be simulated from multi-angles views (e.g. energy efficiency, maintenance cost, CO_2 emission). Even the security risk can be simulated and evaluated from building design if Porter et al. (2014)s' multi-agent-based analysis is applied. In the implementation phase, visualization and scheduling data can be applied to compare the as-planned and the as-build situation so that the project progress and the onsite safety can be monitored. Meza et al. (2014) and Kwon et al. (2014) suggest the application of augmented reality (AR) to mobile devices during the implementation phase. Meza's method especially uses the XML file conversion technique based on the scheduling data in BIM. After the construction, the evaluation in Life Cycle Analysis (LCA) in the project phase would be compared with the actual building running data. In the thorough survey the resident life pattern is analysed and the accuracy of the impact evaluation at the end of service life would improve. During the maintenance phase, the refurbishment and renovation of building can be planned. Similar to construction planning, the impact evaluation can be achieved by following LCA, and the implementation can be monitored. According to the literature survey by Volk et al. (2014), study of BIM application to demolition do not exceed 1% of the publications relating to BIM. The immaturity of BIM application in the demolition industry may be attributed to the strong impact of BIM initiatives at the construction phase or the priority on LCA. However, due to the similar characteristics between construction and demolition projects, BIM application envisages a better performance at both design and implementation phases in demolition among the stakeholders. Moreover, above evaluation techniques for BIM on LCA can also be applicable to optimise the application plan of resulted waste to the new construction (see, for example, Chen and Ma 2013). **With multi-disciplinary information in the element level, demolition impact can be automatically calculated for not only the amount of waste generation but also the treatment cost.** It infers the huge advantage of BIM use for the waste management planning due to **the accurate projection and the certain origin of wastes.**

Accordingly, two main demand gaps identified in Chapter2.2.2., collection of waste purity and origin information and multiple types of impact evaluation are expected to be fulfilled by the application of BIM to the evaluation model. Along with the 4D-CAD approach, the impact evaluation model is developed to enable the dynamic impact analysis at project planning phase. The purity and other multiple impact factors can be quantified in this model which is regarded as the novelty of this approach. The detail description of developed model can be seen at Chapter4.

2.3.3. Social system modelling considering C&D relation

In the social science field, social system tends to be modelled to simplify the complicated interactions of stakeholders' action and allow the impact evaluation of target process in the social system (e.g. CO_2 emission during building lifecycle, population change with economic growth). According to the reviewing of conventional research approach to the waste management, the bottleneck of sustainable recovery for demolition waste was concluded as the lack of direct connection between demolishers and constructers to discuss the waste applicability. In a strict sense, there are some opportunities to contact when the both projects are planned at the same site by the client, in particular when the construction contractor commits the demolition phase. However, the inaccuracy of waste generation at demolition phase makes the planning of waste recovery difficult and this issue has not been solved by the conventional approach yet. Therefore, the project impact model which can estimate the waste purity along the timeline is developed in this research. In order to estimate the potential reduction of environmental impact with this improvement, the social impact model which enables to recreate the impact change with stakeholder behaviour is suggested based on the conventional approach in social science. As the present author's previous research, the social evaluation model for the environmental impact from demolition waste management was developed for evaluating the impact change by onsite waste sorting. This model has been further developed to reflect the relation between demolishers and constructers in this research. Accordingly, the conventional modelling methods for social system are reviewed at the former part. Subsequently, the previous impact evaluation model in previous author's study (in MSc) is explained in detail while the further development of model will be described in the following method chapter (Chapter7).

2.3.3.1. Applicable model type

The applicable social modelling methods can be separated into four types according to their model types as follows. First of all, some models use the conventional data set to put the provisional value for the waste generation and to predict total waste management cost and the relating impacts such as transportation or recycling rate from the simple accumulation. This type of model is designed to make the estimating process simple and easy for users, so that it only tries to describe the waste generation with ratio rather than the complex interactions of factors.

Comparatively, the second type of model aims to describe the significance of factors among multiple factors on the target result. Many studies use AHP to quantify the results of questionnaires from the stakeholders or experts. It includes the sustainability evaluation tools in the demolition industry. For example, a model series named ELECTRE can be used to clarify the excellence of suggested alternatives for each criterion. They also decide the total ranking from their accumulation as a decision making tool for the optimal location of waste management units. Those methods are usually applied to treat qualitative factors. As a result, the assessment with the model is dominated by the qualification method, typically the questionnaires. It causes the necessity to renew the data constantly and to collect the data for each region to follow the change of significance with time and locality. Therefore, this type of model with a single data set is not much reliable or the output is not accurate enough to definitively conclude.

Similar to the second type, an SD model is adopted to describe the complex system of a waste management and to identify the influential factors for a phenomenon such as the waste generation and landfill volume. As mentioned above, there are many relevant stakeholders and factors intricately interacting each other. As a feature of this model, it is able to describe the change of target stock (e.g. waste volume, cost) caused by the impact of other stock change with the feedback loops. This allows the model to adopt complexity, nonlinearity and feedback loop structures which is suitable to recreate a real social system (Hao et al., 2008). Therefore, this is applied to not only in the C&D waste management but also in agriculture, water resources and MSW management to comprehend the system behaviours, fundamental structures and decision rules (Yuan et al., 2012). Since the second type of models quantify the qualitative factors with questionnaires, this model can evaluate the importance of factors from the interactions of whole factors in the process (here the waste treatment). Besides the applied value for the interaction tends to be based on the quantitative value (e.g. the input of the waste management is described by the value of investment), a sensitivity analysis is simultaneously executed to evaluate the robustness of the model.

A Multi-Agent System (MAS) model, as the final type of modelling, is used in some studies to describe the complex system as well as an SD model. There is a large difference in the model algorism between these two. While an SD model tries to depict the whole system with any interactions of stakeholders and factors, a MAS model defines the simple rule for each stakeholder called an agent, and simulates the results composed of those individual acts. Because of the independence of each stakeholder, there is no need to define the relating factors and feedback loops which hinder the model targets to cover a large range of aspects and phases. For instance, as mentioned above, an EcoMa model enables the comprehensive analysis for the waste management from the demolition to construction process with a MAS model. The accuracy of the model is decided by the behaviour rules of agents so that the detail survey is required against the actual stakeholders.

To think about the potential of modelling to evaluate a complex waste management system, SD and MAS models seem suitable especially in terms of suggesting the optimal decisions or testing some scenarios to know their efficiency. As the main difference between them, the approach of model formation is top-down and bottom-up, respectively. An SD model tries to set the system framework to be able to evaluate the target phenomenon, while a MAS model tries to move the individual agent according to practical rules and describes the sequential phenomenon in terms of the statistic view. Accordingly, an SD model is superior to a MAS model, because it can be decomposed into the observable or equation of the whole project (Swinerd and McNaught, 2012). North and Macal (2009, cited in Swinerd and McNaught , 2012) show the entire equivalence of simulation results with both methods individually at Beer Game Simulation and insist the possibility that an alternate approach allows exactly the same result. Swinerd and McNaught (2012), although they admit above insistence, advocate the entity of model suitability for each case and suggest two advantages of the hybrid approach; improvement of model's efficiency and transparency. Based on this concept, they introduce three types of SD and MAS (here, it is called Agent Base (AB)) hybrid model as shown in Figure 20 referring to the study of Shantikumar and Sargent (1983 cited in Swinerd and McNaught, 2012); integrated, interfaced and sequential hybrid.

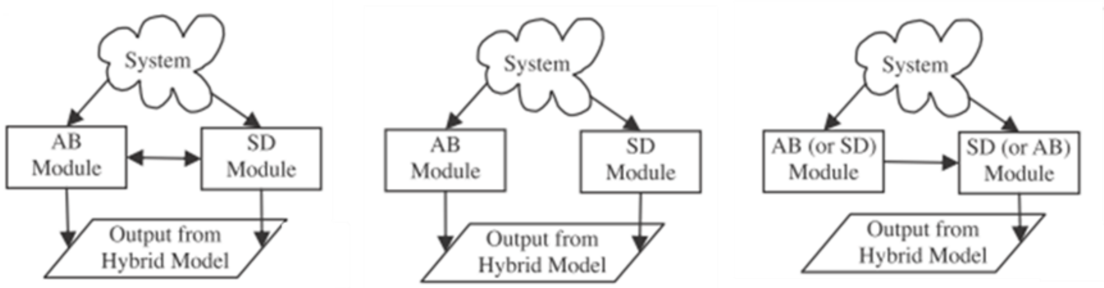


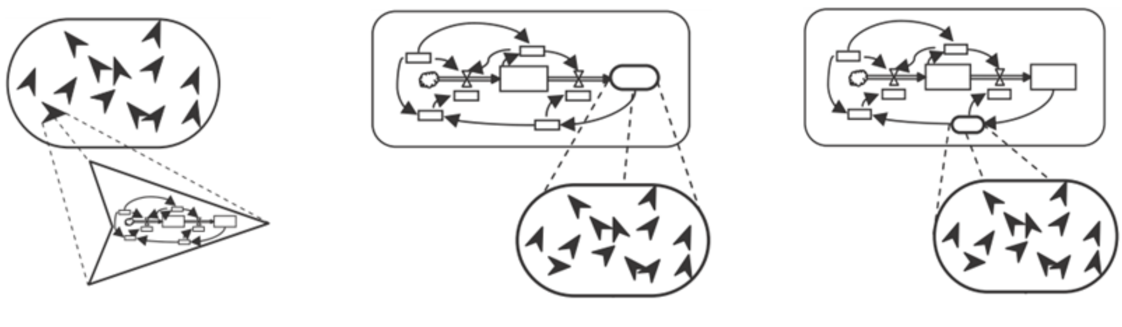
Figure 20 Three patterns of AB and SD hybrid model

Integrated **Interfaced** **Sequential**

(source: Swinerd and McNaught, 2012)

Firstly, the integrated hybrid model is explained in three types as described in Figure 21. Type I, whose framework consists of an AB model, includes an SD model into the individual agents so that the rule of agent movement can be decided by the interactions of several factors. Duggan (2008, cited in Swinerd and McNaught, 2012) develops this type model to describe the companies' alignment movement at the market. While a MA shows the companies' behaviour considering the effect of the social network, SD model defines the three layers framework as a company's internal structure. On the other hand, Type II and III use a SD model as the framework and include an AB model to describe the detail interactions of stocks or the change of interaction as the time passes, respectively. Type II called 'stocked agent' integrated hybrid is applied to describe the detail mechanisms of stocks reflecting its behaviours. Verburg and Overmars (2009, cited in Swinerd and McNaught, 2012) try to understand the influence of regional and governmental demand and policy on the local land change using a Type II model. To describe the interactions among three layers, national, regional and local scale in the time step, the authors distinguish the advantages to put an AB model into the agent and sustain the feedback between local and other scales. With a Type III integrated hybrid model called 'parameters with emergent behaviour', Chaim and Streit (2008, cited in Swinerd and McNaught, 2012) try to develop a government model for the pension fund. It defines people and their abilities to affect the pension governance as agents in an AB model, and people's properties like age, income and health are reflected to their behaviours. Then, the emergent dynamics described by the integrated result of agent behaviours influence the asset and liabilities in the governance system. In addition, Kieckhafer et al. (2009, cited in Swinerd and McNaught, 2012) use the mixture of type II and III which involves an AB model to describe stocks and their change to draw a portfolio strategy against the CO_2 emission regulatory of a new vehicle. The manufacturing decision framework is represented with an SD model and the product class sale is predicted using an AB model. Since the sale is included as one of the stocks in an SD model, the impact from other factors such as the production cost and fuel price on the sale is easy to be assessed, then the impact of the sale is reflected to the decision making. Including above cases, there are many types of possibilities to include the other model to represent target system in a natural way. For instance, it is also possible to apply an SD model to the agents of the AB in Type II, which is actually suggested by Sterman (1985, cited in Swinerd and McNaught, 2012) to recreate the Scientific world with scientific paradigms and their intrinsic activities.

The interfaced hybrid is classified as the second pattern, where each model does not affect others but only the final output. Since there is no certain model suggested by this type of AB and SD hybrid model, Swinerd and McNaught (2012) use the AB and Discrete Event Simulation (DES) hybrid model developed by Dubiel and Tsimhoni (2005, cited in Swinerd and McNaught, 2012) to explain the concept. Their model is designed to simulate the people's movement from the start to finish. While the usual move is ruled by an AB model, there is a train station which is described with the DES model. Though two models coexist in one model, there is no interaction between them except the locations of people. This seems possible to use an AB and an SD model in the similar situation to recreate individual module for an optimal model in one integrated model.



Type I **Type II** **Type III**

Figure 21 Three types of integrated hybrid model

(source: Swinerd and McNaught, 2012)

As the final pattern, a sequential hybrid model is applied when the design, use and condition of some factors are not clear in a single model. An SD model tends to be suggested to visualize the target system, but sometimes a part of the system factors are not clear such as the relation of factors, how to influence others and the accurate condition of factors. The uncertainty of the lower level of factors often causes above difficulties, and 'table function' is used, which puts the value to describe the change of condition usually based on the assumption or judgement. To improve the accuracy of model, the actual factors, their relationships and the change of conditions can be studied by a 'micro-scale' AB model. Through the 'micro-scale' analysis, Homer (1999, cited in Swinerd and McNaught, 2012) can get a simulation-base 'table function' to describe the relation between the service demand and labours' readiness in a field service industry. In summary, the analysis of the first single model helps to develop the second one. Compared to the integrated hybrid model, the process similar as AB model decides the SD model factors. However, the developer of this pattern model does not recognise the proper framework of the second model in the designing phase of the first model. Otherwise, the complete result from a single model is required to describe the second model as He et al. (2004, cited in Swinerd and McNaught, 2012) simulate a national and regional land demand with an SD model and then the local land allocation is visualised with a Cellular Automata (CA) model to satisfy macro demand.

In addition to this, Swinerd and McNaught (2012) introduce two possibilities to increase the modelling flexibilities. Firstly, not only to persist on the collaboration between the AB and SD models but also the other types of models such as the CA and DES to put them into a natural framework. Moreover, it is also possible to put the switch function into the model so that the two types of model descriptions can be achieved according to the circumstances. For instance, in the epidemic model for air links to Bobashev et al. (2007, cited in Swinerd and McNaught, 2012)'s study, as the agent numbers increase and exceed the threshold, the specific law and theorem are applied. They conclude a higher efficiency at treating a large number of agents in terms of the computation. Or just simply, a DES model can be set in an SD model framework to activate certain factors when the event happens. It seems possible to make rules of individual factors simpler to design only for a specific timing, i.e. rules need not to define factors for the whole lifecycle.

2.3.3.2. Previous social demolition impact estimation model developed by author

The generation of demolition impact to the society has been estimated from various social statistic approaches. The following two models; 'Demolition generation model' and 'Environmental impact model', previously suggested by authors are explained in detail in this section. Some required data for the modelling such as population and project statistical data for project generation is referred to public database. An up-to-the-year update of the database is expected to improve the model accuracy especially for the agent behaviour rules and project generation.

Demolition generation model

Estimation of the demolition project by 'Demolition generation model' relies on one fundamental assumption that the number of demolition projects per unit area would linearly correlate with population density. To recreate the more realistic density distribution, the population gradient theory suggested by Clark (1951) is adopted rather than using the population density data for each local authority evenly averaged over the local authority area. According to the theory of Clark (1951), the population density follows Formula.1 to 4. This shows the population density quickly declines outwards as the population gradient value (gamma in Formula.1 to 4 which describes the population distribution shape) becomes larger. The validity of this theory has been proven by many researchers using data of actual cities. This is represented by Bertaud and Malpezzi (2003) who surveyed 48 cities' population gradients for more than 10 years of actual data. They also determined the population density change with the distance from the city centre for each surveyed city as shown in Figure 22 for London. Here, the donut phenomenon, having a peak at 5km from the city centre can be seen, which is caused by the concentration of low population business area at the city core. Because of this, the plot line does not fit properly. This indicates the actual distribution with the exception of the core area would have a higher population gradient than reported (0.024 in Bertaud and Malpezzi, 2003). In addition, Ohtomo (1975) and Kopecky and Suen (2004) determined the population gradient for major cities until 1970 in Japan and the US. Both propose that the gradient tends to increase as time advances, and Kopecky and Suen (2004) insist there is a strong correlation between car ownership and population gradient. The current UK population gradient can be estimated as around 0.35 with data of ONS (Office for National Statistics) (2010b), with about 75% car ownership in the UK. Because of this, a suitable gradient for the UK in 2010 is proposed to be between 0.01 and 0.35.

$$P(x) = P_0 \cdot e^{-\gamma x} \qquad (1)$$

where

P(x): population density at point where x km far from city centre (persons/ha)

P_0: population density at city centre (persons/ha)

γ : population gradient (*this is a coefficient value which is empirically calculated.)

$$\underline{P} = \int_0^\infty P_0 \cdot e^{-\gamma x} \cdot 2\pi x dx = 2\pi P_0 \int_0^\infty x \cdot e^{-\gamma x} dx$$
$$= 2\pi P_0 \left[(x/(-\gamma) - 1/(-\gamma)^2) \cdot e^{-\gamma x} \right]_0^\infty = 2\pi P_0 / \gamma^2 \qquad (2)$$

where

$\underline{P}$: total population of city (man)

$$P_0 = \underline{P} \frac{\gamma}{2\pi} \qquad (3)$$

$$P(x) = \underline{P} \frac{\gamma}{2\pi} \cdot e^{-\gamma x} \qquad (4)$$ (source: Clark, 1951, Bertaud and Malpezzi, 2003)

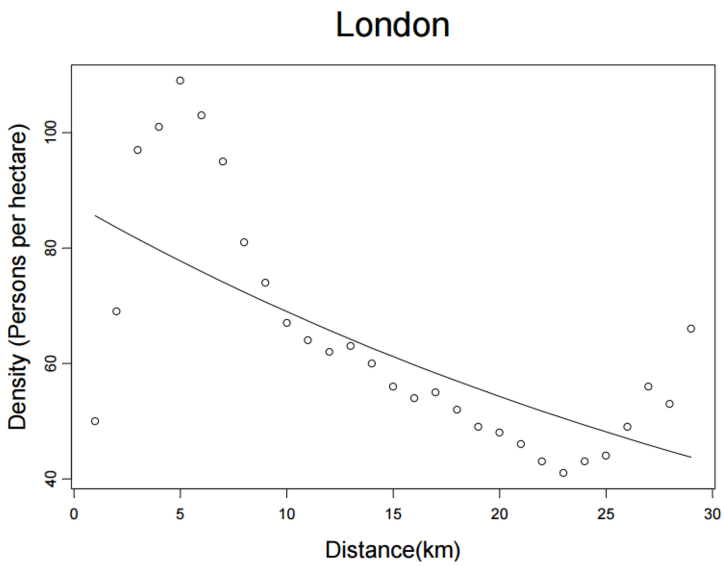


Figure 22 Population density distribution in London

(source: Bertaud and Malpezzi, 2003)

Accordingly, the coefficient for gradient, gamma, is set as 0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30 and 0.35 to compare with actual population density data. In Figure 23, population density of major cities across Great Britain are plotted according to geographical coordinates. Here, North Ireland and other islands are excluded to make this model simple. With population data from ONS (Office for National Statistics) (2010b), each cities' population distribution is calculated following Clark's (1951) formula. The population density can be calculated by superimposition of 5km grid to each cities' population distribution. From this, a comparison of the peak value for London, as show in Figure **24** , allows the most appropriate gamma value for this model. Because gamma=0.20 gives a peak between 8000 and 10000, 0.20 is assumed as a typical gamma value in the following sections.

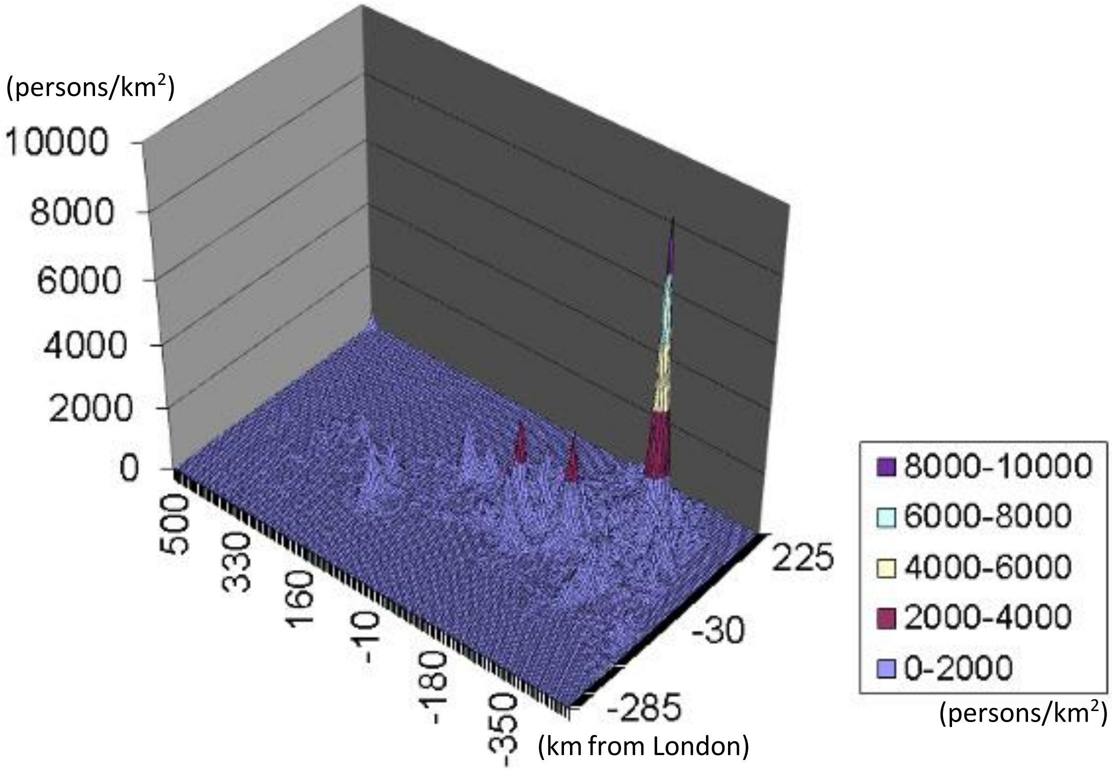


Figure 23 Calculation result for population distribution (gamma=0.20)

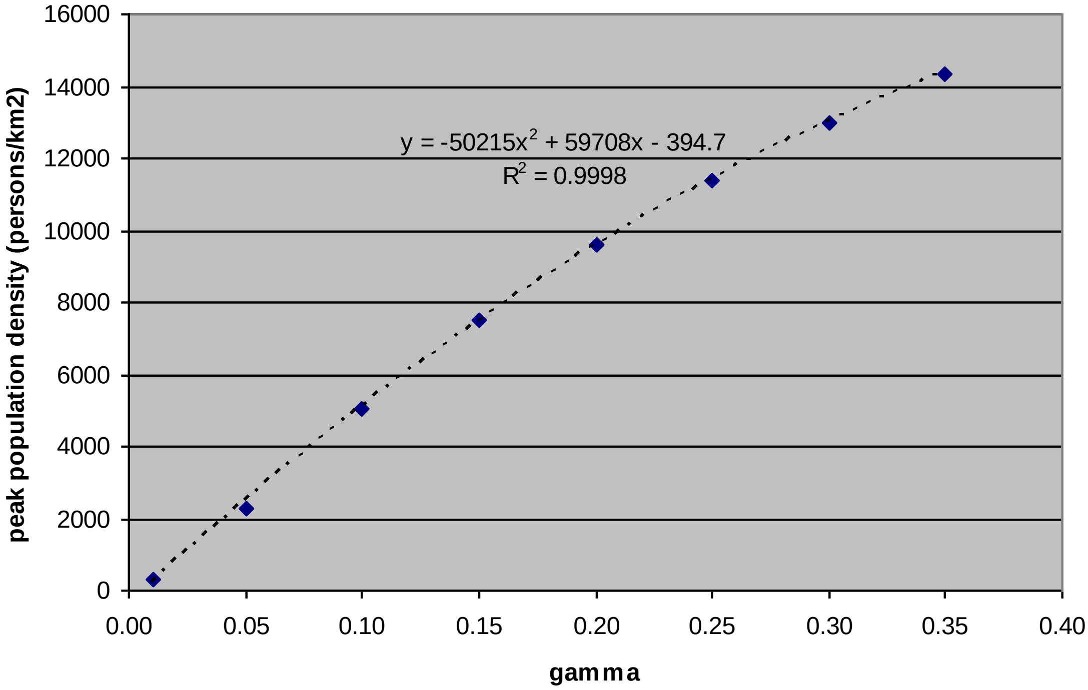


Figure 24 **Change of peak population density in London with gamma**

<Setting of Demolition coefficient>

It should be firstly noted that, in this research, the demolition of dwellings is set as the target due to the strong correlation with population. The demolition data is calculated from the population density and a demolition coefficient. The demolition coefficient is given from the number of dwelling demolition per capita as shown in Table 9 and this data was obtained from local authorities in the survey of ONS (2010a and b). However, the reliability of data was judged as insufficient after calculating the deviation of each value from the data for the last 10 years. Therefore, data for the region of England refers to data from ONS (Office for National Statistics) (2010a), which seems to be more reliable. Data for Scotland and Wales was obtained from The Scottish Government (2011) and Local Government Data Unit ~ Wales (2009). As with data from England, both datasets cover each country's total value, and make no distinction between individual cities. However, the Scottish data only has total number of demolition projects in Scotland so that it is converted to dwelling demolition projects, referring to its share from the statistical data of ONS (Office for National Statistics) (2010b).

Table 9 Result of open questions in questionnaire

	Population (persons)	Total dwelling demolition (/year)	Demolition coefficient
North East	2606625	2323.6	0.00089
North West	6935736	4785.7	0.00069
Yorkshire & the Humber	5301252	2585.7	0.00049
East Midlands	4481431	657.1	0.00015
West Midlands	5455179	2862.9	0.00052
East	5831845	795.7	0.00014
London	7825177	2237.9	0.00029
South East	8523074	1818.6	0.00021
South West	5273726	1008.6	0.00019
England	52234045	19075.7	0.00037
Wales	3006430	519.7	0.00017
Scotland	5222100	1271.6	0.00024
Great Britain	60462575	20867.0	0.00035

*Colored cells are applied to this model (this is because Wales and Scotland have no accessible data for city population). (Source: ONS (Office for National Statistics) (2010a,b) and requested data to ONS, The Scottish Government, 2011 and Local Government Data Unit ~ Wales, 2009)

<Demolition generation with simulation models>

The product value of demolition coefficient and unit population becomes the possible number of demolition projects for the unit grid. By using this value, two methods can be used to simulate time-lapse demolition generation across Great Britain. Here, *"Simulation Program with C"*(Ishikawa, 1994) is referred to for understanding of the fundamental idea of each method.

1. Fixed increment method

This method applies a unit time advance for every point and it has an advantage to comprehend all activities within every single unit of time. As was found in Figure 23, the peak population in London at about 10000 per square km means the maximum number of demolition project is calculated to be about 3 (demolition/year/km2) with the demolition coefficient of 0.00029 for London in Table 9. Thus, the number of plotted point in every grid is lower than 75 ($3*25km^2$) times per year as shown in Figure 25. In other words, a demolition event would not happen more than every 4 days. As a result, one day can be regarded as the time increment.

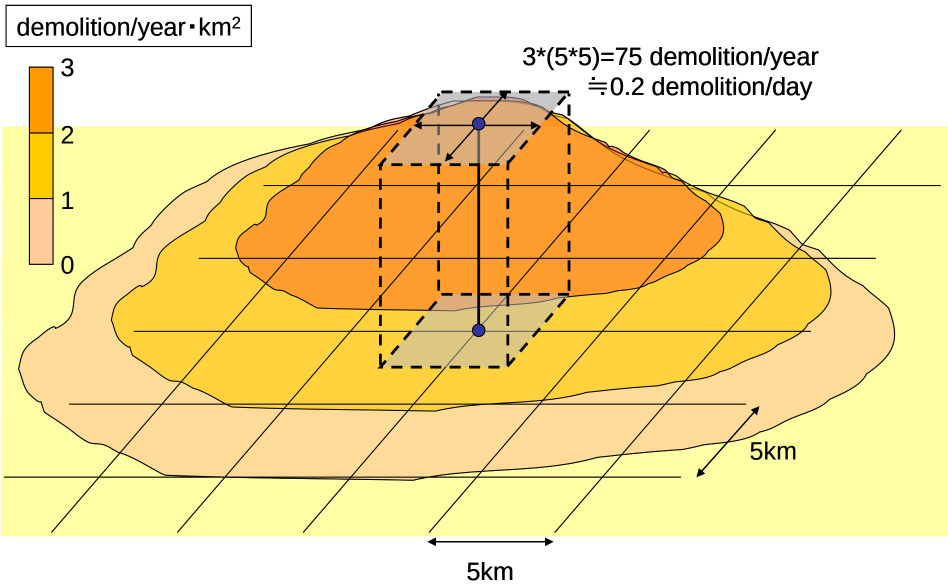


Figure 25 Outline figure for demolition generation at grid point

The demolition 'risk' for every point in single unit time can be written as Formula.5 and when this exceeds a random number generated by the RND function (in an excel2003 VBA macro) which generates a decimal number from 0 to 1 at random, it indicates a demolition event occurs. The demolition event map can be described with a certain set of unit time tests for every grid point.

$$(demolition\ \ risk) = \frac{1}{A} \cdot DT = \lambda_{day} \cdot DT = \frac{\lambda_{year}}{360} \cdot DT \tag{5}$$

where

A: time span for demolition

DT: unit time (1 day)

λ_{day}, λ_{year} : demolition number per day and year, respectively (1 year=360 days)

2. Variable increment method

This method estimates a time advance to the next demolition event, and it has advantages in running the simulation model faster and more accurately compared to the first method. In detail, the times for next demolitions at every grid point can be calculated statistically. The comparison allows the model to advance to the time of the next demolition and saves time checking whole grid point.

If the probability of an event happening per unit time is low, the distribution of total events at a certain time follows the Poisson distribution law. In terms of time span between two events, it follows an exponential distribution. The verification for these theories is explained with formula in "*Simulation Program with C*"(Ishikawa, 1994) in Appendix VI. Assuming the demolition in each grid follows a Poisson distribution law, the occurrence of the next demolition event can be represented by the time (τ) dependent function in Formula.6. Accordingly, the time constant (specific time) to the next demolition event is given by the inverse function of the coefficient λ as shown in Formula.7.

$$f(\tau) = \lambda e^{-\lambda\tau}$$
$$g(\tau) = \int_{-\infty}^{\tau} \lambda e^{-\lambda\tau}\, d\tau = 1 - e^{-\lambda\tau} \tag{6}$$

where

f(τ): density function of τ

λ : average number of occurrence in unit time

g(τ): distribution function

$$\tau = -\frac{1}{\lambda}\log(1 - g(\tau)) \tag{7}$$

Inserting a random number generated by the excel RND function to g(τ) in Formula.7, every demolition event on a unit grid can be forecasted. Once the time is advanced to that specific time, the demolition time is again set with the formula. The demolition generation map can be described with the accumulation of demolition time until it exceeds a defined time for calculation. Through the comparison of two methods in the research, the author found the advantage of the Variable increment method which could complete with less computational burden. Thus, this method has been adopted into the social impact evaluation models included in this research.

Environmental impact model

The environmental impact is evaluated from the pre-treatment phase to the recycled phase for its 'fuel and energy consumption' and 'landfill volume'. For the pre-treatment phase and the transportation phase, data from the Spanish case study of Mercante et al. (2012) is used with the assumption that there is not a significant difference between the situation in Spain and the UK. This is justified by the similar value of waste arising from C&D sector in Figure 14, and as the same European developed countries.

<Demolition flow and setting of coefficient>

The flow of the demolition treatment process is defined in four phases. This is visualized in Figure 26 with the explanation of how to recreate the sorting degree in each process. The change of environmental impact during these phases with different degrees of separation for demolition waste is compared with different proportion of sorted or landfilled. The use of waste on site with onsite crushing is not considered as a possible treatment method in this model. In addition, the reclamation of waste is not considered except clay (brick). Only clay is assumed not to be recovered from off-site sorting and input low recycling energy.

Phase1. Main demolition

Due to the shortage of impact data during the demolition of the structure framework, the energy consumption and CO_2 emissions during this phase are excluded from the impact evaluation. Therefore, the difference of impact value for each treatment scenario is found for the following two phases.

Phase2. Pre-sorting on-site

During this phase, demolished material is sorted before main demolition, which is called pre-sorting. In practice, basic demolition progresses simultaneously with pre-sorting on site. However, this study regards the pre-sorting time as a separate phase and that increased duration implies improved segregation of demolition waste. The trade-off between the increase of environmental impact for pre-sorting and the reduction due to the high rate of demolition waste recycling is a major focus of this study.

The segregation of demolition waste can be classified into five steps, and target material is separated from the waste during those steps. Following this scenario, the rate of disposed waste for inert defines the amount of recycled and landfilled inert material. The steps are explained with the name of the coefficient 'R' which stands for removal rate of each component, and the target material as below, and described in Figure 27.

1. Brick removal: R_B(target: Clay)

The surface brick is removed from a structure separately.

2. Element removal: R_E (target: Ferrous $_{NR}$, Glass, Wood)

Non-structural elements are removed from the structure before basic demolition. Ferrous material categorized as non-reinforcement is also included in this material.

3. Interior removal: R_I (target: Paper, Non-ferrous, Plastic, plaster and other)

The materials used for the interior fabric of a structure are removed from the structure before basic demolition.

4. Reinforcement removal: R_R (target: Ferrous $_R$)

Reinforcement embedded in RC elements is removed. As mentioned above, ferrous material categorized as reinforcement is the target here.

5. Masonry removal: R_M (target: Mineral and Clay)

Masonry material is separated from concrete to send to the sorting plant separately. Low value implies these materials are treated as mixed inert waste off-site.

6. Disposal of inert waste: R_D (target: Concrete, Mineral and Clay)

Some of the inert waste can be sent to a landfill facility for disposal.

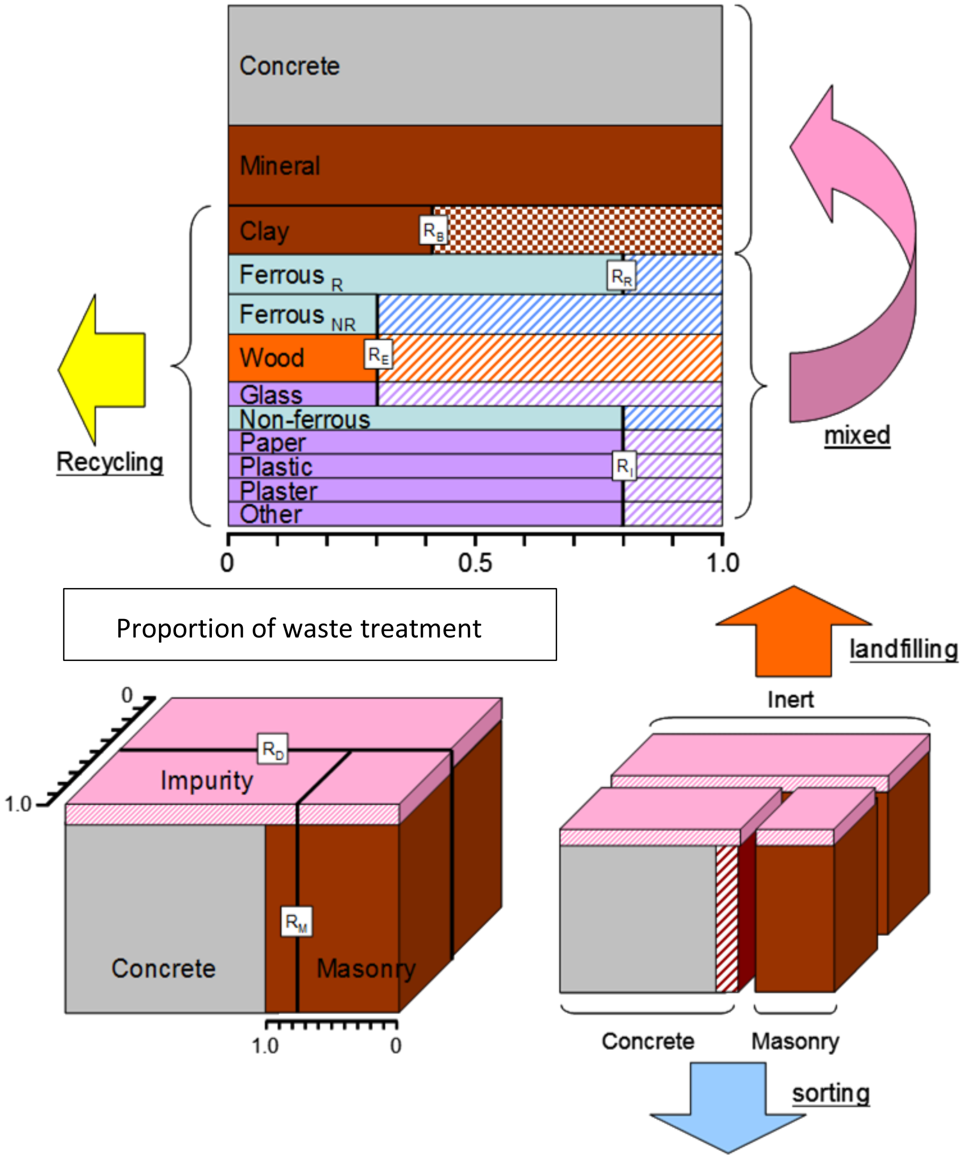


Figure 26 Outline figure for sorting rate and waste treatment

Phase3. Transportation

The material pre-sorted on site is transported to three types of off-site facility; sorting, recycling and landfill. Transportation between off-site facilities is also included in the calculation of total environmental impact.

Phase 4. Treatment off-site

Phase 4.1 Landfilling

Inert waste can be sent to the closest landfill facility from the demolition site, and disposed of. This happens directly from the demolition site and disposal from other facilities is ignored in this study.

Phase 4.2 Sorting

Concrete and masonry waste are sent to the closest sorting facility. After impurities are removed, each waste material is sent to the closest recycling facility from a sorting facility.

Phase 4.3 Recycling

As mentioned above, there are two ways demolition waste components are sent to a recycling facility; from a demolition site directly and via a sorting plant. It is assumed there is no difference in the quality of material from the different sources.

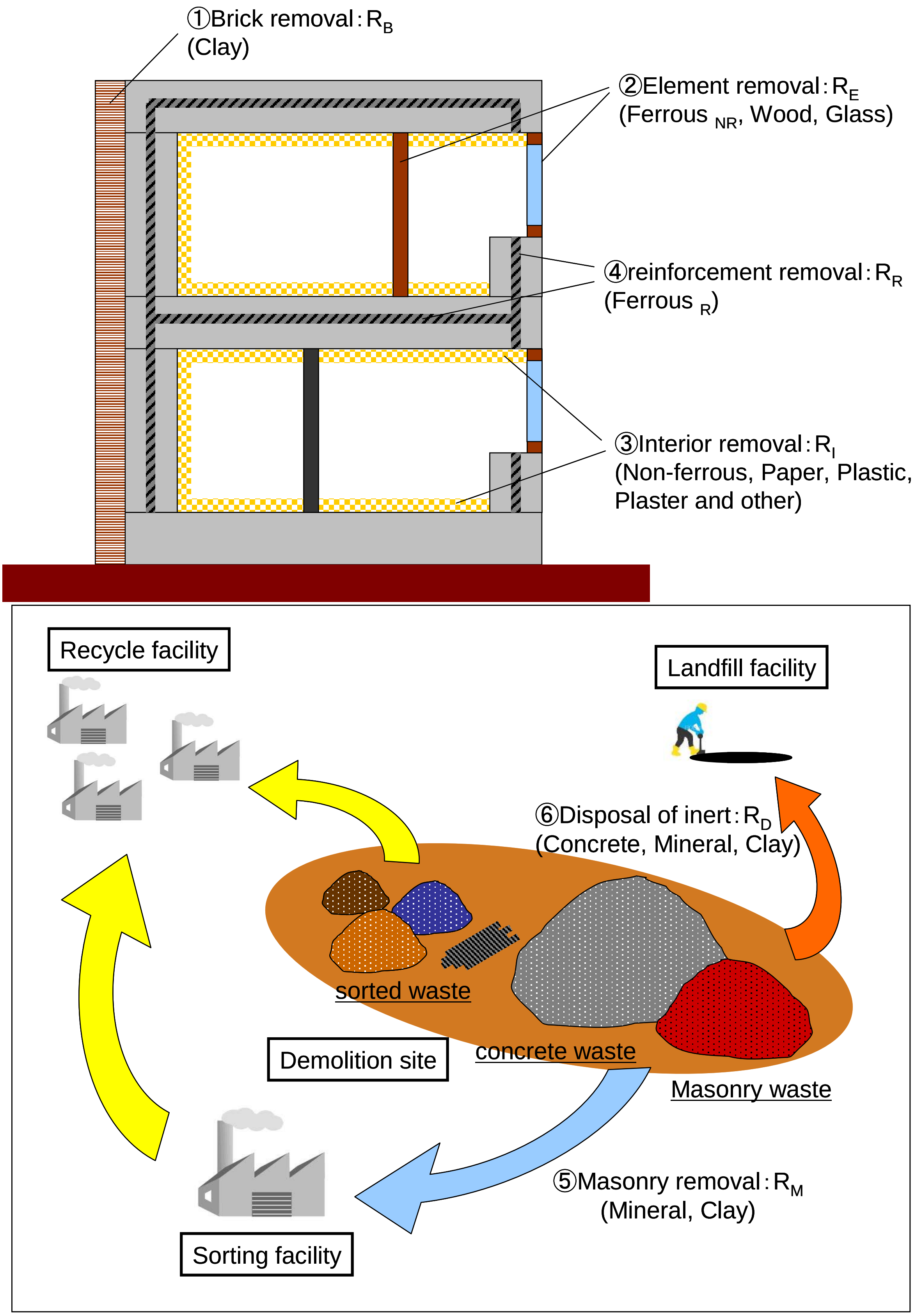


Figure 27 Outline figure for dwelling demolition with segregation coefficient

<Basic value input>

In order to comprehend the amount of waste generation, here, the basic amount of materials for dwelling is calculated as an input. According to the demolition material flow explained above, the input values are set based on the data for dwelling demolition across Great Britain. Comparison of the environmental impacts from model calculations under several scenarios allows discussion of optimal demolition and waste treatment strategy across Great Britain. In this study, the nature of a dwelling is defined as the same as the dwelling demolition used for 'Alcore model' case study as shown in Table 10. This is also based on the above hypothesis that the difference of Spanish and British dwelling designs is ignorable.

Table 10 Dwelling status applied in this model

	Status
Usage	Dwellings
Structure	Reinforced concrete, concrete slabs in first floor
Floor numbers	4
Dwellings per floor	4
Dwelling surface	100
Total surface	16*100 m^2= 1600 m^2
Total mass	2000 tons

(Source: Solís-Guzmán et al., 2009)

Phase1. Basic demolition

Due to the definition of basic demolition as including the separation of reinforcement from RC elements, the reinforcement is assumed to be separated at the conventional sorting rate during this phase. Therefore, additional treatment improves the separation rate depending on this process.

Phase2. Pre-sorting on-site

The conventional sorting rates are shown in Table 11 as mentioned in the 'data collection' section. This value describes how much proportion of each type of elements is sorted out before main demolition. There are some non-inert materials which are present at greater masses at the demolition phase relative to the construction phase in the 'Alcore model'. The separation rate for each material component as a target is defined from the following Formula.8. In addition, the coefficient of disposal of inert waste is added here. This is calculated from the landfill and recycled waste share reported by BRE(Building Research Establishment) (2006).

$$R = 1 - \frac{\left| M_{construction} - M_{waste} \right|}{M_{construction}} \quad (8)$$

where

R: coefficient of sorting rate

$M_{construction}$: total mass share for target material at the construction stage

M_{waste}: total mass share for target material in demolition waste

Table 11 Conventional sorting and disposal rate

Coefficient	value
R_B	0.4
R_E	0.3
R_I	0.8
R_R	0.8
R_M	0.8
R_D	0.1*

*This is calculated from the landfill rate in the UK demolition waste management.

(Source: Solís-Guzmán et al., 2009 and BRE(Building Research Establishment), 2006)

Sorting efficiency is decided by the relation shown in Figure 28 with collected data for three scenarios of no sorting, conventional sorting and complete sorting. Those are plotted in the figure, and correlation lines are drawn to estimate the values of the days in between. For conventional sorting, it is assumed the conventional sorting as mentioned above is achieved within 2 days (see marks on the second day in Figure 28) based on the current demolition practice that no more than 2 days can be spared for 'soft stripping' due to financial and time limitation (Poon et al., 2001). On the other hand, the description of two weeks extra treatment for complete recycling by Hobbs et al. (1997) is converted to 10 days excluding weekends. The environmental impact from sorting is evaluated by dividing the total energy consumption with the treated mass of waste. Here, complete sorting for 10 days implies 2000 tons of sorting. As a result, 200 tons of demolition waste is assumed to be treated per day.

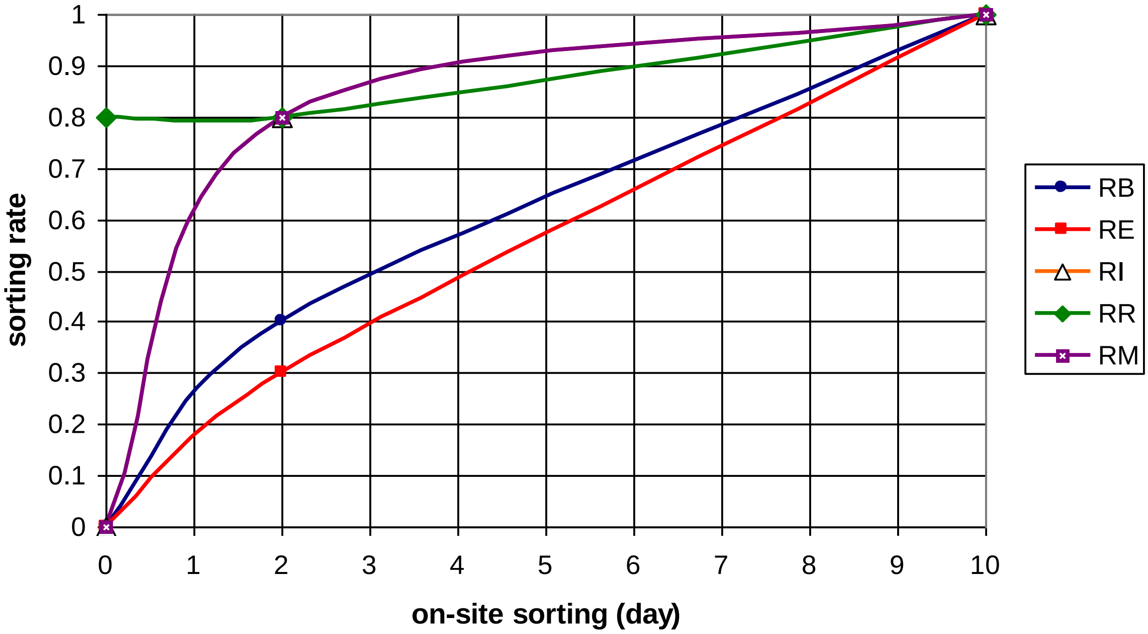


Figure 28 The change of sorting rate with on-site treatment term

<u>Phase3. Transportation</u>

The distance between two places is expressed as a product of their direct distance and coefficient 1.25. This is introduced by Kitagaki et al. (2008) who survey the proportional factor from the comparison between actual road distance and direct distance with geographic information system (GIS). The fuel consumption for each material is given from the data of Mercante et al. (2012) according to transportation purpose as shown in Table 12. Here, some missing materials are added by present author. The value of waste density refers to a report from NOLAN-ITU PTY LTD (1998) and the mean fuel consumption value is assumed from the other materials' correlation between load and fuel consumption as shown in Figure 29. It shows an inverse relationship between load and mean fuel consumption for transportation.

Table 12 Fuel consumption of transportation

Section	Type of waste	Density (t/m3)	Capacity (m3)	Load (t)	Mean consumption (kg diesel/t km)
Site — sorting plant or site — landfill	Mixed and reject	0.98	20	18	0.018
	Inert	1.2	20	18	0.016
	Concrete	1.5	25	25	0.014
Site– recycling facility or Sorting plant – recycling facility	Paper	0.07	20	1.4	0.123
	Plastic	0.06	20	1.2	0.143
	Wood	0.2	20	4	0.048
	Metal	0.33	20	6.6	0.026
	Plaster*	0.2	20	4	0.048
	Glass*	0.7	20	14	0.019
	Other*	0.3	20	6	0.034
Sorting plant – Landfill	Reject	1	8	8	0.03

*Modified part from reference.

(Source: Mercante et al., 2012 and NOLAN-ITU PTY LTD, 1998)

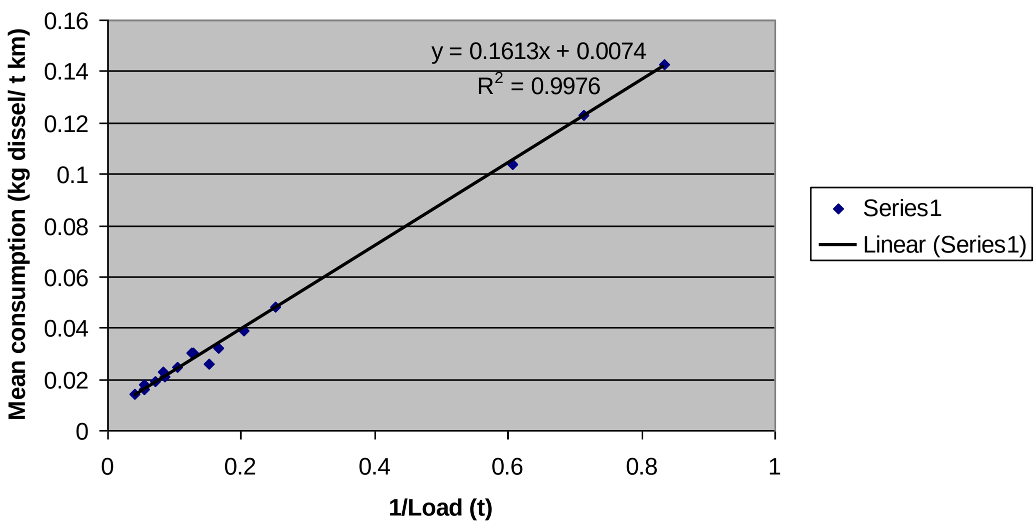


Figure 29 Correlation between load and mean consumption for transportation

(Source: Mercante et al., 2012)

Phase 4. Treatment off-site

Phase 4.1 Landfilling

Mercante et al. (2012) surveyed the average fuel consumption caused by the inert waste landfill operation for two enterprises in Spain. They surveyed that 0.11 and 0.28kg of diesel were used per ton of landfilled waste. Thus, 0.15kg of diesel per ton of waste is applied in this study. In addition, 'landfill volume' is calculated by the conversion from mass to volume with mixed demolition waste density. The value, 0.98 tons per cubic meter, is applied in Table 12.

Phase4.2 Sorting

Mercante et al. (2012) also obtained empirical data for fuel and energy consumption of sorting treatment. This is shown in Table 13 with the conversion to energy consumption. While plant I treats waste without distinction of mixed and concrete waste, plant II treat them separately. Therefore, the impact of sorting for concrete waste and masonry waste applies the value of treatment for 'concrete C&DW plant' and 'Mixed C&DW plant' of Plant II in Table13, respectively.

In addition, the fuel and energy consumption for on-site sorting applies the value for the process of 'Secondary sector' in 'Mixed C&DE plant' in Tabke13 which is mainly achieved by 'manual sorting.

Table 13 Fuel and energy consumption of sorting treatment

Plant type	Process	Diesel fuel (L/t)	Electrical energy (kWh/t)	Energy consumption (MJ/t)
I	Pre-treatment	0.06		2.15
	Primary sector	0.28	1.44	15.22
	Secondary sector		0.62	2.23
	Tertiary sector	0.28		10.04
	Total	0.62	2.06	29.65
II	*Mixed C&DW plant*			
	Pre-treatment	0.05	0.02	1.86
	Primary sector	0.19	0.12	7.25
	Secondary sector		0.06	0.22
	Tertiary sector	0.19	0.24	7.68
	Total	0.43	0.44	17.00
	Concrete C&DW plant	1.02	2.59	45.90

	(MJ/l)	(MJ/kWh)
Conversion efficient	35.9	3.6

(Source: Mercante et al., 2012)

To focus on the efficiency of offsite sorting treatment, Schachermayer et al. (2000) show the empirical result that 80% of organic carbon, 50% of iron and 30% of zinc are recovered from drying process. The values for sorting efficiency for each waste component are assumed as Table 14. Wood, paper and plastic use organic carbon, and ferrous and non-ferrous use iron and zinc values respectively. The other materials set '50'% as the average of these three types.

Table 14 Offsite separation rate

Material	removal rate
Mineral	0.5*
Clay	0.5*
Ferrous	0.5
Non-ferrous	0.3
Wood	0.8
Paper	0.8
Glass	0.5*
Plastic	0.8
Plaster	0.5*
Other	0.5*

*This part is set based on the average value of other material's removal rate..

(Source: Schachermayer et al., 2000)

Phase4.3 Recycling

The evaluation of environmental impact at this phase is decided by the balance between 'fuel and energy consumption' for recycling treatment and saving of 'fuel and energy consumption' for virgin material production. These values are given from the carbon and energy inventory made by Hammond and Jones (2008). The sum of environmental impact for recycling process and the value of recycled material as an alternative material can be calculated from the values in their inventory for embodied energy of recycled and virgin construction material as shown in Table 15. However, because embodied energy for recycled material contains transportation and treatment process, calculation for conventional treatment uses this value to evaluate its impact excluding transportation and treatment process. Then, the other scenarios should use the gap of impact value from the conventional treatment. This ensures the avoidance of multiple counting for each process.

Table 15 Embodied energy for recycled and virgin construction material

Original Material	Recycled Material	Embodied Energy(MJ/kg)		Material Detail
		Recycled	Virgin	
Concrete	Aggregate (Sand*[a])	0.25	0.10	*[a] Depending on impurity
Mineral (Masonry)	Sand	0.23*[b]	0.10	*[b] Gap between Concrete and Masonry process, 0.02 is subtracted.
Clay	Clay	0.09*[c]	3.00	*[c] Clay(Brick) shows reclaiming process enregy consumption.
Ferrous	Steel	9.50	35.30	
Non-ferrous	Non-ferrous	19.64	138.21	Aluminum, Brass, Copper, Lead, Titanium, Zinc
Wood	Timber	3.46	19.12	Hardboad, Hardwood, and Particle Board
Paper	Paper	18.50	32.32	Cardboard and General paper
Glass	Glass	7.85	19.57	Fibreglass and General Glass
Plastic	Plastic	64.50	106.60	ABS, PET and Polystyrene
Plaster	Plaster	2.24	4.86	Plasterboard
Other	Other	0.00*[d]	0.00*[d]	*[d] Environmental impact is ignored.

(Source: Hammond and Jones, 2008 and Department of Environment Climate Change and Water NSW, 2010)

In addition, the proportion of material consumption altered by recycled materials is also considered to evaluate the value of saving energy from recycling. The input and output mass is converted with Table 16. The other materials not mentioned in the table are assumed to have no mass change.

Table 16 Mass change from recycling treatment

Recovered material	Avoided product	Substitution ratio
Paper and core board	Sulphate pulp and core board	1: 0.83
Recycled aggregates	Gravel unspecified, at mine	1:1
Metals[a]	Pig iron	1:1
Wood	Wood chips softwood	1:1
Plastic	Polyethylene, HDPE, granulate (40%), polyvinylchloride (15%), polyethylene terephthalate (40%)	1: 0.81

[a] Assumed ferro metal, since ferro metal represents 96%

(Source: Mercante et al., 2012)

<Distance calculation model>

The two approaches are applied to calculate the distance between facilities in this model. As the first calculation concept, the closest facilities are chosen as the treatment facilities for the demolition waste regardless of their function. This implies recycling facilities for direct recycling from demolition site and for indirect recycling from sorting facility can be different (e.g. if demolished at London and sent to Bath for sorting, it would be recycled at Bath although some waste is directly recycled at London) . This is calculated using 'variable increment method' of 'Demolition generation model' for 1 years (360 days). However, this concept does not consider the treatment and storage capacity. Accordingly, in the second model, the facility capability is set for recycling and sorting facilities to treat only the demolition from one site. These facilities cannot treat further demolition waste until they manage whole waste with their treatment ability. Landfilling facility is not included to consider the capability because the capacity will not be reached within few days but more than decades. For the treatment ability for sorting facility, Mercante et al. (2012) note the average treatment ability is 3000-4500 tons per day. From here, 3750 tons per day is applied for this model. On the other hand, the average value of treatment ability is not given for each type of recycling plant. Therefore, the values shown in Table 17 are used as the facility capability supposing recycling facility scale has linear correlation with the mass of generated demolition waste. These values are decided using mass of recycled material calculated by previous models with conventional scenarios. The facility capability against waste generation volume from single demolition is set as 100, 80, 60, 40, 20, 10 and 1%, respectively. The influence of facility capability is calculated using 'fixed increment method' of 'Demolition generation model' for 1 year (360days) to comprehend daily change. It should be noted that if there is no capable facility in Great Britain, the transportation distance was put 1000km as the probable longest distance from one end of Britain to the other.

The thorough impact evaluation flow was depicted with an example in Figure 30. As mentioned at the beginning, the model was developed in the VBA environment (in excel) and showed a great advantage in data analysis using the excel software.

Table 17 Facility capability for recycling facilities

(ton/day)

	C1	C2	C3	C4	C5	C6	C7
	100(%)	80(%)	60(%)	40(%)	20(%)	10(%)	1(%)
Co	1048.07	838.45	628.84	419.23	209.61	104.81	8.38
M	518.12	414.49	310.87	207.25	103.62	51.81	4.14
Cl	28.76	23.01	17.26	11.50	5.75	2.88	0.23
F	34.55	27.64	20.73	13.82	6.91	3.46	0.28
NF	7.81	6.25	4.69	3.12	1.56	0.78	0.06
W	89.78	71.82	53.87	35.91	17.96	8.98	0.72
Pa	0.48	0.39	0.29	0.19	0.10	0.05	0.00
G	10.57	8.46	6.34	4.23	2.11	1.06	0.08
Pl	16.08	12.86	9.65	6.43	3.22	1.61	0.13
Pb	26.23	20.98	15.74	10.49	5.25	2.62	0.21
O	37.05	29.64	22.23	14.82	7.41	3.70	0.30

On-site Sorting (demolition site)

Treatment day				2
Total Energy use (MJ)				892.00
	Mass (ton)			
	Original	Recycling	Sorting	Landfilling
Co	1077.41	0.00	969.67	107.74
M	583.06	0.00	524.75	58.31
Cl	71.90	28.76	38.83	4.31
F	40.99	29.29	10.53	1.17
NF	9.14	7.31	1.65	0.18
W	111.67	33.50	70.35	7.82
Pa	0.51	0.41	0.09	0.01
G	17.19	5.16	10.83	1.20
Pl	17.03	13.63	3.07	0.34
Pb	29.47	23.58	5.30	0.59
O	41.62	33.30	7.49	0.83

Transportation1 (D to L)

Total Energy use (MJ)				817.28
	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
I	182.51	6.49	0.69	817.28

Landfilling (landfilling facility)

Treatment mass (ton)	182.51
Total Energy use (MJ)	1179.91

Transportation3 (D to S)

Total Energy use (MJ)				7295.66
	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
Co	1159.55	7.09	0.60	4932.74
M, Cl	483.01	7.09	0.69	2362.92

Recycling process

Total Energy use (MJ)				-3828673.33
	Energy efficiency (MJ/ton)		Mass (ton)	Energy use (MJ)
	Gap from Conventional	actual value		
Co	0.00	150.00	1048.07	157209.98
M	0.00	130.00	518.12	67355.05
Cl	0.00	-2910.00	28.76	-83694.05
F	0.00	-25800.00	34.55	-891454.46
NF	0.00	-118570.11	7.81	-925845.18
W	0.00	-15657.02	89.78	-1405685.85
Pa	0.00	-13823.45	0.40	-5540.60
G	0.00	-11720.95	10.57	-123926.89
Pl	0.00	-42103.27	13.02	-548373.77
Pb	0.00	-2620.00	26.23	-68717.56
O	0.00	0.00	37.05	0.00

Transportation2 (D to R)

Total Energy use (MJ)				4758.05
	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
Co	0.00	14.09	0.60	0.00
M	0.00	12.68	0.69	0.00
Cl	28.76	14.25	0.69	282.84
F	29.29	7.98	1.12	261.79
NF	7.31	14.23	1.12	116.58
W	33.50	6.85	2.07	475.02
Pa	0.41	6.65	5.30	14.43
G	5.16	8.74	0.82	36.97
Pl	13.63	9.62	6.16	807.58
Pb	23.58	42.89	2.06	2082.76
O	33.30	13.80	1.48	680.07

Off-site Sorting (demolition site)

Total Energy use (MJ)				61434.62
	Mass (ton)			Energy use (MJ)
	Input	Breakdown	Output	
Co	1159.55	969.67	1048.07	48161.82
M	483.01	524.75	518.12	10416.13509
Cl		38.83		
F	0.00	10.53	5.26	196.88
NF	0.00	1.65	0.49	18.47
W	0.00	70.35	56.28	2104.97
Pa	0.00	0.09	0.07	2.76
G	0.00	10.83	5.42	202.55
Pl	0.00	3.07	2.45	91.74
Pb	0.00	5.30	2.65	99.20
O	0.00	7.49	3.75	140.11

Input Coefficient		Distance result	
Coefficient	Case 2	Type of transport	Distance (km)
RB	0.4	D to L	6.49
RE	0.3	D to R	6.65-42.89
RI	0.8	D to S	7.09
RR	0.8	S to R	2.77-26.95
RM	0.8		
RD	0.1		

Recycling (recycling site)

	Mass (ton)			Energy use (MJ)	
	Input	Output		Transport	Sorting
Co	1048.07	1048.07	RA	9626.45	48161.82
M	518.12	518.12	Soil	4763.21	10416.14
Cl	28.76	28.76	Cl	282.84	0.00
F	34.55	34.55	F	284.91	196.88
NF	7.81	7.81	NF	120.82	18.47
W	89.78	89.78	W	833.09	2104.97
Pa	0.48	0.40	Pa	15.51	2.76
G	10.57	10.57	G	56.98	202.55
Pl	16.08	13.02	Pl	882.74	91.74
Pb	26.23	26.23	Pb	2230.00	99.20
O	37.05	37.05	O	721.99	140.11
		Total		19818.55	61434.62

Transportation4 (S to R)

Total Energy use (MJ)				7764.85
	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
Co	1048.07	7.46	0.60	4693.71
M, Cl	518.12	6.71	0.69	2400.29
F	5.26	3.92	1.12	23.11
NF	0.49	7.67	1.12	4.24
W	56.28	3.07	2.07	358.07
Pa	0.07	2.77	5.30	1.08
G	5.42	4.51	0.82	20.01
Pl	2.45	4.97	6.16	75.16
Pb	2.65	26.95	2.06	147.24
O	3.75	7.56	1.48	41.92

Total process

Landfilled volume (m3)				186.23
Total Energy use (MJ)				-3826601.42
	Mass (ton)			Recycled Rate (%)
	Original	Landfilled	Recycled	
Co	1077.41	107.74	1048.07	97.3
M	583.06	58.31	518.12	88.9
Cl	71.90	4.31	28.76	40.0
F	40.99	1.17	34.55	84.3
NF	9.14	0.18	7.81	85.4
W	111.67	7.82	89.78	80.4
Pa	0.51	0.01	0.40	78.4
G	17.19	1.20	10.57	61.5
Pl	17.03	0.34	13.02	76.5
Pb	29.47	0.59	26.23	89.0
O	41.62	0.83	37.05	89.0

Figure 30 Sample result of flow sheet

2.3.4. Summary

To recap, above section introduces the huge possibility of the model extension with a new type of data application in the demolition modelling. As shown in Chapter2.3.1., adding the schedule information to the building objects with the 4D-CAD gives the visual understanding and the dynamism of model simulation, and enhances the exchangeability of project planning among stakeholders. Similar to this, in Chapter 2.3.2., adding the object property data with the BIM allows the stakeholders at each phase of building lifecycle to exchange the data across phases. Therefore, in order to modify the current 'cradle to grave' LCA to 'cradle to cradle', the BIM data is utilised to evaluate the demolition project with external software in this research. Furthermore, the 4D visualisation and individual impact factors caused by demolition (e.g. cost, CO_2 emission, energy use, and waste generation) are projected with the BIM data for the following waste treatment design. In this research, the 4D-CAD modelling is acquired from BIM and the input data from the users. Same as the conventional researches, relating project impacts are quantitatively analysed and referred to the planning improvement. Moreover, the application of a game engine enhances the benefit of visualization due to the continuous and machine-involved project recreation.

For the BIM application to construction projects, it allows any stakeholder to treat a sematic object-oriented data in the whole lifecycle due to the high exchangeability and interoperability. The ontology feature enables the further data processing even in the external software. Besides this, the BIM information is applicable to the whole life cycle. Although its application is only limited to the maintenance phase, the demolition phase can also exploit the advantage of the BIM application. To summarise the 4D-CAD application, it tries to describe the planning from linking the spatial and schedule information. Because of the structured framework between activities and element objects, each demolition activities can be numerically evaluated from the relating impacts (e.g. workability, risk etc.) derived. By adding the spatial information, visualisation of planning is easily achieved for a better understanding of stakeholders.

For the social impact model introduced in Chpater2.3.3., the waste management tools applied in practice and waste management models suggested by researchers were summarised in this section. The biggest reason why the waste management tools are used is that they allow the users to produce SWMP for free, which is a legal requirement in England for the construction and demolition projects. This is basically held in four processes (planning, implementing, recording and reviewing) and the models offer a prediction of waste generation at a design phase. The achievement rate of project under the plan is assessed through the comparison with the record of implementation. As the advantage of this type of tools, the project record can be collected from users if tools are online-based such as SMARTWaste. Then, the database for a prediction of waste generation becomes larger, well updated, and with more variety. It results in more accurate predictions which attract other users. Moreover, this system can be extended to the other evaluation factors such as energy consumption and necessity of transportation. However, at the same time, it has to be mentioned that there is no model-based prediction tools which are actually applied today. People need the conventional data set though construction and demolition project has largely changed with many factors such as building type, location, surroundings, applied method and mostly design. To solve this problem, a BIM model is suggested to be applied to evaluate a waste model. Since the BIM data gives the detail information for the material components of building elements, it is possible to design the material recovery at the element level. In addition, the material properties such as source, age and the application purpose can be identified from BIM data. Owning to that, the problems caused by the property uncertainty of recycled materials can be prevented. However, this model does not concern about the implementation of demolition. This is commonly mentioned to all suggested models to evaluate the volume of C&D waste generation. The difference of impacts from different demolition methods is not considered in their suggestions though they discuss the impact of the waste amount and component change. Thus, the comprehensive evaluation of project including the impact of demolition implementation can be involved as one of the gaps in modelling of the C&D waste management.

As another feature of suggested models, there are few types of research which cover the whole waste stream. This tendency comes from two reasons, due to i) the importance of certain process and ii) the limitation of research range. Setting the proper target is the most important aspect to develop a model which can contribute in practice. The waste management tools explained above are good examples which appeal to the project design teams for a SWMP production. In this aspect, most of the models are suggested to stakeholders such as demolition and construction project design team, demolition contractor, government and local authority. For former three targets, people focus on individual processes, demolition, construction and recovery processes. On the other hand, the others tend to cover multiple processes such as demolition and recovery to think about the major factors for the waste reduction. The complexity of factors and their interactions or the multi-aspect observations are involved as the huge challenges. As the solution, they need to set the boundary and compromise the influence out of it. This tends to be seen in a SD models which make a framework with interactions of factors. While it has an advantage to be able to involve qualitative factors in a model, it becomes too complicated with a large number of factors. On the other hand, an AB model can follow the whole waste stream from the movement of stakeholders as agents with the behavioural rules. This model does not need to concern the agent interactions or qualitative factors. Nevertheless, it requires a full investigation for stakeholder behaviours. Because of this reason, an EcoMA development team needs to refine targets such as concrete production with recycled materials where a sufficient data has been collected through interviews. Accordingly, the model development to cover the whole waste stream without extreme survey is also involved as the second largest gap to be filled to suggest an optimal waste management.

In summary, the development of evaluation models for demolition implementation and comprehensive waste management covering the whole waste stream are necessary to suggest the optimal waste strategy from demolition to next construction. Through the literature review, the application model of BIM to demolition design is regarded as the most prospective technology today. How to extend and combine BIM with the demolition implementation and exploit the advantages of BIM (detail data for element level) must be the biggest key to enable the evaluation of demolition impact for not only the volume of waste generation but cost, term, energy, water and labour necessity. In addition, as represented by EcoMA, an AB model seems suitable to describe the whole waste stream while a SD model becomes too complicated to describe the whole stream with the factors interactions. However, as aforementioned, it is the real situation that the detailed rule for stakeholders as agents is inevitable to establish an accurate model and the data collection hinders the applicability range. This can be expected to be solved by the adaptation of another type of model in a AB model framework. As applied in other fields to describe the complex system (e.g. social system and decision making system), several model types should be applied to make the total model more realistic. Based on above two possibilities, the evaluation model for an optimal waste management model is suggested and discussed in the following chapters.

Chapter3

<Chapter Abstract>

In this chapter, the methodology and the adopted method are explained from their definition. Following the description of general methodologies adopted in the academic research, the methodologies in this research are carefully applied to accomplish the objectives. For the selection of methods, the conventional researches focusing on the project planning in demolition are summarised in a table to identify the efficient method for each demolition target. Reading this chapter is helpful for readers to understand the validity of adopted methods and their fundamental methodologies.

Chapter3. Methodology

This chapter is separated into two main parts. In the first part, the definition of research and research methodologies are discussed to ensure the selection of the most suitable approach for the present research, in order to achieve the aim and objectives. Following this, the key methods adopted in this research are explained in terms of their concept, target and applied process in the research.

3.1. Research and research methodology

3.1.1. Definition of research

The word of 'research' is defined in the Oxford dictionary as "*a search or investigation directed to the discovery of some fact by careful consideration or study of a subject; a course of critical or scientific inquiry*" (Brock, 2001). Greenfield (2001) explains research as a sequential product with multiple methods, which starts from inquiry to experimental design, data collection, measurement and analysis, interpretation and presentation. Similarly, Black (1999) defines research as the process of answering a question (or questions) with structured processes as shown in Figure 31. He insists the importance of a systematic approach with a structured process in order to encourage the participant researcher in the process to "*ask the right question at the right time*". Questions can be classified into six types for in-depth research which are, in order of depth; i) descriptive, ii) explorative, iii) excavator, iv) predictive, v) explanatory and vi) control as detailed in

Table 18. These are potentially linked to the existing research and setting. Strict setting of variables in a question (or questions) would allow researchers to solve questions satisfactory (Black, 1999).

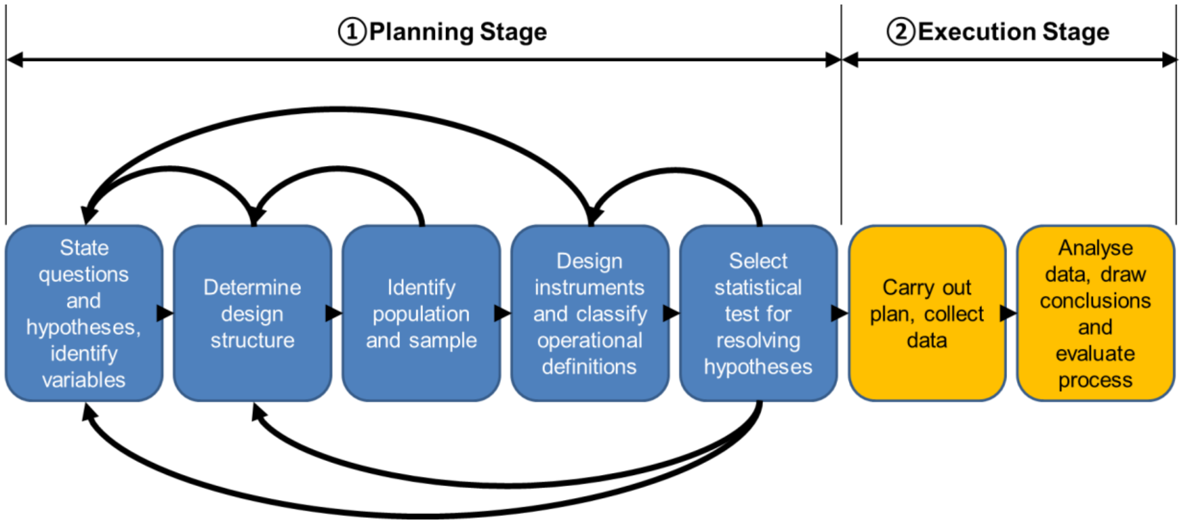


Figure 31 Stages of designing and carrying out research

(source: Black, 1999)

Table 18 Summary of objectives for each research question type

Question type	Objective	Example question
Descriptive	Description of target (e.g. people, event, process and outcome)	*How prevalent is the use of drugs among prison inmate?*
Explorative	Identification of related characteristics or details to observed event	*Is there any relationship between age and perception of quality music?*
Evaluative	Evaluation of process and procedure	*Which assembly-line procedure has the greatest effect on productivity?*
Predictive	Prediction of impact with single variable change	*At which times of the year do people of different age groups prefer to take overseas holiday?*
Explanatory	Explanation of relationship between cause and result	*Which side of the brain is predominantly responsible for computer mouse manipulation?*
Control	Evaluation of independent variable influence to dependent variables	*Is stress in patients about to undergo surgery reducible by specific type*

(source: Black, 1999)

Stacey (1969) categorizes research based on the reasons for conducting it; i) to solve a practical problem (‘applied’ research) and ii) to solve the issue with pure interest (‘pure’ research). In ‘pure’ research, the aim is to advance the knowledge for its own sake. On the other hand, the ‘applied’ research attempts to advance the technology which is expected to lead industrial development such as the goods and processes (Trochim, 2006). According to this definition, the present research is classified as ‘applied’ research as it is an example of engineering research which attempts to reduce the environmental impact of demolition. At the same time, research and applied methodologies can be separated into three based on data types; ‘qualitative’, ‘quantitative’ and mixed approaches (Fielding and Schreier, 2001; Creswell, 2009). According to the philosophical assumption and research aims, different research approaches will be applied. In the next section, two types of approach are introduced to explain an approach taken in this research.

3.1.2. Qualitative and Quantitative approach

3.1.2.1. Quantitative approach

Quantitative research is the oldest type of research since the emergence of social science to describe, predict and explain social biological phenomena (Locke et al., 1998). It is applied for testing objective theories through the examination of the relationship among variables. By applying an instrument to measure or observe participants’ behaviours or attitudes, the theory can be evaluated from the results of quantified variables (Creswell, 2009). The application of numbers for evaluating or describing the relation of variables ensures objectivity in research.

Many researchers broadly classify the quantitative approach into 'experimental' and 'survey' research (Abdullah, 2003, Fellows and Liu, 1997). 'Experimental' research aims to determine a relationship between variables. In order to identify an impact from the target variable, the other variables need to be controlled. It can be conducted both in the laboratory and in the field. Experiment conditions can be more controllable in a laboratory but field-based experiments can be tested in the real world. Although it is advantageous to analyse target variables or their relationships, generalization from the controlled conditions in the experiment is required. Moreover, the theory of phenomenon used for designing the experiment must be validated to ensure that target variables only are influential to the analysed phenomenon.

On the other hand, 'survey' research aims to collect data to advance researchers' knowledge. Interviews and questionnaires are two commonly used methods of data collection. Suitable methods are selected based on the purpose of data collection and the limitation of resources (funding, time, human labourer). Questionnaires are suitable for collecting factual data and interviews are used to collect data in more depth with more time and cost per person. The number of participants should be as many as possible to ensure the generality of results.

Locke et al. (1998) separates the quantitative approach into five types according to the purpose of research as shown in Figure 32. Similarly, Black (1999) introduces five representative types of quantitative research as i) descriptive, ii) normative, iii) correlative, iv) experimental/quasi-experimental and v) ex post facto. Based on these, the features and characteristics of three common research types are summarised in

Table 19. Research aims which can be achieved by quantitative approaches may need another approach as an intermediate step between 'experimental' and 'survey' approaches. After collecting the data with a 'survey' approach for descriptive questions, exploratory or explanatory questions (highlighted in yellow in

Table 19) need an 'experimental' approach. This implies that the quantitative approach can use different research questions for different depths of understanding. However, in order to achieve this, different approaches should be applied in same research to answer the question adequately. As shown in

Table 19, this is also the case with qualitative description. Since it is not suitable for solving 'predictable' and 'control' questions, a quantitative approach may be necessary if the sequential research approach is to be conducted. The mixed approach will be discussed in following section.

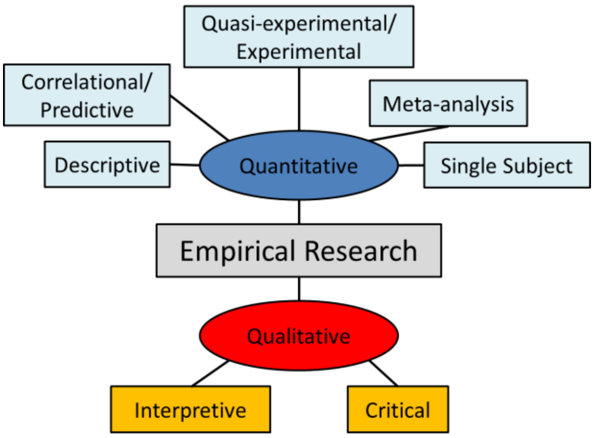


Figure 32 Organization of empirical research

(source: Locke et al., 1998)

Table 19 Summary of research methods used in quantitative research

	Descriptive	Correlational	Quasi-Experimental/ Experimental
Purpose	Description of a sample or subsample for specific variable	Description of relationships among variables to predict variables	Test of difference between group means for few independent variables
Common research format	•Survey research •Political polling •Delphi surveys	•Predictive •Multiple regression •Casual modelling •Path analysis	•Casual comparative •Repeated measures design •Within and between design •Randomized block design
Applicable research technique	•Data collection with instrument for specific variables (e.g. blood alcohol testing) •Paper-and-pencil inventories •Attitude measures •Surveys •Use of statistics to analyse data		

Question	Descriptive	Correlational	Quasi-Experimental/ Experimental	Qualitative descriptions
Appropriate design approach for question types				
Descriptive	√			√
Explorative		√		√
Evaluative		√	√	√
Predictive		√	√	
Explanatory		√	√	√
Control			√	

(source: Locke et al., 1998, Black, 1999)

3.1.2.2. Qualitative approach

The Qualitative approach to research aims to identify a theory which explains the relationship between independent and dependent variables. It tends to be applied for understanding a social or human problem, and researchers attempt to interpret the meaning of data (Creswell, 2009). The main difference from the quantitative approach is the type of variables, which are not countable. Accordingly, this approach is sometimes/often criticised as, merely exploratory, or subjective and not scientific. Due to research aim of interpreting phenomena in terms of human's conception, this approach involves collection and application of empirical materials by case study, personal experience, introspection, life story, interview, artefacts, and cultural or observational texts (Denzin and Lincoln, 2003). For better understanding, researchers deploy a wide-range of interconnected interpretive practices. Multiple application of interpretive practices is usually selected by researchers to describe the target world more generally.

'Action research' and 'case study' tends to be applied for data collection in qualitative approach (Patton, 2002). For 'action approach', it aims to yield the practical result from the systematic enquiry, which tends to be conducted with practitioners. By entering the target filed by researchers themselves, the real data can be collected or experienced from inside of target field. This research method is quite advantageous if the research question is at the exploratory level to enhance the knowledge of field to hypothesize a theory to explain or control the research target at following steps (Mcneil and Chapman, 2005). This is more casual approach to collect the information to attack specific problems within a program, organization or community (Patton, 2002).

On the other hand, 'case study' aims to explore a program, event, activity, process or individual for understanding in depth. With a strategy of inquiry, a variety of data collection procedures are applied to collect detailed information. In order to acquire information in depth, the boundary is set by time and activity (Creswell, 2009). Because of this specific research approach, the collected data or the suggested theories must be generalized before to insist research achievement. To prevent this, three things should be considered; i) ensuring study has more variables, ii) multiple data source, and iii) distinctive strategy for research design and analysis. In particular, a strategy should be designed based on theories for five steps; i) case selection, ii) target specification, iii) setting of final drawing, iv) stipulation of rival theories and i) result generalization. According to the aim of research questions as introduced in above section, research approaches are separated into 'exploratory', 'descriptive' and 'explanatory' case study. As researchers understand their target deeper, the research aims shift from data collection to data interpretation and hypothesising of theory to explain phenomena (Yin, 2003).

3.1.2.3. Mixed application

Mixed application philosophically assumes the use of qualitative and quantitative approaches in one or multiple studies. The mixed approach changes the research from simple data collection or result analysis to integrated research. The overall strength of research can be improved from the advantages of both approaches (Creswell, 2009). It began to emerge in the post-1990 period because qualitative and quantitative methods became compatible, and both can be applicable in empirical research (Denzin and Lincoln, 2003). This is more and more important for current research. Since research topics and structures have become more and more complicated, model applicability to both types and data exchangeability between them is increasingly important. In order to clarify the features of three methods approaches (quantitative, qualitative and mixed research), Creswell (2009) summarise them in

Table 20. Based on this, the robustness of mixed application for both, qualitative and quantitative type of data, is regarded as the most suitable approach for the present research. For instance, theories need to be suggested by making interpretation of data in a qualitative approach, and they will be tested validities in a quantitative approach. The results of simulation or the developed models through testing are again validated by practitioners, in which a qualitative approach is used for collecting feedback.

Table 20 Qualitative, quantitative and mixed research methods

	Qualitative research	Quantitative research	Mixed research
Philosophical assumption	•Constructivist / advocacy / participatory knowledge claims	•Post-positivist knowledge claims	•Pragmatic knowledge claims
Employed strategy for inquiry	•Phenomenology, grounded theory, ethnography, case study and narrative	•Surveys and experiments	•Sequential, concurrent and transformative
Employed methods	•Open-ended questions, emerging approaches, text or image data	•Closed-ended questions, predetermined approaches, numeric data	•Both open- and closed-ended questions, both emerging and predetermined approaches, and both quantitative and qualitative data and analysis
Research aims	•Positions him- or herself •Collects participant meaning •Focuses on a single concept or phenomenon •Brings personal values into the study •Studies the context or setting of participants •Validates the accuracy of findings •Makes interpretations of the data •Creates an agenda for change or reform •Collaborates with the participants	•Tests or verifies theories or explanations •Identifies variables to study •Relates variables in questions or hypotheses •Uses standards of validity and reliability •Observes and measures information numerically •Uses unbiased approaches •Employs statistical procedures	• Collects both quantitative and qualitative data •Develops a rationale for mixing •Integrates the data at different stages of inquiry •Presents visual pictures of the procedures in the study •Employs the practices of both qualitative and quantitative research

(source: Creswell, 2009)

3.2. Adopted methods

The inefficiency of current demolition and demolition waste management in terms of sustainability was identified from the literature review. Including the development of a collaboration system between demolishers and constructers, seven objectives were suggested (details can be seen in Chapter1.2.) in the present research. In order to select the optimal methods to achieve those objectives, the conventional approaches to the project planning reviewed in Chapter 2.2.1. were used in the present research. The applied methods and research properties (e.g. title and aims) are summarised in Table 21. It should be noted here that all the references were written as PhD theses so they are also useful for learning the structure of a PhD thesis for tackling the issues in demolition and demolition waste management.

According to the summary of references in Table 21, all the research references adopt two methods, 'Literature review' and 'Knowledge acquisition' at the beginning of research. 'Literature review' is commonly applied to understand the background or the conventional research focusing on the target topic for the further development of a research approach. For the 'Knowledge acquisition', the approach can be separated into two main types corresponding to each objective; i) knowledge extraction from specialists and ii) collection of feedback from the stakeholders. Similar to the literature review, knowledge extracted from people or participants is converted and stored as compatible data, which is used in the references for a deeper understanding of the industry or the structuring of the demolition project flow for both implementation and project planning. Compared to this, the attitude or opinions of stakeholders are also regarded as knowledge (or more likely the knowledge-based response) to be collected. This is an exploratory approach in which researchers survey an unfamiliar field (or industry) without any clear theory in order to identify the issues or gaps within the target field. For instance, Quarmby (2011) asked demolition practitioners the new processes which should be added for the adoption of secondary or sustainable products in practice. By using open questions, he aimed to elicit the beliefs held by the practitioner and based on the results, he summarised practitioners' awareness of sustainable resource application and clarified the onsite risks or issues identified by onsite workers. Not only the identified issues but the thoughts of practitioners are a useful resource here to estimate the feasibility of future recycled material application.

Then, based on the collected knowledge, most of the referenced authors applied the 'system suggestion' for demolition project planning to solve the current inefficiency. Then, 'database construction' and 'model development' often follow the system suggestion to include the new function in the system, and store the applied data. Because research topics and focuses tend to be too specific to find any previous model, models are frequently developed by researchers. As seen in Fox (1994), the demolition cost estimation model was developed based on the acquired knowledge. This model was adopted into the suggested Demolition Estimation System (DES) to calculate the total cost by linking to the quantity estimation function in the system. Accordingly, the system enabled users to estimate the result cost for the trust structure with data input.

As the final step, 'validation' was applied to the whole research which developed models. Although the applied methods are same as the knowledge acquisition (e.g. interview and questionnaire), another objective is to collect feedback on the suggested models or systems. For the rapid prototyping applied by Abdullah (2003) the cycle of 'model development/ modification' and 'validation' was repeated to make the best version of the system in the end. From the results, researchers can identify the benefits and limitations of the suggested model or system. Based on this, suggestions for how the research could be continued in the future are made in the conclusion of the theses.

After these examples of structured research, six methods were chosen to accomplish the objectives mentioned in Chapter 1.2. in the present research. Describing the research flow, these methods and output are summarised in terms of the thesis structure as shown in Figure 33. In the following section, the details of each key method are introduced to explain the content of the research to readers. It should be noted here that the 'case study' method was altered to 'pilot study' due to the limitation of data access.

Table 21 Conventional research focusing on the project planning in demolition

	Fox, 1994	Fletcher, 2001	Abdullah, 2003	Qu, 2010	Quarmby, 2011	Present thesis
Research title	Knowledge-based systems for the demolition industry	Developing disassembly strategies for buildings to reduce the lifetime environmental impacts by applying a systems approach	Intelligent selection of demolition techniques	Demolish-IT: the development of a process management tool for the demolition industry	Safe, healthy and sustainable demolition	Development of an impact assessment tool for demolition
Research aim	Validation of the advantage of **IT approach** to demolition industry by establishing the rule-based work estimation system based on practitioners' knowledge	Validation of the reduction potential of lifetime environmental impact with **appropriate disassembly strategies**	Development of a decision support system for demolition engineers to select the most **appropriate demolition technic** for target structure	Development of a **demolition process management system using ICT** to encourage the integration of stakeholders	Identification of the significance and key factors for the **sustainability development in demolition** sector	Reduction of demolition environmental impact with **C&D collaboration system** (by developing demolition impact evaluation tool)
Adopted methods						
i) Literature review	✓	✓	✓	✓	✓	✓
ii) Knowledge acquisition	✓	✓	✓	✓	✓	✓
iii) System suggestion	✓	✓ (LCA approach)	✓	✓		✓
iv) Database construction	✓		✓ (involved in system)	✓		✓
v) Model development	✓		✓	✓		✓
vi) Case study	✓	✓	✓			* (altered by pilot studies)
vii) Validation	✓		✓	✓		✓

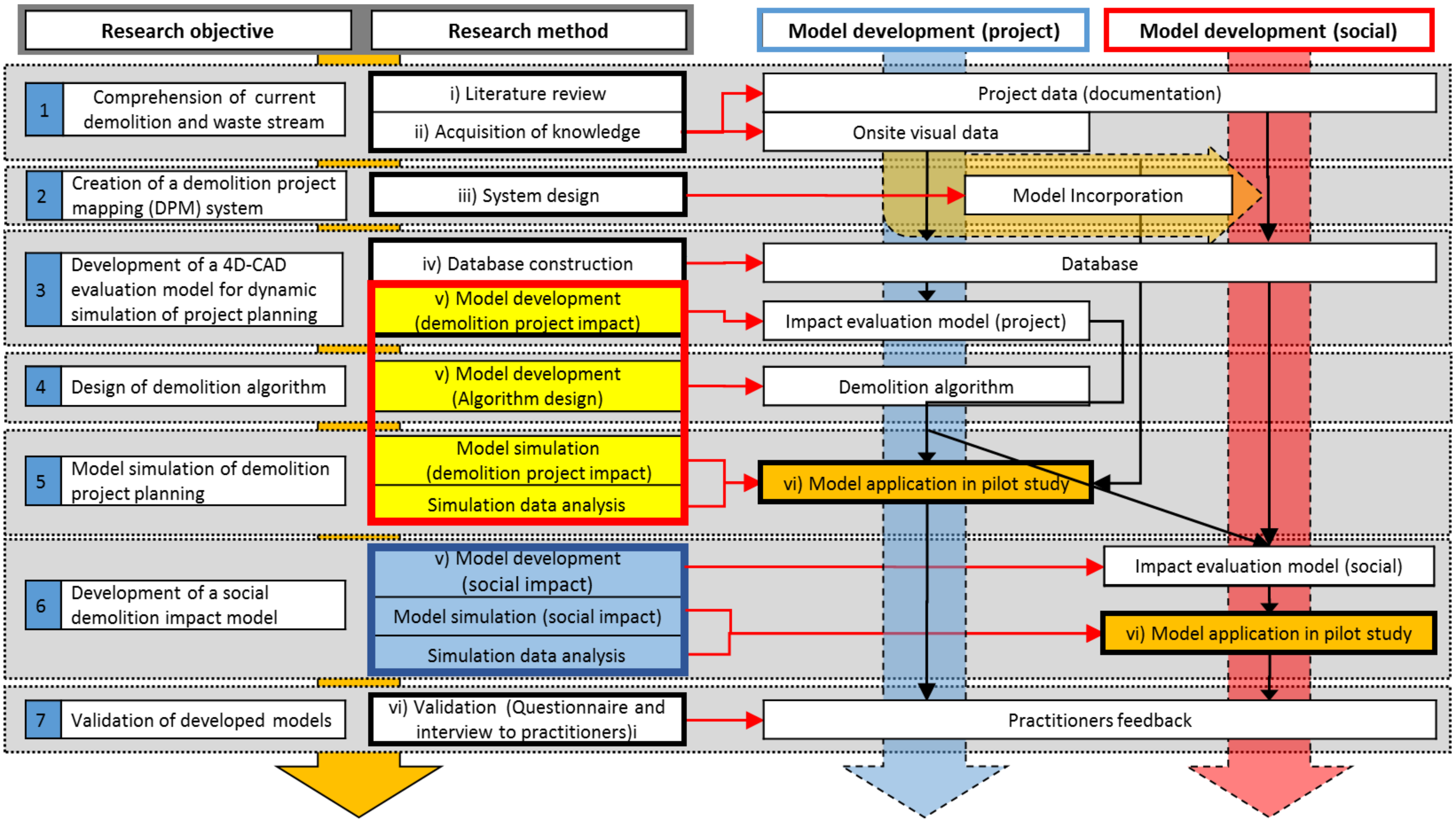


Figure 33 Abstract figure of thesis structure with method application

3.2.1. Literature review

Research success is largely underpinned by the efficient and effective information retrieval. This is more obvious in science, technology and medicine field in which searching techniques largely on electronic forms of information delivery. To enhance the efficiency of data collection, researchers must define the topic to be covered and identify suitable data source for own research (Greenfield, 2001). Based on this idea, three phase of process were selected as the topics at the first step of literature review to find a social gap in demolition; i) project planning, ii) project implementation and iii) waste management phases. The review was conducted from two viewpoints; i) how each process is implemented in practice and ii) what types of social gaps have been identified by other researchers, and how they have approached them. Consequently, three research gaps were identified and prospective research approaches in other research fields were selected as the second topics of literature review. '4D-CAD application', 'BIM application' and 'social system modelling' correspond to the demand of 'accurate waste estimation (in dynamic)', 'multiple impact evaluation' and 'transformation of waste recovery system', respectively. For the data source, it mainly relied on books and journals which is relatively accessible for students. In addition to this, documents and publications issued by organization in demolition industries such as IDE or National Federation of Demolition Contractors (NFDC) were covered to understand the industrial trend or emerging issues. Moreover, the act, regulations and standard related to demolition or demolition waste management were surveyed to comprehend the circumstance of stakeholders.

3.2.2. Knowledge acquisition

Knowledge acquisition is an important stage because the quality of knowledge underlying decides the power and utility of system. The process consists of eliciting, analysing and interpreting of knowledge to solve the particular issues (Kidd, 1987). This method tends to be adopted by researchers to extract the knowledge from non-literature sources. Therefore, casual acquisition of knowledge from people can be involved as the exploratory research for identifying a social gap. In this research, the same approach was attempted with a questionnaire method to demolition practitioners. However, due to the poor response, it was shifted to the individual negotiation with practitioners to share the information of their demolition projects. Project document and visual data were suggested to utilise the information extracted from sites. The detailed information is summarised in following section. It should be noted that the amount of shared information was not sufficient enough to generalize so that literatures written knowledge and visual data collected on internet were also referred to compensate those gap.

3.2.2.1. Project document review

This approach has been adopted for two reasons; i) comprehension of current demolition practice onsite and ii) acquisition of reference data for demolition project planning. Through the understanding of practice, the demolition project can be broken down into the individual processes. Based on this, the demolition implementation can be modelled precisely and it results in more accurate evaluation of project planning and a versatile tool for practitioners. In addition, current demolition planning approaches also give a huge opportunity for finding issues in project planning today. The decision making phase, especially, and how this happens in practice, is quite vague to the researchers This is connected to the third approach, communication during the document survey with practitioners, which allowed the comprehensive understanding of information in each document.

The second viewpoint is directly connected to the following model development for the project impact evaluation. In order to achieve a discussion for project planning quantitatively, it is necessary to develop an evaluation model for demolition. In an effort to validate the model after development, the actual project data has to be applied for the comparison. Because of this, site and project and demolition impact data were collected to model the implemented plan and compare its result with factual data.

To achieve the objectives of the above two points, demolition project documents which were offered by practitioners were reviewed, and their contents were reflected to the model and database framework. For the comparison of impact with simulation result, building design, site information, and project design were primarily collected in this review. How they were applied will be explained in detail in the following model development section.

3.2.2.2. Visual data collection

Visual data (e.g. video, time-lapse photo, etc.) has the same aim as the first approach; to understand the current demolition practice onsite. Compared to the previous approach, the significance of this approach can be seen as its ability for dynamic comprehension. It is a current bottle-neck that demolishers cannot follow the project uniqueness derived from the project environment and dynamic features, which results in a huge gap between the conventional model evaluation and actual impact in demolition. To establish the 4D-CAD application as its solution, the demolition order for element objects is set to guide the demolition machines for execution in this model as shown in Figure 34. Visual data analysis was decided as the best source for this.

Although the tracking function in 3D-CAD software would be applied to automate the process in the future development (as seen in Figure 35.), at this stage/ in this research, it has been done manually to convert their patterns into the model algorithm with programming language. This was applied in the model simulation to recreate the practice implementation. By comparing the project planning with the designed optimal demolition algorithm, the potential of impact reduction from project designing with this model can be validated. Chapter 3.4 and Chapter4 give details of the development of optimal demolition algorithm and the pilot study for the impact reduction of actual project planning, respectively.

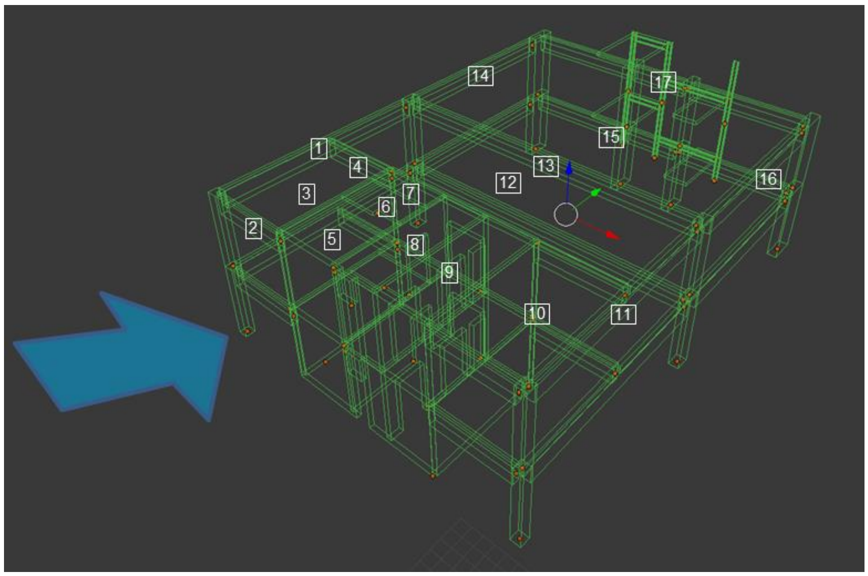


Figure 34 Demolition order converted from time-lapse data

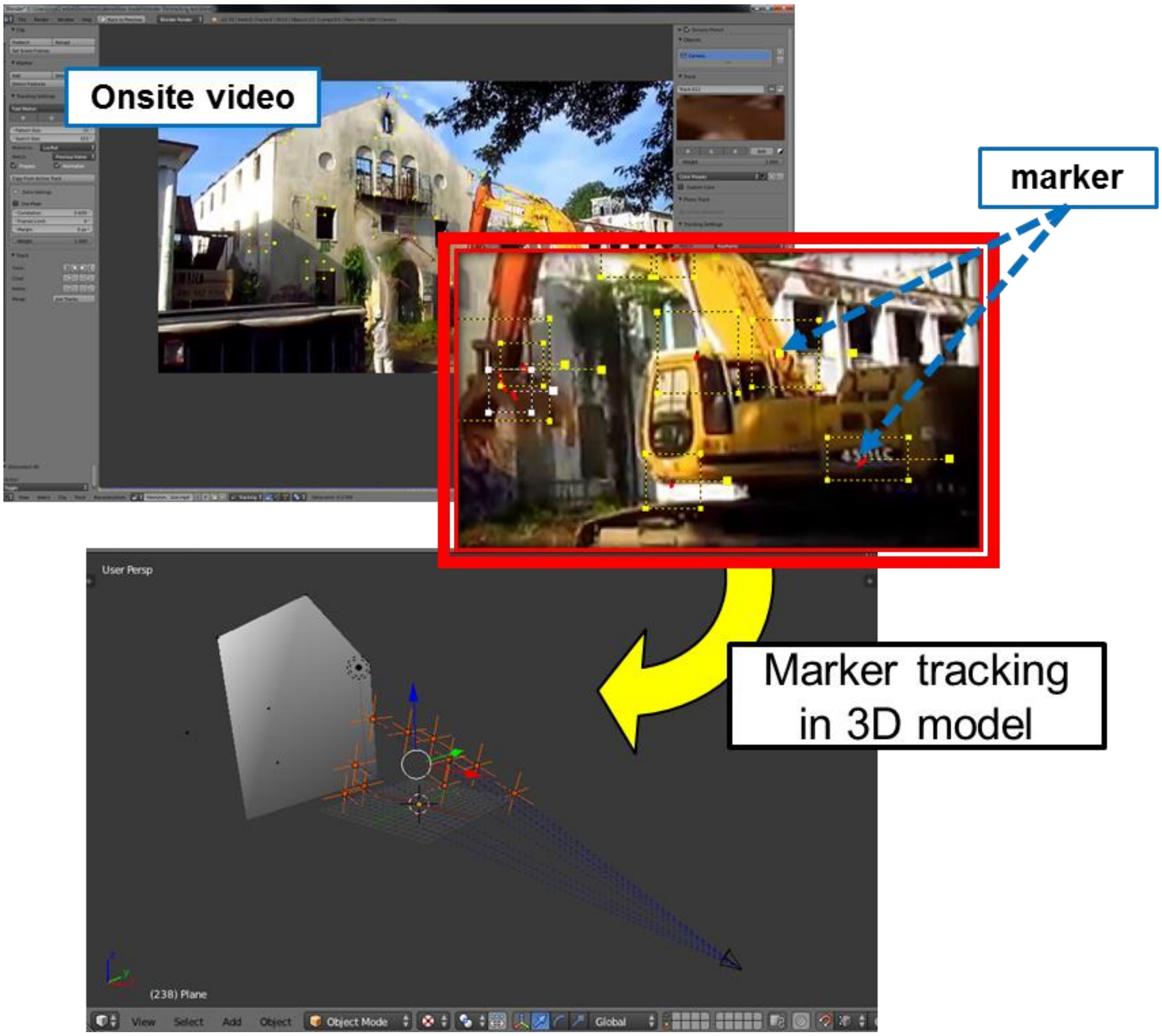


Figure 35 Machine manoeuvre data extraction from onsite video (in the 3D-CAD software, Blender)

3.2.3. Database construction

Data collection in practice has been achieved with the support of demolition practitioners in England. Three different approaches were adopted to collect data. First of all, the project documents were reviewed to discover conventional demolition approaches in practice. In addition to storing these in the database, the projects were chosen for the model application pilot study. While the building design and site information were used for modelling site conditions, the actual onsite impacts (e.g. cost, waste generation, etc.) were numerically compared with the simulation results of the project impact model. Secondly, onsite visual data is collected to understand the conventional demolition systems. From the repeated pattern in the data, the typical demolition orders in demolition systems were identified and converted into algorithms to store in the database. These algorithm patterns were used to recreate the demolition strategy in the model application phase. Finally, demolition practitioners were asked to give feedback on the research approaches using two different scale oriented models (project-based and society-based). Questionnaires were used for asking about the usability of models quantitatively while open questions, which mainly asked about recommendations for future development were obtained from individual interviews conducted by the author. This results are discussed in Chapter 7 before closing the thesis with the authors view.

3.2.4. Validation

This approach has been adopted for two reasons; i) better comprehension of current demolition practice onsite and ii) acquisition of feedback from practitioners for developed models and systems in this study. For the first objective, communication with practitioners during the document survey allowed for better understanding of information within documents. On the other hand, the feedback from practitioners was regarded (by the researcher) as the best source to validate the proposed model. Due to the nature of model development, it has inevitably been theoretical and that risks losing touch with practitioner demands. This situation strongly implies low expectations of the model or system application in the real world. Due to the fundamental purpose of this engineering research, a contribution to society, the practicability of model needs to be prioritized.

General validation methods can be summarised as Table 22 based on Carter (2015) and Qu (2010), who suggested the process management tool for demolition and applied several methods for model validation., This research chose interviews and questionnaires for validation due to the advantages of these methods. Questionnaires were used to ask demolition practitioners questions about model usability and functionality, and showed great advantages in respect of the quantity of collectable data and its comparability. This allowed numerical comprehension of feedback and analysis of the strengths and weaknesses of the model. In addition, interviews were adopted to elicit practitioner ideas due to the flexibility of questions. To exploit the professional experiences, the reasons for extreme scores given in the questionnaires were firstly asked in open-question style. Then, views on current problems of the model were elicited to obtain recommendations for further development of the model. The results will be discussed in detail in Chapter10.

Table 22 Summary of general validation methods

Method	Purpose	Advantages	Challenges
Questionnaires	To collect large information from target with less time and burden	•Anonymity of answer •Inexpensive •Data comparability •Large collectable data •Many sample to refer	•Careless feedback •Proper sampling •Closed question
Interviews	To get better understanding which is hard to cover with questionnaires	•Deep and wide data range •Encouragement of answerer commitment •Flexibility of question	•Time and cost consuming •Difficulty of analysis •Risk of bias
Documentation review	To comprehend research target without interruption by survey	•No interruption to related people •Existed data •Few bias on data	•Time consuming •Limit of available data •Inflexibility of data
Observation	To collect comprehensive information of research target, for each process	•Actuality of data •Data applicability to similar target	•Difficulty of analysis •Survey influence on result •Costly
Focus group	To dig down a topic into deep through group discussion	•Generality of data •Survey efficiency	•Difficulty of analysis •Difficulty to organize
Case studies	To fully comprehend research target by comparison of case examinations	•Structured understanding •Comprehensive for everyone	•Time consuming •Less generality

(source: Carter, 2015 and Qu, 2010)

Chapter4

<Chapter Abstract>

In this chapter, the collaboration support system between demolishers and constructers (DPM system) whose development is justified in the hypotheses is explained. System framework is firstly described with the applied data type and the mechanism of dynamic simulation of demolition projects. From the service to be offered by the DPM system mentioned at the final part, readers can get the clear vision of the practical use of the system in the future.

Chapter4. Method I: Development of DPM system

In the literature review, the understanding between demolition and future construction clients was regarded as the keystone of demolition waste recovery as the next construction resource. Construction project teams specify the degree of reuse and recycling in the project, and decide the project design from the benefit evaluation produced by the recovery. It implies that less availability of demolition waste around the construction demand can reduce the recovery benefit and discourage them to be more sustainable. In other words, the more information about demolition projects taking place nearby they can access, the more feasible it is to apply the waste recovery. In this research, therefore, a matching system between demolition and construction project teams is designed for the solution, referred to as the DPM system after the application of Demolition Project Mapping. In this system, the visualization of the demolition project and generated impact are mainly adopted to evaluate the project design for better understanding among whole stakeholders. This is expected to encourage them to pursue the optimal planning. Since the optimization here means the maximization of stakeholders benefit, it does not necessarily result in the most sustainable option. However, regarding the high cost of landfill or offsite waste treatment, the quantitative recognition of project impact is expected to lead them to sustainable options.

This chapter explains the system's framework and process detail. It will be followed by the introduction of the core tool of this system, an impact evaluation model for demolition project (model description in Chapter5 and result discussion in Chapter7). Then, an impact evaluation model for society is introduced to analyse the prospective impact reduction from the application of this system (model description in Chapter6 and result discussion in Chapter8). Through the case studies, both models are discussed at the end of this work (result comparison in Chapter10 and conclusion in Chapter11).

4.1. System framework

The system framework of the DPM system is firstly introduced as Figure 36. As seen there, this system consists of six steps (except green highlighted step) for the two stakeholders, demolition and construction teams. Firstly, demolition teams decide to use the matching system for three purposes; i) evaluation and optimization of planning, ii) advertisement of their own project to construction teams for better waste recovery (or site sales) and iii) documentation for SWMP. In the process, the users input the project planning data to the evaluation tool (the project impact evaluation model which will be introduced in Chapter4) via the system database. Then, the simulation result returns the result of the estimated demolition impact. Comparing the several project plans in those two steps, demolition teams eventually decide the one as the final project design and uploaded on an open mapping service, such as

'Google Maps'. Here, although 'Google Maps' is sited as the first probable choice for ease of imagination, the other Map software can play this role as well. Assuming the use of 'Google Maps', the project information should involve site location, building information (structure type, floor number, age, etc.), project planning (terms, demolition system, order of operation, waste generation, simulation animation, etc.) given as a simulation result and land price.

Followings are the steps for the users of construction teams who aim to find the most suitable construction sites for green building construction. Project distribution can be seen by the construction teams as shown in Figure 37. The registered demolition projects are located on Google Maps according to the site addresses, and once keywords are typed into the search engine several possible project planning would be shown next to the map. The construction users would select a few demolition projects and start to move on to the final step, the negotiation with demolition users who uploaded. When the both reach agreement on the contract, they can develop the final project planning to optimize the onsite productivity from two point of views, demolition and construction. Then, the demolition teams can document the SWMP from the project planning data through this system.

The above steps are separated into three main phases as shown in Figure 36; i) data application (step1), ii) model simulation (step2, 3) and iii) DPM application (step 4, 5, 6, 7). In the following sessions, the main phases are introduced in depth.

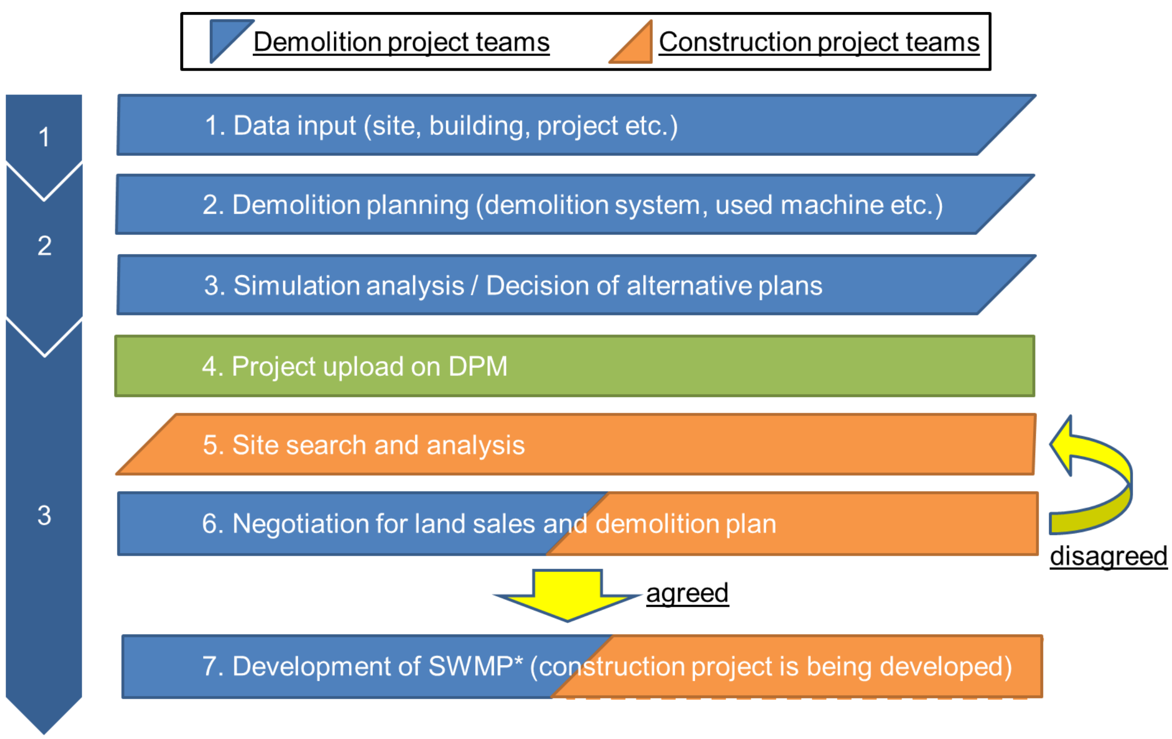


Figure 36 Main process flow

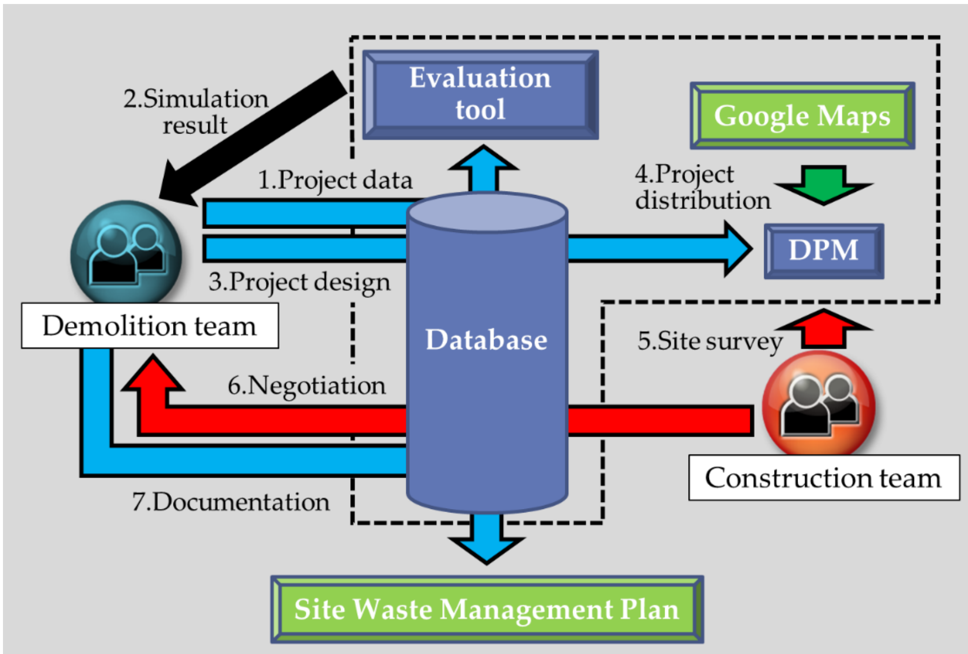


Figure 37 Framework of matching system

4.2. Data application

In the evaluation model, project planning is recreated by many selected data by users as project designers. While demolition projects contain a great deal of unique information such as site location and building design, common practice and resource can be seen among projects. To minimize the user burden and support planning, several types of general value (or algorithm) dataset stored in the database are available to refer to for most of the planning modelling phase in the model. For instance, the machine application does not need to input the whole information but asks for the machine product name. Then, according to the designated product name, the evaluation model recreates the machine model based on the manufacturer's official catalogue including the machine mobility and properties data (e.g. fuel consumption). The previous projects' data is also the important data source to acknowledge the demolition planning trend. Referring to this, future users can find the prospecting demolition systems for each site circumstance (e.g. top-down for urban congested). Furthermore, this information can be used to find the preferable project design for better productivity in demolition. Further detail of data application would be explained by each database type in the, 'database construction' section below.

4.3. Model simulation for project planning

The individual demolition evaluation model is adopted to evaluate the potential impact generation from the project planning. Although this will be explained later in depth, the model is composed of four steps of data input and one execution step. Firstly, target buildings to be demolished need to be modelled with 3D-CAD based on 2D design or BIM data. If BIM data is accessible, it is also advantageous to extract the comprehensive objects data used for following steps. If no 2D design or BIM data exists, laser scanning or observation by specialists should be alternatively applied to create a target building model. This step aims to comprehend the physical information of the building (e.g. location of element and material property) to numerically distinguish the access limitation and the projected time to disassemble elements. For second step, element treatment should be designated. This process decides the way of element treatment (e.g. preservation, soft-stripping and demolition). The model can recreate the partial demolition and evaluate the impact of soft-stripping before the demolition of loadbearing elements with this function. Following this, the applied machines data should be input by users. Scale, mobility and machine property value are installed in the model to simulate the impact caused in the whole project. At the fourth step, an demolition system should be selected to decide the demolition order of elements based on the above project design and demolition algorithm. Following input of the above data, the model simulation is executed with movie in 3D-CAD. From 3D visualization, the demolisher can confirm the order of demolition, and it can be regarded as the alternative proof to documentation of the demolition plan for SWMP regulation. Since the demolition impact for each factor (e.g. cost, energy and water consumption and waste generation) is shown live, demolition project team can modify their own plan to maximize project benefit. Project design and model simulation for reuse of building framework or high level of disassembling allows construction teams to assess the suitability of demolition site for own construction site. This is explained in the following section about system establishment.

4.4. DPM application

According to the model simulation, demolition project teams decide to upload the demolition plans to the web-based Demolition Project Map. It should be noted that the suitability of the plan from the demolition team may not match the one from construction teams so that somehow diversity of choices might be important. Consequently, construction teams start to find a suitable construction site from the search on the DPM. As mentioned above, it would be designed for construction teams to easily access necessary site information and alternative demolition plans. Similar to original 'Google Maps' design, site and building detail information is shown with links to designs and demolition project movies at the left side of the window. Further detailed information can be shown in the webpage which is accessible from the blue project name on the top, which is 'Hub reconstruction' or 'Hub annex reconstruction' in Figure 38. For right side of the window, geographic information of demolition site is described. Since site location is one of the biggest factors for construction teams, visualization of site distribution seems quite useful to compare alternatives and find the optimal choice. This geographic information also enables the understanding of the distances from resource suppliers. Thus, the supply chain data collected for waste management impact model should be used here and give further information, and construction project teams can analyse the feasibility of construction on the site.

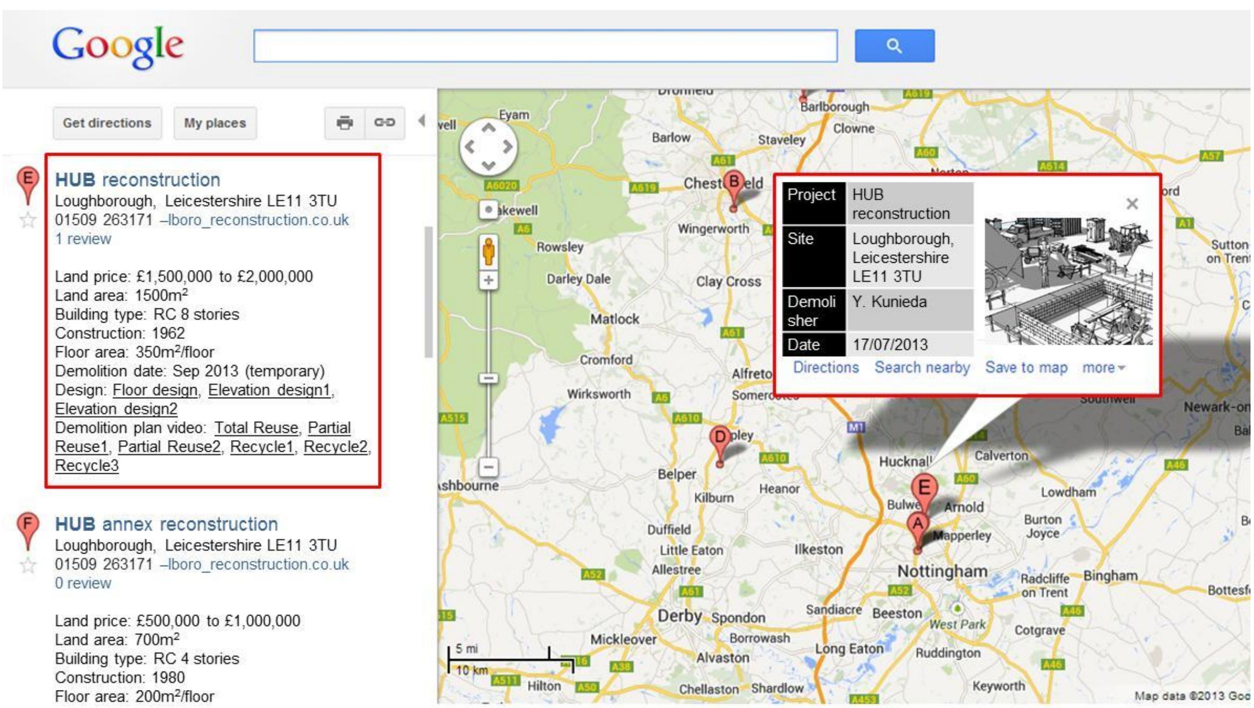


Figure 38 Abstract image of site searching at matching system with Google Maps

(source: Google, 2013)

Once the construction team finds the feasibility of construction at a particular site, they can make contact with demolition teams via the site of this system. Recording these contacts can be applied to understand the deciding factors of the construction site, and it can be applicable to the social impact evaluation model. Besides this, the recommendation function of search engines such as Google or Amazon can be adopted to help future users to find prospective alternatives according to their project demands. For the land contract between construction and demolition teams, they have to clearly define the responsibility for the contract and related loss. If the negotiation is not agreed by both sides, it will be returned to step five, to find new alternatives. Otherwise, the demolition project would be modified including the waste conditions between two teams. After designing offsite waste management with quantitative dataset, a comprehensive demolition plan can be designed. Ideally, as the final step, datasets input in three respective phases can be applied to the documentation of SWMP; i) project information at data application, ii) project impact estimation at model simulation and iii) waste management proposal at the end. The input style of SMARTWaste may be able to be referred to as the online input method as shown in Figure 39. In the same manner, the SWMP documentation for the new construction can be simultaneously created in this system with further development.

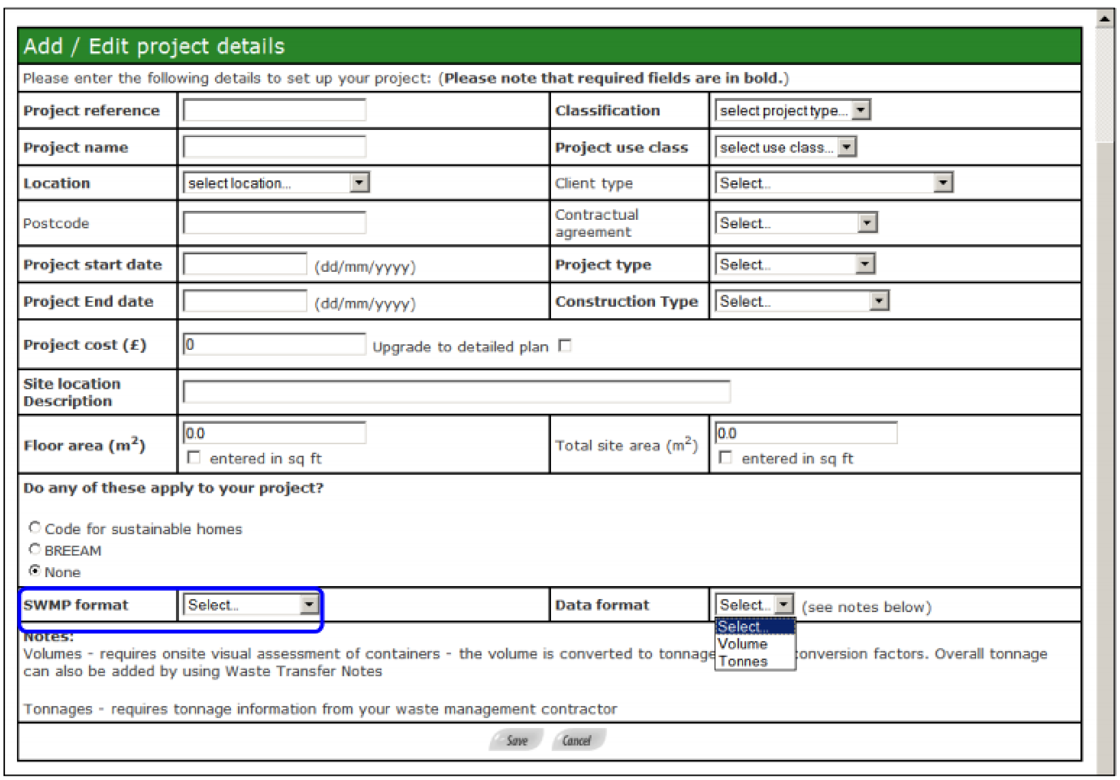


Figure 39 Input form of SMARTWaste

(source: BRE, 2009)

Chapter5

<Chapter Abstract>

In this chapter, the database referred to the calculation of necessary information is explained for the waste generation in the DPM system (described in the previous chapter). It mainly consists of four types of data; i) demolition method algorithm, ii) property of applied machines, iii) element material component and iv) impact conversion rate. Following the description of data application flow in the DPM, each type of data will be explained with the data content to be involved. Through this chapter, readers can comprehend how and with which data each impact can be calculated. Due to the limit of space, the detail datasets are contained in Appendix4.

Chapter5. Method II: Database construction

A referable dataset is essential in this research to make the demolition impact evaluation model more accurate and user-friendly. To clarify the target of each data application, the database was categorized by the target type of application. Data type, source and image of application are described in the following sections. The model validity should be understood from the actual value for each dataset seen in the Appendix4. It should be noted that the word 'impact' in following sections is defined as the influence caused by the target activities in demolition project. Although the final goal of this research is to minimise the environmental impact from demolition, the impact would be mainly estimated from three factors cost, environmental impact (CO_2 and gas emission and fuel consumption) and generated waste volume. Furthermore, the use of labours is also considered to make the model more useful for demolition users to design project planning.

5.1. Framework of database

In this research, the impact evaluation model for demolition is developed in the Blender with the platform shown in Figure 40. As described there, there are two main steps for the interchange of data between users and models; input and output. In the input phase, the users are only required to prepare the data of the building to be demolished while other demolition strategies can be designated by the optional choice which is retrieved from the database. Then, the simulation result would be extracted as the demolition impact evaluation at the output phase. This interchanged data can be summarised in the Table 23, which explains the demanded information, data type and its data source. While the target building and site conditions need to be imported by users using BIM or related tools (e.g. SketchUp having import add-in from Google Maps), other data can be stored and referred from the database. It allows the reference of old project design so that the designed project data can be stored as the reference data.

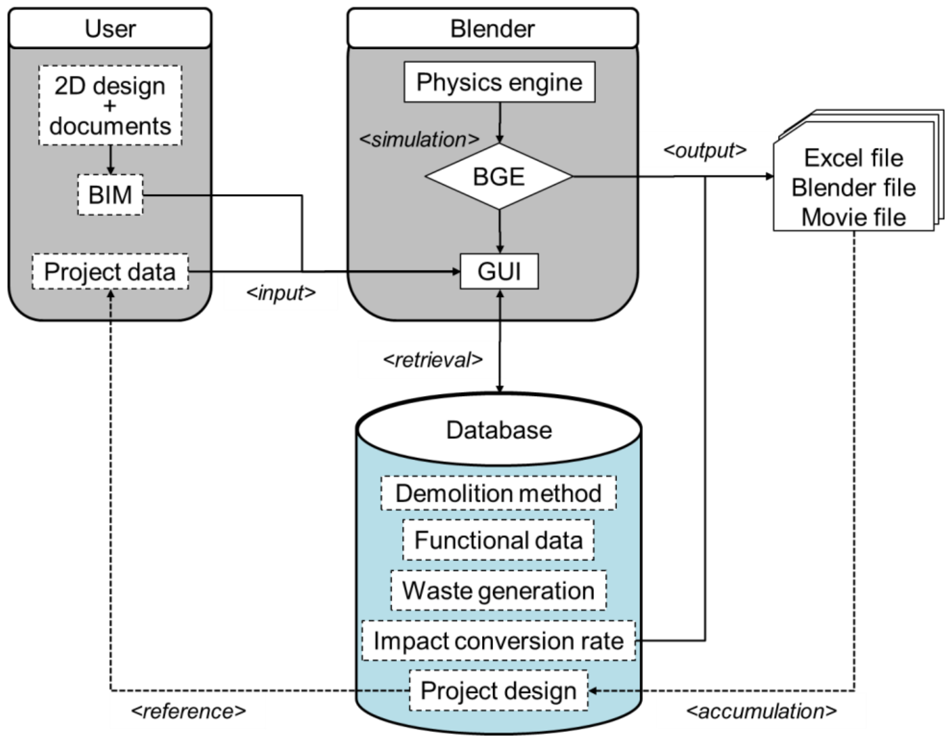


Figure 40 Platform of 4D-CAD impact evaluation model

Table 23 Interchanged data through the simulation process

Demanded Information	Data Type	Data Source
Input Phase		
Target building model	**Building information model (BIM)**	**User**
Target site model	**3D site model**	**Google Maps (with SketchUp add-in)**
Demolition method	**i) Demolition method (algorithm)**	**Database (Onsite visual data)**
Demolition machine	**ii) Functional data (Machine property)**	**Database (Machine product catalogue)**
Output Phase		
Waste component	**iii) Waste generation (Element property)**	**Database (Onsite data, Reference data)**
Total impact	**iv) Impact conversion coefficient**	**Database (Reference data)**
	Composite waste treatment (soft-stripping)	
	Individual waste treatment	
	Burden conversion (CO_2, NO_x)	

5.2. Content of dataset

According to the visual data analysis of onsite demolition, the applicable patterns of demolition system are interpreted as algorithm data and added to the database, and used in the individual demolition model. The resource database also set the target of machine type, waste type and related treatment for the other information input and output phases. Then, the impact coefficients which convert each type of impact from the duration of activity in terms of cost, energy and CO_2 emission are set to evaluate the total demolition impact with different project planning.

5.2.1. Demolition method

Here, demolition method is described with the algorithm, of demolition order as the pattern which is applicable to machine movements in the demolition impact evaluation model. In detail, each individual building element is numbered their order of demolition, and the demolition machines aim to destroy them from the youngest number in turn. In order to decide the demolition order of each element, the users are required to choose demolition i) system, ii) direction and iii) starting point before simulation. The further detail of game logic to recreate demolition in the Blender can be explained in the following model development section which explains the software detail of Blender in Chpater6. Main methods of its demolition order algorithm are explained according to the type of demolition system which is introduced in the previous literature review chapter. Detail algorithm descriptions can be seen in Appendix2.

5.2.1.1. Top-down

The top-down system demolishes the building from the top to the bottom along the building framework. The whole process consists of the cycle of four steps for each floor level, i) dismantling or demolishing of horizontal elements (slab and beam) and ii) vertical elements (column and wall), iii) unloading wastes to the ground level and iv) dismantling upper level scaffolding (if necessary). Crushing methods tend to be used to remove the concrete for demolition of the large volume elements such as slab and wall. Otherwise dismantling methods such as ‘cutting’ and ‘shearing’ would be applied to recover the resource as elements for next use. In addition, felling methods are applicable to vertical elements using gravity and the imbalance of element weight. This can be achieved by both pulling with the machine, wire rope and controlled implosion. After descending to the ground level, elements can be securely and properly sorted or directly sent to the offsite facility.

Regardless of the type of treatment, there are manual and machine methods. In current demolition sites, however, self-propelled machines with several types of attachments for above objectives are most frequently applied due to the limited work space and the difficulty of machine transportation to the high places. Therefore, in this research we only focus on the recreation of machine application in the model. The designation of the demolition order would be decided by the following algorithm and the demolition machines would accordingly demolish the building. Unloading process would be achieved by two ways, by cranes as the dismantled element or through the debris chute as the waste. This would be decided by the designation of crane as the transportation mode. Otherwise, the debris chute should be chosen for the way of waste descent.

5.2.1.2. Machine demolition

Machine demolition system is regarded as the whole building demolition while the top-down system treats each element of the building. The main idea for this system is to demolish the building from the outside with the machines' equipped wide range arm such as high reach excavator or crane with wrecking ball, which allows the elimination of labour work at heights or with machines. If the existence of reinforcement is structurally ignorable, the demolition order should be set according to the designated direction. High reach excavators have several types of attachment the same as the compact self-propelled machines applied in the top-down system. Therefore, if the target building has stout steel frameworks or dense reinforcement which requires several attachments for shearing, cutting or felling, the demolition order should be set based on the element types. In this case, firstly concrete parts would be destroyed by crushing or hitting to reveal the embedded reinforcement or steel frameworks. Then, shear type and fork type attachments are applied to cut off elements from the neighbour elements and pulled out. Besides the soft-stripping before the demolition of main structure, mixed waste would be sorted manually or by machines at the ground level. The sorting efficiency would be less effective after all the element types are treated at once, which would be happened in this system.

Obviously, this system is assumed to be processed by machines except the sorting by hand. Machines can demolish the building in two ways: aiming at each target element directly or at the bearing frameworks to lead to the collapse of supported element group. However, due to the difficulty of structural analysis in this 4D-CAD model the latter pattern of demolition can be only recreated with many assumptions. Therefore, in this research we only focus on direct element demolition in the model. The designation of the demolition order would be decided by following algorithm and the demolition machines would accordingly demolish the building. Here, the demolition patterns are described with three options besides the direction settings. When considering reinforcement, drilling and shearing can be applied to cut. To simplify the model, objects are duplicated in the model as covered concrete and embraced reinforcement. Then, a rule is set not to treat reinforced elements before the covering concrete is removed with onsite manner. In the second option, a building would be treated for each floor. Similar to this, in the third option, the demolishers are asked if demolition should be achieved in certain horizontal ranges. This would be more efficient if the demolished debris hinders the machine approach to target elements and work at far distance.

5.2.1.3. Implosion demolition

Implosion demolition is also regarded as the whole demolition system. This should be achieved with pre-weakening and implosion processes to wreck the whole building structure. Structural engineering and explosives knowledge is required for the project design and FEM (Finite Element Method), DEM (Discrete Element Method) and AEM (Applied Element Method) have been suggested for the blasting analysis (Lupoae and Bucur, 2009, Uenishi et al., 2010). Although a similar equation to FEM is applied to the simulation of deformable bodies in Blender, structural analysis with the above methods has not been officially developed. Thus, so far this demolition system, implosion process, could not be able to be applied in this model.

5.2.1.4. Combined system

Demolition can be implemented by a combination of the above systems to maximise the productivity or minimize impacts to neighbour such as noise, vibration or even safety risks. The top part of high-rise buildings (higher than 5th or 6th storeys), for example, are often demolished by top-down system, and high-reaching excavators are applied from the ground to demolish the remaining building parts which is relatively less time-consuming and safer for the elimination of works by labours in the machine application place. Otherwise, the implosion system is suggested to apply for the dismantling of framework elements. This is involved in the process of the top-down system. The short and quick demolition also makes the process swifter and safer.

In order to extend the flexibility of this model for more accurate re-creation of project planning, the target building can be separated into several parts, and the demolition order setting algorithms can be individually applied as part of the project planning with single demolition system.

5.2.2. Functional data (Machine property)

Machine types applied to the demolition project can be principally separated into four according to the most prescribed demolition industry magazine; i) excavators, ii) bulldozers, iii) wheel loader, iv) trucks and v) cranes. Here, the performance handbook of Komatsu (2011) and Caterpillar (2015) and the fuel saving calculator tool designed by Liebhherr (2014) which updates the current average value for each machine are referred in order to comprehend the fuel consumption for each machine. Although the fuel efficiency cannot be calculated only by the engine spec but also many factors such as weight and wheel size, the above data show great fitting with the net engine power. Therefore, in this study, the fuel consumption for each machine is assumed to be evaluated by a simple linear line with the calculated coefficient (fuel consumption/net horse power). Because of the scarcity of data, the machines from the other manufacturers are assumed to have similar fuel efficiency against the engine spec. This assumption is applied to other demolition impact factors as well. For the machine scale and mobility, the official catalogues are referred to and the average value for the same scale of machine can be given if no data is available. Ideally, the database for each machine type should be enriched through the input process by users. Next, the brief explanation of each machine type and target factors are described with coefficients. Each properties can be summarised as Table 24.

Table 24 Interchanged data through the simulation process

Machine manufacturer	e.g. Caterpillar, Komatsu, Doosan, Hitachi etc.
Machine ID	e.g. 312D, PC600, DX210, 350LC etc.
Engine horse power (PS)	Net power should be applied (gross power can be transferred)
Fuel Efficiency (L/h)	Onsite data (assumed by the manufacturer and horse power)
Machine scale (m)	Scale of bucket, stick, boom, track and cab
Machine mobility (km/h, rpm)	Travel speed, Swing speed
Weight (kg)	Operating weight, Load weight (calculated from bucket capacity)

5.2.2.1. Excavator

The main function of excavators is digging and lifting with the attached bucket on the long boom for the materials hauling. With simple digging and loading operation, the bucket side and bottom can be used to scrape off and compact the soil or the closed hook on the bucket, called ‘eye’, allows the lifting of roped instruments. Moreover, the current excavators can adopt various types of attachment such as jackhammer, shears and grapplers so suitable excavators should be decided from the mobility and reachability based on the application purpose. In order to simplify the model in this study, the excavator equipment is assumed to be a bucket type only. The treated volume and the speed of unit movement are pivotal in terms of the productivity under this assumption. Therefore, bucket size and its operating speed (e.g. swing, and travel) must be given with the machine scale for the accessibility and reachability.

5.2.2.2 Bulldozer

This is a blade attached tractor which is mainly applied to excavate the ground surface and push the material ahead as the surface earthmover. According to the machine size, the size of the attached blade is changed so that the larger machines show greater operating ranges. For the dense soils, use of the bulldozer with front-end loaders shows better productivity compared to the excavators. If the surface is hard, the shank ripper attachment is applied to scratch the ground before excavation and pushing. The ripping production is decided by the covered distance and the speed of bulldozer which is affected by the type and density of material. However, in this study, only the pushing function is applied to the bulldozer model to make a model simple.

5.2.2.3. Wheel loader

This is a tractor type loader which is basically used for the material moving and re-handling. Since the most popular type is the front-end wheel loader, it is most commonly confused with ‘front-end loader’. In order to make the model simple, ‘wheel loader’ is defined simply as the front-end wheel loader in this study. These loaders tend to be articulated so that they show good movability on rough ground conditions. In the limited space, the small loaders are often used due to their high mobility and compact vehicle size. The skid-steer loader type which is equipped with an arm to the rear body is preferable for scooping and hauling the material in small work spaces. The wide diversity of attachments including bucket extends its availability, such as augers, cold planers, tillers and rakes, trenchers, compactors and brooms.

5.2.2.4. Trucks

Trucks are applied for earthmoving or material transportation. It is composed of the tractor and trailer parts the sizes of which are decided by site condition and needs of the load. It tends to be applied with excavators and loaders to haul off soil or materials (especially waste in demolition). According to the road condition of target transportation, on rough site or highway, the setting of frame, suspension and motors are adjusted. Articulated trucks tend to be used to improve the manoeuvrability at the rough road condition. When choosing the trucks, besides the trailer volume and shape, the unloading function needs to be considered for the efficient charge and discharge.

5.2.2.5. Cranes

a) Telescoping boom mobile cranes

This crane is quite suitable for a short time and a limited number of lifts from two aspects, mobility and cost. Compared to the other types of crane, it can be driven to the site on public roads and assembled in a short time. With the short-time setup, the onsite mobility allows for the minimum number of crane hire which is very economical. Light and medium lifting capacity cranes tend to be preferred for the application for this type.

b) Lattice boom crawler cranes

Due to the diversity of attachment, this crane can be seen on most types of construction projects such as excavation with dragline, compaction and wrecking with balls. Most of the lattice boom cranes have a back boom with a main boom as a derrick which transfers the compressive load to the back of the crane cab and the counterweights. Thanks to this structure, a guy derrick crane and a sky horse crane (which has shorter back boom) have about eight and three times larger capacity compared to the basic crawler cranes. While the cost of application is cheaper than tower cranes, the movement caused by the load on the end of boom and the crawler tracks is unstable. A flat travel surface and the balance of load need to be planned before the implementation.

c) Tower cranes

Tower cranes have mainly three different types varying in their construction; i) self-erector, ii) horizontal jib crane and iii) luffing jib crane. While the self-erector has a slew ring at the base of tower and rotate on the bottom, the other types slew at the top of mast or main boom.

Self-erectors can be mounted on wheeled chassis, rail-going or crawler and work as mobile cranes. Although it needs the space for setting, compact lifting is available similar to small scale horizontal trolleys or mobile cranes.

On the horizontal jib crane, the trolley slides along the front horizontal jib to adjust its operating radius and drop the hook to the target. It has two different types of structure on the top, ‘A’ frame and flat top. Similar to the derrick structure introduced above, the load on the front jib can be supported by back jib via ‘A’ frame and achieve higher capacity. Considering the height, the flat top type is more suitable for near to airports or adjacent oversailing cranes. Both of them require the space for erection and dismantling but can be fixed to the building structure.

Luffing jib crane has two jib types, single or multi component, and its angle and radius can be altered. While these flexibilities allow for compact lifting compared to the horizontal jib cranes, capacity is less and lifting speed is slower which results in more energy consumption than the others. It can also be erected within buildings but the wind load needs to be considered to avoid blowing over.

5.2.3. Waste generation

After the model simulation in Blender with the above three datasets (for target building, demolition method and machine property data), soft-stripped elements, waste generation and machine application would be returned as raw data. Before extracting the project impact directly as the simulation result, it has to be refined to improve simplicity and comparability of data. Accordingly, as the first step, the generated element waste is converted to the individual waste type (which was reviewed in *2.1.2. Waste utilization*). This enables users to decide if waste should be sorted more to avoid the offsite recovery as mixed waste. According to the amount of each waste type, wastes are assumed to be sent to the offsite facilities and the total demolition impact can be calculated as the impact for material treatment. To accomplish the waste decomposition, ideally, the value contained in the uploaded objects data in BIM should be applied for the precise analysis. For example, Cheng and Ma (2013) applied the AutoDesk Revit API function with Material Type data to sort the elements from the component as shown in Figure 41. In case there is insufficient information, the conversion rate between elements to each waste type will refer to the value in Table 25 which was measured by Jalali (2007) in the actual case study. In the same manner, the proportion of used material for 'doors' and 'windows' are based on the value in Figure 41. It means that if there are two types of materials derived from window, glass for 150m^3 and steel for 50m^3, people can assume 0.75m3 of glass would be generated from 1m^3 of window. The volume rate of reinforcement in each type of element (foundation, column and beam) applies the value in Table 25to adjust the volume of waste generation at the impact estimation phase when RC building is demolished without considering reinforcement at demolition simulation.

Element Category	Element Name	Material Type	Volume(m3)	Number
Walls	Exposed - 115mm Brk	Masonry - Brick	9823.436	6554
Doors	Double Metal Panel	Wood - Dark	92.699	2060
Doors	Double Metal Panel	Wood - Light	32.959	2060
Doors	Single Wood Shutter with Pe...	Wood - Dark	6.345	235
Doors	Single Wood Shutter with Pe...	Wood - Light	13.630	235
Windows	Double Shutter Window	Glass	12.175	2435
Windows	Double Shutter Window	Wood - Sheathing - plywood	46.265	2435
Windows	Double Shutter Window	Wood - Dark	75.485	2435
Windows	Window-Trim Single Metal P...	Glass	3.381	1127
Windows	Window-Trim Single Metal P...	Wood - Sheathing - plywood	19.159	1127
Windows	Window-Trim Single Metal P...	Wood - Dark	22.540	1127
Floors	Floor slab-100mm	Concrete - Cast-in-Place Concrete	5615.137	47
Floors	Floor slab-100mm	Cement Plaster, Plain	842.241	47
Structural Columns	300 x 450mm	Concrete - Cast-in-Place Concrete	275.807	683
Structural Columns	300 x 450mm	Masonry - Brick	7.85	3
Stairs	Res-Conc-300 Tread 150 Ri...	Concrete - Cast-in-Place Concrete	80.168	88
Beam	400 x 800mm	Concrete - Cast-in-Place Concrete	1.919	119
Reinforcement	Steel-Reinforcement	Metal - Steel	182.700	240

Figure 41 Data correspondence between element and materials in AutoDesk Revit (Cheng and Ma, 2013)

Table 25 Material component for each element type without designation

	t	m3	Rate(%)
Foundation*			
Concrete elements		24.0	
reinforcement	1.0	0.1	0.5
concrete part		23.9	99.5
Structure(col,beam)*			
Concrete elements		82.0	
reinforcement	9.0	1.1	1.4
concrete part		80.9	98.6
External wall*			
masonry		285.0	100.0
Interior wall*			
plasterboard		350.0	100.0
Ceiling*			
plasterboard		310.0	100.0
Door**			
Wood			100.0
Window**			
Window elements		179.0	
glass		15.6	8.7
Wood		163.4	91.3

(source: *Jalali, 2007 and **Cheng and Ma, 2013)

5.2.4. Demolition Impact conversion rate

Following the decomposition of waste elements of individual waste type, there are still three different types of conversion required for the total demolition impact calculation; i) composite waste treatment, ii) individual waste treatment and iii) conversion between different types of impacts. The first conversion is the evaluation of the impact of soft-stripping process. Assuming that the workload and cost for the soft-stripping of certain elements would not differ throughout the UK demolition industry, the unit impact of stripping (as the first conversion rate) would be set for each type of building element. If the volume of target is known, the total impact of stripping can be evaluated as the soft-stripped phase impact. Secondly, the impact of waste treatment process can be calculated from the generation volume of both stripped waste and recovered debris. The unit impact of recovery treatment (as the second conversion rate) is multiplied by the volume of waste, and the total value would be regarded as the whole impact on the recovery phase. At the end of the process, several types of impact should be normalized to compare the comprehensive impact of project planning in terms of environment. Although the environmental aspect would not be more prioritised than cost or terms in practice, it is still beneficial to analyse the prospective environmental result caused by the project planning maximizing the users benefit. This is expected to make users aware of how much the project sustainability would be improved from the lean project planning. Expanding the view to the social scale, the significance of the reduced impact on the environment for the UK society can be also discussed from this. Therefore, the conversion of impact to the common impact is set as the third conversion rate to be explained in following.

5.2.4.1. Composite waste treatment (soft-stripping)

Here, the requirements of labour and machines for soft-stripping are stored as the data to be used in the model. These values are mainly based on ‘Payment in Construction: A Practical Guide’ by BCIS (2014). The main focus is the duration of treatment and the hourly cost for each of them. The element type and material type which values are stored in the reference are listed in Table 26. Here, not only demolition but also the deconstruction for the reuse and the repair/renovation data are added to the partial demolition or refurbishment in the model simulation. The actual value of dataset can be seen in the appendix.

Table 26 Accessible data list from references for required cost and workload for each type of soft-stripping

		concrete	mineral	clay	ferrous	non-ferrous	wood	other
Wall	Ru		√	√				
	Rc	√	√	√			√	√
Column	Ru							
	Rc	√			√			
Beam	Ru							
	Rc	√			√		√	
Floor	Ru							
	Rc	√					√	√
Roof	Ru							
	Rc	√					√	√
Door Window	Ru					√	√	
	Rc					√	√	
Staircase Landing	Ru							
	Rc	√				√	√	
Covering	Ru							
	Rc		√					

Ru: Reuse
Rc: Recycle

5.2.4.2. Individual waste treatment

Generation waste in this research can be separated into two types, soft-stripped element and recovered debris after the machine demolition. Both of them are simplified by having two main options in practice as shown in Figure 42. According to the availability of onsite application, the treatment impact may need to involve the transportation impact. It should be noted that the ways of impact evaluation for waste generation and offsite recovery are slightly different in the two models, the demolition project and the social impact model. For the project model, as it is not concerned about the other facility decision, the average distance between site and facilities are applied to decide the transportation burden. On the other hand, the social impact model applies the distance to the facilities which accept the site waste. It may result in the extension of transportation distance, which shows the advantage of onsite application rather than the offsite recovery. Each impact value for the elements and individual materials can be seen in the appendix.

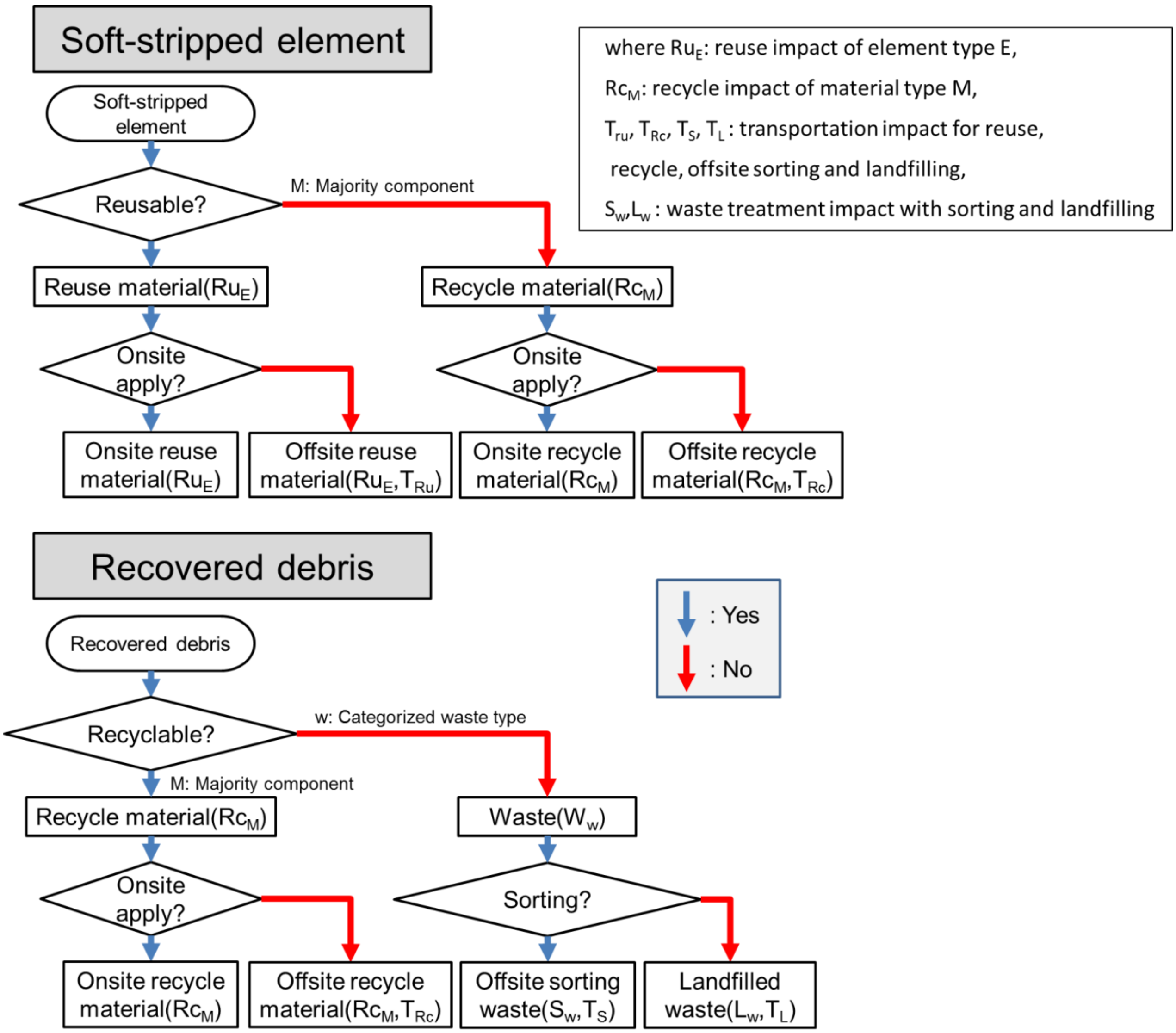


Figure 42 Framework of the waste treatment and related impacts

5.2.4.3. Conversion between impacts

According to the BREEAM system, there are three steps to evaluate the environmental impact as a 'Eco point' from the different type of impact values; characterization, normalization and weighting. In characterization, each impact can be converted to the main environmental phenomena such as climate change or acid deposition with equivalence factor due to the significance of effect based on Table 27 suggested by BRE. In some case, a single factor is involved in more than two phenomena. For instance, NOx can enhance acid deposition and eutrophication. Although this calculation allows for knowing the direct value, it is difficult to comprehend its degree. Thus, as the next step, the value is compared to the certain impact as a benchmark, and this is called normalization. In this research, the environmental impact of projects can be converted to the number of UK citizens who produce the equivalent impact. To comprehend the whole impact from the project, the weighing value suggested by BRE (2007) which is used in BREEAM is applied to calculate the whole phenomena influence, which allows comparison of each project or benchmark. Although it is arguable which edition's BREEAM weighing values are most suitable to replicate actual phenomena, here the weighing factor of BRE from the 1999 study is used. The calculated value is applied to discuss the influence of DPM system application to the UK society in the Discussion chapter. It is to be mentioned that the study of 1999 was chosen rather than 2006 because the proposed factors were more relevant to the impact types caused by demolition project.

Table 27 Environmental impact conversion rate

	Climate change, kg CO2eq (100 years) / kg	Acid deposition, kg SO2eq / kg	Human toxicity (to air), kg tox / kg	Low-level ozone creation, kg ethen eq / kg	Eutrophication, kg PO4eq / kg	Fossil fuel depletion, / tonne	Minerals extraction, / tonne	Waste disposal, / tonne
Energy from Fossile Fuels	0	0	0	0	0	1	0	0
CO2	1	0	0	0	0	0	0	0
CH4	21	0	0	0.007	0	0	0	0
NH3	0	1.88	0.02	0	0.35	0	0	0
N2O	310	0	0	0	0.13	0	0	0
NOx	0	0.7	0	0	0.13	0	0	0
NMVOC	0	0	0.022	0.416	0	0	0	0
CO	0	0	0.012	0	0	0	0	0
SO2	0	1	1.2	0	0	0	0	0
Cadmium	0	0	580	0	0	0	0	0
Chromium	0	0	6.7	0	0	0	0	0
Copper	0	0	0.24	0	0	0	0	0
Lead	0	0	160	0	0	0	0	0
Mercury	0	0	120	0	0	0	0	0
Nickel	0	0	470	0	0	0	0	0
Zinc	0	0	0.033	0	0	0	0	0
Minerals	0	0	0	0	0	0	1	0
Wastes	0	0	0	0	0	0	0	1
UK impact (per person)	12269	58.9	90.7	32.2	8	4.09	5	7.2
weighting factors*	0.35	0.05	0.065	0.035	0.04	0.11	0.05	0.06

*the value from the 1999 study of BRE is applied

(source: BRE, 2007)

Chapter6

<Chapter Abstract>

In this chapter, the project impact evaluation tool is explained to simulate the project planning with above datasets in dynamic. At the beginning, the adopted CAD software for tool development, Blender, is explained with its feature, and the induction of the tool framework. Readers can acquire deep understanding of the tool usability here from the step by step guidance of its use. In the latter part, the conversion of demolition methods to algorithm is suggested to approach from two different aspects; i) machine operation and ii) demolition order (of elements). Since these algorithms are examined in Chapter8, readers can expect better understating from revising that part before proceeding that chapter.

Chapter6. Method III: Development of project impact evaluation tool

Impact evaluation for the individual demolition project is set as the objective in this study. Quantitative comprehension of project impact enables better understanding for stakeholders and further improvement of planning through the comparison. Accordingly, the suggested model for the individual demolition impact evaluation is explained in this session.

6.1. Model development

In order to develop a model which enables 'dynamic' and 'automated' evaluation in demolition, a 4D-CAD software 'Blender' was chosen because of the uniqueness of the software. Besides the above two required factors, 'user-friendly' and 'data compatibility' were added to the decision factors assuming the application to practice (i.e. uses by demolishers without modelling knowledge) and the further analysis (i.e. adoption of external software for comprehensive understanding). In this section, the feature of Blender and the evaluation model framework are explained first. Then, the actual process for users in model application is described for both data input and output phases.

6.1.1. Blender application

6.1.1.1. Feature of software

Blender is the free open source software which allows users to create, render and simulate the modelled objects with different specialized modes; Blender render, Blender Game Engine (BGE) and Blender Cycle for animation rendering, gaming and ultra-realistic rendering. The specialized mode design, the adoptions of a graphical user interface (GUI), Python platform and Bullet Physics Engine ('Bullet') make it user-friendly and show high performance at 3D graphics, animation and further application such as gaming and physical simulation.

The platform of Python, the object-oriented, interpreted and interactive programming language, is applied in Blender as an Application Programming Interface (API). With API, developers and users can edit user interface applicable data, create elements, change and execute functional tools and define settings in Blender with little programming knowledge (Blender (2014). Moreover, Python scripting helps complicated game logic description and enables the interactive application with external programs.

The physics engine, Bullet, allows users to simulate the advanced physics in Blender modelling. This free open source engine written in C++ is applied to movie production, gaming and 3D authorising tools including Blender. To be customizable and modular for developers, it is composed of different types of library as Figure 43 and it computes the rigid body physics with the data structure shown in Figure 44. Here, Bullet especially shows a good performance at the collision detection under different types of situation. Availability on discrete and continuous, rigid and soft body and concave and convex mesh collision shows the robust applicability and provides more realistic simulation. In addition, the different types of constraint solver can be applied to limit objects movement as combined objects in the real world. Accordingly, models in Blender can be constrained and collide with each other under physical law regardless of collision, body and mesh types as above mentioned (Coumans, 2012).

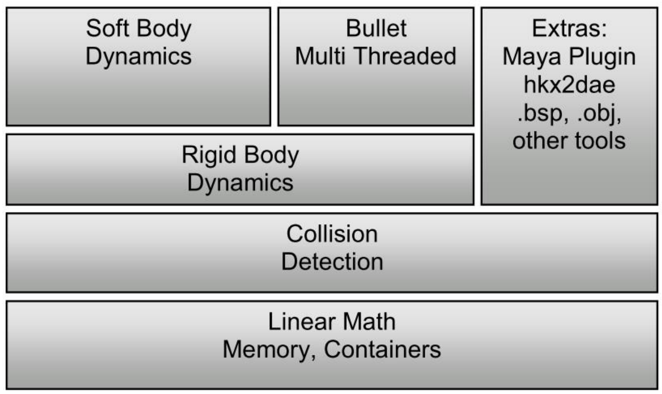


Figure 43 Main component of the Bullet Physics Engine (Coumans, 2012)

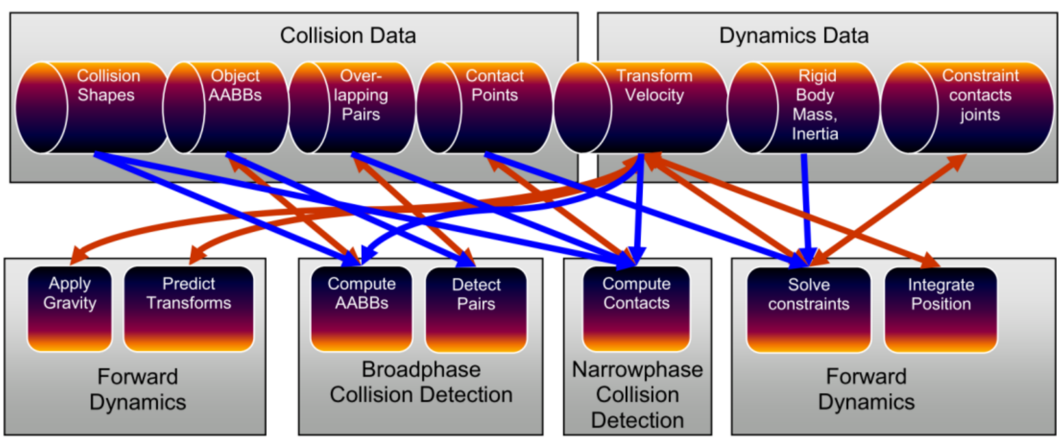


Figure 44 Data structure in rigid body physics pipeline in Bullet (Coumans, 2012)

6.1.1.2. Blender Game Engine (BGE)

In this study BGE is used to develop an evaluation model due to the rendering availability, which is continuously updated in real-time to reflect the user interaction whereas Blender render cannot reflect users input once it starts. To achieve this, BGE equips a logic editor comprised of specialised parts called 'Logic Bricks' as shown in Figure 45. This simple user interface is composed of three types; 'Sensor', 'Controller' and 'Actuator. Objects are controlled in BGE through the three steps: receiving the input with 'Sensor', combining the impulse from sensors with 'Controller' and manipulating the objects with 'Actuator'. In addition to the simple logic with GUI, the complex control can be achieved with Python scripting as 'Controller' and the action edited by keyframing in Blender render is adoptable in 'Actuator'. Following the logic setting, BGE can be executed. To think about the objectives for animation, BGE can be saved as the movie file using Python code. For the function of impact evaluation, any set of values can be output to external software with 'Logic Bricks' such as the time of collision or the volume of target object.

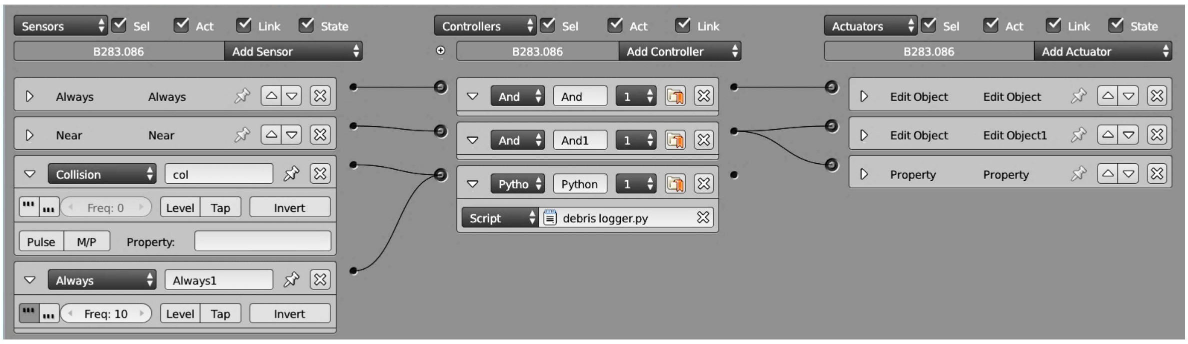


Figure 45 Setting object logic with Logic Bricks in BGE

6.1.1.3. Application of Blender to construction research

Due to the high compatibility, Blender is frequently applied in conjunction with other software. There are two meanings of changeability here, the ease of data exchange and the availability of interactive application. For the former ability, Blender is applied to enhance the visualization effect of models in visual aid tools. For example, Indraprastha and Shinozaki (2009) use Blender to render the texture map on the urban scape GIS data for virtual mapping creation in the game engine software, Unity 3D. On the other hand, Gore et. al. (2012) recreate construction space model in Blender render with 3D point cloud data produced from 2D photos.

Compared to these relatively simple applications, the interactive application with other programs allows complicated simulation. For static simulation, Kulahcioglu et. al. (2012) use Blender for Building LCA. After the target building is recreated in Blender from BIM, the environmental impact is evaluated with the LCA tool, 'GABI'. According to the returned value, the building model is coloured as a visual aid. Similar to this, Pitman and Watts (2011) try to integrate the building ability analysis by using Blender with Computational fluid dynamics (CFD), lighting and heat-transfer analyses. Combined, these studies show three advantages of Blender application; less user input, integration to one software and possibility for further evaluation such as cost, resident comfort and building physics.

For dynamic simulation, a reality of simulation is pursued so that the runtime control of objects is quite important as the application of physical law. Accordingly, BGE is used to achieve the complex logic design and the runtime interaction with other programs using Python script. Lind and Skavhaug (2012) apply BGE to the simulation of automated production system. The robot motion control is designed in class by the external emulation system software (e.g. PyMoCo) and the order is exported and applied to robot parts on real-time in BGE as shown in Figure 46. As the emulation order can be utilised directly to the actual robot control, it gives the advantage of emulation setting at conceptual design, implementation and run-in for the new production control system. In the study of El Nimr and Mohamed (2011), the construction operation composed by four different types of decision factors is designed by High Level Architecture (HLA)-based Simulation Visualization framework as shown in Figure 47. Multiple models in a group called 'federation' are simulated spontaneously and their interaction is considered. With four types of federation (e.g. resource allocation, site construction) simulation, the site visualization is achieved and translated into the order in BGE to move objects with designed logic. The authors emphasize the effectiveness of the 3D visual simulation using BGE in which GUI requires minimal code writing skills for users for the complex interaction representation.

To summarise, Blender can provide a wide range of possibilities for interactive program application and the accurate runtime simulation beside the simple ability for visual support tool. Interactive appreciation enables the outsourcing of complicated computation, and the result can be interpreted by Python API in Blender. Thanks to GUI, users can construct the simulation system with minimum programming skills. In addition, the accurate runtime simulation is especially beneficial to enable the operation simulation in 4D. Furthermore, the applicability of the physics engine is expected to result in the realistic simulation for the demotion behaviour in this study.

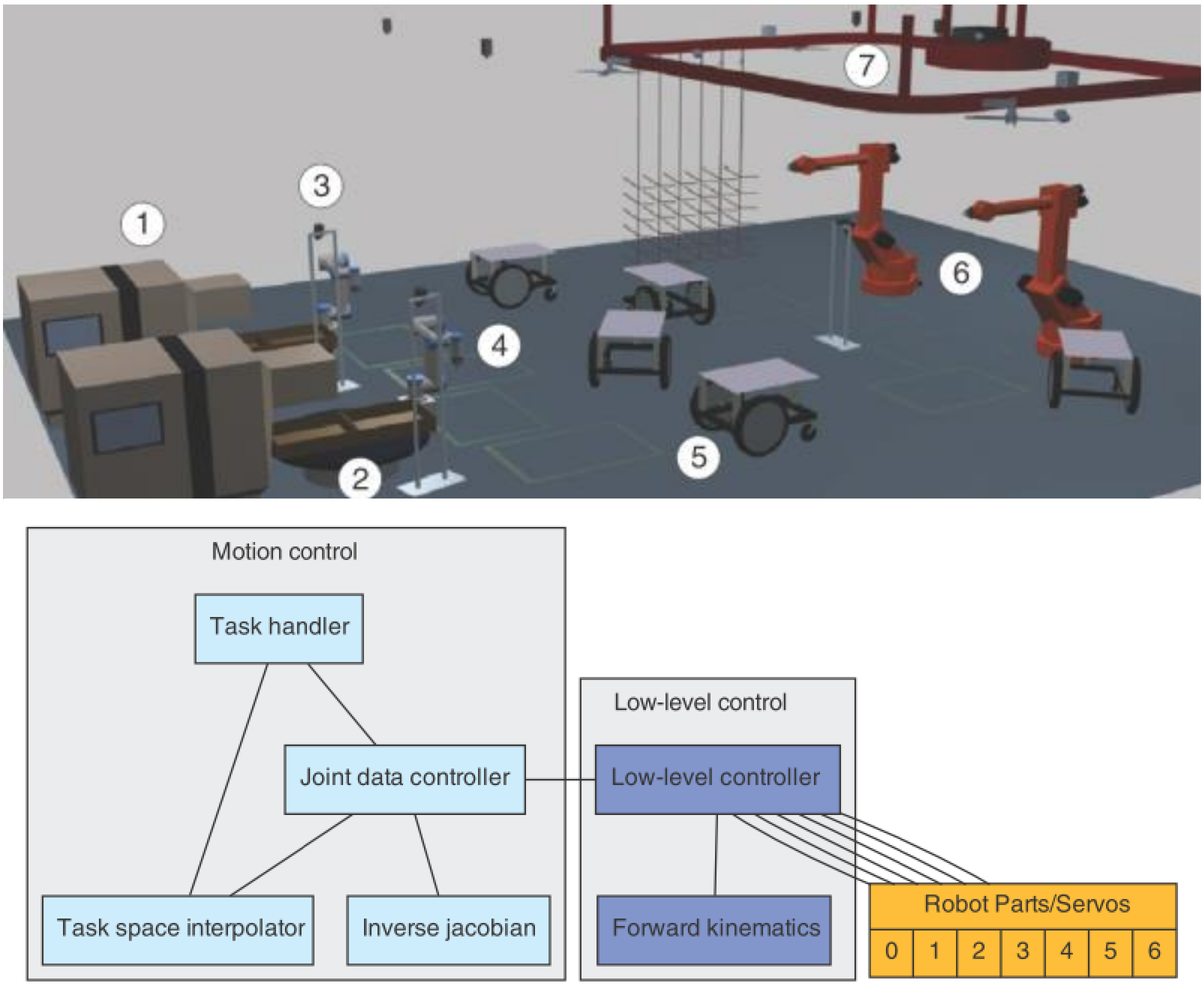


Figure 46 Simulation image and flow chart for production operation with BGE by Lind and Skavhaug (2012)

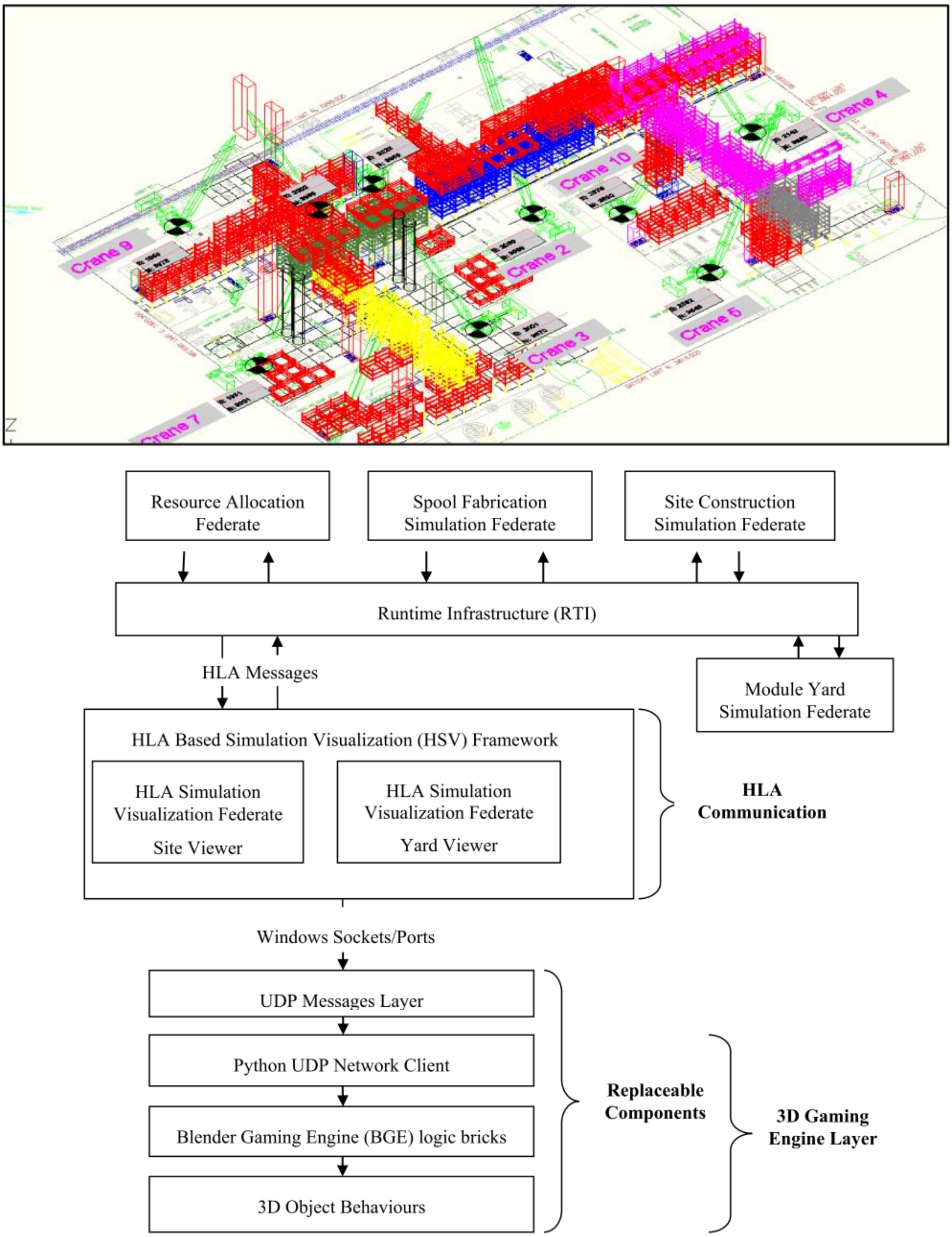


Figure 47 Simulation flow chart for construction operation with BGE by El Nimr and Mohamed (2011)

6.1.2. Model application system framework

6.1.2.1. Platform with Blender

The 4D-CAD impact evaluation model proposed in this study is shown in Figure 48. Blender is used to develop the evaluation model by program scripting with Python. The main processes in this platform are i) input of project plan to Blender by users, ii) data retrieval from database, iii) model simulation by BGE using physics engine and iv) output of simulation result. For the input of the project plan, users need to input two different types of information, site information and project plan. Due to the high compatibility of Blender with other 3D-CAD tools (e.g. SketchUp, Autodesk etc.), users can easily import the model data file to recreate the target building and surrounding environment. Although it is ideal to be able to import BIM data files, 2D building design and the construction document data can be applied to create the model alternatively. In addition, GUI panel supports users to designate a project plan which processes are explained in the following section, 'evaluation processes'. Through the GUI panel, users can access the database and refer to the previous values and patterns. Therefore, the application of demolition method would be achieved by a simple choice from the list. Waste generation and functional data from the previous Site Waste Management Plan (SWMP) prevents the time-consuming survey of similar project planning for users. According to the designated project detail, Blender sets models and game logics to manoeuvre demolition machines in the game engine. BGE simulation with the equipped physics engine returns the demolition impact estimation in three different file types; excel, blender and movie files as time-lapse impact change, project design and the visual data respectively. Users utilise this result as the decision support to maximise their benefit in demolition, and the accumulation of these simulation data enhances the robustness of the database for future project planning.

6.1.2.2. Evaluation flow

This system can be classified by five phases (see Figure 48) in terms of evaluation flow; 'Plan input', 'Modelling', 'Execution', 'Utilization' and 'Analysis'. As with the platform, the whole process is achieved via the model developed in Blender. First 'Plan input' corresponds to the input of the project plan as explained above. First of all, site information is imported from other 3D-CAD tools (e.g. SketchUp, Autodesk etc.) and followed by the setting of the demolition plan. The setting of the demolition method is achieved by the selection of demolition pattern, machines and layout. It should be added here that these two steps are the only burden for users, the following steps would be automatically run by python scripting. For instance, at the modelling phase, the former input values are interpreted for the modelling of target buildings and demolition machines. Game logics for machines are simultaneously decided based on the demolition pattern and other properties, and applied in the execution phase. As a result, demolition machines start to aim target elements of the building in order and the debris movement would be recreated close to reality with the physics engine. The export of data on time during the simulation gives the time-lapse change of demolition impact corresponding with machine movement. As an output, visual data is saved as a movie file and impact data can be exported to external software such as Microsoft Excel to draw time-lapse impact change figures. The Blender file, movie file and impact projection sheet are contained in the project file as the prospective plan. These project files are eventually applied to the demolition steps; documentation, implementation and project planning (optional). Besides the roles to verify proper project planning and to support progress management, it encourages new construction project teams to utilise demolition wastes. This will reduce the necessity of waste treatment and result in budget savings for demolishers and the reduction of the environmental burden of construction.

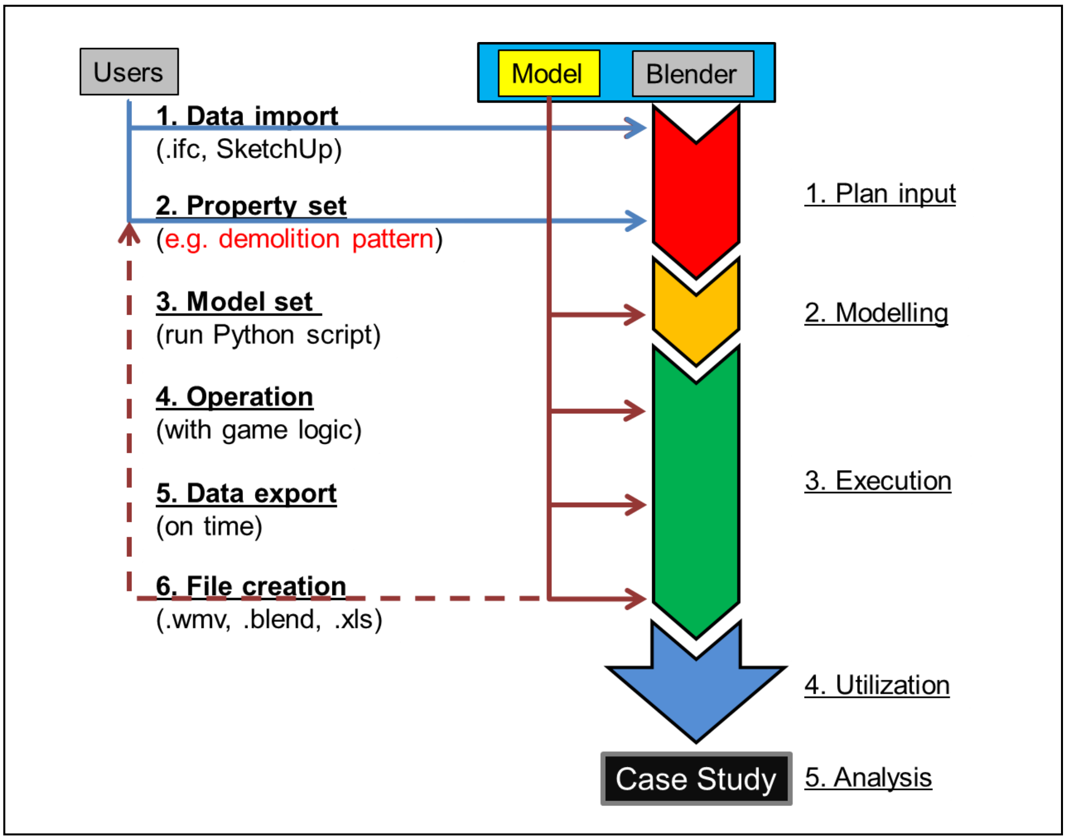


Figure 48 Schematic diagram

6.1.3. Detail processes of user input for evaluation

The following processes are achieved by users through the developed panel as shown in Figure 49.

6.1.3.1. Input site information

Site layout and building model can be imported to Blender at the 'Building model import' stage. Users can choose the BIM data file of the target building from a browse tab and add the model with 'Import button'. In addition to the site's own layout, the surrounding site circumstance data is important in deciding the demolition project plan regarding the line of movement, neighbour influence etc. Since the Google Earth data can be modelled in SketchUp, the surrounding locational information can be imported to Blender as shown in Figure 50 (where the orange square describes the target demolition site and the black building is to be demolished). Thus, demolition design would be location specific.

6.1.3.2. Designation of element treatment

Users can classify the elements for the target treatment from the suitable treatment method in the demolition phase. In the 'Treatment of elements' stage, users can register elements into 'preserved', 'soft-stripped' and 'ground' groups, and they would be changed colours as Figure 51. While 'Soft-stripped' elements are removed before demolition, demolition machines are operated so as not to damage elements to be 'Preserved'. Cost and labour investment for stripping is calculated with conventional data to describe the extra impact at preliminary treatment. Moreover, the reservation of elements allows the evaluation of partial demolition impact in refurbishment or renovation projects. Regarding a 'ground' element as the path of demolition machines, the site boundary corresponds to the movable area of machines in the BGE simulation.

6.1.3.3. Decision of demolition method

Demolition method is designed by type and direction in the 'Demolition Method' stage. According to the chosen type, the algorithm of demolition order for composed elements is decided based on the previous demolition projects. When the algorithm applies with 'Set' Button, whole elements apart from those registered above are numbered as Figure 52. As demolition machines decide to demolish elements in order from small to big number, users can tailor them manually if the algorithm does not reflect as planned. Total path among targets are automatically calculated and shown after numbering. Users can compare several demolition methods to find the optimal solution from this value.

6.1.3.4. Registration of machines

After setting the order of demolition, demolition machines to be used must be registered at the 'Demolition machine' stage. From the tab menu, users can choose a suitable demolition machine type. This returns the default size for each body part and users can modify the scale to recreate the accurate model. When registered, users need to define the role of machines to clarify the phase they are to be applied to. Multiple registration and designation of these roles enables the users to simulate complicated project plans in demolition. Modification or cancellation of registered machines are available at any time.

6.1.3.5. Execution

When the setting of demolition machines is complete, Blender has enough information to simulate the demolition project. Users should choose the save folder for output and click the 'Run simulation' button at the 'Model simulation and export' stage. Once clicked, the model elements are segregated into the unit cube to recreate the destruction of elements by hitting with demolition parts. In reality, these units will be demolished only when a larger impact than their material strength is applied. However, the function to measure the confliction impact is disabled in Blender. Accordingly, elements are replaced by small cubes (called unit cubes) and demolition is recreated by the corruption of these unit cubes once touched by demolition machines. Here, it assumes the impact always exceeds its durability. After setting of models, game logic need to be applied to those models for the BGE simulation. Demolition machines contain game logic when registered, therefore, at this step game logics are prepared to monitor the movement of machines and measure the waste generation to comprehend the time-lapse impact change. Through the simulation, machines keep chasing target elements according to the number of demolition order, and eventually impact data is exported to the other software such as Excel before the file closes. Based on the simulation results, users can modify the plan continuously until it achieves project requirements.

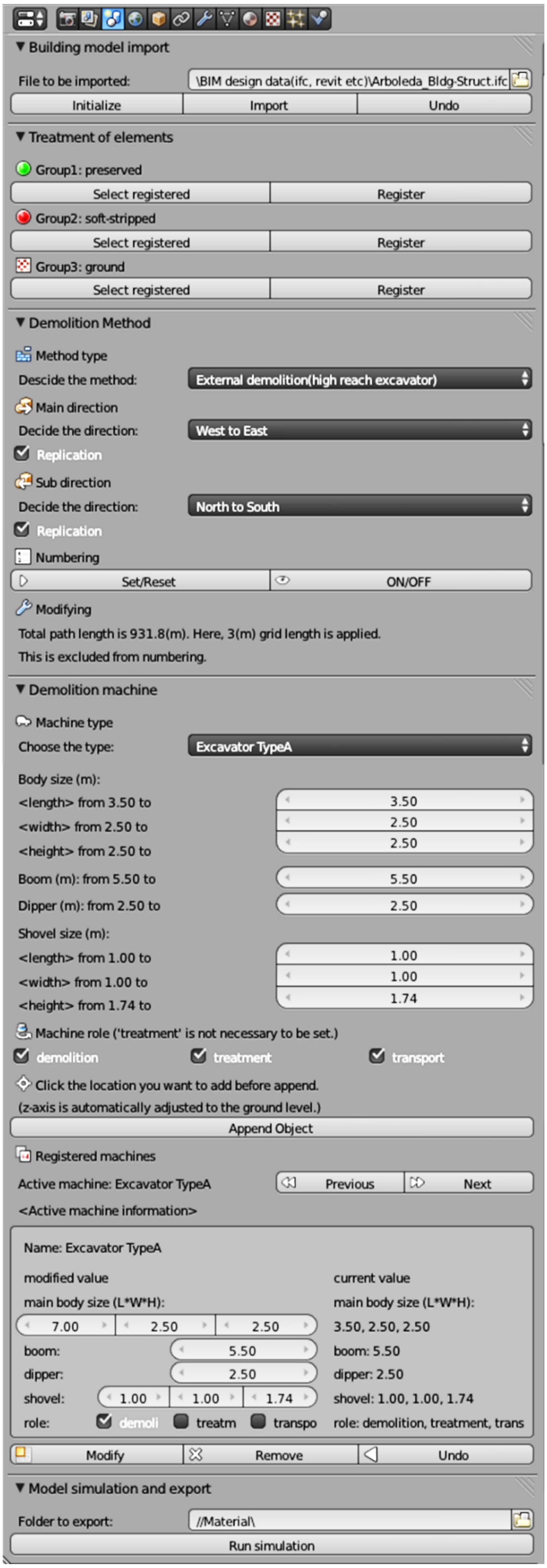


Figure 49 Developed panel for user input

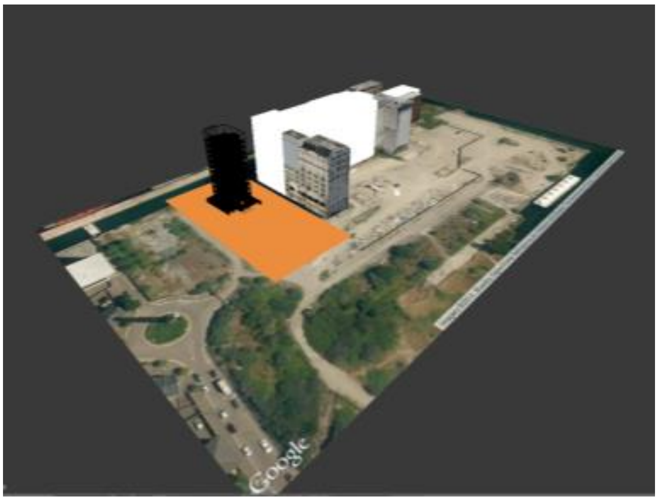


Figure 50 Import neighbour information from SketchUp

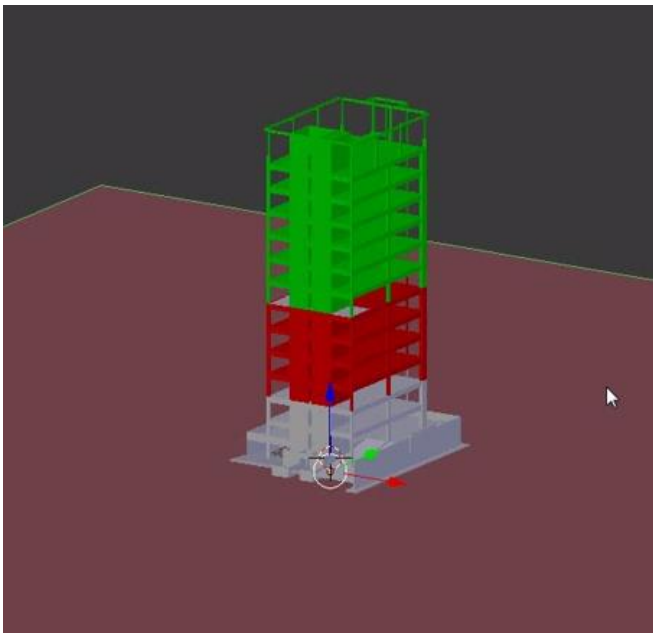


Figure 51 Registered elements in a target model

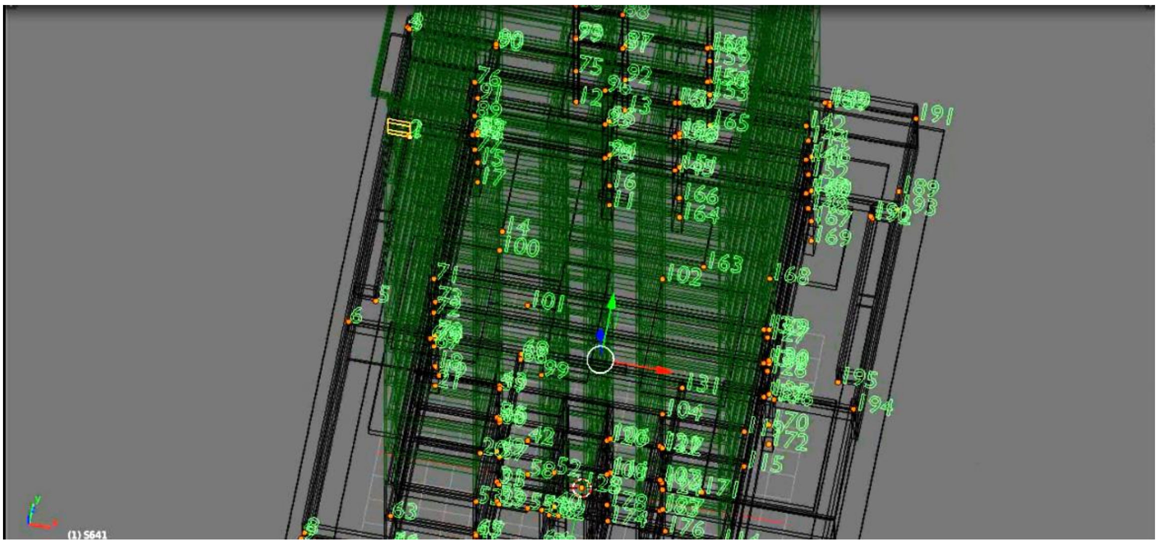


Figure 52 Demolition order setting with number for registered elements

6.1.4. Detail processes of impact output

In terms of output data, the subsequent processes to the simulation should be explained for better understanding of the model. The impact flow can be visually summarised as Figure 53. As the result of the simulation, three different types of raw impact value data can be collected; i) soft-stripped element, ii) machine application and iii) waste generation. For each impact type, the value needs to be converted to the same unit for impact (e.g. MJ, kg CO_2 eq) to compare with the actual onsite value in the pilot study. Conversion of impact is justified in the following clauses. In addition to this, the environmental impact is also calculated to evaluate the improvement efficiency in terms of project sustainability. As mentioned later, the optimization algorithm which was designed for the minimization of machine use was analysed to see if it could result in the reduction of environmental impact at the same time. Including the converted impact value of waste generation with the recovery impact data in the database, the reduction rate of environmental impact was applied to the social impact evaluation model, which allowed calculating the influence of the DPM system application on society. For the other angles of project analysis such as the waste purity map and machine productivity will be explained in the pilot study chapters for each project.

It should be noted that the impact conversion flow would be explained for each step with figures and formulas in following clauses. Basically, the variables applied in formula are all introduced in the same figure. Those variables will not be explained later to avoid the repeat of word explanation.

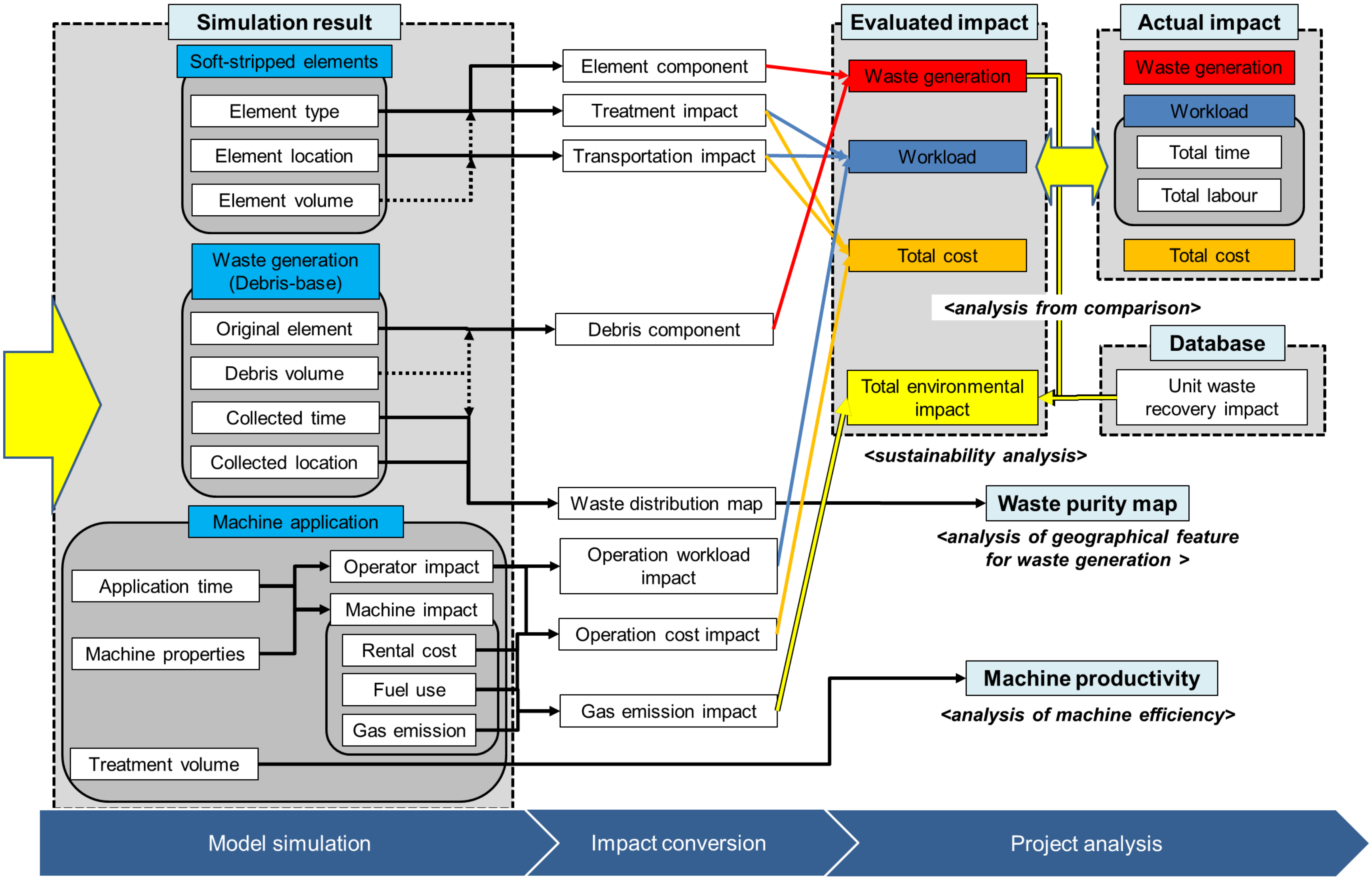


Figure 53 Impact conversion flow after the model simulation

6.1.4.1. Soft-stripped elements

The model simulation returns three types of information for element soft-stripping; element type, volume and collected location. Based on those data, waste generation, work load and cost are calculated through the flow of Figure 54. As described here, the unit treatment impact and the generated waste component for the removal can be decided by the target element type based on the database. Waste generation can be calculated as the total of products between unit element component and element volume. For the workload and cost calculation, the transportation burden needs to be added to the treatment one above. Due to the geographic limitation in the congested site circumstance, the objects transportation can be assumed to be along paths. The distance is simplified and calculated from the sum of coordinate value gaps between the target element and the collection point in three axes as formulated in Figure 54. The coefficient α is set here to convert the value from distance to impact. Based on the BCIS (2014) dataset, the labour and cost impact of conveyance were decided to be 0.012(Man-Hours/m*m^3) and 0.1372(£/m*m^3) respectively.* Using those values, the impacts in the phase of treatment and transportation are summed up as the total impact of workload and cost.

 *Due to the shortage of actual conveyance data, the impact value for 'Hand loading and transporting and depositing in spoil heaps' in the BCIS (2014) was applied here. According to the two value sets for 25m and 50m conveyance, the value gap was regarded as the conveyance of unit volume object for 25m. Divided by 25, the unit distance and volume impact was evaluated.

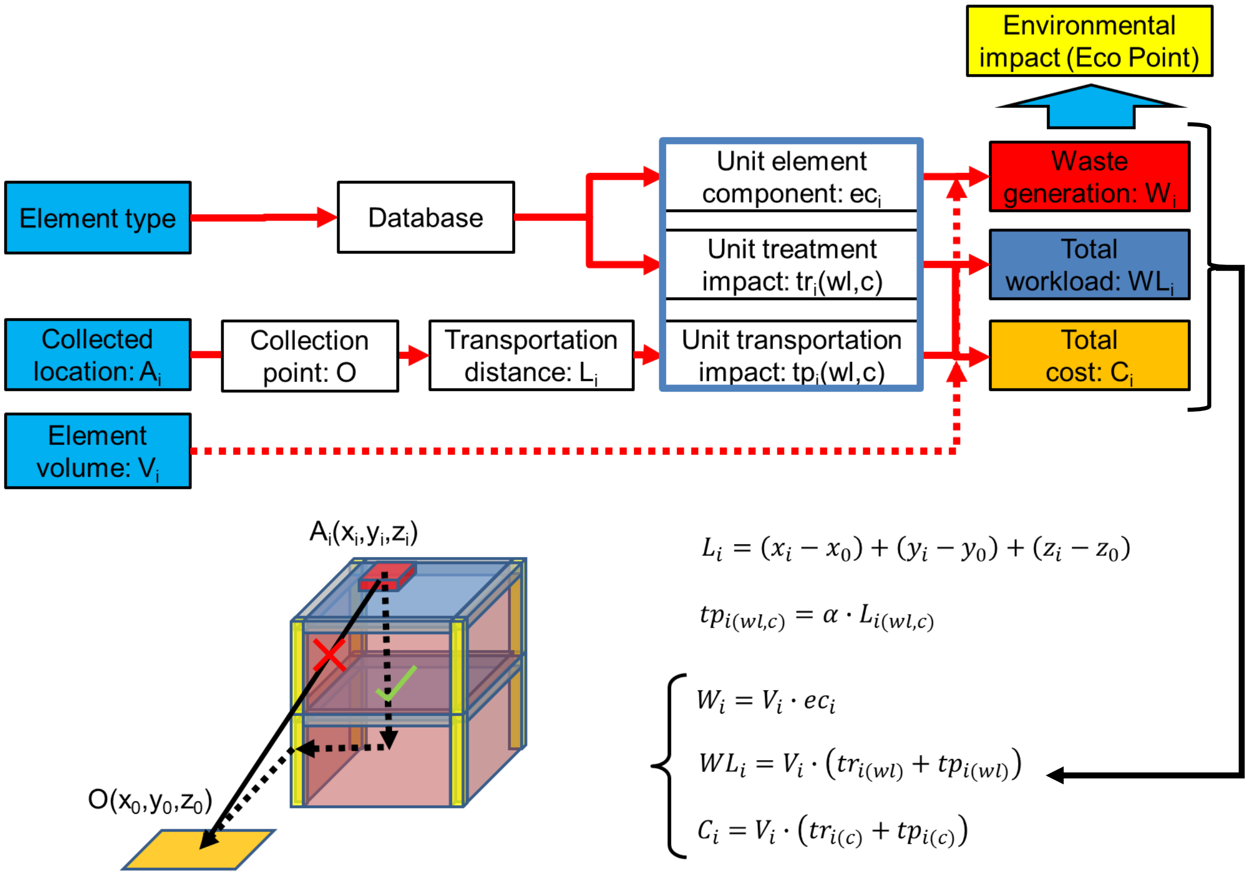


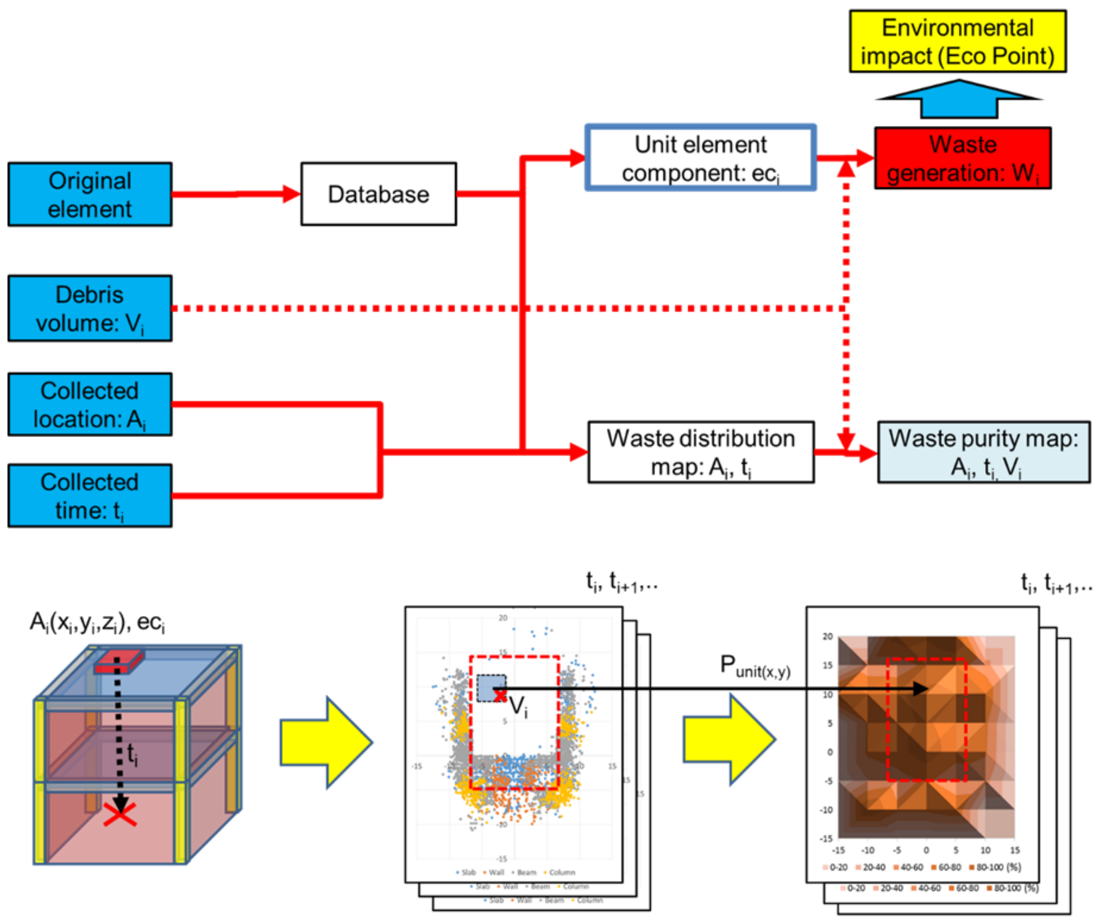
Figure 54 Impact conversion flow with soft-stripped elements data

where α: conversion coefficient of transportation impact (introduced in footnote)

*Due to the shortage of actual conveyance data, the impact value for 'Hand loading and transporting and depositing in spoil heaps' in the BCIS (2014) was applied here. According to the two value sets for 25m and 50m conveyance, the value gap was regarded as the conveyance of unit volume object for 25m. Divided by 25, the unit distance and volume impact was evaluated.

6.1.4.2. Waste generation

There is a demolition impact conversion flow related to the waste generation as seen in Figure 55. The model simulation returns four types of information for each recovered debris as the waste generation data; original element type, debris volume, collection time and location. Similar to the soft-stripped elements, waste generation can be found from the total of products between the unit original element component and debris volume. On the other hand, , the waste distribution can be depicted as a map by using the time and location information. By adding volume on the map, the purity of the map can be analysed and that result suggests the better strategy of waste collection or the prior phase, structure demolition. In detail, the proportion of majority waste component type against the total waste volume is calculated as the waste purity for each unit area. Discussion of demolition planning could be extended to the ease of waste recovery in terms of waste purity which will be described in the pilot study chapter.



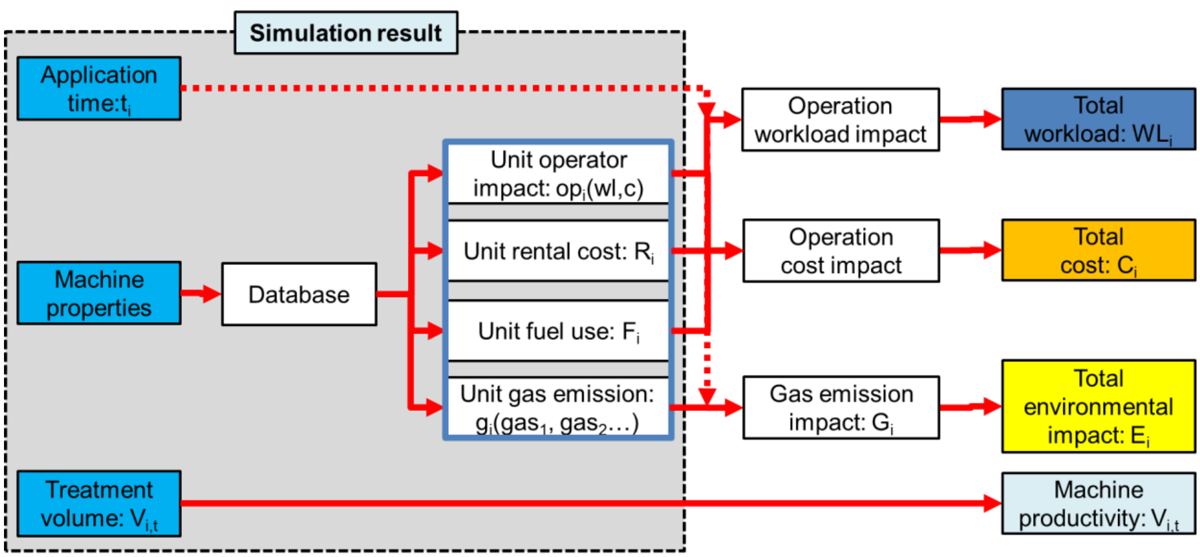
$$P_{unit(x,y)} = \frac{\sum V_i \left\{ i \middle| ec_i = ec_{M_{unit(x,y)}}, A_i \in unit(x,y) \right\}}{\sum V_i \{ i | A_i \in unit(x,y) \}}$$

Figure 55 Impact conversion flow with waste generation data

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

6.1.4.3. Machine application

As shown in Figure 56, the model simulation returns three types of information for machine application as the first step in the model output; application time, machine properties and treatment volume. The value of time and machine properties are, in the second phase, converted in the model to the impact value caused by both operator and machine. The required skill of the operator to be hired gives the workload impact and the salary cost in the project. Besides this, the machine application adds the rental and fuel cost as the machine impact. The emission of gas caused by the fuel combustion such as CO_2 and NO_x is also measured to convert them into the environmental impact. With the waste generation value evaluated by the other two types of result data, project planning can be analysed in terms of environmental impact. The improvement of project sustainability with the optimal algorithm should be evaluated in terms of its availability. Following this, how the installation of DPM system to the actual society can make the UK's construction industry improved would be projected in the social impact evaluation model which is explained in the next section.



$$G_i = A \cdot g_i(gas_1, gas_2 \ldots) = \sum \alpha_{gas_i} \cdot g_{gas_i}$$

$$\begin{cases} WL_i = t_i \cdot op_i\,(wl) \\ C_i = t_i \cdot (op_i(c) + R_i + \beta \cdot F_i) \\ E_i = t_i \cdot G_i \\ V_{i,t} = \int_o^t V_i \end{cases}$$

Figure 56 Impact conversion flow with machine application data

where A: gas impact conversion matrix, α_{gas_i} : conversion coefficient for type$_i$ gas, β: fuel cost conversion coefficient (£/L)

6.2. Theoretic setting of demolition order

Simulation approach with computer modelling is utilised for designing an optimal demolition method. A large volume of calculations achieved by computer shows a huge advantage on the result comparison and finding a best solution. In order to suggest the optimal project planning for users (demnolition project planners), the correlation between demolition designs and selected project planning is analysed and the founded theory will be applied . The project goal is set as the maximization of benefits to the demolishers through the whole project in terms of the total project cost. Duration of machine use and waste treatment costs resulting from demolition were considered as main factors for the project price. Accordingly, algorithms of 'machine control' and 'demolition order setting' are suggested in this research.

This section is separated in two parts for the different algorithms, 'machine control' and 'demolition order setting'. In each part, the detail of target movement which is supposed to be optimised with algorithms is explained. With several movement options identified in demolition sites, scenarios are set to recreate those movements with suggested algorithms as shown in Table 28. Through the model simulation in Chapter4, the above movement algorithms are compared in terms of the significance of demolition impact. The potential gap between the optimal and conventional demolition planning is regarded as the expectation of impact reduction with the model application. The value is used in Chapter5 to estimate the total impact reduction in the UK, which is the decisive factor of model application for the society. Then, the significance of the benefit from the model application with the expected barriers to be overcome is discussed in Chapter7.

Table 28 Suggested algorithms for theoretic setting of demolition order

target algorithm			target output
optimization target	target machine operation	target setting	
machine control	individual	path finding	machine operability
		element demolition	
		relocation	total demolition impact
		arm folding	
	tandem	machine traveling	machine operability
		waste collection	total demolition impact
demolition order setting	tandem (excavator+bulldozer)	locational setting	machine operability
		material setting	total demolition impact

6.2.1. Machine control algorithm

Machine control can be separated into 'individual' and 'tandem' movement. While individual movement of machines such as location change for target hitting or arm folding largely depends on machine operators, the 'tandem' movement needs to be considered the interaction of multiple machines. Accordingly, the common rules should be set at the project planning phase. This is not only related to the machine workability but also to the waste purity which is affected by the timing to be collected.

6.2.1.1. Individual machine control

In this research, demolition machines were assumed to have mainly two functions; transportation and machine specific roles (e.g. excavating, smashing, dumping etc.). Due to its commodity, pathfinding algorithms were commonly applied to any types of machines for basic transportation movement. In addition to this, the algorithm for the demolition movement for excavators was designated with three steps; i) demolition order setting, ii) location adjustment and iii) target hitting. The behaviour of collection role machines such as dozers and loaders was defined in the tandem algorithm in the next section, whose behaviour is more affected by demolition process achieved by other machines.

6.2.1.2. Tandem machine control

In practice, multiple machines need to be employed for completing a project within the limited time scale. In this case, how to operate multiple machines may result in huge differences in the total productivity. Not only optimising for machine productivity but also for onsite safety, the risk minimisation for collision or contact among machines is to be most prioritised. Accordingly, in this section, movement decision algorithms are discussed for how to response to the movement of surrounding machines. Relocation timing and the rule of aversion from an opposing machine are set in the traveling algorithm. While it is mainly assumed for the case of two demolition machines, the collecting movement for such as dozers and loaders is designed to find the optimal algorithm in terms of productivity and waste purity. In an effort not to hinder demolitions machines operating by working too close, proper distance and the collection order algorithm would be set to compare quantitatively in Chapter6.

6.2.2. Demolition order setting algorithm

The optimal algorithm for demolition order in element scale is surveyed in this section. Demolition order tends to be empirically decided by machine operators in the practice of demolition works seen in visual data. The same as the hitting each target, the distance from the machine tends to be referred for deciding the next target element. In order to compare the demolition efficiency with order setting, location and the material type of elements are used for algorithms aiming to minimise demolition impact.

6.2.2.1. Locational setting

Compared to the selection of target from distance, the sorted order from element location might result in more efficiency in terms of operating time and relocation necessity. In addition to this, the generated waste would be more suitable for recovery due to the location and element type resulting in sorted order. According to this, the distanced-based choosing algorithm and the location-based sorting algorithms are suggested as the individual element demolition. As mentioned before, both algorithms are expected to shorten the arm movement and the machine travel distance. Including the recovery impact of generated waste, the superiority of algorithms would be compared with the total demolition impact in the next Chapter.

6.2.2.2. Material setting

This is the approach to maximise the efficiency of waste recovery by setting order based on the material type. Application of a material-based classification algorithm is expected to be a powerful tool to sort the target into material groups. The sorted minor materials are to be eliminated in advance from the site property to prevent comingling different types of materials in order to collect individually with high purity. It may, however, be a trade-off between the machine use and the waste sorting similar to the situation of labour investment to soft-stripping. The more sensitive the demolition, the more time and cost for machine application would be increased. On the other hand, the pure waste generation may prevent the sorting and treatment process and it can be sold as a resource to next constructors. This method is also beneficial to sort the contaminated waste from the rest. For example, the radiated internal concrete walls in nuclear power plants can be demolished afterwards the other elements which would be regarded as non-hazardous waste. It would result in the minimum treatment risk and burden in terms of cost, labour investment and sustainability from the whole demolition processes.

In order to achieve this goal, the material-based classification algorithm is applied to the element materials. This basically sets the order according to the material types from the one having the least volume onsite. However, it may cause a problem if the machine approach to target elements is not be considered at the same time. For instance, the plaster walls as the internal non-structural elements cannot be treated individually but involve the other structural elements. To prevent this inefficiency, the convex hull algorithm* is applied to identify the accessibility of each element type. Like peeling fruit, target buildings are selectively demolished from external walls. To recreate this demolition order, the element locations are plotted on the ground plan (ignoring the vertical coordinate) with two assumptions; i) wastes would be naturally mixed with other wastes disposed in a vertical direction by gravity and ii) building designs tend to have similar floor design for each floor. Considering the access to targets, the elements are sorted by location into two types, external and internal (e.g. wall). The order of main demolition starts from the external elements (mainly walls) with the material-based classification algorithm. Then, the horizontal elements (mainly slabs) are demolished to improve the accessibility of internal elements. For this rule, buildings with the same material type such as RC do not show any advantage but increase the operation time because of the unnecessary relocation for selective demolition. Therefore, this algorithm is applied to the masonry structure in the pilot study where slabs and walls are composed by RC and bricks respectively. The trade-off between the increase of machine operation time and the improvement of recovered waste purity will be discussed.

 *This algorithm raps building elements with a smallest convex polygon, and machines would be only allowed to mobile outside. Owning to this rule, machines will never crash into building objects which might cause a fatal accident in reality.

Chapter7

<Chapter Abstract>

In this chapter, the social impact evaluation tool is explained to simulate the potential impact reduction from the practical application of the DPM system. After describing the tool framework, each process is explained in detail. Readers can understand the order of the environmental impact evaluation processes using the suggested Agent Base (AB) model. Since the tool is applied to the pilot study in Chapter9, readers are recommended to come back to this chapter for better understanding.

Chapter7. Method IV: Development of social impact evaluation tool

In order to assess the contribution of DPM system application to the UK society, the social impact caused by demolition projects needs to be evaluated in this study. To achieve this, the author adopts the social impact evaluation model of demolition waste recovery which was developed in his own MSc thesis (see Chapter2.3.3.2.). This model was developed with the Visual Basic for Applications (VBA) and composed of three individual models; 'Demolition generation model', 'Waste treatment model' and 'Environmental impact model'. Related two models, 'Demolition generation model' and 'Environmental impact model', are extended to demolition implementation and new construction phase, which allows for analysing the reduction of waste and natural resource consumption from the DPM system application (which matches demolition and construction projects). With different scenarios for the system application, the expected reduction of impact is evaluated and discussed in the following pilot study chapter.

It should be noted that this original model is classified into multi-agent (agent-based (AB)) model. Based on the sorting rate of onsite demolition waste, demolition contractors decide how much waste is to be send to each offsite waste treatment facility. Treatment facilities will decide the acceptance of waste from the demolition sites according to their treatment capacity. As represented by EcoMA introduced in Chapter2.3.3.1., AB model has a huge advantage on the evaluation of whole waste stream even when there is little information on interactions among factors. Accordingly, the social impact evaluation model in this research is developed by the extension of the waste recovery model which the author developed in previous study to the AB model. Since that previous model was developed to evaluate for pre-demolition and waste treatment phase, main demolition and construction phases need to be added in the social impact evaluation model in this research. In order to describe the structure of new social impact model, the framework and the details in each process are introduced in this section. The actual simulation and discussion for the expected impact reduction with DPM system application will be presented below in the pilot study chapter.

7.1. Framework of the social impact evaluation model

The framework of the model to evaluate the social impact of demolition is described in Figure 57. It can be separated into four main phases and three decision steps as follows:

1. Project generation (with 'Project generation model')
2. Agent algorithm setting (with algorithm)
3. Total impact evaluation (with 'Total impact model')
4. Sensitivity analysis

Each decision step becomes the core of the main phase, and the accumulated result and algorithm parameter with repeated cycles of steps would eventually be used for the checking of model sensitivity as the final step. Although those three decision steps were involved in the previous research model as shown in orange in Figure 57, the further factors (which are highlighted in yellow) are recently added to extend the impact evaluation to the interaction between demolition and construction teams. This is also developed to evaluate the potential reduction of environmental impact from demolition with DPM system installation. Accordingly, the development for the further impact evaluation in each process is mainly discussed with the comparison between new and old model in the sections below. As seen in the figure, many different types of factors ha been appended in the algorithm parameter. Therefore, a flowchart is selected to describe the algorithm for each agent in the clause of agent algorithm setting.

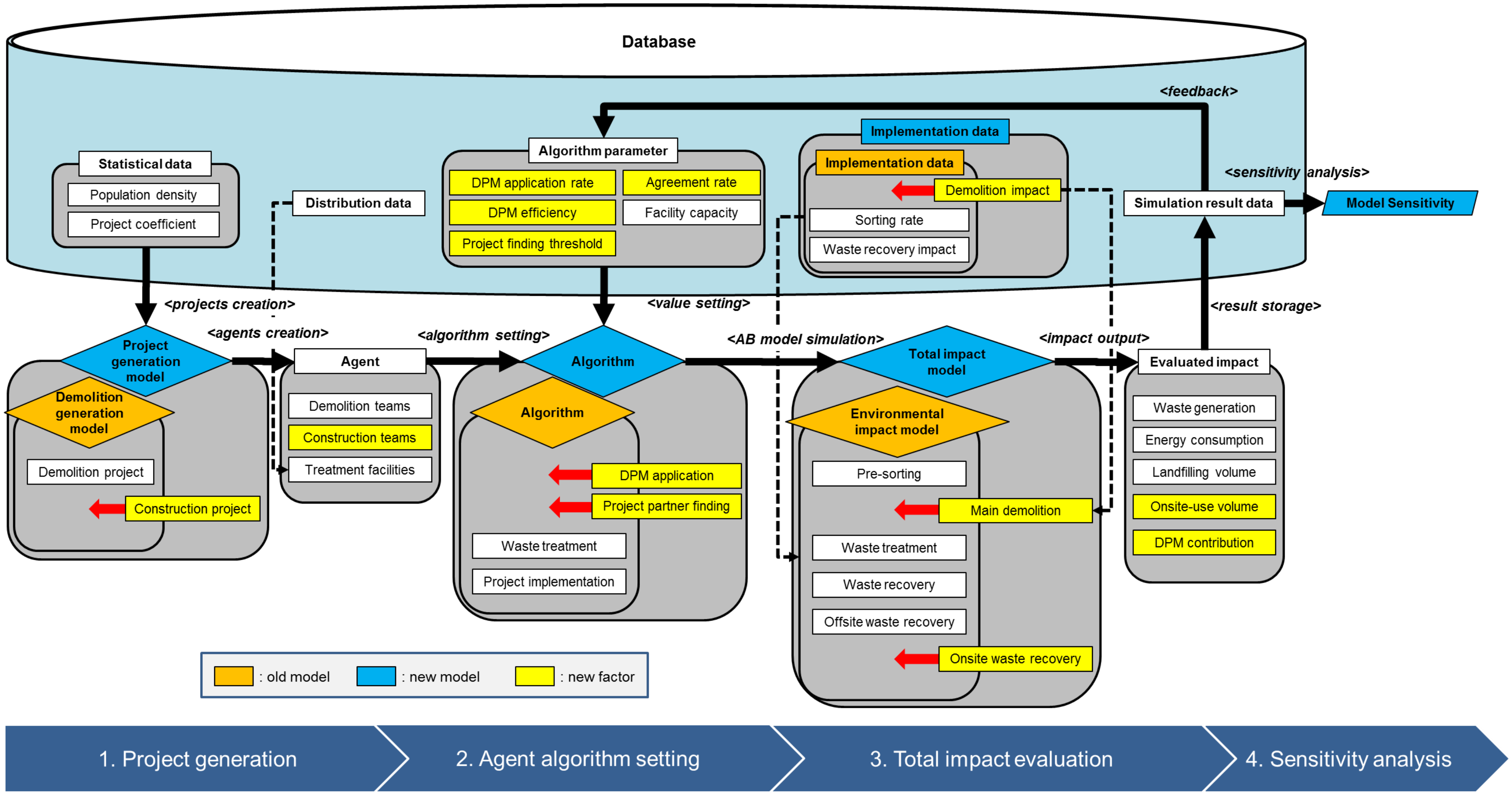


Figure 57 Framework of the social impact evaluation model

7.2. Evaluation process detail

7.2.1. Project generation

The 'Demolition generation model' is applied in this process. As the same manner as demolition projects, the construction coefficients for each local authority in England, Wales and Scotland are suggested from the ONS data as shown in the below Table 29. According to this data, the probability of project generation in the unit per day is given. Based on this, the generation of projects for each day would be checked. When generated, the random location in the unit would be set as the project site location for calculating the transportation burden with facility location data later. This is based on the fact that that the unit is small enough to ensure the probability distributes evenly. In addition to this, building type, floor area and cost are set for each project. The statistical data for the building type as shown in Table 30 can be applied to designate the building type so that construction teams can narrow down the suitable construction site. For the floor area and cost, value distribution is difficult to describe from the actual distribution based on the statistical data. Accordingly, in this model, the distribution is assumed as the nominal distribution. Using the minimum and maximum value, the deviation value is set under the assumption that whole projects are involved in the 95% of certainty (i.e. maximum and minimum gap is equivalent to 4σ). With above assumption, the distribution can be described as Figure 58. The random function in Excel is applied to generate the value following the probability density function. In order to check the validity of those assumption, the influence from the change of deviation value is analysed with the set of deviation value: σ at the sensitivity analysis.

$$\Leftrightarrow \sigma = \frac{X_{\min} + X_{\max}}{4} \qquad (6)$$

where

σ : deviation, X_{min}, X_{max}, X_{ave}: minimum, maximum and average statistic value , f(x): probability distribution function

Table 29 Construction coefficient in the Great Britain

	Population	Total construction	Construction coefficient
North East	2606625	6406.2	0.00246
North West	6935736	16871.5	0.00243
Yorkshire & the Huml	5301252	13279.2	0.00250
East Midlands	4481431	14620.0	0.00326
West Midlands	5455179	13303.1	0.00244
East	5831845	18502.3	0.00317
London	7825177	18420.8	0.00235
South East	8523074	24696.9	0.00290
South West	5273726	16508.5	0.00313
England	52234045	142816.9	0.00273
Wales	3006430	7936.9	0.00264
Scotland	5222100	22404.6	0.00429
Great Britain	60462575	173158.5	0.00286

*The values in coloured cells are applied to this model.

(Source: ONS (Office for National Statistics), 2010a)

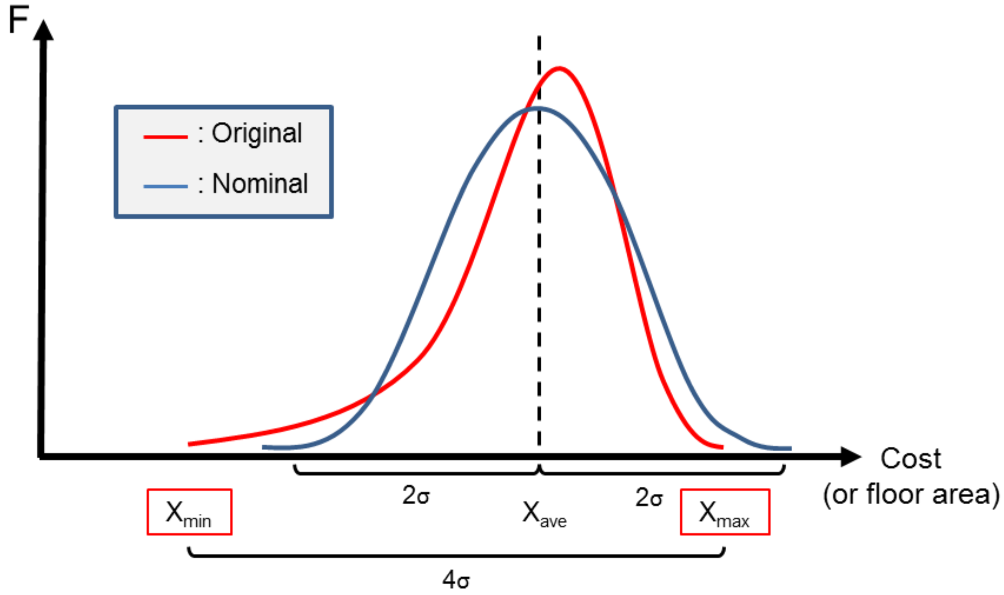


Figure 58 Adjusted distribution from statistic values

Table 30 Number and proportion of dwellings types built in the UK in 2005

	number(000s)	%
Masonry	20633	92.7
Cavity	14387	64.7
Solid - 9" thick	4230	19.0
Solid - over 9" thick	1813	8.2
crosswall	203	0.9
Timber	519	2.4
old (pre 1919)	79	0.4
new (post 1919)	440	2.0
Concrete	941	4.3
boxwall and crosswall	242	1.1
in situ	434	2.0
precast	265	1.2
Metal frame	124	0.6
Total	22217	100.0

(source: Communities and Local Government, 2007)

7.2.2. Agent algorithm setting

After the generation of demolition and construction projects on the map of Great Britain, the model regards them as the individual agents (demolition and construction project teams, respectively). Besides the offsite waste treatment facilities, three different types of agents make their decision under the set rules. The process flow for those agents can be summarised in the Table 31, and each agent algorithm can be described in a flowchart as Figure 59 below. As mentioned in the first row of the table, the application of DPM is the first step for both active agents, construction and demolition teams. Since there is no actual data for the application rate among those project teams, it naturally becomes the tentative value. The transition of DPM installation impact must be analysed as the model sensitivity before discussing the system significance. As the second step, those active agents try to find a project partner according to the threshold value for several factors as shown in Table 32. Precisely, construction teams try to find the acceptable projects for their construction and send offers to them. According to the agreement ratio (which is provisionally set but supposed to be decided by questionnaires to demolishers), demolition teams decide if they accept the offer or not. As introduced in the flowchart, active agents have T and t variables. It explains the time limit for each project to conclude the contract so that the projects which cannot acquire any partner would be considered as an individual project in which waste would be treated by offsite facilities or use only virgin materials for construction (i.e. no onsite waste recovery can be expected). Regardless of the conclusion of a contract, demolition teams need to find the offsite facilities for each type of waste at the third step. Assuming that facilities would accept the offer except for the capacity limit, facilities just try to find the availability of waste acceptance and answer the demolition teams. Then, at the final step, the treatment volume for each agent is counted to calculate the whole impact caused by those process.

Table 31 Process flow for agents

		Active		Passive
		Construction teams	Demolition teams	Offsite facilities
1	DPM application decision	1. Decide the use of DPM system for project design 2. Decide uploading own project on DPM system	Decide the use of DPM system to find the site	-
2	Project partner finding	Find and negotiate to demolition teams ⇔ (1)	Decide the offer from construction teams	-
3	Waste treatment planning	-	Ask the availability of treatment to facilities ⇔ (2)	Check own capacity to accept offers
4	Project implementation	Record the amount of recycled waste application	Record the amount of waste sent to offsite	Record the amount of waste treatment

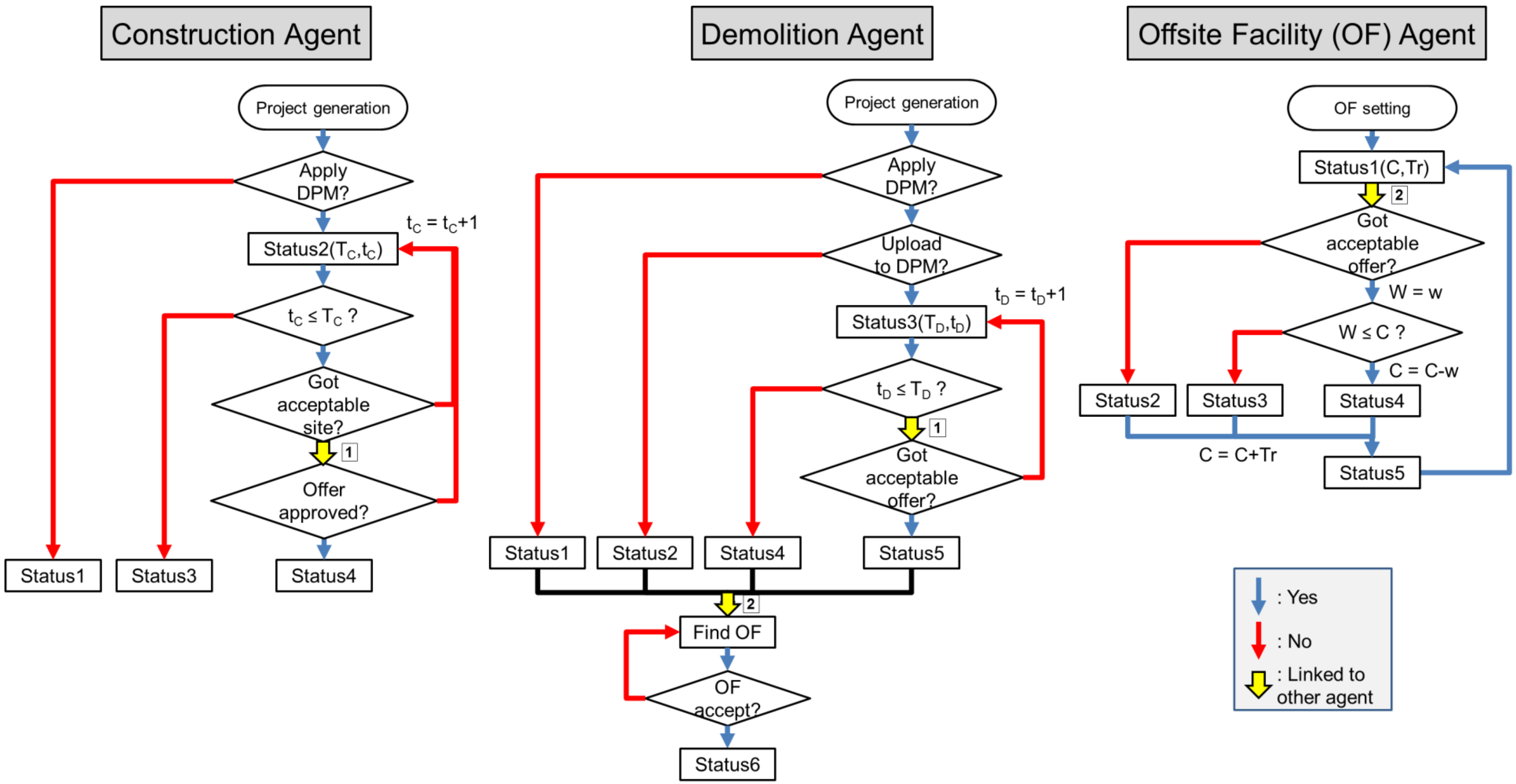


Figure 59 Framework of the social impact evaluation model

where OF: Offsite Facility, C: capacity of OF (t), Tr: treatability of OF (t/day), W: waste mass (t), w: offered waste mass (t), T: project affordable time (day), t: spent time (day)

Table 32 Agent factors to set threshold values

Construction teams		Demolition teams		Offsite facilities	
Factor	Variable	Factor	Variable	Factor	Variable
Site location	L (distance(km))	Agreement rate	P (rate (%))	Capacity	C (mass(t))
Site scale	A (floor area(m^2))	(Project term)		Treatability	Tr (work(t/day))
Building type	B (type (SRC, RC, Steel, Wood, Brick, other)	(Recovery rate)			
Recovery rate	R (rate (%))	(Site layout)	all factors are Involved		

7.2.3. Total impact evaluation

According to the result of recorded treatment amount in the previous phase, the total impact derived from the whole waste recovery process can be summarised as the previous 'Total impact model'. Here, the two extended foci, main demolition and construction use impacts, need to be adopted into the new model as shown in Figure 60. The impact from the main demolition process is set by the product of floor area and coefficient which is calculated from statistical data. If the project adopted the impact evaluation model in DPM system to their project planning, the project impact can be calculated from the product of the original impact value and the impact reduction rate (improvement efficiency). The value of impact reduction rate will be calculated in the following pilot study chapter. Then, if the project would be followed by the construction team, the applicable amount of waste can be regarded as onsite material and distinguished from the offsite waste recovery process. The total social impact was calculated from the average distances between stakeholders in the previous model which were not concerned about the project scale distribution. However, the new model evaluates the project impact individually so that the project scale effect which may require relatively long journey to offsite facilities is expected to be precisely analysed. This approach is more advantageous to clarify the significance of waste recovery onsite to avoid the bulk of waste from offsite recovery stream.

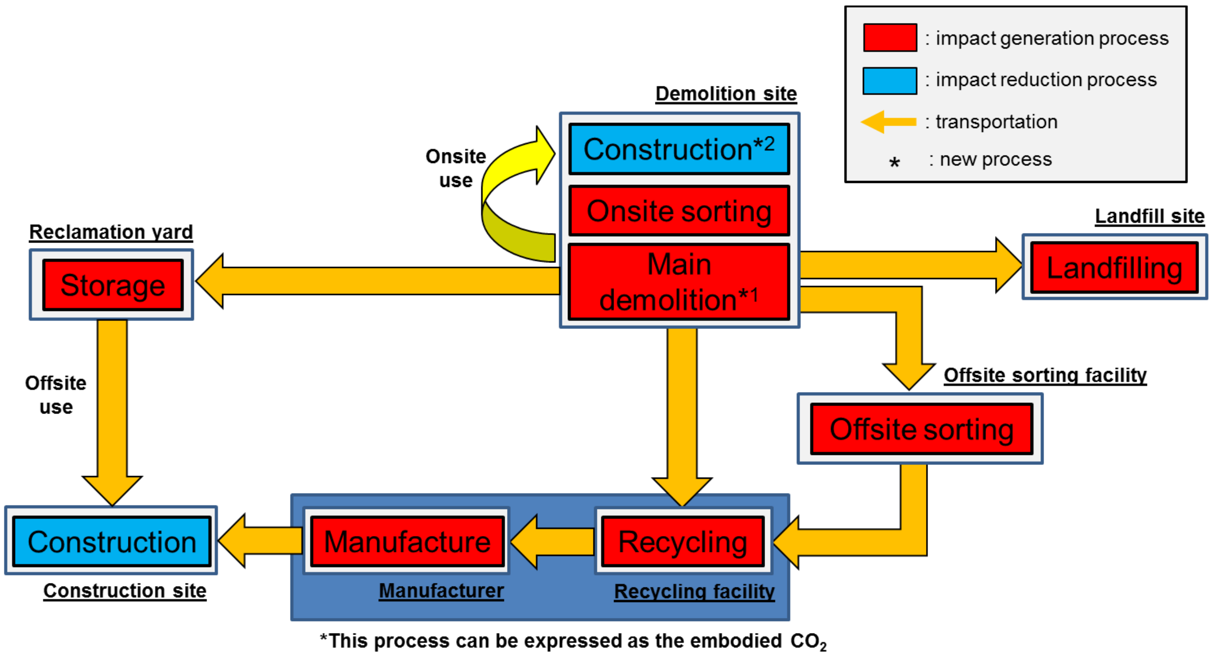


Figure 60 Framework of the total impact evaluation model

7.2.4. Analysis of model sensitivity

This model contains many variables to estimate the impact reduction from the application of the DPM system. Therefore, the sensitivity for each variable must be discussed to show the versatility of the model. The following property values are involved in the sensitivity analysis. According to this, the suggestion of DPM application will be shown how it is advantageous to the current UK society in terms of social sustainability.

<Target of each analysis>

1. **Indirectly influential factor for matching**
   a. Dispersion of demolition and construction project (e.g. project size, project type)
   b. Border of project satisfaction for construction project teams
      (e.g. location, site scale, cost, length of finding, etc.)
   c. Agreement rate between demolition and construction teams
2. **Directly influential factor for matching**
   a. Application of DPM system for construction and demolition project teams
      (e.g. application and uploading rate of own project)
   b. Constructors awareness of recovery waste application

3. Influential factors for transportation distance among stakeholders

a. Project satisfaction thresholds for construction project teams
(Acceptance rate of construction teams for recovery facilities)

b. Capability of offsite waste treatment facilities (recycling and sorting plants)

c. Waste recovery strategy (sorting and disposal rate)

4. Influential factor for DPM application impact

a. Improvement efficiency with DPM application (k_i, k_r, k_t)

Chapter8

<Chapter Abstract>

In this chapter, the project impact evaluation tool explained in Chapter6 is examined in a pilot study. Following the preliminary survey with a prototype tool and the comparison of different algorithms, the actual project BIM data is applied to validate the model usability in practice. The potential of practical realization and the drawbacks of the tool are considered based on the result. Readers can know the expected impact reduction from the DPM application on the project basis in this chapter.

Chapter8. Findings I: Pilot study for method III (Project impact)

The pilot study is separated into two chapters according to the impact evaluation target; i) individual demolition projects and ii) society (of the UK in this research). This chapter focuses on the model application to the individual project. Three phases of the pilot study have been held. In the first phase, the prototype model which could only recreate the demolition process by free-fall of elements was applied to the target building recreated by BIM data. Following the applicability validation of 4D-CAD and BIM data to the demolition impact evaluation with a prototype study, the algorithms suggested in Chapter3.4 are compared to decide the optimal suggestion, and the potential of impact reduction with the theoretical approach is evaluated. Finally, the practical application was analysed by the application of the model to the actual BIM design data for the construction project on the University of Bath's campus. The robustness of the model is validated with the BIM for the actual building design. In addition to the application in practice, the recreation of three main demolition methods currently applied in practice is also introduced at the end.

8.1. Prototype model development

Using the building design data in 'ifc' format uploaded by Vectorworks (2015), a five-storey building was recreated in Blender as the target building to be demolished by simple machine demolition methods in the BGE simulation (as seen in the fourth process of Figure 48). To comprehend the accuracy of the simulation result, the model by Solís-Guzmán et al. (2009) is applied to compare the estimation result of waste generation from the total building floor area and their experimental data. This follows the tradition of Cheng and Ma (2013) in the verification of their own BIM-based model for demolition, which used the Solis et al., model. In the Solis et al 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;

$$V_{dem} = Fl \times M \times F_{dem} \tag{1}$$

where V_{dem} is demolition waste volume (m^3); Fl is the floor area per level (m^2); M is the number of floors and F_{dem} 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 by Cheng and Ma (2013). Referring to their value of demolition waste volume factor, total demolition waste volume can be estimated as Table 33.

Table 33 Estimation result of waste generation with the Solis et al model

Element type	S (m²)	N	total (m²)	Demolition waste volume factor (F_{dem})(m³/m²)	Total demolition waste volume (m³)
Slab + beam	234	5	1170	0.4340	507.8
Wall	234	5	1170	0.1200	140.4
Reinforcement + column	234	5	1170	0.1300	152.1
				Total	800.3

8.1.1. Scenario setting

In this pilot study, as described in Figure 61, a five-storey building is demolished by the external demolition method with one high reach excavator in which boom and dipper are 15m and 9m. Main and sub direction of demolition orders are set as ‘South to North’ and ‘West to East’ through the demolition method panel so that the target building is demolished from the south west to the north east corner. It should be noted that demolition at higher levels is prioritised as the actual onsite implementation in terms of health and safety. Following this, two patterns of machine relocation are set as the machine logic setting to compare the demolition impact as shown in Figure 62; (i) demolishing the next target in arm range without changing location (scenario1: ‘fixed’) and (ii) changing the location to the nearest accessible position to each target (scenario2: ‘movable’). The impact difference caused by machine use should be numerically compared with transportation distance and total time to complete the whole building demolition. Therefore, the transportation distance and the treatment volume of waste have been measured to evaluate the change on time scale. On the other hand, for the waste generation impact, time-lapse change of waste generation needs to be described from three different aspects; (i) waste distribution, (ii) total waste generation and (iii) waste purity within the unit area. In the simulation, units of demolished elements return the time, location, material type and volume when they hit the ground, which is regarded as the timing to becoming waste. Based on the multiple data, waste distribution map, purity map and generation map are drawn to visually understand the demolition progress and geographical features.

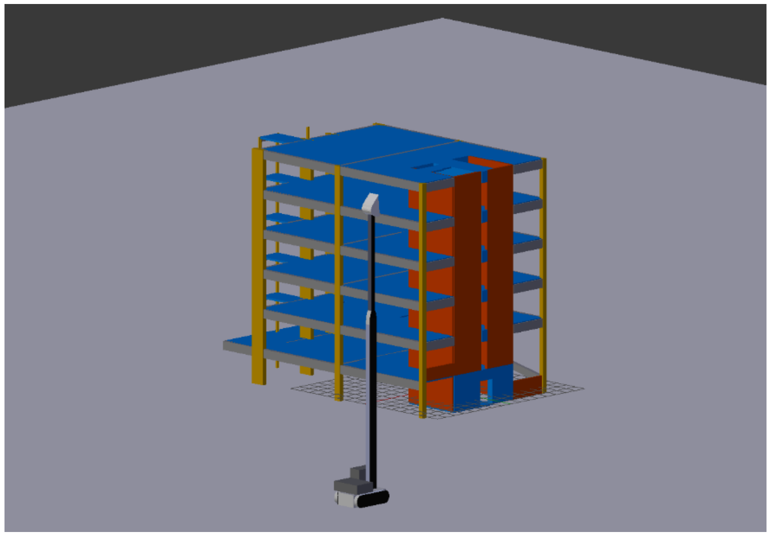


Figure 61 Automatic demolition by the registered machine in BGE

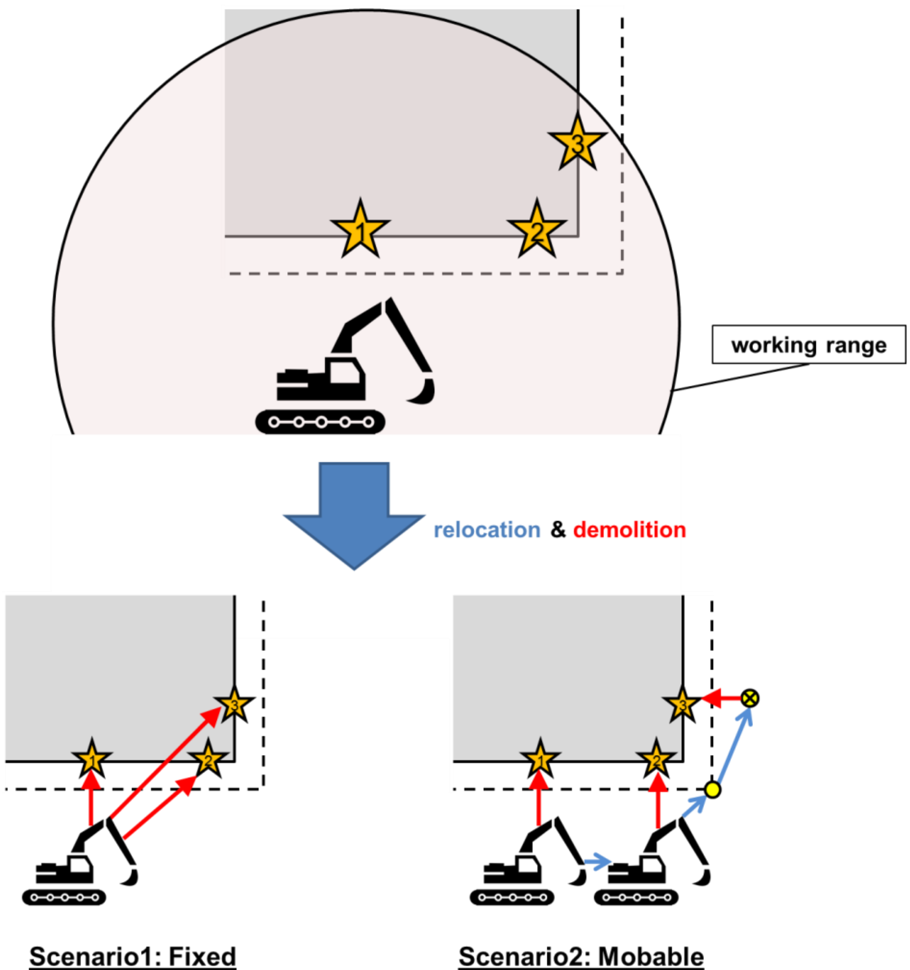


Figure 62 Relocation setting for two scenarios

8.1.2. Result and discussion

Simulation results for both scenarios are shown in Table 34. Most of the unit objects which compose the building elements have been recorded as waste objects. The generated waste volume of each element type showed negligible differences between demolition strategies despite of the large gap in the period of demolition. This is also true of the generated waste volume for each element type. Compared to the estimation result of the Solis et al model, while beams and slabs show similar volumes wall and column volumes actually become less than half. This can be attributed to the moment frame structure of the building and no partition and external walls set in the design model. With the high accuracy of object measurement to become waste, this model simulation is expected to achieve the accuracy required to facilitate demolition planning.

Machine impact for the simulation of scenario1 (‘fixed’) and comparison with scenario2 (‘movable’) are shown in Figure 63. According to the total distance result, the excavator only moves twice to demolish targets in scenario1. It results in less than 60m transportation compared to 2200m in scenario2. Since the interference from other building elements is not considered in this simulation, there would be some opportunities for operators to change the location of the excavator more than this in the actual demolition. Even though, it is quite a convincing explanation of why the actual operators try to stay at one place as long as possible to save the transportation distance and increase their demolition efficiency. In terms of total time consumption in the simulation model, it saves 20% for total implementation with fixed treatment strategy. Although there are recently many assumptions by authors for the time-scale for each process, the accuracy for the time-scale evaluation would be improved by referring to the actual demolition data (e.g. machine properties, onsite visual record etc.). The gradient of treatment volume in the figure shows the efficiency of demolition treatment. For instance, the decrease of gradient from 400sec (in following part, the time scale is described with computation time with sec) in scenario1 can be explained by the shift of target from large slab unit to small column unit at the end of demolition. The lower demolition efficiency for scenario2 is also visualized from the lower gradient compared to scenario1 due to the time-consuming location change. Therefore, the efficiency of demolition method and the required time for each process can be read from the machine impact data in this model simulation.

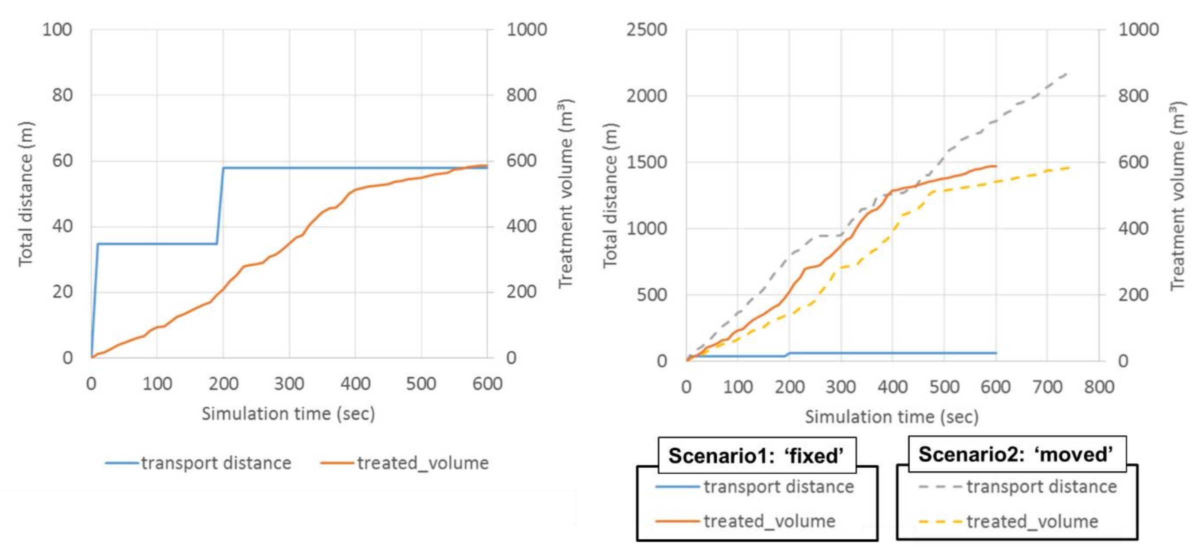
Waste generation for the simulation of scenario1 (‘fixed’ with solid lines) and scenario2 (‘movable’ with dashed lines) are shown in Figure 64. Here, each element type is described with different colour. As the whole wall elements are located at the south side and columns are more set at the north side, walls (with an orange line) have been demolished within 200sec and columns waste increases its volume from 400sec. The latter timing just fits in the timing of the reduction of the demolition efficiency in scenario1 in Figure 63, and the same thing can be found at 500sec for scenario2. Comparing the two scenarios, there are no differences except time scale. This is caused by the same order of demolition for both scenarios and the simplification of element demolition as the free fall of each element unit. Application of actual hitting of the target with the shovel part is expected to recreate more accurate behaviour of object scattering, which causes a difference from the machine attachment and target layout.

Time lapse change of waste generation discussed above can be seen in the successive waste distribution maps as Figure 65, where the same colour is applied for wastes as the original elements. Demolition progresses from south to north, and walls have been demolished until 200sec and north side columns have been demolished from 400sec in scenario1. Moreover, this map shows the relation between original and generated location as waste for each element type. Due to the moment structure of the building, columns are mainly located at six points (i.e. four corners and two intermediate points) to form a framework. Following that geographic feature of the target building, the waste of columns and connecting beams forms similar layout on this map. In contrast, the slab's distribution is slightly biased to the south part. This is explained by the effect of lower level slabs which sustain wastes generated from above slabs. As clearly seen in 200sec and 300sec figures, wastes are generated except the middle square area. The south edge of this square fits to the border between the first and second parts of the slabs, which are composed of three parts from south to north for each floor level. After the collapse of the first slab part for whole levels, the slab waste from the second part drops down to the lower level for each collapse. Since the collapse advances from the south, some waste slides south and spills from lower support to land on the wastes from the first slab part. In Figure 66, the waste generation rate map is shown in the left panel and the purity of the waste is plotted in the right panel. The peak of generated waste volume is located almost at the middle of that border. The other peak is also on the border of the second and third slab parts due to the overflow from the remaining slab. In a similar manner, at 500sec, some slab waste is dropped even to the north side of the third slab part. This kind of analysis is also useful to survey onsite health and safety. Due to the dynamic and temporal feature of demolition projects, interactions among labourers and machines must be minimized to avoid the risk of accidents. The animation of model simulation as shown in Figure 67, should be used with other waste generation data. 2D and 4D visualization allows project designers to comprehend the time-lapse change of geographic features on site so that risk assessment and zoning with the site map can be achieved.

Given the limitation of waste recovery for the next construction, the information of waste purity is also quite beneficial for demolition planning. Therefore, a purity map is produced based on the location and volume of generated waste for each element. Unit grid is cut with 5m grid length for both x and y axis, and the volume rate of the majority waste type is plotted on the centre of the grid as shown in Figure 68. While the centre part of the building shows a high value of purity, the value declines as it approaches columns and beams location. Since the target building has almost the same floor design for each level, the purity level stays at this high purity. If it were more complex, demolition designers need to consider the scheduling for waste transportation based on the time-lapse change of waste distribution and the local features. In this pilot study, the waste purity at north side has been declined after 400sec because of the following column demolition (see Figure 68). Accordingly, demolition should be temporarily halted at 400sec and waste recovered before the remaining building elements are mixed into other types of waste. Even after the whole demolition, waste can be recovered with high purity if extracted locally. As seen in the lower row in Figure 68, when the grid size decreases, the purity for each grid becomes higher. Although time-consuming to recover waste in small scale by labourers or small vehicles, critical treatment at small area seems feasible. This plan should be considered with the generated waste volume to maintain the onsite work productivity.

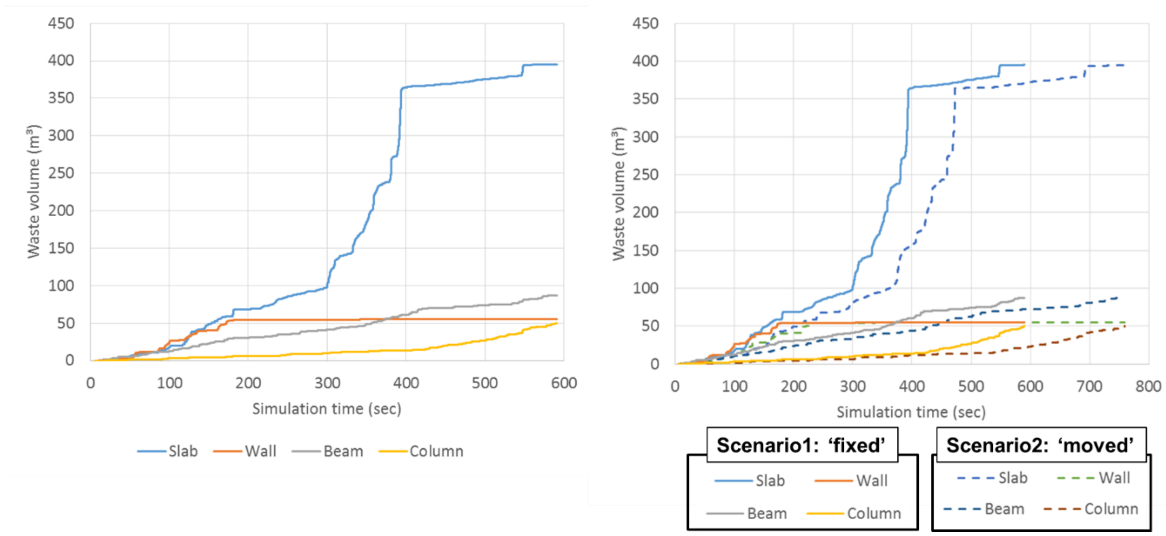
Table 34 Simulation result of waste generation compared with the Spanish model

Scenario	time	object number		measurement	waste volume (m^3)				
		measured	total	accuracy (%)	Slab	Beam	Wall	Column	total
1	590.4	11185	11547	96.9	352.6	87.1	92.6	50.1	582.4
2	759	11151	11547	96.6	352.0	87.0	92.6	50.0	581.5
				Solis et al model	507.8		140.4	152.1	800.3



scenario1: 'fixed' **scenario1 and 2: 'movable'**

Figure 63 Result of machine impact



scenario1: 'fixed' **scenario1 and 2: 'movable'**

Figure 64 Result of waste generation

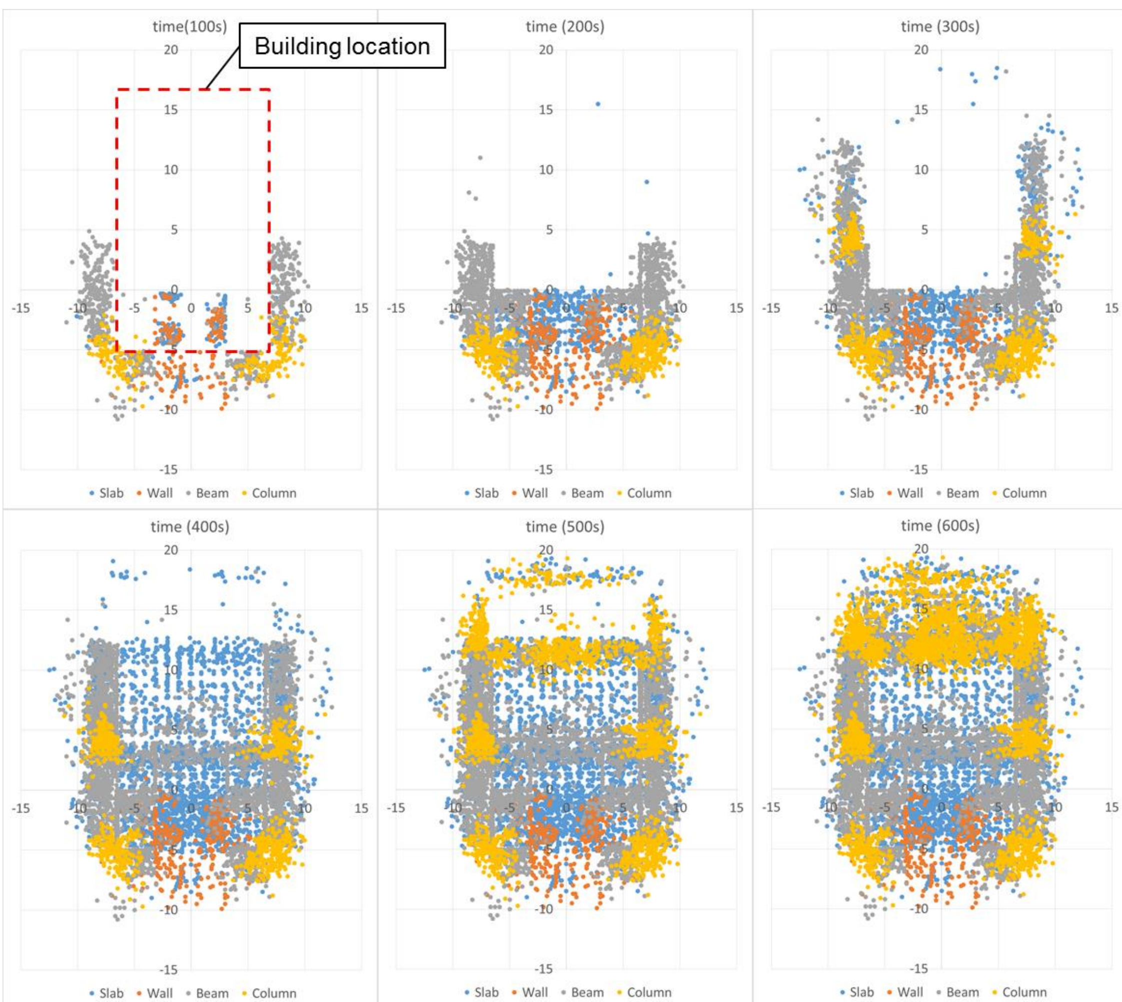


Figure 65 Waste distribution map (scenario1: fixed)

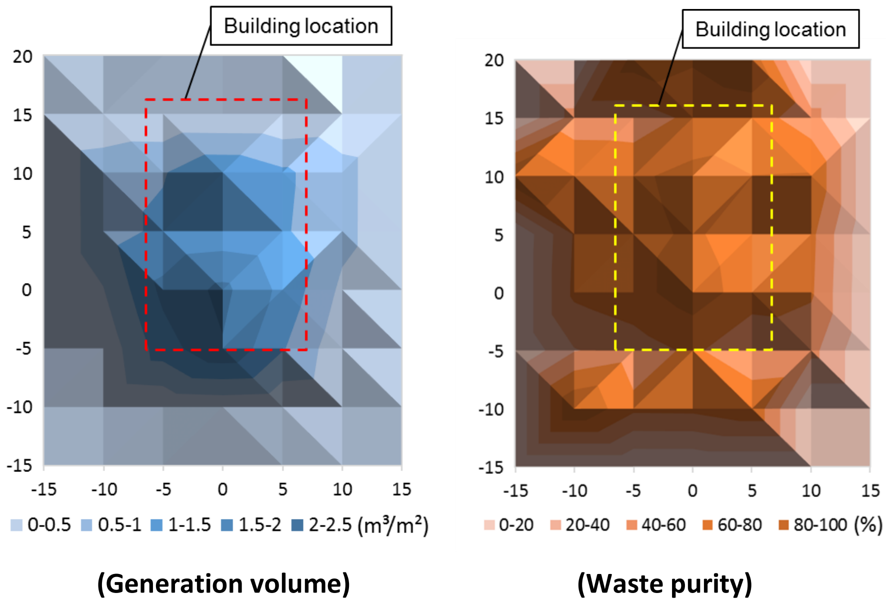


Figure 66 Waste generation map and Waste purity map (scenario1: fixed)

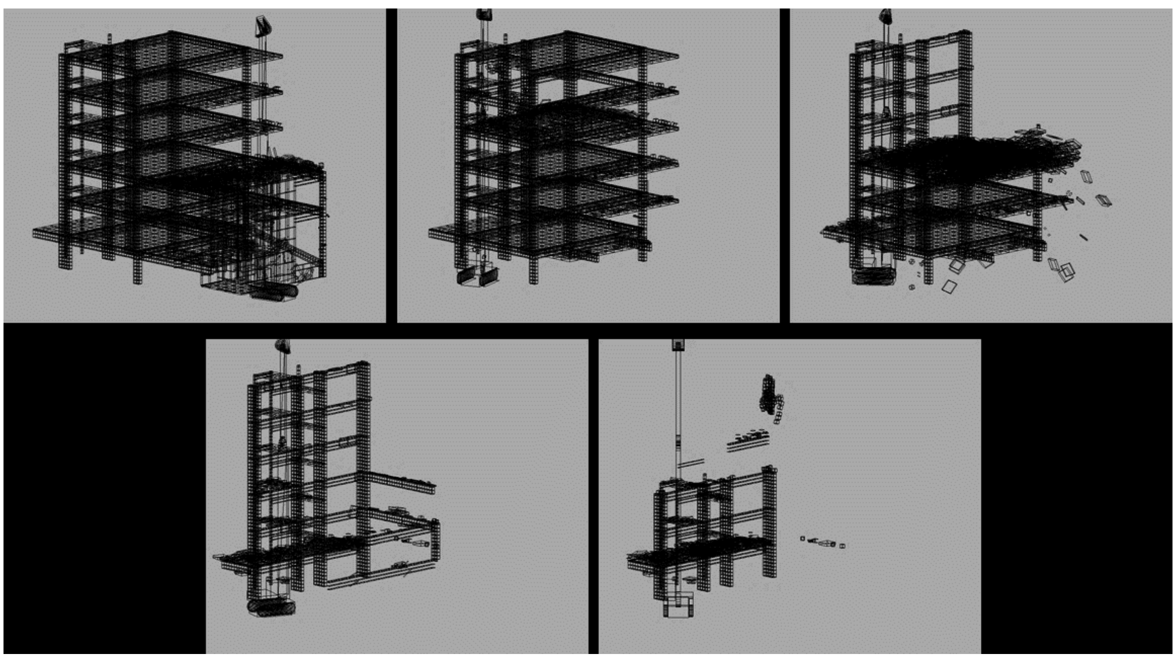


Figure 67 Animation of model simulation (scenario1: fixed)

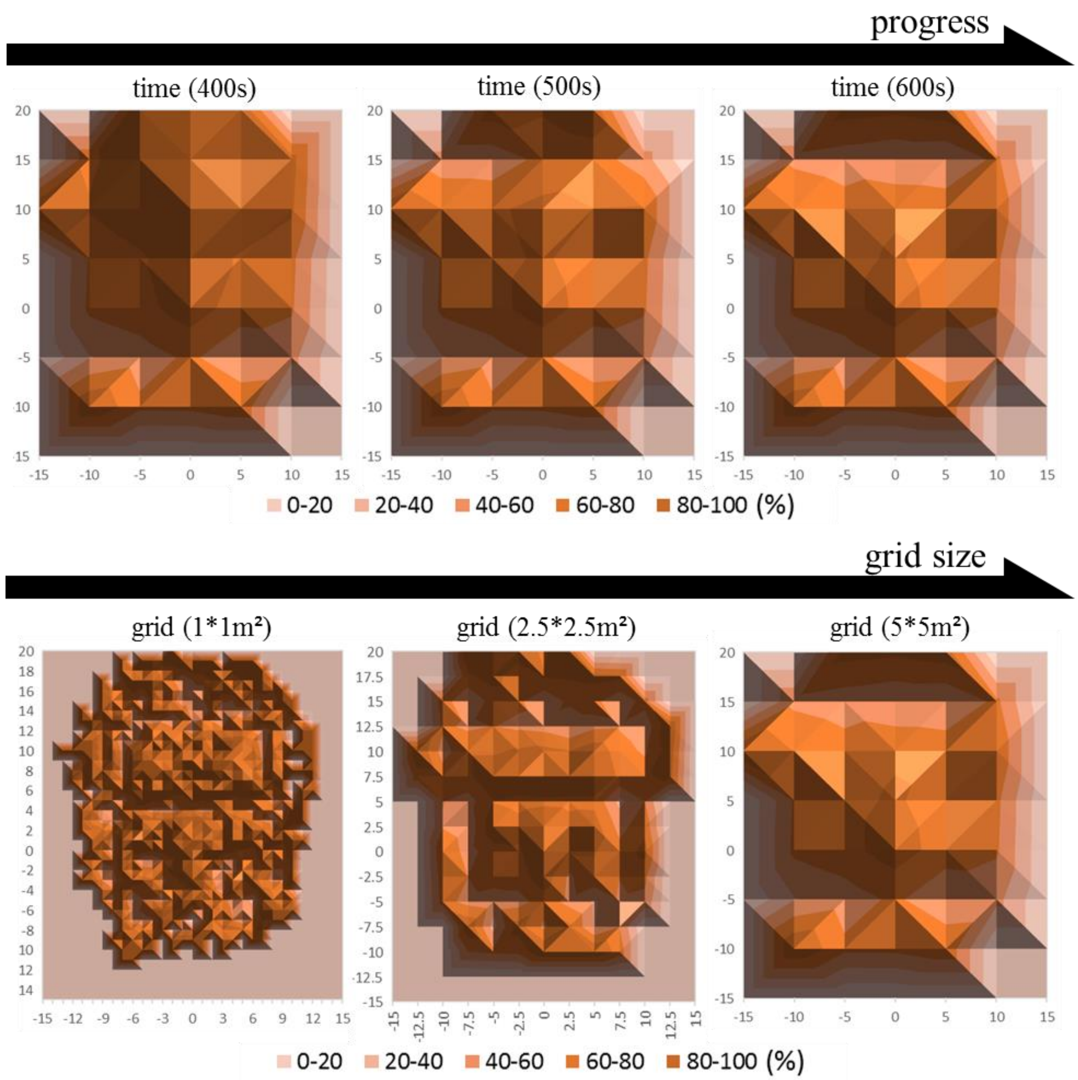


Figure 68 Change of waste purity map (scenario1: fixed)

8.2. Algorithm comparison

In this section, the suggested algorithms at Chapter3.4 are compared to decide the optimal algorithms for the machine operation and the demolition order setting. The target building data used in the prototype pilot study was applied to this pilot study too. In order to clarify the contribution of waste purity to the impact reduction, external wall elements were added to the original design as visualized in Figure 69, and the volume of each elements changes as in Table 35. By setting the element type of wall and slab as brick and concrete respectively, the difference of total impact between a material considering method and a non-considering method can be identified. Table 36 classifies target algorithms according to the aim of optimization, 'machine control' and 'demolition order setting'. Based on the number of machines to be operated in the simulation, the scenarios defer their settings. In addition to this, the target of output through the pilot study decides the style of impact estimation. If the machine operability is only required to survey, excavators are only set to measure the total operation time for demolition. On the other hand, the total demolition impact can only be evaluated with waste collection and the resulting treatment impact. Thus, a bulldozer needs to be added to the model for waste collection for the evaluation here. Through the evaluation of impact for several options, the setting with the minimum (optimum) financial impact is chosen as the final decision of demolishers. In addition to the comparison with the average financial impact to scale the budget saving, the environmental impact for the decision and the average are also compared with 'Eco point', as explained above, the environmental impact evaluation system suggested by BRE. This aims to measure the impact reduction resulting from the financial-oriented demolishers' decision with the model application. In theory, selecting the lower price project planning implies the reduction of machine operation time so that the fuel consumption from machine operation is simultaneously saved. The correspondence between two impacts are analysed in this chapter and that value of sustainable improvement is used in the next chapter to quantitatively justify the application of the suggested system.

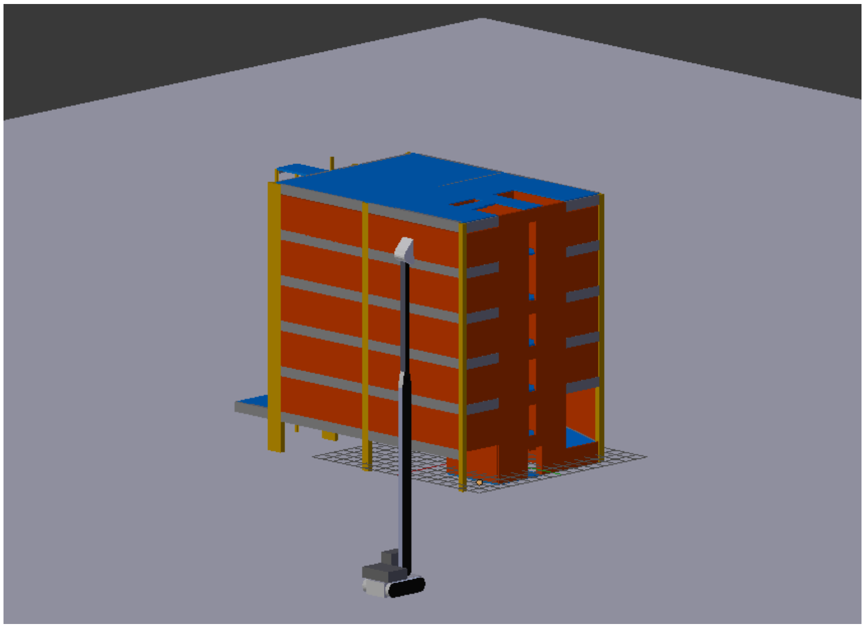


Figure 69 Automatic demolition by the registered machine in BGE

Table 35 Component of target building

	object	waste volume (m³)				
	number	Slab	Beam	Wall	Column	total
Original	11547	353.0	87.7	97.9	50.3	588.8
Modification	13406	353.0	87.7	240.7	50.3	731.7

Table 36 Compared algorithms list

target algorithm			target output
optimization target	target machine operation	target setting	
machine control	individual	path finding	machine operability
		element demolition	
		relocation	total demolition impact
		arm folding	
	tandem	machine traveling	machine operability
		waste collection	total demolition impact
demolition order setting	tandem (excavator+bulldozer)	locational setting	machine operability
		material setting	total demolition impact

8.2.1. Machine control

Pilot study of 'machine control' algorithms are separated into two types corresponding to the number of machines to be focused on. 'Individual' operation types target a movement of one excavator which is the most frequently applied onsite. Although it has many different types of attachment according to the purpose and circumstances, a bucket is set as the attachment in the pilot study because of the widest range of hitting point in which debris is more probably mixed with others. So that the difference of the waste treatment impact can be compared clearly between the demolition planning with and without regarding the waste purity. In order to survey each algorithm in wide demolition options, the different types of fundamental theory described by algorithm)) of demolition order setting and scale of machines (excavator) are tested. For the order setting, four different types of building segmentations which are suggested in Chapter3 are applied as shown in Figure 70. Beside this, the demolition machine with an arm (boom and dipper) which can reach all the elements of the target building from the ground is selected to be applied. As mentioned above, the target output is set for the machine runtime to survey the 'machine operability' while the total impact is evaluated for others to consider the waste purity impact. Each scenario setting is explained below.

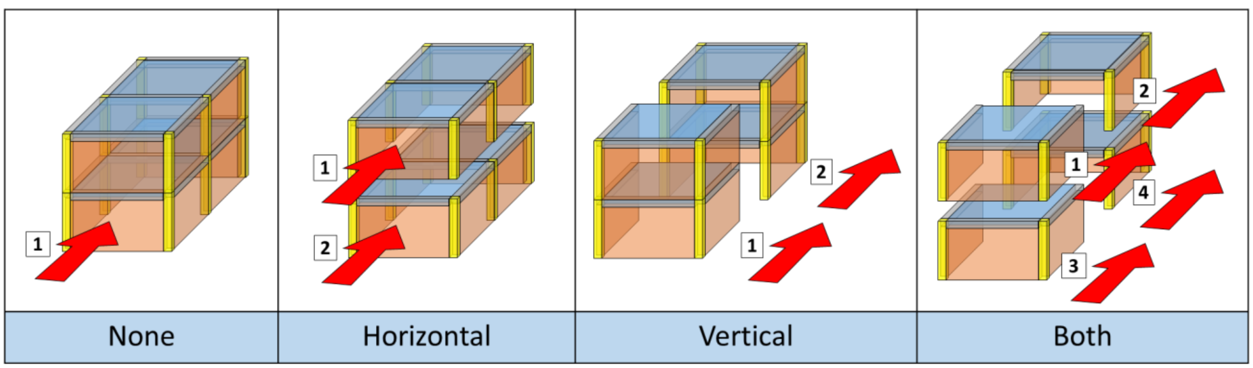


Figure 70 Four patterns of demolition order setting

8.2.1.1. Individual machine operation

Scenario setting for each algorithm which focuses on the individual operation is summarised in Table 37. The detailed description of each scenario can be seen in Chapter3.4 with concept drawings. All types of algorithms are validated with the same machine and the demolition order setting as shown in Figure 71 and Figure 72. The red highlighted scenarios are set as the default setting, and the best algorithms for each comparison are replaced in the next comparison. As a result, the final suggestion shows how much improvement can be achieved with a theoretical approach. As aforementioned, the different length of arms (booms and dippers) are attached to excavators to identify the operation efficiency of algorithms. In the 'Caterpillar Performance Handbook Version.45' (Caterpillar, 2015), the machine setting of 22m length arms on the excavator '385C' is introduced as the general setting of the super long reach excavators. On the other hand, there is a movie uploaded online which recorded the onsite application of Caterpillar '5110B' with 90m arms at demolition (Dream machines, 2016). It implies the feasibility of arms application between 22-90m onsite. Since the target building has about 17.5m height to the top and 6.5m distance from the center to the edge, slightly more than 18.5m of arms are necessary to hit the whole target with arms from ground. In this pilot study, the general setting 22m and its 1.5 and 2 times longer arms (33m and 44m respectively) are applied to compare their workability. The rental cost is modified according to the relation between arm length and rental cost as shown in Figure 73. The mobility spec and the cockpit scale apply the value of Caterpillar '390D' which is the largest machine on the list.

Table 37 Estimation result of waste generation with the Solis et al model

target setting	scenario		target output
path finding	1	edge fixed	machine operability
	2	edge updated	
element demolition	1	sorted with location	
	2	decision with distance	
relocation	1	continuous relocation	total demolition impact
	2	except working range targets	
	3	except working rangeand visible targets	
arm folding	1	setting to highest	
	2	setting to next	

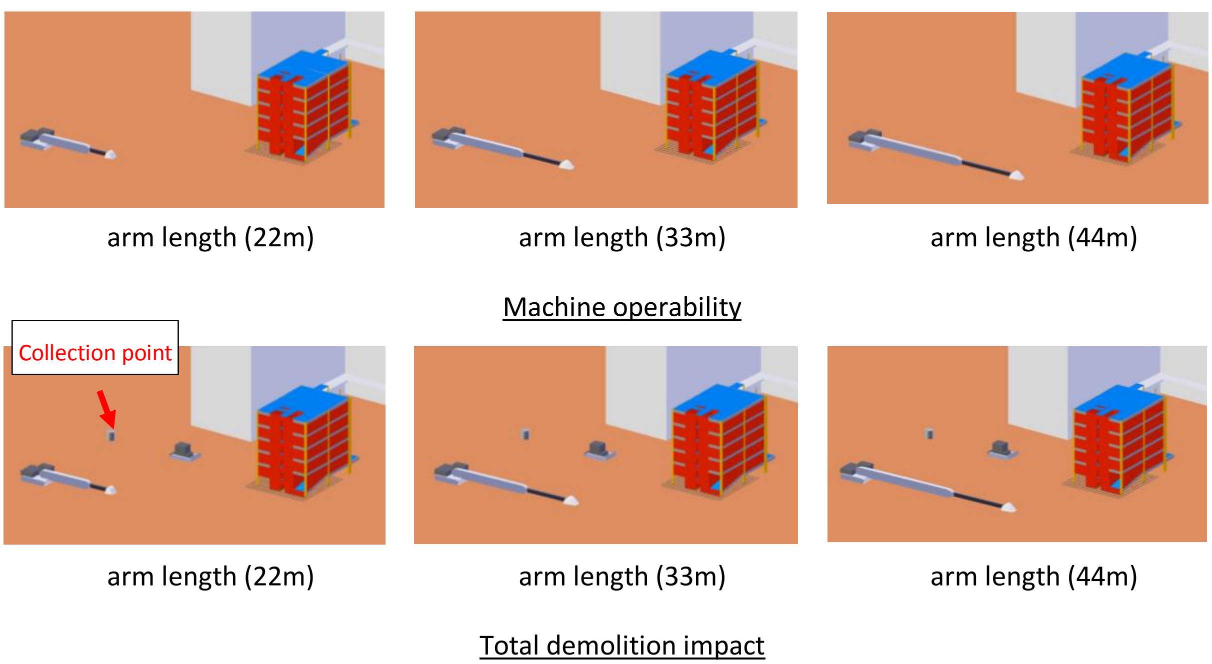


Figure 71 Machine application setting (individual machine operation)

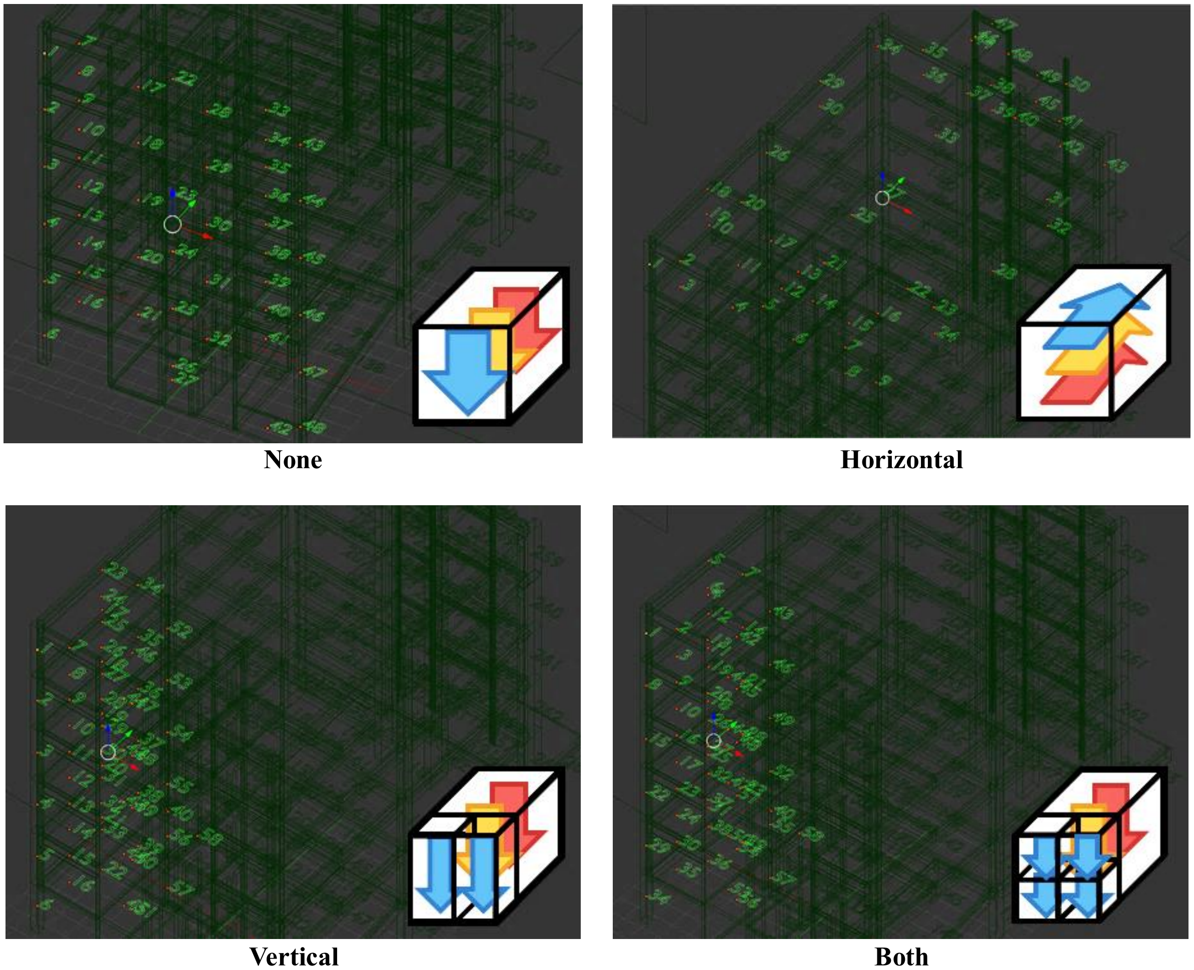


Figure 72 Demolition order setting (individual machine operation) *

<u>*showing the order of demolition with numbers and the coloured arrows (blue>orange>red)</u>

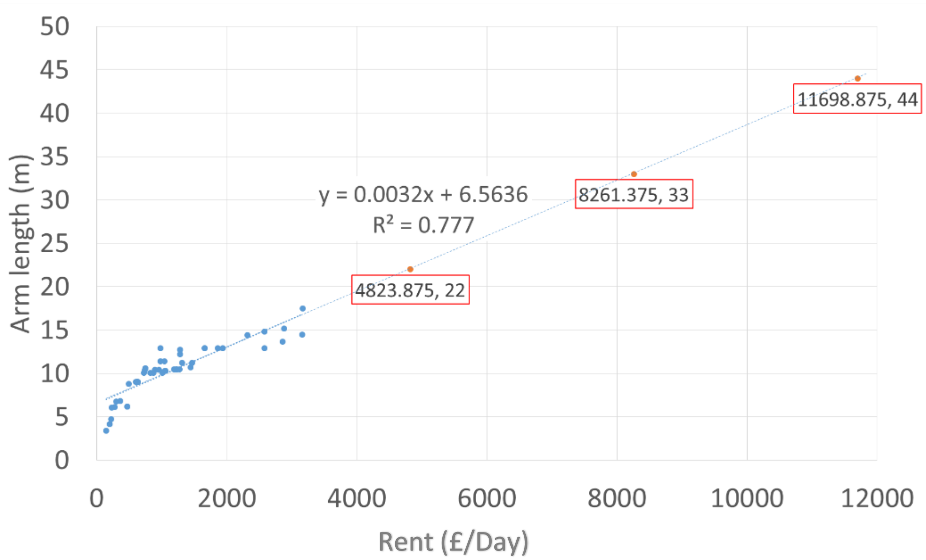


Figure 73 Relation between cost and arm (boom & dipper) length

8.2.1.2. Tandem machine operation

While the single demolition machine only is considered in the previous section, multi machine operation is considered to improve the total productivity on site. The target setting of machines and the suggested scenarios are summarised in Table 38. The detailed description of each scenario can be seen in the appendix with concept drawings. All the types of algorithms are validated with the same machine and the demolition order setting as shown in Figure 74. Same as the application of the single machine, the target output is set for the machine runtime to survey the 'machine operability' while the total impact is evaluated for others to consider the waste purity impact. The order of demolition in the tandem operation can be visualized as Figure 75.

Table 38 Estimation result of waste generation with the Solis et al model

target setting	scenario		target output
machine traveling	1	single traveling	machine operability
	2	multiple traveling	
waste collection	1	closest from collection machines	total demolition impact
	2	farthest from demolition machines	
	3	closest from demolition machines	

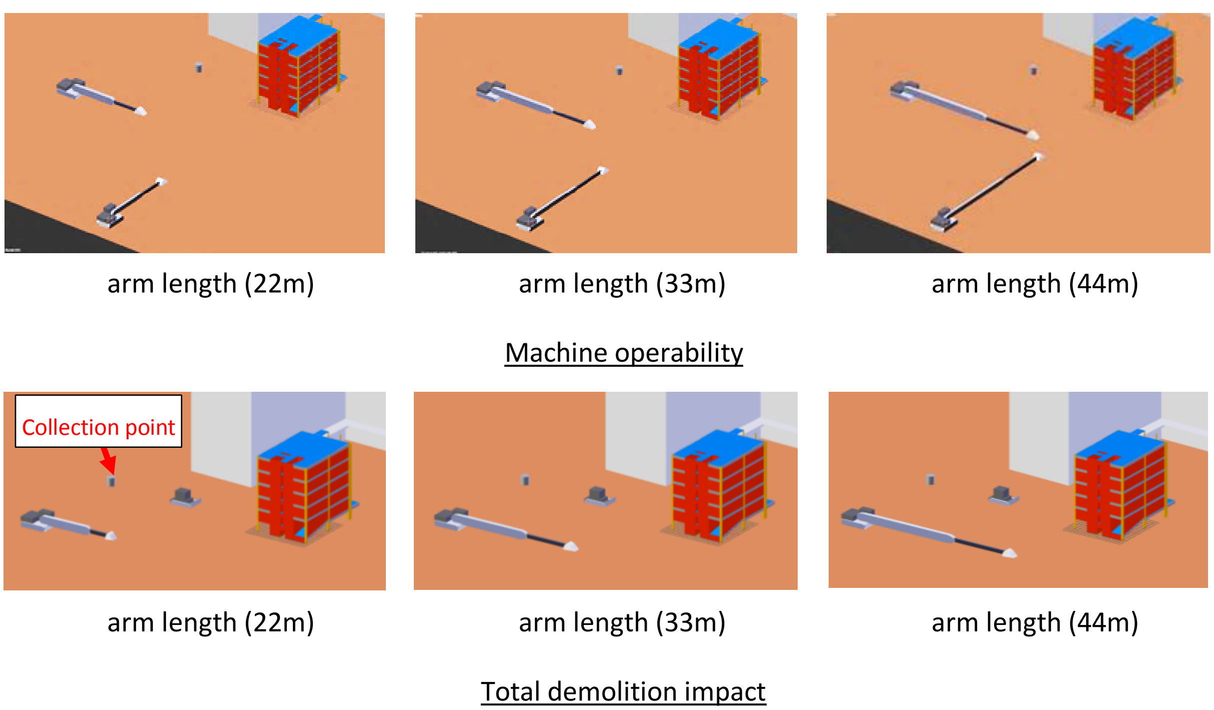
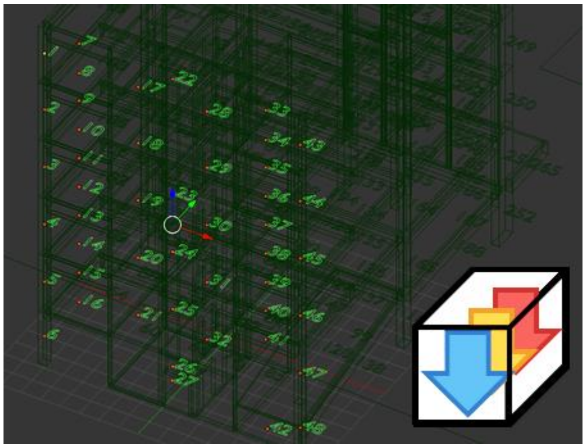
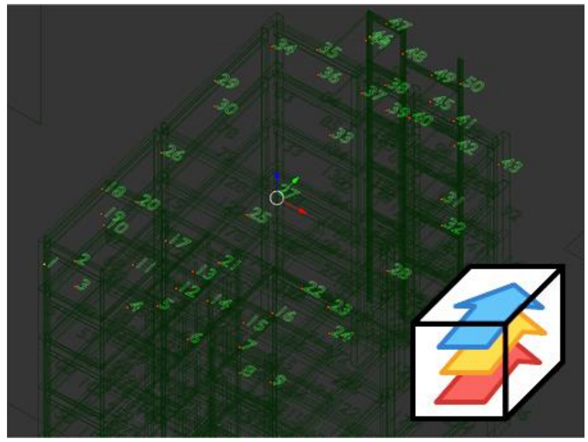
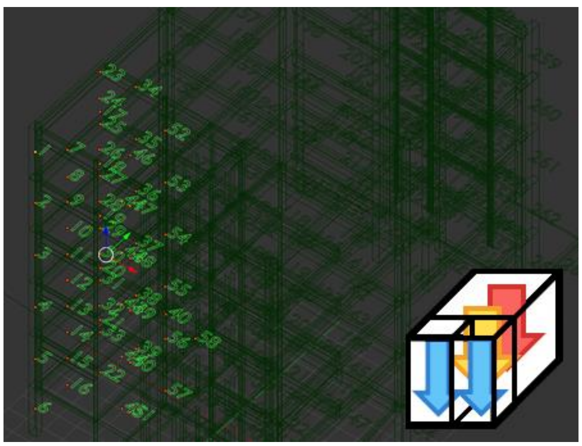
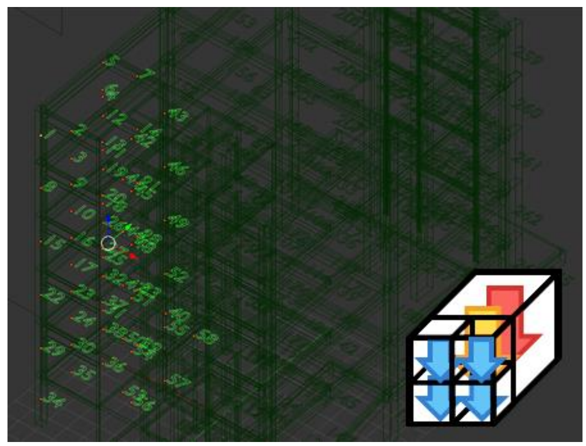


Figure 74 Machine application setting (tandem machine operation)

None **Horizontal**

Vertical **Both**

Figure 75 Demolition order setting (tandem machine operation) *

***showing the order of demolition with numbers and the coloured arrows (blue>orange>red)**

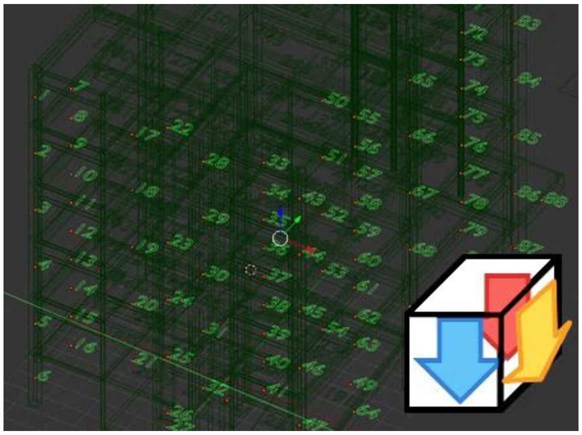
8.2.2. Demolition order setting

In the previous section, the machine operation was considered in two phases; i) individual and ii) tandem operation, which aimed to validate the advantage of the simulation approach to the machine operation. In this section, the importance of the demolition order setting is quantitatively analysed with suggested algorithms which are summarised in Table 39. For the locational setting, the same result which was simulated in the previous section with the best machine operation settings is applied to compare with the algorithm of the closest element demolition. Both methods aim to minimise the transportation distance from different approaches.

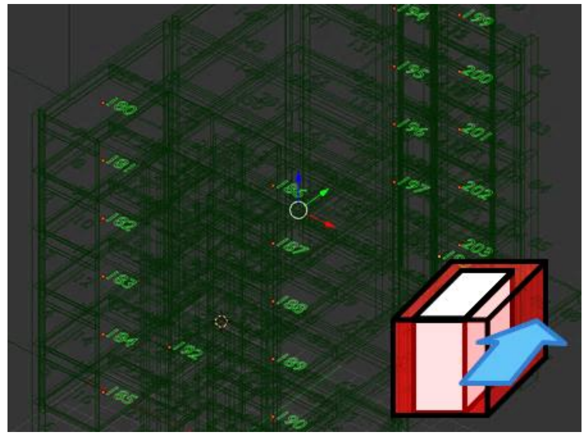
On the other hand, the material type is considered at the setting of the demolition order to improve the total demolition impact with better waste purity. The demolition order is set as Figure 76 when the material type is referred. In order to compare the efficiency of demolition planning with others, above two suggestions are evaluated with total demolition impact together. To enhance the waste purity, all scenarios apply the collection algorithm in which a bulldozer preferentially collect the closest waste from the demolition machine (i.e. the most recently demolished debris).

Table 39 Estimation result of waste generation with the Solis et al model

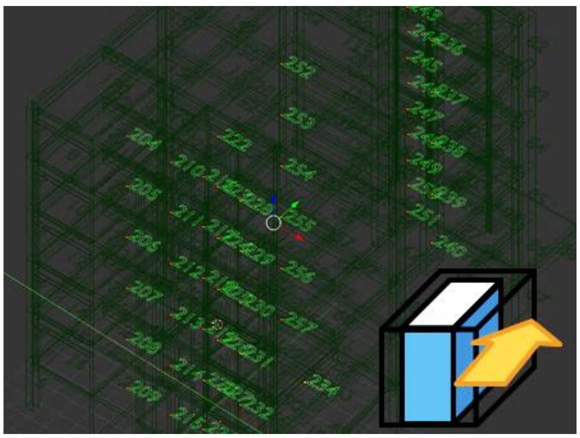
target setting	scenario		target output
locational setting	1	sorted with location	machine operability
	2	decision with distance	
material setting	1	sorted with location	total demolition impact
	2	decision with distance	
	3	sorted with material	



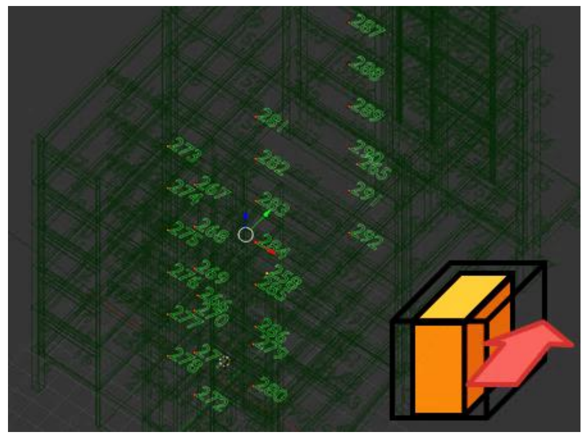
Step1. External elements



Step2. Floor elements (outside)



Step3. Internal elements



Step4. Floor elements (inside)

Figure 76 Demolition order setting (material-based)

***showing the order of demolition with numbers and the coloured arrows (blue>orange>red)**

8.2.3. Results and discussion

The suggested algorithms for both the machine operation and the demolition order setting are compared from the simulation results. Scenarios are sorted according to the target of outputs; the machine operability and the total demolition impact. While the machine operability only concerns the machine productivity with the total operation cost, the total demolition impact is considered to adopt the waste treatment impact in which the user can apply the weight for each factor with their preference. Therefore, the benefit-oriented method can simultaneously fulfil the sustainable improvement with an optimal planning in this model.

8.2.3.1. Machine operation

Individual and tandem operation of machines are separately examined to identify the optimal operational algorithms for each process (target selection, relocation and destruction). According to the result, the correlation between the concept of algorithm and the tendency seen in the resulted impact can be discussed in following sections.

Individual machine operation

The machine algorithm for the path finding and the demolition order among element units are compared with the machine operability as ‘group A’ algorithms. The simulation results of the operation time and the total cost from the machine application are summarised in Table 40. In addition to this, the further demolitions are simulated with intermediate arm length of the excavator for the ‘None’ scenario. The change of impact with different length of arm allows to clarify the influence of arm length in precise. The result for both the operation time and the cost are visualized in Figure 77 and Figure 78. Compared to a demolition from the outside of the original building space (as an accessible area), a flexible relocation with updated information for area accessibility results in a short time and cost effective operation with any length of arm. Similar thing can be seen in the accessible space updated scenarios with different order of element component destruction. While the order is aligned by unit location in the control scenario (edge updated scenario), the distance-based decision from machine is a more intuitive approach frequently seen in practice (‘decision with distance’ is described with green lines in figures). According to the result, the practitioners can find the more efficient approach through this simulation. This is also applicable to the selection of the optimal arm length. Based on the project impact estimation from two factors, the optimal project design is possible to be suggested from the users’ request. For a short time operation, 33m arm is recommended while a 22m attachment must be suitable for cost saving.

The optimal demolition order setting can be suggested from the impact comparison as shown in Figure 79 and Figure 80. Since the rental cost is proportional to the operation time, the shapes of figures are quite similar between them. As shown in the former figures, the financial and time optimization can be achieved by 22 and 33m arms. Between demolition order scenarios with same arm length, ‘None’ scenario which demolishes building regardless of a building framework shows the superior performance from both aspects. A demolition regardless the structural framework allows the dynamic destruction compared to the others. In particular, the horizontal approach which demolish buildings for each floor is quite time-consuming because of the remaining structure of the lower floors hindering the machine access. Since far objects tend to be selected as a target rather than vertical demolitions, a machine needs to relocate the position with longer path which results in almost double duration and cost. The model application at the project phase prevents those problematic approach in advance so that the project cost can be largely diminished. When the optimal operational cost is compared with the average cost of simulated setting (i.e. the average cost of Table 40), it can be calculated from the following accumulation equation.

$$\Delta C = \frac{C_{optimal} - C_{average}}{C_{average}} = \frac{C_{(update,Arm22)} - {\sum\sum C_{(i,j)}}/{i*j}}{{\sum\sum C_{(i,j)}}/{i*j}} = \frac{901-2478}{2478} = -0.636$$

where ΔC: the rate of cost change, $C_{(i,j)}$: each case for scenario and arm length

So that approximately 63% of cost can be improved. Even at the comparison among Arm22 except ‘Horizontal’ scenario which is too inefficient and unrealistic to be applied in practice, 21.4% of cost can be saved. Although in a narrow sense this should be discussed with the waste treatment cost, a strong potential of the computational approach is showed here to improve the machine operation strategy in practice.

Table 40 Operation impact for the individual machine operation (group A)

	None			Horizontal			Vertical			Both		
	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44
Operation time (min)												
edge fixed	105.8	93.1	113.4	198.7	231.6	320.3	108.7	90.6	105.4	109.3	102.8	109.9
edge updated	89.7	76	103.4	199.6	207.5	292.6	116	92	121.6	108.9	103	106.4
decision with distance	127.3	104.3	112	182.4	213.4	276.4	123.8	107.8	139.4	137.6	103	119.3
Operation cost (£)												
edge fixed	1063.3	1602.36	2763.9	1996.88	3986.1	7806.6	1092.4	1559.3	2568.9	1098.4	1769.3	2678.6
edge updated	901.46	1308.05	2520.1	2005.93	3571.3	7131.4	1165.8	1583.4	2963.7	1094.4	1772.8	2593.3
decision with distance	1279.3	1795.13	2729.7	1833.07	3672.9	6736.6	1244.2	1855.4	3397.5	1382.8	1772.8	2907.7

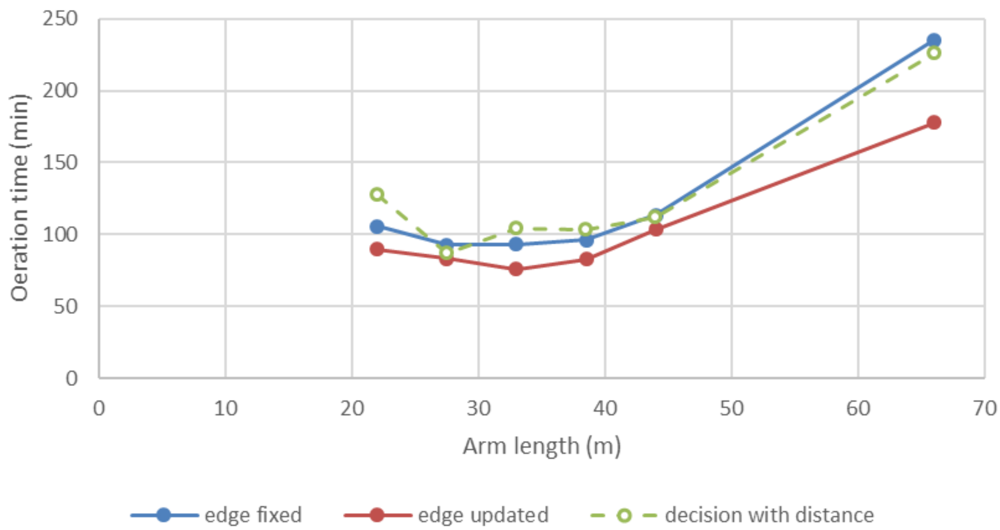


Figure 77 Operation time change with applied arm length (demolition order='None')

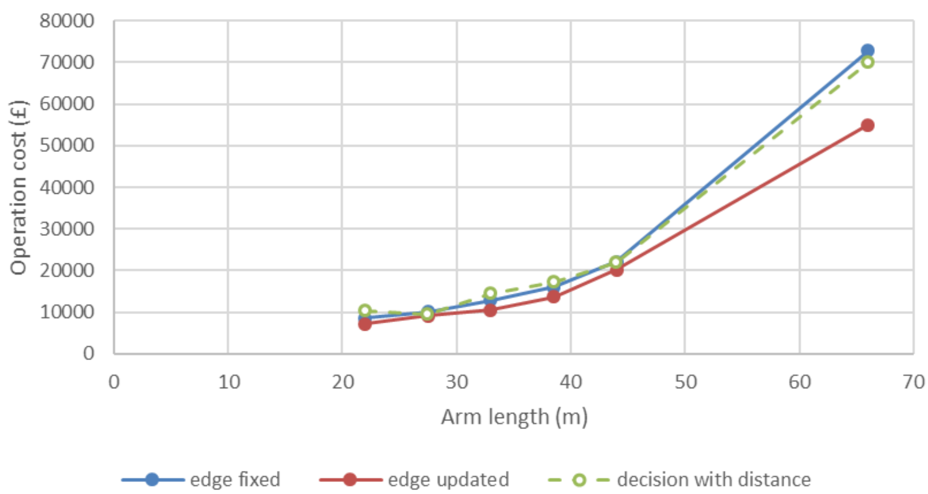


Figure 78 Operation cost change with applied arm length (demolition order='None')

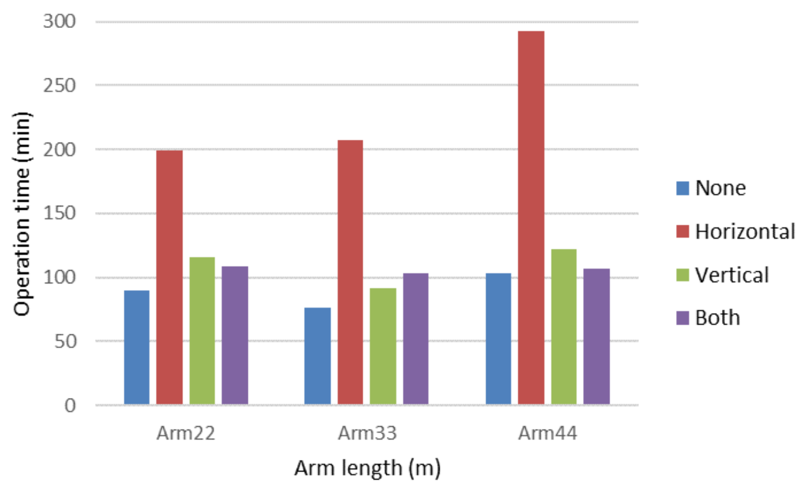


Figure 79 Operation time change with arm length and demolition order (with 'edge updated' algorithm)

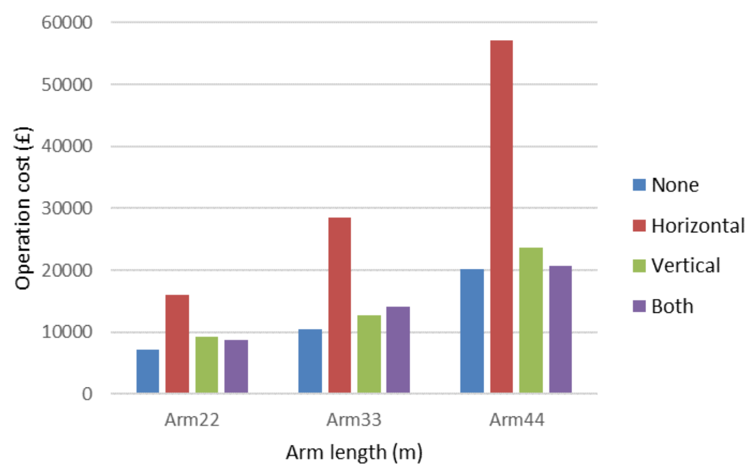


Figure 80 Operation cost change with arm length and demolition order (with 'edge updated' algorithm)

Following this, the machine relocation and the arm folding algorithms are evaluated with the total impact in the 'None' scenario with six arm length as 'group B' algorithms. The waste collection and the machine operation data allows more comprehensive cost and environmental analysis here. The operational time for each scenario are shown in Table 41 and Figure 81. In terms of the work duration, the frequency of relocation with algorithms are reflected to the length of operation. Accordingly, the demolition strategy to hit the whole objects in range without relocation shows a better result. If the height of bucket before the machine rotation is considered, there are no huge difference except with the long arm. The difference may be attributed to the accidental hitting of surrounding objects at rotation. To identify the influence of those, the environmental impacts and the cost are also visualised in Figure 82 and Figure 83.

Table 41 Operation time for the individual machine operation (group B)

Operation time (min)	None					
	Arm22	Arm27.5	Arm33	Arm38.5	Arm44	Arm66
continuous relocation	94.2	82.1	76.7	83.1	90.1	165
except working range and visible targets	78.1	74.6	63	67.3	71.4	164.3
except working range target	71.3	65.3	53.3	52.4	71.7	160.9
setting to next	76.3	61.3	57.4	56.4	60.9	97.3

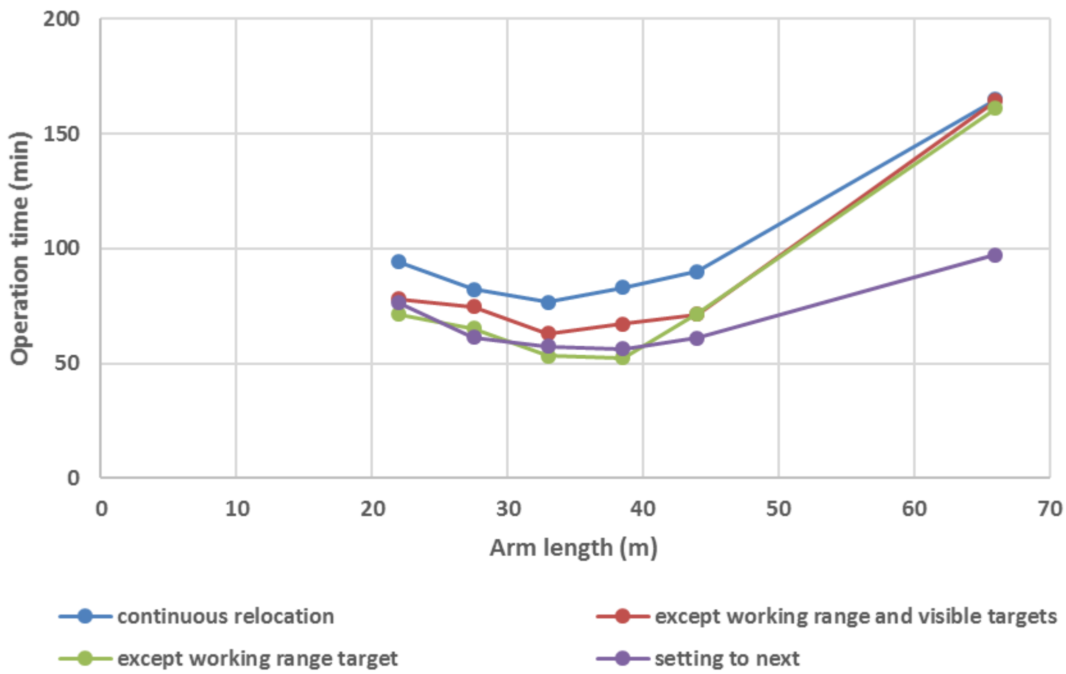


Figure 81 Operation time change with arm length (with 'None' scenario)

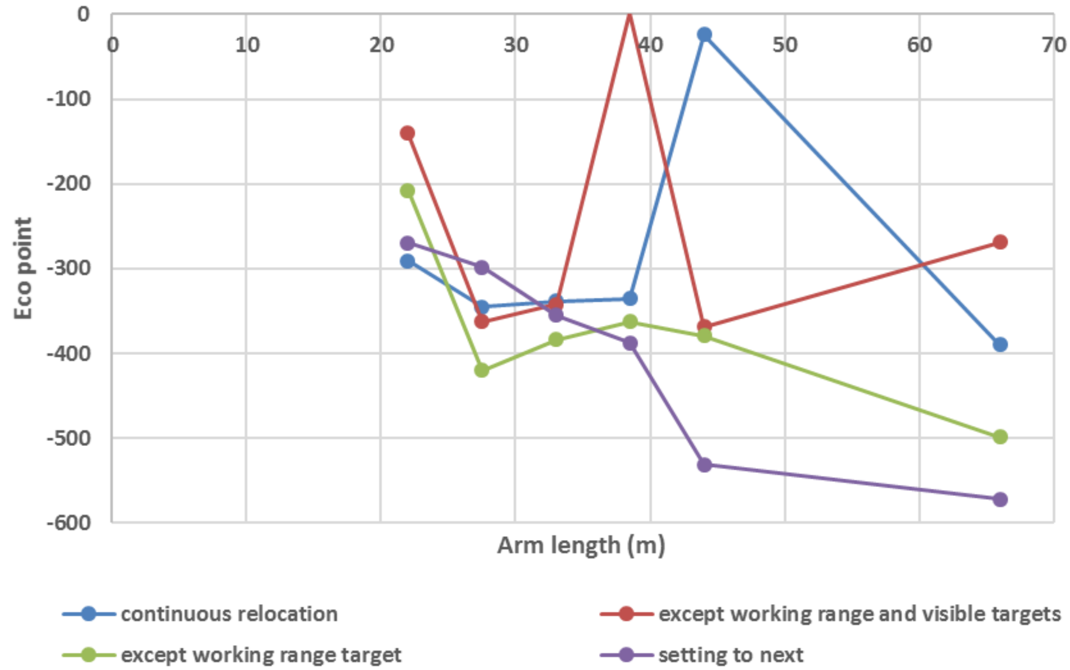


Figure 82 Eco point change with arm length (with 'None' scenario)

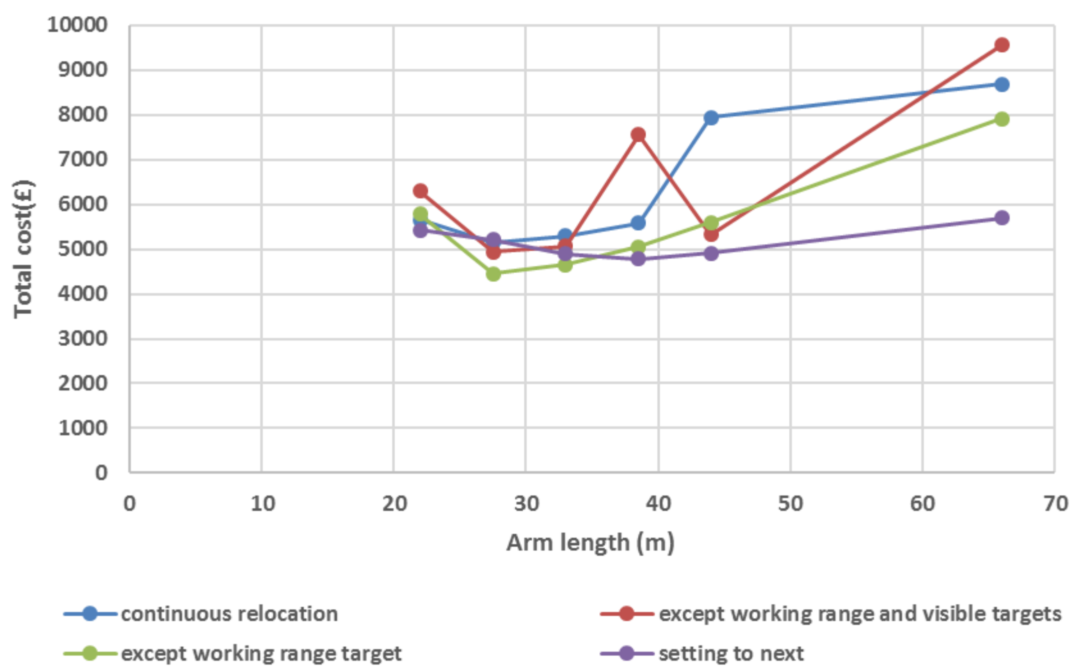


Figure 83 Total cost change with arm length (with 'None' scenario)

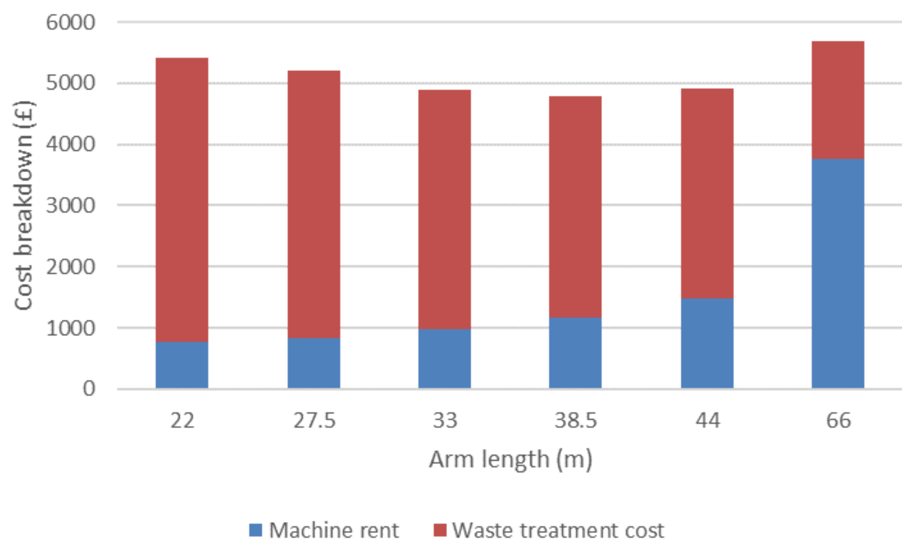


Figure 84 Cost breakdown change with arm length ('setting to next')

The total cost in Figure 83 is essentially dominated by machine operation cost, which is proportional to the operation time shown in Figure 81, and the waste treatment cost, which can be represented by the eco-point in Figure 82. In Figure 82, there is a trend where the shortest arm cases seem worst in terms of the eco-point, while the longest arm cases show best values in three demolition strategies. The large fluctuation found in this plot is due to the number scatter of scoops with better purity of 95%. This tendency can be explained by the following situation. Shorter arms hit the building in the angle close to horizontal direction when the arm is dropped, which gives destructed material large horizontal momentum. Largely scattered wastes are collected in a bucket with various components. On the other hand, longer arm machines hit the building mostly in vertical direction, which causes much smaller waste distribution. The collected waste in the former case should be so low purity waste that they cannot be recycled but to be sorted or brought to landfill. In Figure 82, the cost breakdown is shown for the 'setting next' case shown with purple lines in other three figures. The machine rent increases with arm length for machine time and cost. Since the reduction of waste treatment cost becomes more with a longer arm, total cost variation among them becomes within 20 %. It allows wider selection of arm length with similar cost, which was not possible without consideration of waste impact.

Tandem machine operation

Tandem machine operation algorithms are separated by the type of machines to be involved; between demolition machines or demolition machines with collection machines. For the multi demolition machine application, four demolition order scenarios were simulated to compare the proposed algorithms from the machine operation time and rental cost. The result for the operation time and the cost for the four scenarios are summarised at Table 42 and Figure 85. The impact difference with scenario is shown with the cost. While most of the part shows the same tendency as other algorithms, Horizontal scenario with Arm22m shows relatively high cost. It might be affected by the other machine when they try to relocate because of the far target setting in 'Horizontal' scenario.

With the mono operation result simulated in the previous section, both traveling algorithm impacts are visualized in Figure 86 and Figure 87. Between single and multiple operation, the further flexibility of machine operation slightly accelerates the whole process. Compared to this, the progress improvement from the demolition with single machine is more drastic. But once the cost is compared the single operation is more cost-effective in terms of individual productivity. Without any synergy effect, most of the interactions hinder the operation each other so that the total operation time would never be twice faster than single operation. Through the evaluation of the prospective loss with multiple machine operation, the trade-off between the cost efficiency and the time shortening can be decided based on a users' optimization condition.

Table 42 Operation impact for the tandem machine operation

	None			Horizontal			Vertical			Both		
	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44
Operation time (min)												
single traveling	45.4	35.9	47.2	81.9	58.5	94.8	46.6	35.5	62.5	43.8	35.2	60.5
multiple traveling	43.6	32.9	45.5	77.8	58.9	62.7	45.6	32.4	43.7	42.9	34.4	56.4
Operation cost (£)												
single traveling	912.52	978.668	1624.7	3405.72	2851.6	7336.7	936.64	1222	3046.6	880.36	1211.7	2949.1
multiple traveling	876.34	896.885	1566.2	3235.22	2871.1	4852.4	916.54	1115.3	2130.2	862.27	1184.1	2749.2

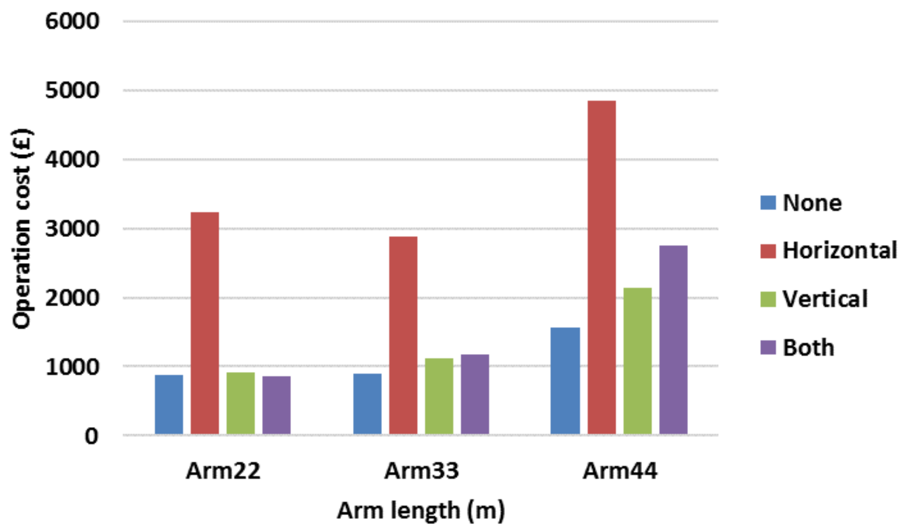


Figure 85 Operation cost change with arm length and demolition order (with 'multiple travel' algorithm)

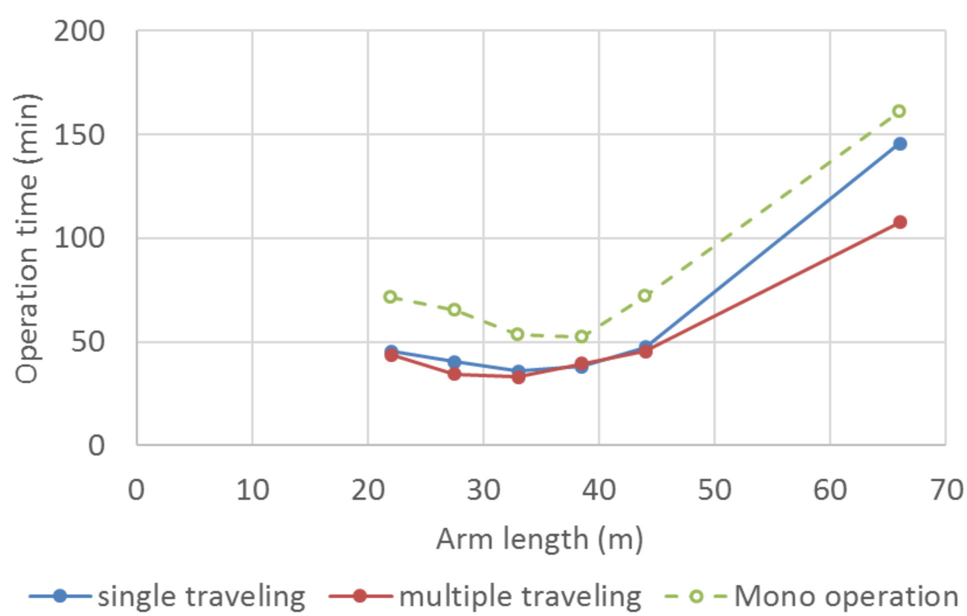


Figure 86 Operation time change with arm length (with 'None' scenario)

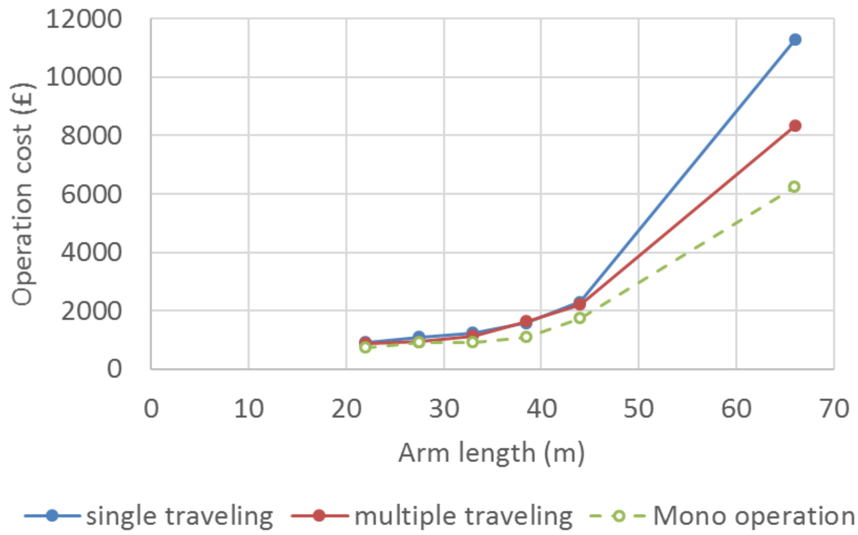


Figure 87 Operation cost change with arm length (with 'None' scenario)

For the machine interaction between demolition and collection machines, total demolition impact is applied to assess the significance of the collection strategy on the recovery waste quality and treatment cost. The result of the operation time is summarised in Table 43. Compared to the other algorithm comparison, the gap of operation time is quite moderate. As a result, the waste treatment cost is dominant in total cost (seen in Figure 88 and Figure 89). Although it needs to be discussed at the result of demolition in which the element material type is considered, the waste generation which is close to the destruction process results in the mixed waste recovery rather than others collection methods. The proper collection strategy can reduce the cost up to 10% from the waste treatment impact, and there is no significant delay of demolition progress due to the interaction between the demolition and the collection machines. Accordingly, the simple strategy change of collection may reduce the cost and improve the waste recovery rate largely without largely affecting the destruction process. As mentioned before, the result of the eco point shows relatively large deviation. More simulation with different type of condition should be held to understand the influence of collection strategy. The influence of waste collection with different demolition order for elements are analysed at the next section.

Table 43 Operation time for the tandem machine operation with waste collection algorithms

Operation time (min)	None					
	Arm22	Arm27.5	Arm33	Arm38.5	Arm44	Arm66
closest from collection machines	80.3	58.8	51	54.7	57	106.4
farthest from demolition machines	82.5	56.6	52.3	54.7	58.4	106.4
closest from demolition machines	82.2	58.8	52	54.7	58.4	106.4

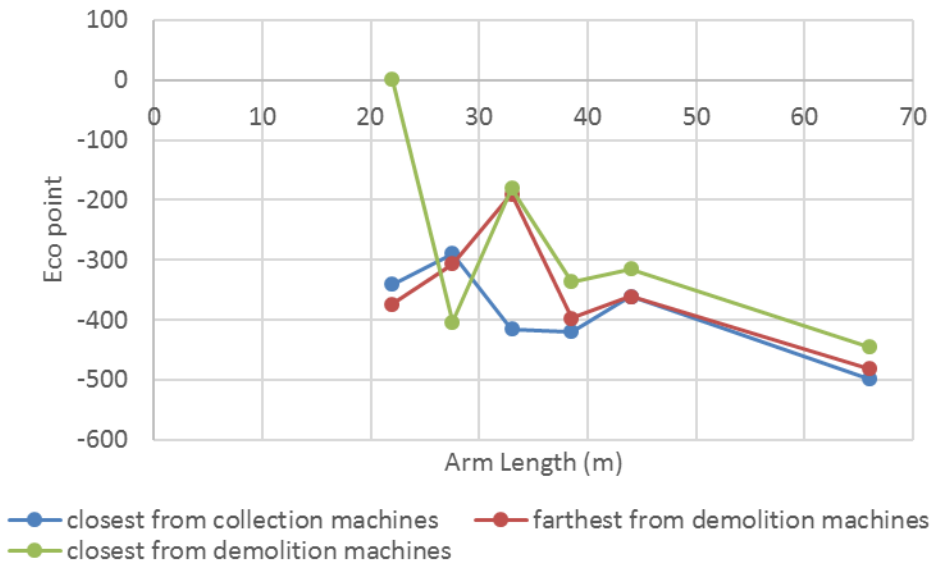


Figure 88 Eco point change with arm length for the waste collection algorithms (with 'None' scenario)

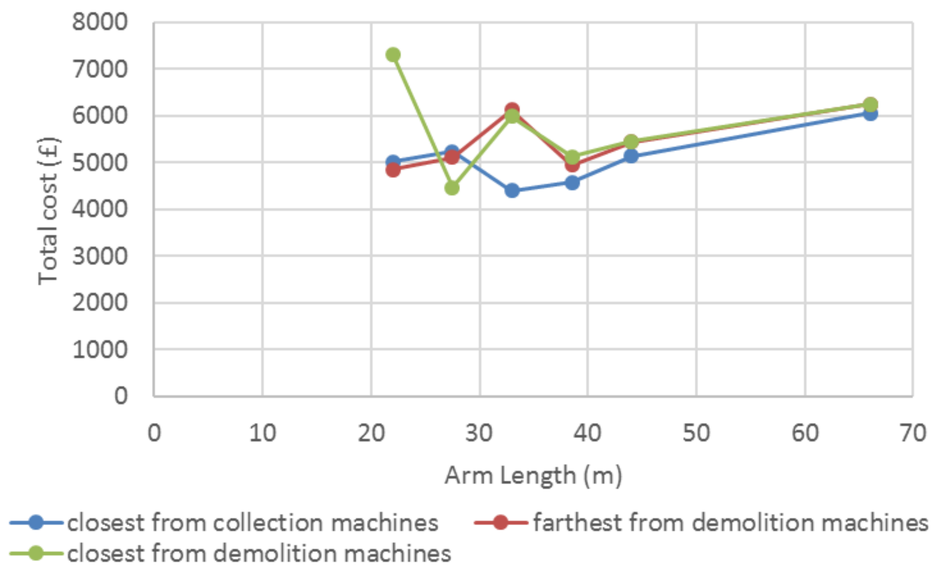


Figure 89 Operation cost change with arm length for the waste collection algorithms (with 'None' scenario)

8.2.3.3. Demolition order setting

Demolition order is decided by the object location and the directions of progress which are decided by users at the project planning phase in the previous section. In this section, the other two order setting algorithms are suggested to compare the efficiency of machine productivity and the project planning. For the distance-based algorithm which can be seen in the practice operation, the reduction of relocation necessity by targeting the closest elements is expected to minimize the operation time so as the final cost. After the simulation between the location based and the distance-based, the operational times and costs are resulted as Table 44. When the cost is compared as Figure 90, the distance based algorithm shows more cost increase than the location based algorithm. It might be resulted from the inefficiency of element selection. Although the inefficiency with short am is not that obvious, as the arm become longer, the unplanned order of element demolition compels longer transportation to operators.

Table 44 Operation time with demolition order setting algorithms

Impact	Distance			None			Horizontal			Vertical			Both		
	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44	Arm22	Arm33	Arm44
Time (min)	75.7	57	80.4	82.2	52	58.4	154.5	118	105.1	82.9	59.9	82	90.3	69.3	84.5
Cost(£)	760.77	981.04	1959.6	826.09	894.98	1423.4	1552.7	2030.9	2561.6	833.12	1031	1998.6	907.49	1192.7	2059.5

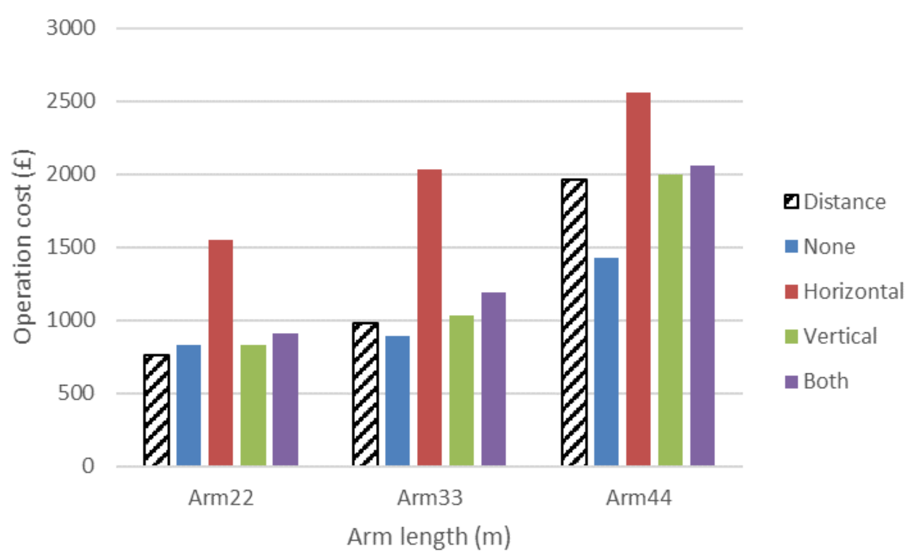


Figure 90 Operation cost change with arm length and demolition order (distance vs location)

As seen in the previous section, the waste recovery improvement can contribute the cost reduction and it results in the high improvement of the demolition sustainability. In order to compare the operation time of demolition order algorithms with and without regarding the waste material type, the material-based demolition planning is compared with the location and distance based algorithms. After the simulation, the result is summarised as Table 45. The eco point and the cost can be visualised as Figure 91 and Figure 92. Regardless of the attached arm length, the project cost is ordered in location, material and distance based planning. When the eco point is referred for the performance of waste recovery, the material based algorithm shows relatively better performance than average. However, the advantage is not that obvious and sometimes the locational algorithms performs well. Since this evaluates the volume of waste which exceeds the purity requirement (95%), the average value of waste purity is added to discuss the efficiency of waste recovery. Assuming that the extra onsite waste sorting may achieve the waste recycling, the high average for this value implies the better potential of recycling and the waste treatment cost reduction. However, as shown in the Figure 93, the result of waste purity does not show the significant gap with other two algorithms. Even though the other two collection algorithms are applied to validate the efficiency of material recovery, not large difference is identified (seen in Figure 94 and Figure 95). It can be attributed to the demolition with a bucket attachment which tends to involve surrounding wastes. Therefore, the efficiency of waste separation according to the material type is not that obvious as it is expected. To exploit the material classification for the waste collection, more selective demolition attachment or method should be applied in the future approach.

Table 45 Operation time change with arm length for demolition order setting algorithms

	None					
	Arm22	Arm27.5	Arm33	Arm38.5	Arm44	Arm66
sorted with location	82.2	58.8	52	54.7	58.4	106.4
decision with distance	75.7	70	57	59.7	80.4	112.6
sorted with material	72.8	60.7	57.9	62.3	73.6	106.8

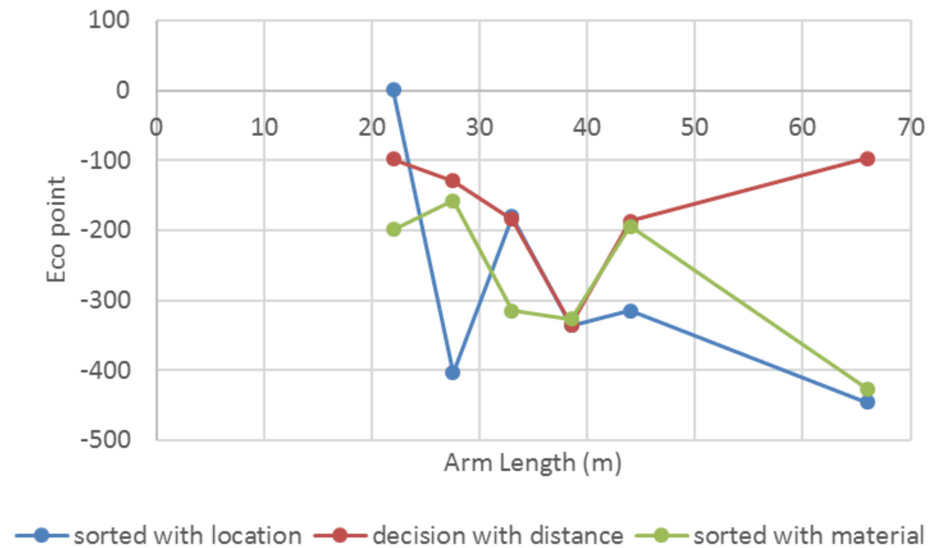


Figure 91 Eco point change with arm length for demolition order setting (with 'None' scenario)

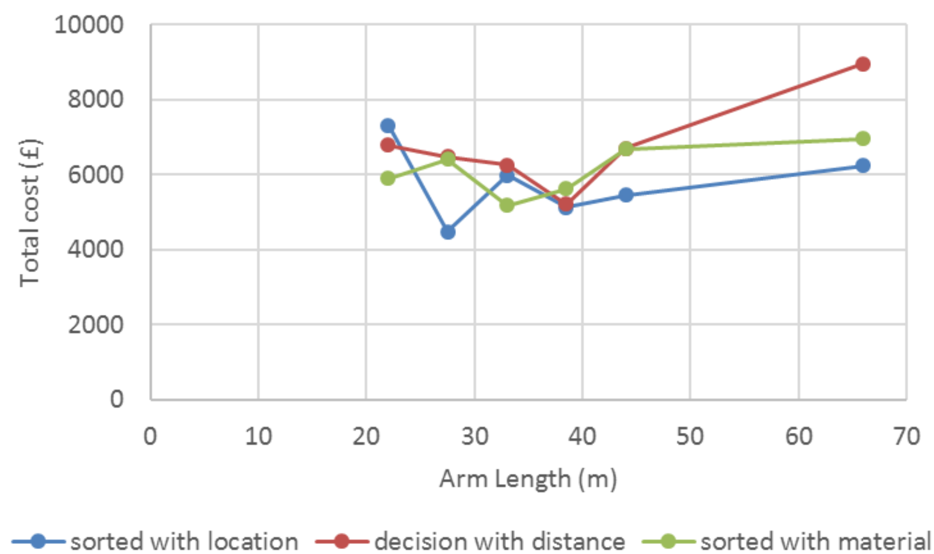


Figure 92 Operation cost change with arm length for demolition order setting algorithms (with 'None' scenario)

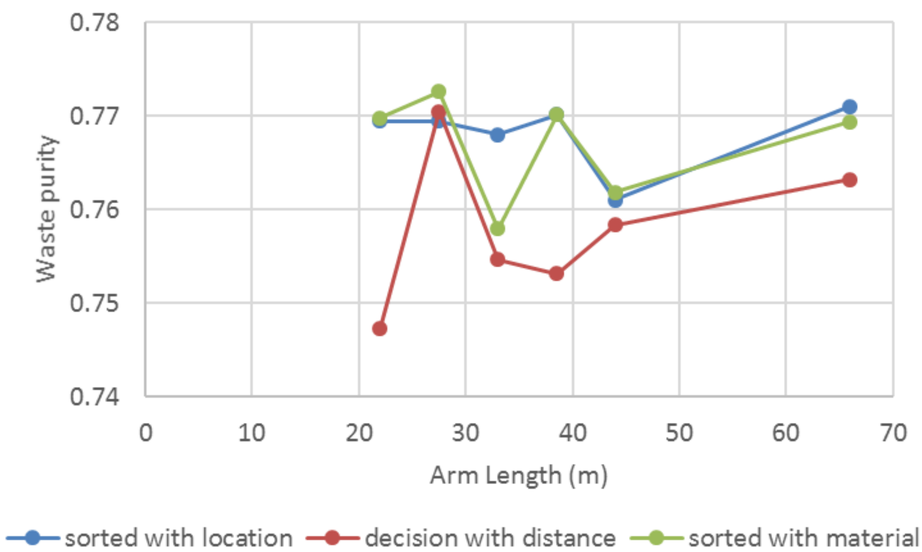


Figure 93 Waste purity change with arm length for demolition order setting algorithms

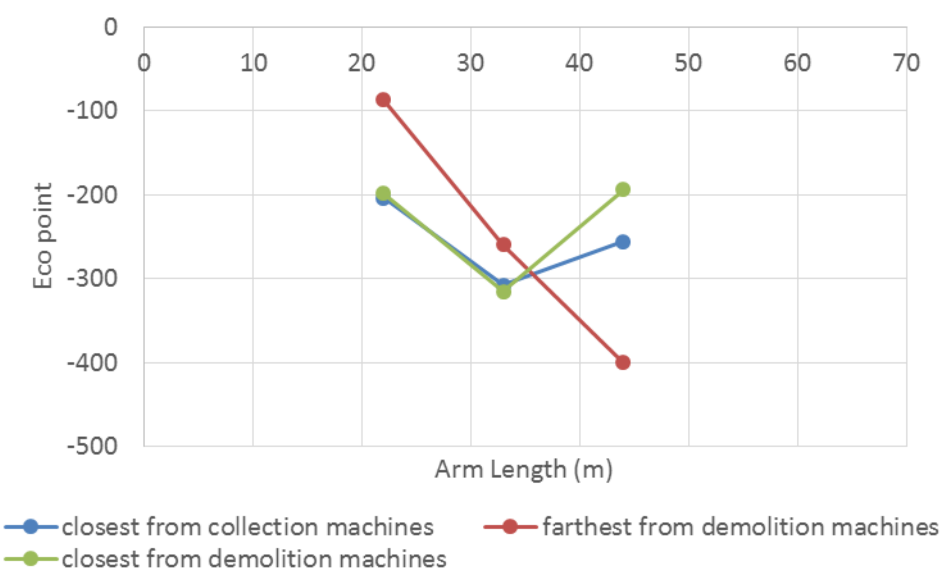


Figure 94 Eco point change with arm length for the material based algorithm with different waste collection algorithms (with 'None' scenario)

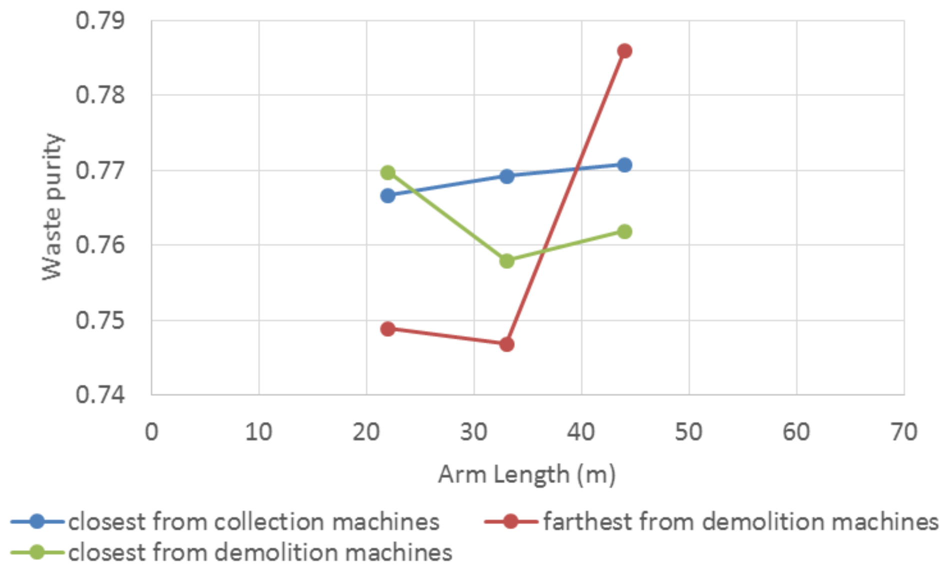


Figure 95 Waste purity change with arm length for the material based algorithm with different waste collection algorithms (with 'None' scenario)

8.3. Practical case

Demolition project planning with suggested algorithms was examined with BIM data having little information (object model with element information) which was designed based on the actual high-rise apartment building in Spain. However, it, only contained four types of building elements (beams, slabs, columns and walls) and the external wall was not included in the design. Due to the legal requirement in 2016 (according to the UK Government mandate enforced from the 4th of April, 2016), the BIM application becomes the social standard in the construction industry for public projects. In order to analyse the adoptability to these advanced project data and the ability of the suggested model, the construction design drawn for the actual construction project in the BIM is examined in this section. This data was offered by the Projects and Asset Team at the Department of Estates Estate, in the University of Bath as shown in Figure 96. The Building design was suggested to the construction plan at the University of Bath campus with the agreement of that team. Due to the limit of data accessibility to the final building design (e.g. safety for terrorism), the project candidate plan was alternatively chosen. The prospective contribution at the future demolition process is estimated through the model simulation. Due to the significance of data volume (about 5,500 original objects data while the previous BIM data contained 300 objects data), the part of building is selected as the demolition target which is highlighted in a red square in Figure 96. After setting the scenario to compare the different project planning, the applicability and the ability of the model suggestion will be discussed based on the simulation output.

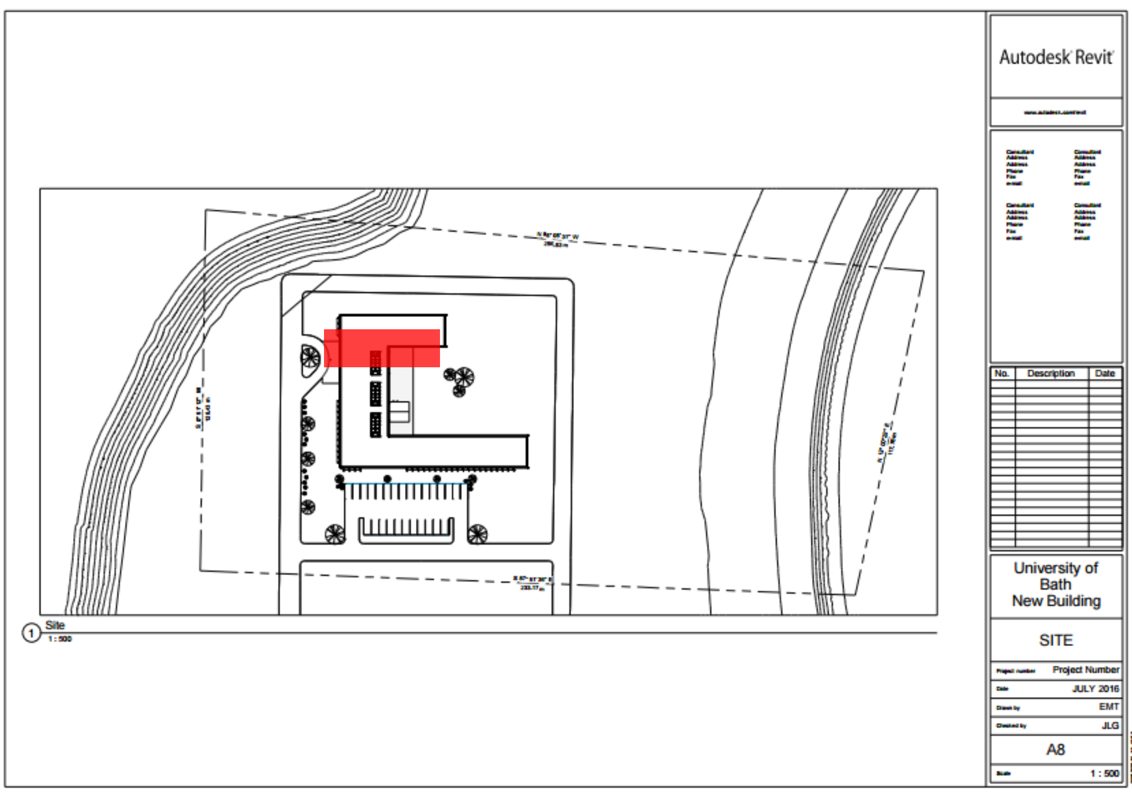


Figure 96 Building design data offered by the Estate and Asset Team of the University of Bath

8.3.1. Demolition target

The detail of the target building information is explained in this section. This was a part of the extension project of the university property with the rapid expansion of applicants. The target building design was suggested for a teaching building so that the majority of rooms were designed to be used for classes. It was situated at the west part of campus with parking spaces surrounded by many trees as shown in Figure 97. The building properties and the structural characteristics are summarised in Table 46. Compared to the demolition target used in the previous two sections, the scale is approximately six times larger in terms of element volume. Due to the significance of computational burden in the model, only the north side of the structure, which is circled in red at the above figure, was intended for the model application. The data of the volume and the number of elements is arranged in Table 47. Elements are originally classified with more segmented material types, and the ifc Global Unique Identifier (GUID) allows to specify the properties of objects for the following phases (e.g. analysis of heating efficiency with thermal conductivity data). For examining the applicability of this model to the BIM data used in the actual project, the maintenance of data quality and the convertibility to the impact factors are set as the principle objectives in this pilot study. Accordingly, the correspondence between material and waste types is analysed to see if the data degree could be maintained through the impact evaluation process. In addition, the description of impact factors with different levels of preciseness in BIM data is studied to evaluate the impact convertibility.

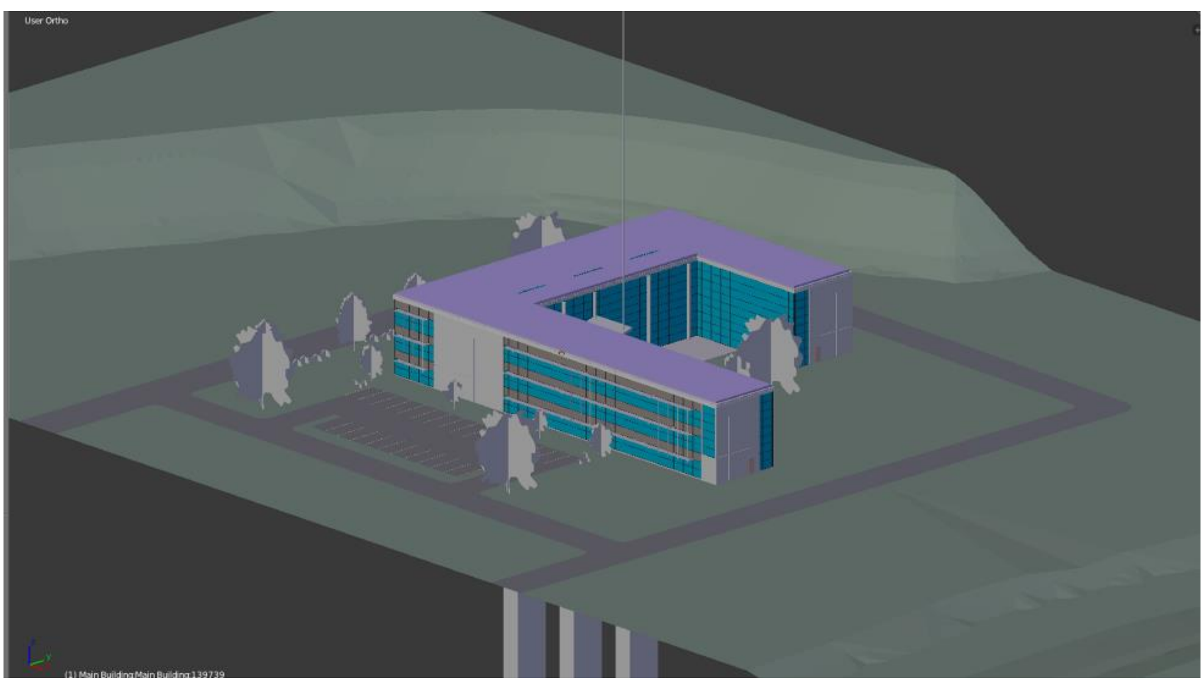


Figure 97 Construction site of the target teaching building on the University of Bath campus

Table 46 Structural detail

Property	Data
Client	University of Bath
Construction site	Claverton Down Rd, Bath BA2 7AY
Building name	University of Bath New Building
Building purpose	School building
Structure type	RC frame without brick infill
Floor area	(GF) 1647 (1F) 1609 (2F) 1604 (Total) 4860m^2
Height	(3 stories) 12 m

Table 47 Comparison of the object and the element number

	object number (segmentation)			waste volume (m³)					
	before	after	unsegmented	Slab	Beam	Wall	Column	Other	total
Prototype Case	247	11547	0	353.0	87.7	97.9	50.3	0.0	588.8
Algorithm Case	293	13406	0	353.0	87.7	240.7	50.3	0.0	731.7
Practical Case (original)	5519	-	-						
Practical Case (selected)	1326		86 (6.4%)*	568.6	0.0	408.9	72.1	56.9	1106.6

*segmented with another attempt to simulate with the other objects

8.3.2. Scenario setting

In this pilot study, three-stories school building is demolished by the external demolition method with one high reach excavator that's total arm length (boom and dipper) is set based on the result of the above algorithm case study (33m as a result). The objectives are set as the evaluation of the model applicability to the actual project data in BIM, and also the evaluation of the model ability as the decision support tool. While the model applicability is evaluated though the whole model application process from the BIM data input to the result output, the model ability is evaluated by the scenario comparison with the details of which are explained in Table 48. As compared in the previous pilot study, three different types of demolition strategies are chosen and compared; i) demolition (deciding order) with machine distance, ii) demolition (deciding order) with element location and iii) demolition (deciding order) with material type and location. All the single and tandem machine operation algorithms are standardised as shown in Table 48 to accurately compare the demolition impacts of each strategy for both cost and environmental impact (with the Eco point). Therefore, the potential benefit produced with the model application can be calculated by the product of savings at the machine operation and the strategy selection which can be written as the following formula.

$$I = 1 - I_{st} \cdot I_{mc} = 1 - \left(1 - \frac{\bar{E}_{st} - min\,\{E_{st_i}\}(i = 1,2,\cdots m)}{\bar{E}_{st}}\right) \cdot \left(1 - \frac{\bar{E}_{mc} - min\,\{E_{mc_i}\}(i = 1,2,\cdots m)}{\bar{E}_{mc}}\right)$$

where I: impact improvement rate, E_{st}: Eco point result of project planning in the strategy pilot study, E_{mc}: Eco point result of project planning in the machine control pilot study)

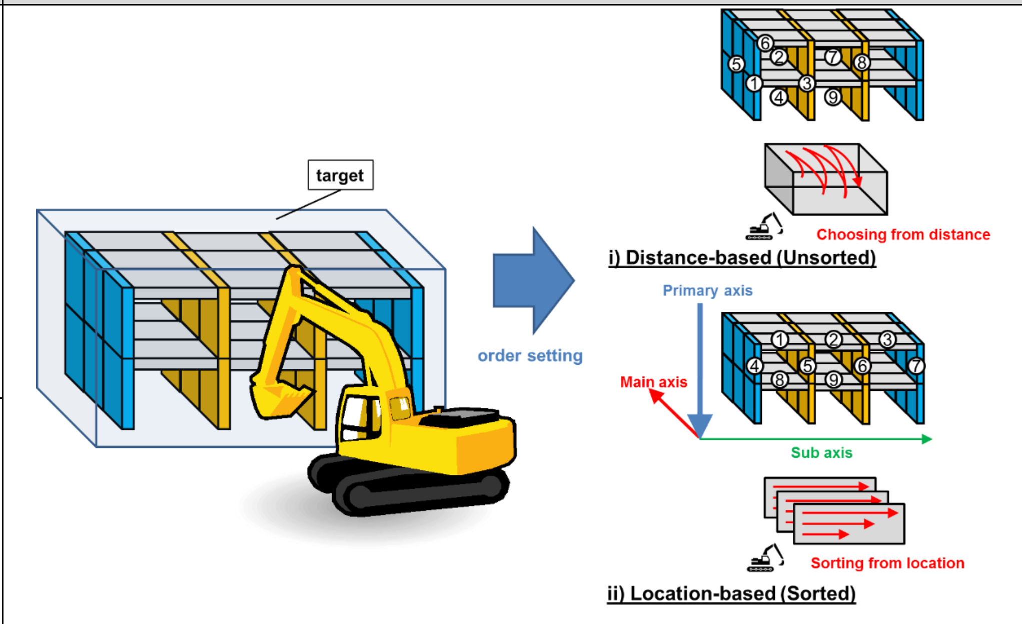
e.g.) when $\bar{E}_{st} = 800$, $min\,\{E_{st_i}\} = 600$, $\bar{E}_{mc} = 1000$, $min\,\{E_{mc_i}\} = 800$

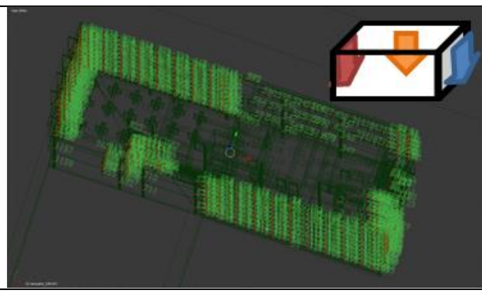
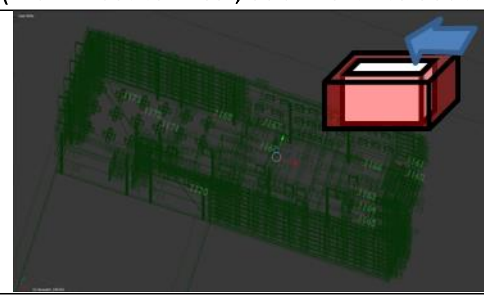
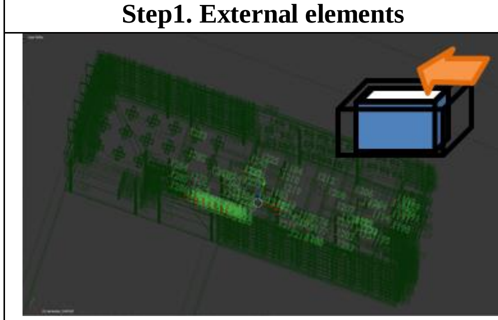
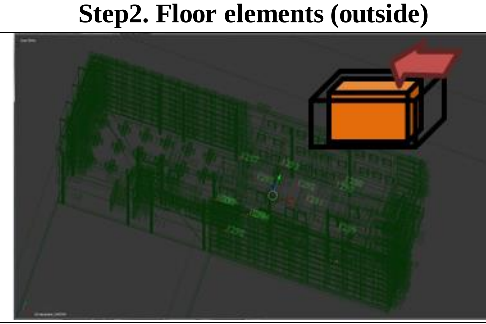
$$I = 1 - I_{st} \cdot I_{mc} = 1 - \left(1 - \frac{800 - 600}{800}\right) \cdot \left(1 - \frac{1000 - 800}{1000}\right) = 1 - 0.75 \cdot 0.8 = 0.4^{*}$$

*40% of improvement can be expected from the model application

In addition to this, the element tracking in the model simulation is added to this pilot study to validate the model ability. Considering the risk of onsite workers, neighbours and other related stakeholders to waste treatment, hazardous wastes (e.g. asbestos or isotopes) were the biggest issues in terms of the health and safety. This theory can be also applicable to the radioactive wastes generated from the demolition of nuclear power plants. In order to isolate those hazardous wastes from the others, the tracking function of target elements is developed in the simulation model. This function is surveyed with the efficiency of risk identification. In detail, there are two possible pieces of information which can be given as the output of the model simulation; i) element unit location tracking and ii) component rate of each waste bucket. The unit tracking is relatively easy to be achieved by adding the order code in Python to target units to keep sending the location information during the whole simulation process. Similar to this, the original elements of the collected by bucket in bulldozers are all identified. Accordingly, the mixed rate of hazardous wastes is also estimated for every single content of bucket loaded to waste skips. These two estimations are analysed by assuming some asbestos is found from the part of the ceiling at the demolition survey according to BS6187 (BSI, 2011). In order to minimize the computational burden, only a part of ceiling element is regarded as hazardous here (the elements ID '168996'). The ability of tracking for all of the component elements are analysed from the demolition to the loading process in the benchmark scenario of this pilot study.

Table 48 Scenario setting

<table>
<tr><th colspan="2">Scenario</th><th colspan="2">Demolition algorithm description</th></tr>
<tr><td>1</td><td>demolition with machine distance</td><td colspan="2" rowspan="2">

(Main: East to West, Sub: North to South)</td></tr>
<tr><td>2</td><td>demolition with element location</td></tr>
<tr><td rowspan="4">3</td><td rowspan="4">demolition with material type and location</td><td></td><td></td></tr>
<tr><td>Step1. External elements</td><td>Step2. Floor elements (outside)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Step3. Internal elements</td><td>Step4. Floor elements (inside)</td></tr>
</table>

8.3.3. Result and discussion

8.3.3.1. Model applicability to a real project model

The emerging issues found in the practical pilot study are summarised in Table 49 with suggested solutions. Before starting the project simulation, there were three steps required as a preparation process; i) data import from the BIM, ii) target classification and iii) object modelling. After importing the building target and the surrounding objects from the BIM data, some element objects are visually identified in a strange location which is thought to be due to errors in the data import process. In addition to this, the decoration data which is typically seen for the precise building design is included to give better understanding of building scales and environment. For example, human and furniture objects are set inside and tree objects surround the structure. Accordingly, further manual classification is asked for object treatment in the demolition process. To prevent the user burden, the object selection function in GUI is added to allow users to select the same material type objects at once.

Data treatment with programming language also confronts some difficulties with both the data complicity and the significance of volume. Compared to the simple object shapes in the previous case studies (mostly in prism shaped), some slabs and walls have more complex shapes with voids which are difficult to segment. In addition, the sphere or curve elements such as lighting elements or the hybrid elements such as doors and singles cannot be segmented in the current model. As a result, about 6% of elements cannot be segmented with the current segmentation function at the first step. In order to treat the whole element in the simulation, solutions are suggested for each type of issues as the second step (seen in Figure 98). For instance, the complicated element model can be replaced by a circumscribed prism. This is because the simplicity of algorithms should be prioritised more with the great volume of objects (more than 40,000 units after the 120 minutes for segmentation). Even in the model simulation, the number of objects largely affects the simulation time. The lean scripting of the algorithm is more important to maintain the model applicability to the actual demolition. The trimming of the target building is another possible approach to reduce the file size, and this method is applied in this pilot study. In particular, when the algorithms frequently need to examine the whole objects such as finding the closest element for the machine, the calculation time will exponentially increase

At the impact evaluation process, the output data needs to be more flexible for the model robustness. In order to maintain the precision of material/waste property in the imported BIM, the impact output uses the same material list as the original data set. Based on the primary material each waste material is sorted and classified separately. Simultaneously, the final impact estimation aims to maintain the exchangeability for project planning regardless of the BIM data quality. The conversion list as shown in Table 50 can be used to sort wastes into the main element types. The template of impact estimation with this unified classification allows users to analyse the project planning with the same figures and tables after the simulation. It is also important to have the common conversion table which prevents changing the result with the interpretation of individual users. The common table should be shared and updated by the users through the model application which can improve the exchangeability of model results between users and projects. It should be noted that the simulation speed is widely variable due to the computation burden (especially when with the precise data). The animation of model simulation on the PC monitor speeds up as the elements are removed by machines. Except for the application of a high processing capability computer, the periodical renderings taken in the simulation need to be connected to create the animation along the uniform time axis with significant volume data.

Table 49 Emerging issues in the application to a real project BIM

Issue	Related process	Solution
Error at data exchange	BIM data import to Blender	1. Manual modification 2. Improvement of software exchangeability (in the future)
Involvement of decoration data (e.g. human, furniture)	Target classification	1. Manual classification 2. GUI development (done)
Object segmentation (data complicity)	Object modelling	1. Improvement of GUI
Object segmentation (data volume)		1. Leaning programing codes for GUI 2. Target minimization Segmentation of building target
Model simulation		
Detail element type designation	Impact estimation	1. Development of conversion table 2. Updating as database

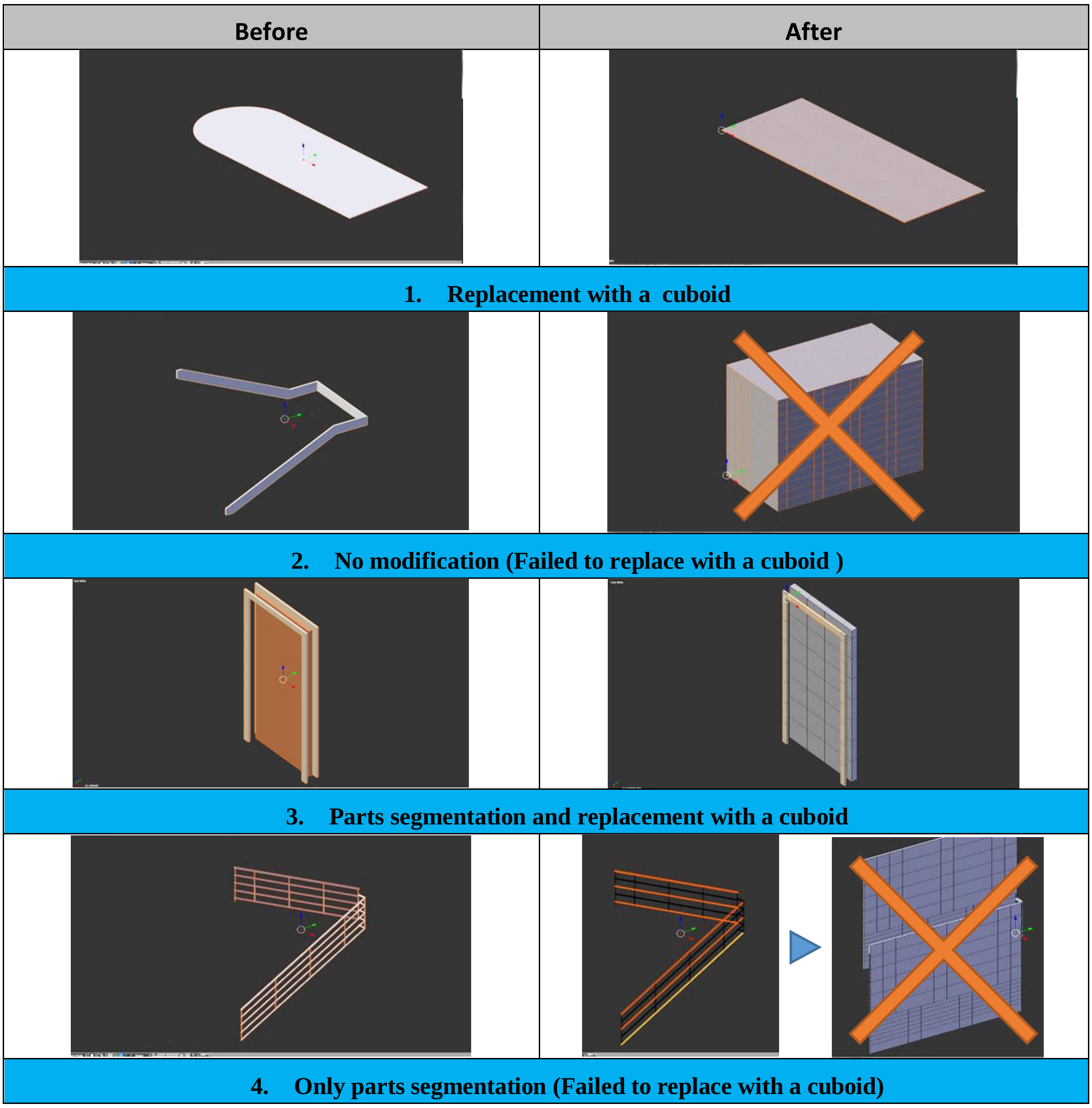


Figure 98 Segmentation steps to treat the complex shape elements

Table 50 Material type conversion table

Original material ID	number	volume	Material type	Element type
IfcWallStandardCase	50	233.9	Concrete	Wall
IfcWall	2	8.0	Concrete	Wall
IfcStairFlight	2	15.4	Concrete	Staircase
IfcSlab	3	126.5	Concrete	Slab
IfcRoof	1	161.3	Concrete	Roof
IfcRailing	6	10.9	Steel	Staircase
IfcMember	5	96.1	Concrete	Wall
IfcFurnishingElement	75	19.7	Other	Other
IfcFlowTerminal	2	0.0	Glass	Other
IfcBuildingElementPro	4	6.7	Other	Other
734980_Metal - Paint Finish - Paint Cafe Matte	8	16.2	Metal	Other
273405_Ceiling Tile 600 x 600	18	41.9	Clay	Slab
272435_Paint - Maroon Glossy	3	1.7	Other	Covering
271960_Door - Panel	3	2.4	Wood	Door
271948_Door - Frame	17	7.9	Wood	Door
223950_Metal - Aluminum	4	0.9	Metal	Other
1777629_Concrete - Precast Concrete - 35 MPa	4	14.1	Concrete	Column
1624663_Metal - Sunscreen	3	0.2	Metal	Other
1622369_SHADE SUPPORT	4	3.6	Metal	Other
143961_Metal - Aluminium, Black-Anodized	767	9.6	Metal	Other
142407_Stone - Granite	42	5.2	Mineral	Covering
141823_Glass	294	21.1	Glass	window
141336_Plasterboard	4	11.5	Plasterboard	Covering
141227_Insulation / Thermal Barriers - External Wall Insulation	4	21.1	Concrete	Covering
140645_Concrete - Cast-in-Place Concrete	49	58.0	Concrete	Column
140387_Default Floor	2	212.6	Concrete	Slab

8.3.3.2. Model ability as a decision support tool

Impact comparison

The real project model of the school building in the AutoCAD Revit is demolished by three different demolition strategies with the demolition order algorithms suggested in Chapter4.2.3.3. Here, the decision of demolition order with distance is assumed as the original approach of demolishers which can be only recreated without any computational approach. According to this, the gap with this control scenario is regarded as the potential improvement with the application of the present model. The cost of demolition is assumed as the primary decision factor of demolition teams, and the sustainability improvement from the cost-based selection is regarded as the improvement potential from the strategy selection in this model. The result of three pilot studies is summarised in Table 51, in which the total impact and the cost and the eco point breakdown for each process are summarised. In particular, the volume of generated waste is described with both the available usage volume and the treated volume. Based on this result, the improvement rate against the strategy of 'decision with distance' which is assumed as a typical strategy in practice is calculated in Table 52. Accordingly, the 'sorted with material' algorithm (defined in Chapter8.3.2.) becomes the most effective planning in terms of time, cost and sustainability. This is derived from the superiority of machine operation and waste recovery. Since the demolition order in material-based strategy is performed along with the building boundary (like peeling a fruit), the machine operation becomes more efficient which results in the short and reasonable operation time.

'Sorted with material" strategy provides an advantage in sustainable collection process too. The same material in the building destructed in a continuous operation, so that the purity of a component in a bucket tends to exceed 95 % threshold. Recyclable waste mass listed in the 6th column of Table 51tells so much increase of recyclable waste (8.4 to 129 m^3). Similar signature is found in the 'location sorted' strategy (8.4 to 97.5 m^3). It is because the material component is mostly common to adjacent portion of the building, then the destruction proceeding in one direction produces rather high purity waste. Therefore, the 'location sorted" strategy gives 20 % better cost merit, even the operation time is the same to the 'distance' strategy.

For farther details, the waste impact is examined in terms of the eco-point to compare different factors shown in Table 52. Recycling of waste gives a few % increase of eco-point, and machine operation cost improves 10 %. As a result, total eco-point was improved from 26 to 431 seen in the 4th column from the right of Table 51 (same thing is found in Table 52 too).

Reconsideration of the demolition process in practice will save the waste impact and eco-point. It has to be mentioned that the choice of demolition plan is able to create such large effect. In order to estimate the demolition impact to the society will be examined in the next chapter quantitatively.

Table 51 Demolition impact for demolition order setting algorithms

	Total			Machine use		Waste generation								
	Time (min)	Cost (£)	Eco point	Cost (£)	Eco point	Cost (£)	Eco point	Reusable (m3)	Recyclable (m3)	sortable (m3)	other (m3)	Reused (m3)	Recycled and	Waste (m3)
Distance	170.6	10492.4	-25.9	2489.4	2.2	8003.0	-28.1	0.0	8.4	902.3	0.0	0.0	820.5	90.2
Location	170.6	8452.8	-324.3	2437.4	2.1	6015.4	-326.5	0.0	97.5	820.3	0.0	0.0	835.9	82.0
Material	149.1	7536.0	-431.1	2230.8	1.9	5305.3	-433.1	0.0	129.4	791.1	0.0	0.0	841.3	79.1

Table 52 Evaluation of impact improvement with different strategies

	Improvement rate against 'decision with distance'					
	Time	Cost	Total Eco point	Eco point for machine use	Reused waste	Recycled and sorted waste
decision with distance						
sorted with location	0.000	-0.194	-11.503	0.021	0.000	0.018
sorted with material	-0.126	-0.282	-15.620	0.106	0.000	0.025
				ki	kr1-ru	kr1-rc

where ki: impact improvement of demolition impact with DPM application, kr1-ru and kr1-rc: impact improvement of waste reuse and recycle rate with DPM application (all of those coefficients are introduced in Chapter9 for evaluating the social impact improvement with DPM application)

Element tracking

The hazardous ceiling elements contaminated by asbestos are tracked in the simulation for validating the model ability. The element units are tracked at two statuses; i) onsite debris and ii) waste in a skip. During the process between being demolished and conveyed to the skip, the target units keep recording the own location periodically. They can be plotted as described in Figure 99. This shows the complete paths of hazardous wastes, and it illustrates the risk of the onsite workers being exposed to asbestos when they cross this path in their operations. This result can also visualize how much the preliminary treatment can suppress the risk of exposure to the hazardous waste. By reducing the number of units from the result assuming the detoxification of asbestos, it can be regarded as the efficiency of pre-treatment. According to the simulation result the hazardous risk can be visualized in terms of how drastically it would protect the operators from the exposure to asbestos. In addition, the mixing risk with other waste can be evaluated at each waste loading process as shown in Figure 100. This is also a useful resource to decide the proper waste treatment for each skip and alert the waste operators with the quantitative data.

The strongest advantage of this research is the dynamism and continuous 4D information for the hazardous risk. Even in the latest study of asbestos exposure risks (by Zijlstra, 2014) which also applies to the actual project BIM, the risk is only estimated by integrating the design, schedule, and asbestos data contained in the BIM as described in Figure 101. It requires the schedule data for the whole process, and it can only discuss the exposure risk at the element level and intermittently. Compared to this, the present suggestion can clarify the waste distribution at the object level with a sequential path so that the elimination of the hazardous waste can be considered from not only the pre-treatment process, but also the demolition and the collection strategy. As Zijlstra (2014) insists, the comprehensive visualization and the integration of the risk and the process are the most important to control the asbestos onsite. Accordingly, the demolition process needs to be comprehended for both machines and human labour in its further development so that the hazardous waste path can be more comprehensively linked to the risk to humans in the simulation. This is also said of the other processes which require human tasks such as the manual preparations (e.g. hand hammers, shears) or the water sprinkle to prevent the airborne particles during the machine operation. It would be necessary to treat the demolition process at the working level. However, since the demolition project rarely applies BIM approach to the project planning, the preparation of a database need to be started for this.

The time behaviour of hazardous waste as is shown in Figure 4 could be changed by the demolition planning. If the time periods of hazardous material collection are concentrated by connecting each event in the plot, it may simplify the treatment of hazardous material in the whole project and reduce the risks to be mixed with other wastes. This is useful support for demolishers to plan the projects with less risk.

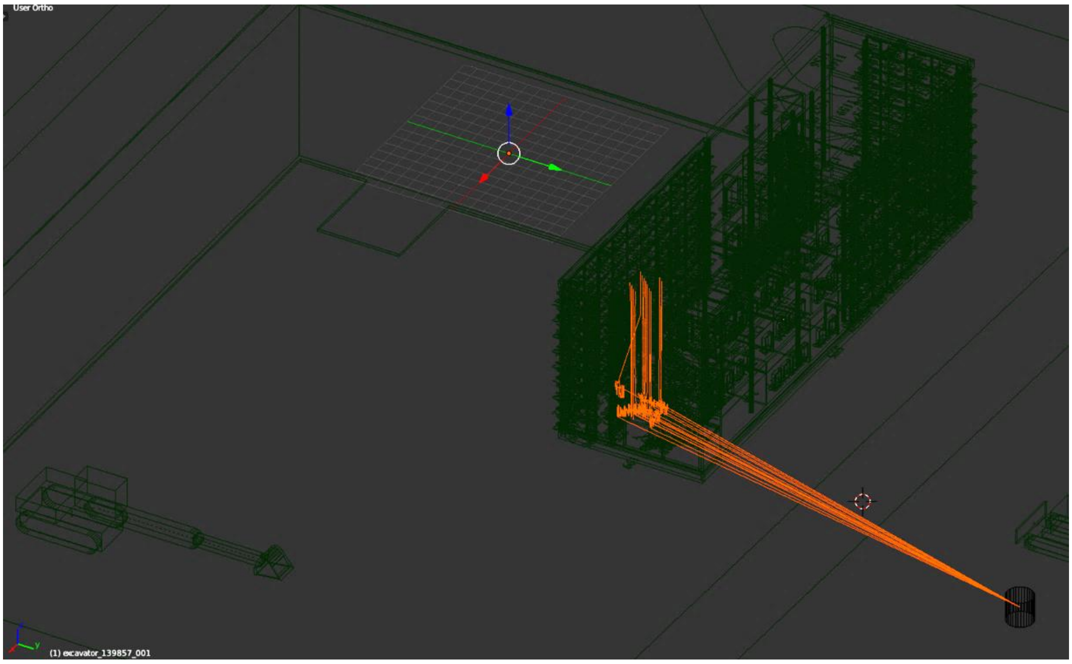


Figure 99 Hazardous waste tracking data plotted on the sitemap

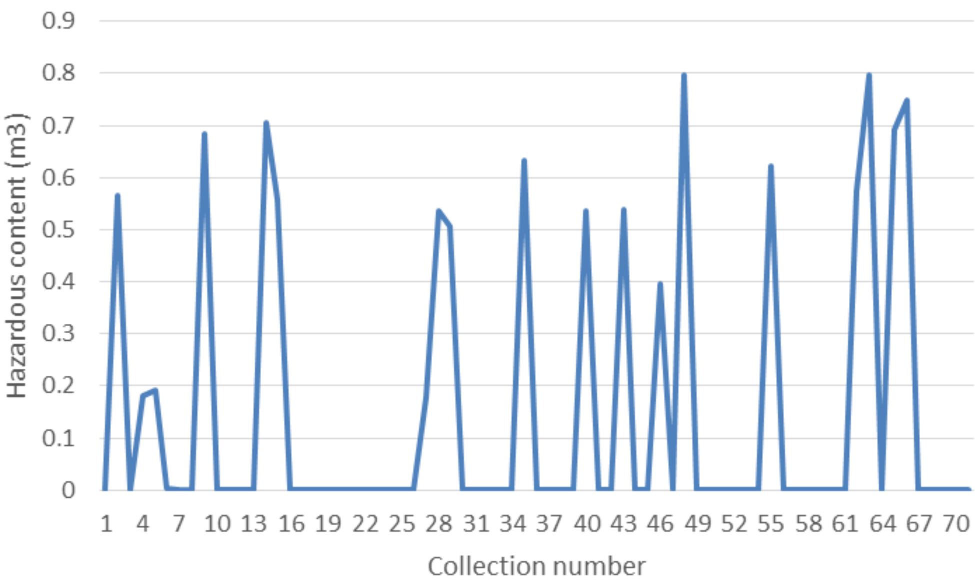


Figure 100 Mixing risk of hazardous waste for each collection

Figure 101 Automatic visualization of identified objects conflicted with asbestos (Zijlstra, 2014)

8.4. Summary

In this chapter, the waste impact evaluation model for demolition projects are suggested with four main steps. As the first step, the prototype has been developed to validate the availability of the dynamic and automated machine operation and the impact evaluation in a 4D-CAD software. Through the pilot study with a simple ifc. building design, the model achieves to recreate the demolition impact from the waste management and the machine productivity. In particular, the locational and material type of waste data allows users to comprehend the waste generation information from both visually and quantitatively. Due to the limitation of waste recovery for the next construction, the information of waste purity is quite beneficial for demolition planning. Accordingly, the onsite mapping of the waste generation and the purity in the model is expected to be a huge contribution to designing the waste collection plan.

Following this, the model is developed to quantify the impact into three different types of factors; i) time, ii) cost and iii) environmental impact ('Eco point'). With this quantification of the impact, the efficiency of project planning becomes comparative, so that optimal algorithm settings in the modelling can be decided through the result comparison. According to this, as the second step, the algorithms suggested in Chapter3.4. is compared in the pilot study with a masonry building model based on the previous pilot study target. The algorithms for 'machine control' and 'demolition order setting' enables to minimise the operation time and cost. This is the huge advantage of the model application for the users who can quantitatively decide the project strategy before the implementation. In addition, the result of the environmental impact shows the recyclability of collected wastes. In order to utilise those findings in practice, the validity of model result must be empirically tested by the comparison with the impact values in many actual demolition projects.

As the final step, the model applicability to the real project BIM which is required in the public construction project from 2016 and the model ability as the decision support tool is examined. Three demolition strategies are applied to the actual school building model in AutoCAD Revit as BIM data offered by the University of Bath. In this pilot study, the challenges of the application to the real project BIM are identified for four steps in simulation; i) data import from the BIM, ii) target classification, iii) object modelling and iv) result analysis. In particular, the different preciseness of the waste material type classification needs to be adopted in the model at the result analysis to make the result comparative. A material conversion table is suggested to unify the waste element type so that the environmental impact and the waste distribution can be visualized in the common level of accuracy at the output. In addition to this, the model ability as a decision support tool is shown by the comparison of three different demolition strategies with the demolition order setting algorithms suggest in the previous case studies. In this pilot study, the suggested strategies show better results compared to the control scenario ('distance-based'), from three different factors; duration, cost and environmental impact. For the location-based strategy, the generated waste is much easier to be sorted into each demolition type. Accordingly, more waste can be recycled which results in the reduction of the environmental impact and the waste treatment cost compared to the control scenario. Similar to this, the material-based strategy demolishing buildings along with the building boundary also shows a better possibility of waste recycling with short duration of operation. Besides the advantage from the waste recovery aspect, the shorter machine operation enables further cost reduction. For the target demolition of this pilot study, the waste treatment impact occupies the large share of cost and environmental impact (around 95% and 60-80%, respectively). Due to this large proportion, the impact improvement for the waste recovery overwhelms the reduction of the operation time. Although it should be concluded with more additional surveys, the importance of waste recovery for several impact factors (cost and Eco point) is shown in this pilot study.

In addition to this, the tracking ability is assessed its usefulness in the safety analysis. By collecting the locational data of hazardous element units constantly in the simulation, the risk of exposure to the hazardous waste can be visualized along with the time scale. This function is expected to be more advantageous when the demolition target will be a nuclear power plant in which further safety management is required for labours.

Chapter9

<Chapter Abstract>

In this chapter, the social impact evaluation tool explained in Chapter7 is examined in a pilot study. Different from the former chapter, the social impact evaluation is difficult to compare with the actual value in result. Accordingly, the sensitivity analysis is applied to individual impact factors and their influences on the social impact are compared. Readers can know the expected total impact reduction due to the DPM application on society basis in this chapter.

Chapter9. Findings II: Pilot study for method IV (Social impact)

The second major finding in this research is produced by the social impact evaluation model, which is initiated by the author's previous research at the University of Dundee. This whole process can be simply summarised as Figure 102 which steps are introduced here. i) "Project generation": The construction and demolition statistical data (number of projects in counties of UK) from ONS (2010a, b, c) was applied to both projects in UK. Both statistical data were interpreted as agents (e.g. a demolition project is regarded as a demolisher at a position in the area randomly), and roles of stakeholders, such as construction, demolition and off-site facility agents, were retrieved from the database which is created in Chapter3 (see Figure 106; Framework of the social impact evaluation model). ii) "Sensitivity Analysis": Following the geographical distribution, waste and material flow were decided by the decision-making algorithm for each stakeholder as the agent in the Agent Base (AB) model. Here, the influences of each parameter of the algorithm and other property values on the demolition impact were analysed. iii) "Scenario Analysis": After fixing the value of each property from the sensitivity analysis, three scenarios were set to compare the future sustainability by applying the DPM system to practice fully or partially. Waste treatment impacts derived from segmented phases were calculated with spreadsheets as shown in Figure 103 which describes the impact of each step from demolition to any recovery steps. Correlation between the scenario and partial impact change allows for further understanding of sustainability improvement. iv) "Impact Scale Analysis": As the final step, the spreadsheet displayed in Table 53 was applied to convert the processes listed in Table 54 to the environmental impact factors. Multiple factors could be unified into the Eco point through normalization with conversion rate and a weighing table (Table 55) proposed by BRE. This enabled the impact comparison among different scenarios which are introduced in the next session.

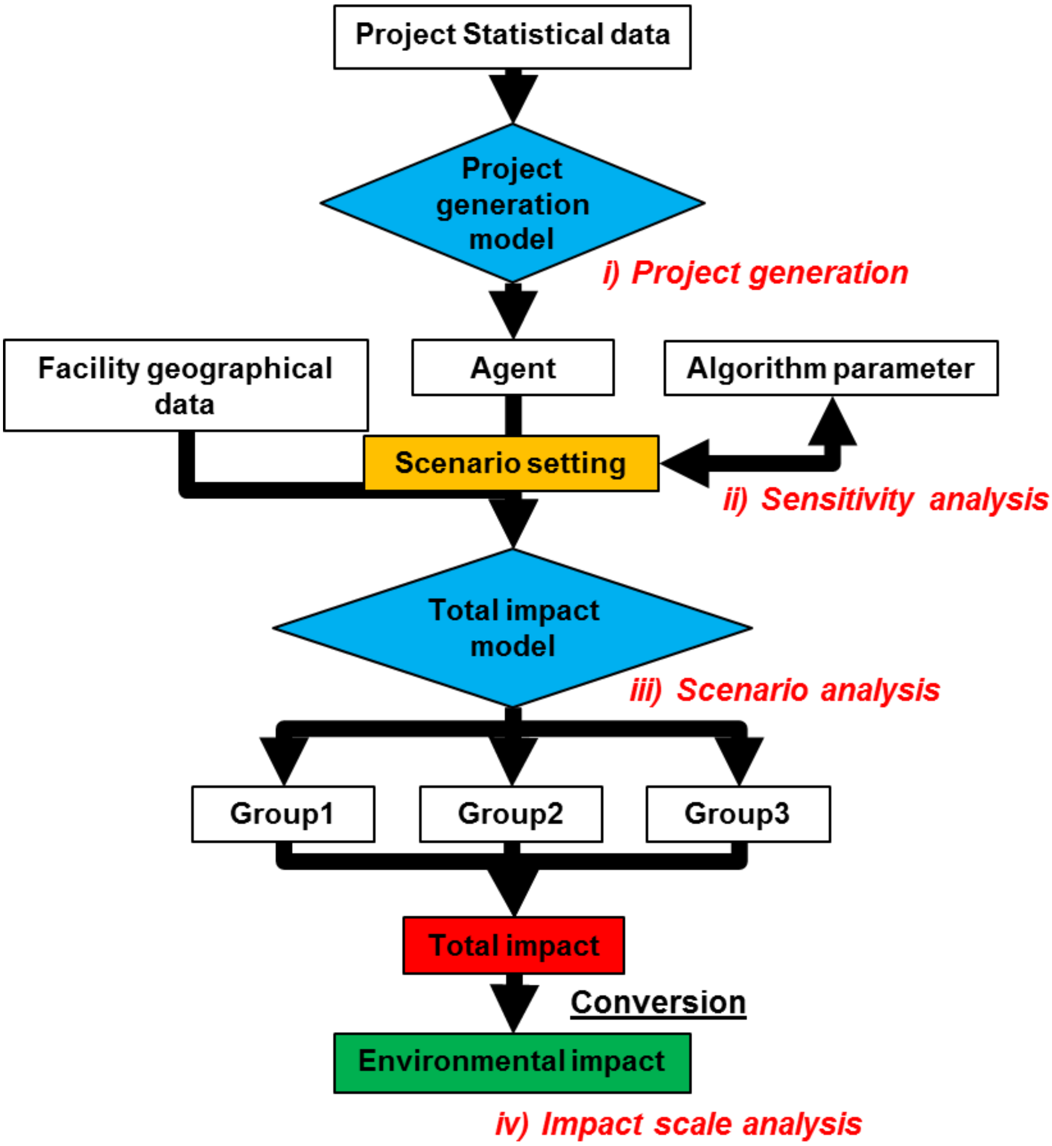


Figure 102 Impact evaluation flow in the social impact model

Reclamation (reclamation yard)

Total Energy use (MJ): 0.00

	Mass (ton)	Embodied gap(MJ/ton)	Total gap(MJ)
Co	0.00	-100	0.00
M	0.00	-100	0.00
Cl	0.00	-3000	0.00
F	0.00	-35300	0.00
NF	0.00	-186585	0.00
W	0.00	-19120	0.00
Pa	0.00	-32320	0.00
G	0.00	-19570	0.00
Pl	0.00	-106600	0.00
Pb	0.00	-4860	0.00
O	0.00	0	0.00

Transportation1 (D to Y)

Total Energy use (MJ): 0.00

	Mass (ton)	Distance (km)	Efficiency	Sum (MJ)
Co	0.00	12.28	0.60	0.00
M	0.00	12.28	0.69	0.00
Cl	0.00	12.28	0.69	0.00
F	0.00	12.28	1.12	0.00
NF	0.00	12.28	1.12	0.00
W	0.00	12.28	2.07	0.00
Pa	0.00	12.28	5.30	0.00
G	0.00	12.28	0.82	0.00
Pl	0.00	12.28	6.16	0.00
Pb	0.00	12.28	2.06	0.00
O	0.00	12.28	1.48	0.00

Demolition (demolition site)

Demolition impact (MJ): 29321.51
Treatment day (446MJ/day): 2
Total Energy use (MJ): 30213.51

	Mass				
	Original	Reuse	Recycling	Sorting	Landfilling
Co	1077.41	0.00	0.00	969.67	107.74
M	583.06	0.00	0.00	524.75	58.31
Cl	71.90	0.00	28.76	38.83	4.31
F	40.99	0.00	29.31	10.51	1.17
NF	9.14	0.00	7.31	1.65	0.18
W	111.67	0.00	33.50	70.35	7.82
Pa	0.51	0.00	0.41	0.09	0.01
G	17.19	0.00	5.16	10.83	1.20
Pl	17.03	0.00	13.63	3.07	0.34
Pb	29.47	0.00	23.58	5.30	0.59
O	41.62	0.00	33.30	7.49	0.83

Transportation4 (D to L)

Total Energy use (MJ): 830.81

	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
I	182.51	6.60	0.69	830.81

Landfilling (landfilling facility)

Treatment mass (ton): 182.51
Total Energy use (MJ): 1179.90

Transportation3 (D to S)

Total Energy use (MJ): 7340.14

	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
Co	1159.54	7.13	0.60	4962.81
M / Cl	483.00	7.13	0.69	2377.32

Transportation5 (D to C)

Total Energy use (MJ): 0.00

	Mass (ton)	Distance (km)	Efficiency	Sum (MJ)
Co	0.00	16.16	0.60	0.00
M	0.00	16.16	0.69	0.00
Cl	0.00	16.16	0.69	0.00
F	0.00	16.16	1.12	0.00
NF	0.00	16.16	1.12	0.00
W	0.00	16.16	2.07	0.00
Pa	0.00	16.16	5.30	0.00
G	0.00	16.16	0.82	0.00
Pl	0.00	16.16	6.16	0.00
Pb	0.00	16.16	2.06	0.00
O	0.00	16.16	1.48	0.00

Transportation2 (D to R)

Total Energy use (MJ): 4828.16

	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
Co	0.00	14.01	0.60	0.00
M	0.00	12.62	0.69	0.00
Cl	28.76	14.16	0.69	281.00
F	29.31	6.88	1.12	225.86
NF	7.31	6.69	1.12	54.77
W	33.50	9.66	2.07	669.76
Pa	0.41	8.02	5.30	17.39
G	5.16	14.40	0.82	60.90
Pl	13.63	8.79	6.16	737.81
Pb	23.58	43.21	2.06	2098.40
O	33.30	13.84	1.48	682.26

Off-site Sorting (demolition site)

Total Energy use (MJ): 61434.06

	Mass (ton)			Energy use (MJ)
	Input	Breakdown	Output	
Co	1159.54	969.67	1049.27	48161.57
M / Cl	483.00	524.75 / 38.83	516.90	10416.09763
F	0.00	10.51	5.26	196.60
NF	0.00	1.65	0.49	18.47
W	0.00	70.35	56.28	2104.97
Pa	0.00	0.09	0.07	2.76
G	0.00	10.83	5.42	202.55
Pl	0.00	3.07	2.45	91.74
Pb	0.00	5.30	2.65	99.20
O	0.00	7.49	3.75	140.11

Construction (construction site)

Total Energy use (MJ): -4035604.83

	Mass (ton)			Recovered
	Original	Landfilled	Recovered	Rate (%)
Co	1077.41	107.74	1049.27	97.4
M	583.06	58.31	516.90	88.7
Cl	71.90	4.31	28.76	40.0
F	40.99	1.17	34.56	84.3
NF	9.14	0.18	7.81	85.4
W	111.67	7.82	89.78	80.4
Pa	0.51	0.01	0.40	78.4
G	17.19	1.20	10.57	61.5
Pl	17.03	0.34	13.02	76.5
Pb	29.47	0.59	26.23	89.0
O	41.62	0.83	37.05	89.0

Transportation6 (R to C)

Total Energy use (MJ): 32537.55

	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
Co	1049.27	23.52	0.60	14808.68
M	516.90	21.74	0.69	7754.74
Cl	28.76	23.68	0.69	469.95
F	34.56	11.21	1.12	434.01
NF	7.81	10.99	1.12	96.11
W	89.78	15.27	2.07	2838.15
Pa	0.40	11.28	5.30	23.97
G	10.57	20.10	0.82	174.23
Pl	13.02	12.71	6.16	1020.06
Pb	26.23	69.17	2.06	3737.02
O	37.05	21.53	1.48	1180.62

Recycling (recycling site)

Total Energy use (MJ): -4157643.35

	Mass (ton)		Embodied	Total gap(MJ)
	Input	Output	gap(MJ/ton)	
Co	1049.27	1049.27	150	157390.76
M	516.90	516.90	130	67197.40
Cl	28.76	28.76	-2910	-83694.05
F	34.56	34.56	-25800	-891690.79
NF	7.81	7.81	-160646	-1254388.61
W	89.78	89.78	-15660	-1405953.28
Pa	0.48	0.40	-13820	-5539.22
G	10.57	10.57	-11720	-123916.87
Pl	16.08	13.02	-42100	-548331.15
Pb	26.23	26.23	-2620	-68717.56
O	37.05	37.05	0	0.00

Transportation7 (S to R)

Total Energy use (MJ): 13887.90

	Mass (ton)	Distance (km)	Efficiency (MJ/t*km)	Sum (MJ)
Co	1049.27	13.15	0.60	8280.41
M / Cl	516.90	11.72	0.69	4181.81
F	5.26	4.80	1.12	28.23
NF	0.49	4.57	1.12	2.53
W	56.28	7.93	2.07	923.58
Pa	0.07	6.43	5.30	2.51
G	5.42	13.39	0.82	59.48
Pl	2.45	7.16	6.16	108.21
Pb	2.65	42.45	2.06	231.91
O	3.75	12.49	1.48	69.23

Figure 103 Impact evaluation spreadsheet in the social impact model

Table 53 Conversion spreadsheet to environmental impact factors

			Total	Fossil depletion	Gas emmision			Metal elution							Minerals extraction	Waste disposal	Water use
				Energy from Fossile Fuels	CO2	NOx	CO	Cadmium	Chromium	Copper	Lead	Mercury	Nickel	Zinc	Minerals	Wastes	Water
				toe	kg	kg	kg	kg	kg	kg	kg	kg	kg	kg	ton	ton	litres
Landfilling	Co	ton	2029629.67					101.48	568.30	0.00	101.48	243.56	60.89	0.00			
	M	ton	1098364.98					10.98	39.54	362.46	4.17	472.30	87.54	768.86			
	Cl	ton	81269.51					0.00	7.31	7.31	1.63	0.00	6.50	311.26			
	F	ton	22004.82					0.00	263.40	42.69	0.00	0.00	328.75	0.00			
	NF	ton	3444.85					2.89	23.67	2.22	3.02	5.78	2.75	260.95			
	W	ton	147250.21					0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	Pa	ton	192.73					0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	G	ton	22670.47					0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	Pl	ton	6417.54					0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	Pb	ton	11103.02					0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	O	ton	15682.35					0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	Landfilled volume	ton	3438030.14					115.35	902.22	414.69	110.30	721.63	486.43	1341.07			
Energy use	Demolition	MJ	569162173.12	13594.20	39528312.92	796431.55	757952.89	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Transportation	MJ	1119439738.86	26737.36	77745089.86	1482221.14	849944.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Reclamation	MJ	0.00	0.00	-5960277635.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-30045398.45	-35556303.13	-54451763.80
	Recycling	MJ	-78321685384.98	-1870681.32				0.00	0.00	0.00	0.00	0.00	0.00	0.00			
	Off-site Sorting	MJ	1157294899.69	27641.51	74402678.10	1193111.19	684161.66	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9199482.51
	Landfilling	MJ	22226864.86	530.88	1543655.76	31102.17	29599.50	115.12	887.01	412.27	110.04	721.17	469.63	1316.04	0.00	3438030.14	0.00
	Total Energy use	MJ	-75450123678.31	-1802177.36	-5767057898.37	3502866.04	2321659.04	115.12	887.01	412.27	110.04	721.17	469.63	1316.04	-30045398.45	-32118272.99	-45252281.29
Recovery	Co	ton	19766180.91		-395323618.10	0.00	0.00								-19766180.91	-21545137.19	-25300711.56
	M	ton	9737420.83		-292122625.00	0.00	0.00								-9737420.83	-10321666.08	-8568930.33
	Cl	ton	541796.71		-10835934.17	0.00	0.00								-541796.71	-579722.48	-682663.85
	F	ton	651072.52		-286471909.34	0.00	0.00								0.00	-651072.52	1536531.15
	NF	ton	147095.01		-2159120185.57	0.00	0.00								0.00	-215066.14	-23579192.97
	W	ton	1691273.81		-2283219645.83	0.00	0.00								0.00	-1353019.05	67650.95
	Pa	ton	7550.49		-4756807.34	0.00	0.00								0.00	-5587.36	-213527.80
	G	ton	199176.28		-123489295.66	0.00	0.00								0.00	-197184.52	-485990.13
	Pl	ton	245355.40		-390115079.11	0.00	0.00								0.00	-203644.98	2760248.20
	Pb	ton	494084.50		-14822534.91	0.00	0.00								0.00	-484202.81	14822.53
	O	ton	697864.42		0.00	0.00	0.00								0.00	0.00	0.00
	Total Recovery	ton	34178870.87		-5960277635.03	0.00	0.00								-30045398.45	-35556303.13	-54451763.80

Table 54 Related processes for environmental impact factors

Impact factor	Conversion	Related process
Fossil depletion	toe/MJ	Crude oil consumption as total energy impact
Gas emission (CO_2, NO_x, CO)	kg/MJ	Demolition (machine use)
		Transportation (truck)
		Recovery of embodied CO_2
		Offsite sorting (diesel combustion)
Metal elution	kg/MJ	Metal elution from landfilling
Mineral extraction	ton/ton	Recovery of minerals (Concrete, Mineral, Brick (Clay))
Waste disposal	ton/ton	Recovery of wastes (all type of waste)
Water use	L/ton	Prevention of water use from material recovery
		Offsite sorting (water use)

Table 55 Environmental impact conversion rate

	Climate change, kg CO2eq (100 years) / kg	Acid deposition, kg SO2eq / kg	Human toxicity (to air), kg tox / kg	Low-level ozone creation, kg ethen eq / kg	Eutrophication, kg PO4eq / kg	Fossil fuel depletion, / tonne	Minerals extraction, / tonne	Waste disposal, / tonne
Energy from Fossile Fuels	0	0	0	0	0	1	0	0
CO2	1	0	0	0	0	0	0	0
CH4	21	0	0	0.007	0	0	0	0
NH3	0	1.88	0.02	0	0.35	0	0	0
N2O	310	0	0	0	0.13	0	0	0
NOx	0	0.7	0	0	0.13	0	0	0
NMVOC	0	0	0.022	0.416	0	0	0	0
CO	0	0	0.012	0	0	0	0	0
SO2	0	1	1.2	0	0	0	0	0
Cadmium	0	0	580	0	0	0	0	0
Chromium	0	0	6.7	0	0	0	0	0
Copper	0	0	0.24	0	0	0	0	0
Lead	0	0	160	0	0	0	0	0
Mercury	0	0	120	0	0	0	0	0
Nickel	0	0	470	0	0	0	0	0
Zinc	0	0	0.033	0	0	0	0	0
Minerals	0	0	0	0	0	0	1	0
Wastes	0	0	0	0	0	0	0	1
UK impact (per person)	12269	58.9	90.7	32.2	8	4.09	5	7.2
weighting factors*	0.35	0.05	0.065	0.035	0.04	0.11	0.05	0.06

*the value from the 1999 study of BRE is applied

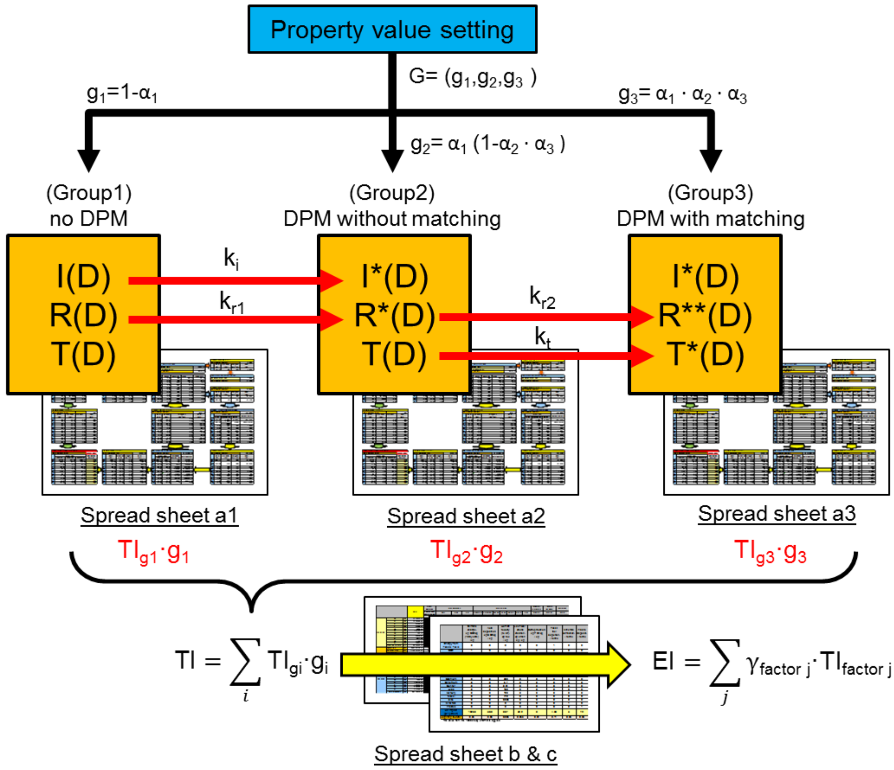
(source: BRE, 2007)

9.1. Scenario setting

As the starting point to examine the flow in Figure 6, three main scenarios are set in this pilot study to identify the efficiency of the environmental impact reduction**.** In the scenarios, followings are three steps specified with the usage of the present demolition model; Demolition Project Mapping (DPM) system.

1. **No application of DPM system (present state)**
2. **DPM system application to individual demolition teams as the decision support tool (no matching function is applied)**
3. **DPM application to both demolition and construction teams and possible matching.**

Scenarios are defined by how many steps the society proceeded to adopt the DPM system. Environmental impact can be summarised in the following formula on next page so that its value would be dependent on the choice of scenarios. In a scenario achieving all three steps, demolition projects could be categorized into three different groups at the steps mentioned above, as are shown in Figure 104. The number fraction of projects in each group becomes another pivotal factor which affects the total impact value. Here, α_1 is set as the fraction of projects which just registered to DPM, α_2 is the fraction of projects who uploaded their data into DPM among the registered projects, while α_3 is the fraction of projects which achieves to the contract between demolishers and constructors. In Figure 103, the flow of demolishers is shown from the top and that of constructors from the bottom. Therefore, the significance of each factor is discussed as the sensitivity analysis in the next section. It deserves to be mentioned that the first two scenarios can be regarded as the specific case of scenario 3, when g2 and g3 =0 for scenario 1 and g3=0, scenario 2, respectively.



where G: group separation for demolition teams, g_i: rate for group i, α_i: DPM use coefficient I,

I(D): demolition impact, R(D): recovery rate, T(D): transportation and treatment impact,

$k_{i,r,t}$: impact improvement coefficient for I,R and T,

Ti_{gi}, TI, $Ti_{factor\ j}$: total impact for g_i, sum and factor j,

EI: environmental impact, $\gamma_{factor\ j}$: conversion rate of factor j

Figure 104 Impact evaluation flow with demolishers classification

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ure 104.

$$Total\ impact = Demolition\ impact \quad + Waste\ recovery\ impact$$

$$= I(D) + R(D) \cdot T(D)$$

$$= I(D) + W(D) \cdot (T_W(D) + Tt) + M(D) \cdot (T_M(D) + E)$$

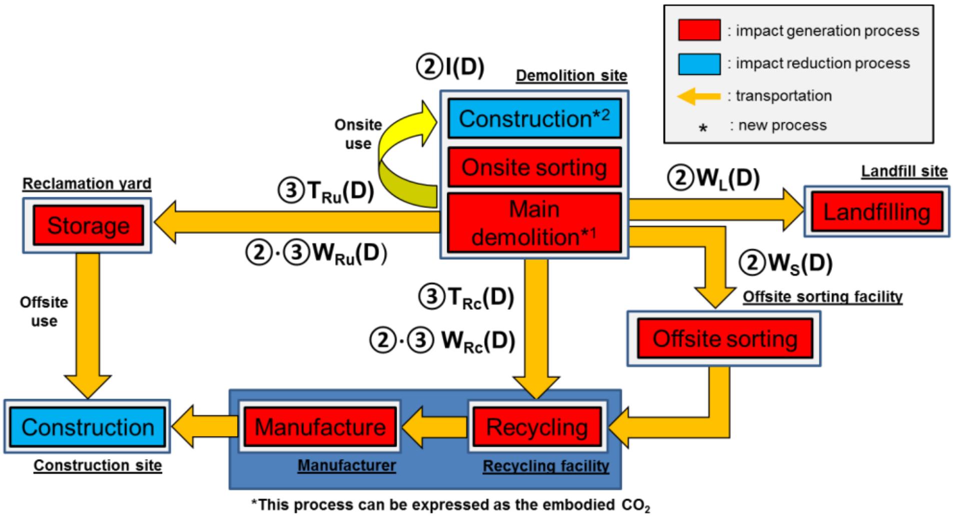
where $R(D) = (W(D) \quad M(D)),\ T(D) = \begin{pmatrix} T_W(D) + Tt \\ T_M(D) + E \end{pmatrix}$

$$W(D) \cdot (T_W(D) + Tt) = W_{Ru}(D) \cdot (T_{Ru}(D) + Ru) + W_{Rc}(D) \cdot (T_{Rc}(D) + Rc)$$

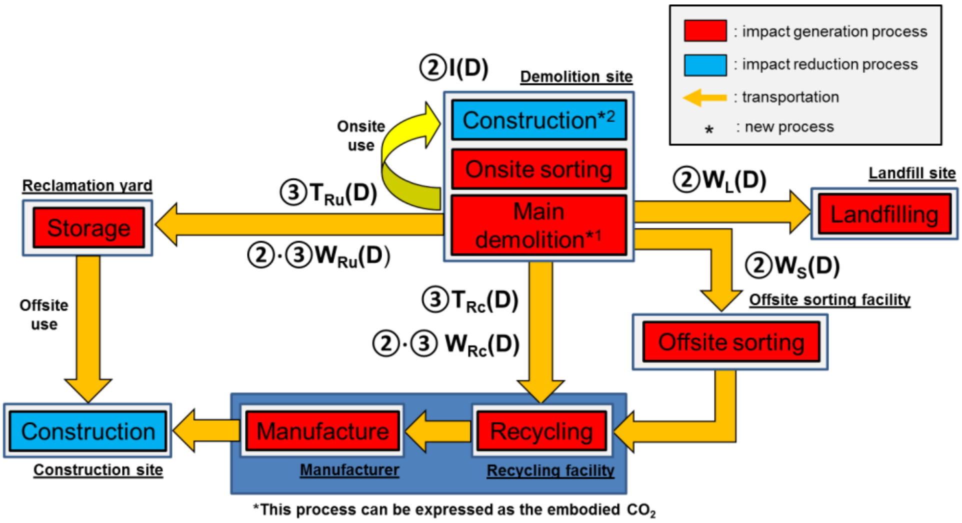
$$+ W_S(D) \cdot (T_S(D) + S) + W_L(D) \cdot (T_L(D) + L)$$

where $W(D) = (W_{Ru}(D) \quad W_{Rc}(D) \quad W_S(D) \quad W_L(D)),\ T_W(D) = \begin{pmatrix} T_{Ru}(D) \\ T_{Rc}(D) \\ T_S(D) \\ T_L(D) \end{pmatrix}, Tt = \begin{pmatrix} Ru \\ Rc \\ S \\ L \end{pmatrix}$

Differences among the three results can be simply explained with the Figure 105. Compared to the present states, the installation of the project impact evaluation model and its optimisation algorithm to the demolition project (in scenario 2) can reduce the demolition impact and change the generated waste treatment volume to permit more sustainable recovery (i.e. I(D), W_S(D) and W_L(D) become less, and W_{Ru}(D) and W_{Rc}(D) become larger). Once the construction teams start to apply the DPM system to the site survey, the waste recovery rate with reuse and recycling would be increased and the average distance of the transportation for the both processes would be shortened (i.e. T_{Ru}(D), T_{Rc}(D), W_{Ru}(D) and W_{Rc}(D) become less). Several different values were set to each coefficient and the robustness of impact evaluation was analysed. Detailed description is given in the following section. The meaning of each value in society is also summarised for ease of imagination.



where I(D): demolition impact (including onsite recovery),
W_{Ru}, W_{Rc}, W_S, W_L(D) : waste volume for reuse, recycle, offsite sorting and landfilling,
T_{Ru}(D), T_{Rc}(D) : transportation impact for reuse and recycle



where I(D): onsite impact,
W_{Ru}, W_{Rc}, W_S, W_L(D) : waste volume for reuse, recycle, offsite sorting and landfilling,
T_{Ru}(D), T_{Rc}(D) : transportation impact for reuse and recycle

Figure 105 Framework of the total impact evaluation model

The number of project teams for each group can be described in Figure 106. Demolition and construction project teams are assumed to be independent on each other so that the decision making would not be affected by other projects. Those stakeholders are categorized into groups based on the sustainability awareness and the attitude towards DPM application. In this model, the high awareness of sustainability for the construction team implies enough maturity to apply the recovered material to the project. Through the project analysis among stakeholders, they would reach agreements on property sales and collaboration in terms of the project. To simplify the modelling, there is no more than one contractor allowed for each demolition project. If there is no agreement between demolishers and constructers for the onsite waste recovery, the whole demolition and construction process would be treated by offsite treatment facilities and virgin materials would be respectively applied in projects.

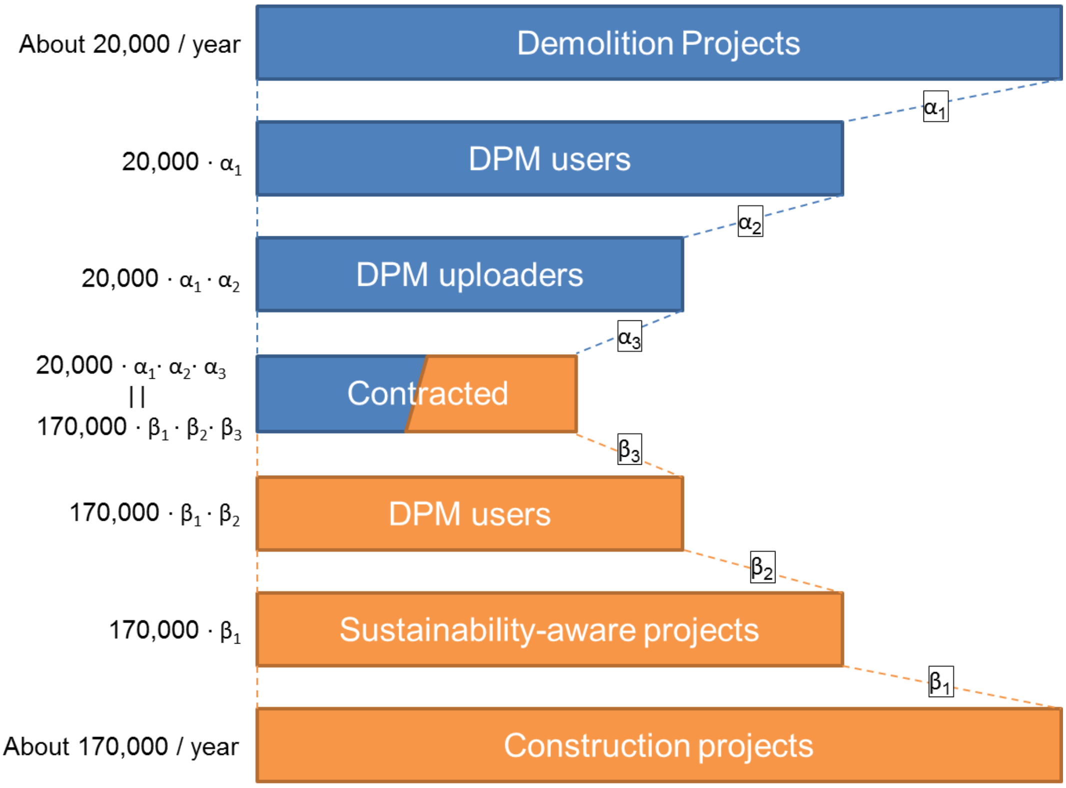


Figure 106 Framework of the total impact evaluation model

9.2. Sensitivity analysis

Agent based decision making models have large advantage in the recreation of the macro scale phenomena with micro scale property settings. In other words, the algorithms of individual agents decide stakeholders' actions, and the total results in society are the accumulation of these actions. Therefore, the social impact depends on the parameters of algorithms as well as the number of projects with enough utilization of DPM. This section explains the framework to examine the sensitivity of factors influential to the final social impact. The first step is to estimate factors and conditions to contract the DPM agreement. Except agreements, material flow is determined by other factors and settings, mainly by the transportation distance, which is also affected by some practical reasons. Then the social impacts are simulated with various factors and settings, which are varying in some range, to estimate the improvement efficiency especially of DPM application. Following is the summary of them and details are described in the next section (9.3.3)

1. Influential factors for the material flow I (Agreement rate: α3, β3**)**
   a. Dispersion of demolition and construction project
      (e.g. project size, project type)
   b. Project satisfaction thresholds for construction project teams
      (e.g. location, site scale, cost, project timing, etc.)
   c. Agreement rate between demolition and construction teams

2. Influential factors for the material flow II (transportation distance)
   a. Properties of construction project team
   b. Properties of treatment facilities

3. Scenario analysis and environmental impact scale analysis

   3-1. Influential factors for group sorting rate

   a. Application of DPM system for construction and demolition project teams
      (e.g. DPM application to demolition projects enhances α_1, while uploading of demolition project data raise α_2)
   b. Constructors awareness of recovery waste application (setting of β_1)
      (Uploading of construction push up β_2)

   3-2. Influential factors for impact value

   a. Project satisfaction thresholds for construction project teams
      (Acceptance rate of construction teams for recovery facilities)
   b. Capability of offsite waste treatment facilities (recycling and sorting plant)

c. Waste recovery strategy (sorting and disposal rate) (R(D))

3-3. Influential factors for DPM application (impact improvement coefficient)

Improvement efficiency with DPM application (k_i, k_r, k_t)

In the previous section, the impact evaluation was explained as the unified calculation process for three main values; i) group sorting rate (G or of α1, α2 and α3), ii) impact value (I(D), R(D) and T(D)) and iii) impact improvement coefficient (ki, kr, kt).

For the group sorting rate, the number of stakeholders in a group was changed by the coefficient values (α_1-α_3 and β_1-β_3) as well as the extreme scenario settings above (never applied DPM or only applied for project improvement and not for constructors). The sensitivity of the property values which indirectly affect the matching rate were surveyed first. For example, distance between demolishers to constructors should not be so far, or floor size and implementation terms should not be so different. Baseline values for each property were set in Table 56 and only the target value was individually altered to analyse the sensitivity. Subsequently, the application rate for demolition and construction teams was regarded as the directly related variables for agreement rate. How the increase of DPM users would affect the total impact of demolition and which teams should be more encouraged to be involved in DPM were studied.

Table 56 Default values for the related properties to agreement rate (α3, β3)

Constructor	PDM user rate	0.025	β1β2
	Distance limit	10	
	floor area gap limit	0.1	
	searching term	28	4weeks
Demolisher	PDM uploader rate	0.05	α1α2
	agreement rate	0.5	
	searching term	14	2weeks

For the sensitivity analysis of the impact value, transportation distance was chosen as the major factor for the impact evaluation in addition to the value setting of onsite impact and recycling rate. In the basic algorithm, demolition teams tried to find the closest offsite facilities to prevent a long journey. On the other hand, the construction team pursued the recovery materials without considering the distance from the site of their own project. Satisfaction rate was set to select the site from multiple choices to recreate this situation. Once the capability of facilities was considered, demolition waste may not be accepted by the facilities. As a result, extra transportation would be required for each waste type. The influence of recovery rate was also considered here. This is based on the assumption that the larger the waste quantity was sent to the offsite waste flow; more likely the treatment facilities were occupied by other projects.

Finally, the sensitivity of impact improvement with DPM application was discussed. The result value in the previous project pilot study was set as the control value. To make the model estimation more realistic, the value was assumed to be varied to negative range for the onsite impact (i.e. assuming the probability of impact increase with DPM application). The merits derived from more sustainable waste recovery were compared with the significance of negative impact in the worst scenario. Those different settings were regarded as the probability range for scenario 3 and the model usability through the comparison with the others is discussed in the next chapter.

9.3. Result and discussion

As shown above, simulation results were discussed in three phases, i) sensitivity, ii) scenario and iii) impact scale analysis. At the property value setting phase, each factor value was varied in assumed range. The average value and the standard deviation were calculated with 100 times repetition of one-year simulation run. In order to analyse the correlation between scenario and environmental impact scale together, scenario with different conditions will be compared one by one in this section. At the end, the impact improvement coefficient, ki, and other k-factors are studied to confirm the usefulness of DPM.

9.3.1 Influential factors for the material flow I (Agreement rate)

9.3.1.1 Sensitivity analysis for DPM agreement rate

In order to estimate demolition impact to the society, the material flow from demolishers to constructors based on the DPM agreement is discussed first. Achieving the contracts requires good matching of properties of construction and demolition projects. Accordingly, the property values are discussed from two points of views.

Properties of construction project teams

There were three steps for the construction teams to find the availability of contracts with demolition team on the preferred sites; i) date selection, ii) project property checking and iii) negotiation. A project generation date (or project generation dates) is registered in the DPM system to scan the applicable demolition projects for each construction project. To be precise, they could stretch back to the date for searching demolition teams which is waiting an offer until the demolition and stretch forward to a future date for their own searching time. After the date selection, construction teams did check the project requirements one by one; building type, floor size and location distance. Eventually they sent an offer to the demolition team, and if it were denied, they would repeat the same action until the available list scanning is completed. The change of number of project agreements depending on each variable is described with the following sections. All cases use the same project dataset of PDM coefficients (α1·α2 and β1·β2) given as Table 5, so that they handle 18838 demolition projects in total and PDM users are given to be 942 and 4361 for demolition and construction.

Distance limit

The first parameter examined here is the distance between a demolisher and a constructor. A constructor checks the possibility to get material from a demolisher in the near distance first. The contract is successful with certain possibility with given values in Table 5. If not constructor continues to check other demolisher until the distance limit, the demolisher determined beforehand. The relation between distance limits and agreednumbers is described in Figure 107 with logarithmic scale for horizontal axis. This sigmoid curve shows the decline of number increase from 10^1.5(=30) km range. This may mean the number density of demolition projects within a relatively short range (about 30km) from construction projects, especially in cities. Since both projects were generated in proportion to the population density, the distance between them became quite close in a big city. This data shows that the distance of 30km allows about half of demolition teams to reach agreement. Distance would be reduced once the uploaded number of demolition projects on DPM system increased. It will be discussed in the section below with user rate changes. Questionnaire survey of the construction stakeholders must answer the required number of demolition projects uploading their information which maintains project distance within a feasible range for them. However, not only focusing on the distance but the geographical features such as city scale or in opposite, the distance from other competitive facilities may need to be considered to make the model to reflect user behaviour.

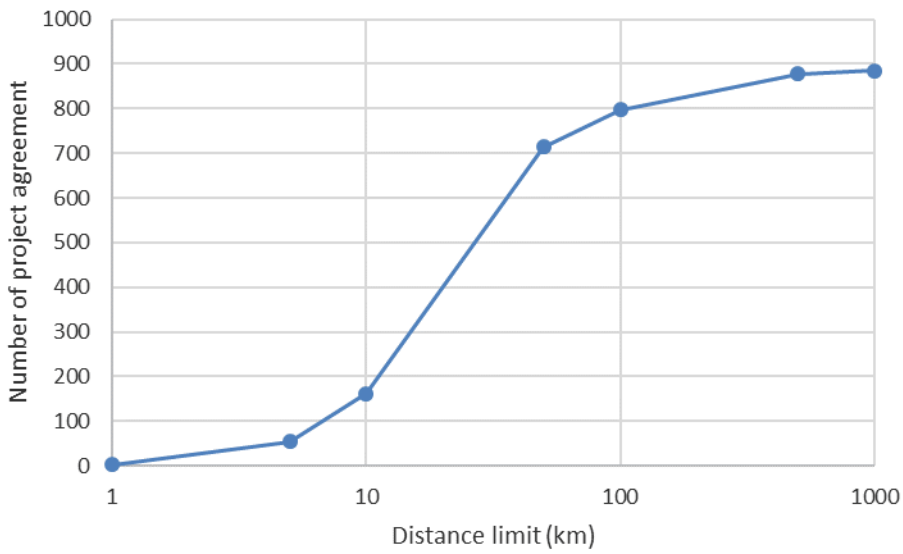


Figure 107 Number of project agreement change with distance limit

Floor limit

The second parameter studied is the project size represented by floor size. If the demolition project size is too small, not much enough supply of material can be expected from the demolition project. Once the floor size of a constructor is determined, the fraction of demolition is obtained from the size distribution of the demolition project. The relation between floor limit and number of project agreement is described in Figure 108. Since the distribution was assumed as the nominal distribution, the increment rate decreased as the acceptable gap became larger and larger. It was also remarkable that the total number exceeded 500 at the end. Comparing the result with distance limitation in Figure 11 (floor area gap limit is assumed to be 10 %), if there was no size limitation, more than 500 projects could find the target within 10km. In the further model development, recovery volume especially for onsite should be influenced by the floor gap to recreate the efficiency more realistically.

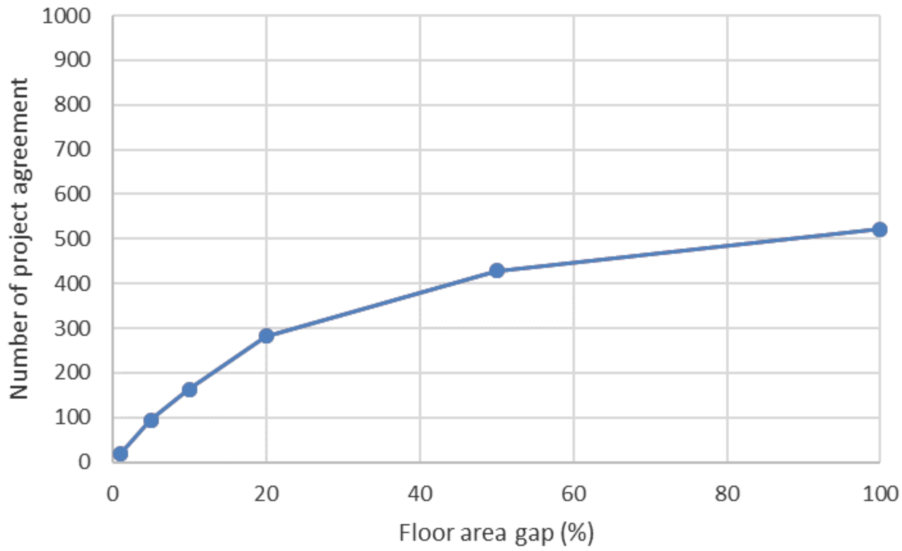


Figure 108 Number of project agreement change with floor area gap

Searching term

The third parameter examined is the coincidence of project periods. A constructor looks for a demolition project whose waste is available within certain time period. Here, number of projects of not only construction but also demolition are plotted in Figure 109 and Figure 110, respectively against the term gap (days) acceptable for both projects. Both searching terms decided the duration of scanning to find candidates. Therefore, both results showed almost the same shape of curve. Difference seen at the beginning was derived from the default gap value between construction and demolition searching term, 28 and 14 days respectively. Since the expectation of agreement per day can be regarded as very nearly constant, it could be described with following formula. Therefore, the expotential trend line well accorded with both curves. This result showed that stakeholders could increase the agreement rate by extending the searching term. Within 5 months, it would exceed 50% regardless of others duration.

$$P(day) = 1 - (1 - \mathrm{p})^{day}$$

where P(day): expectation of agreement until day, p: expectation per day

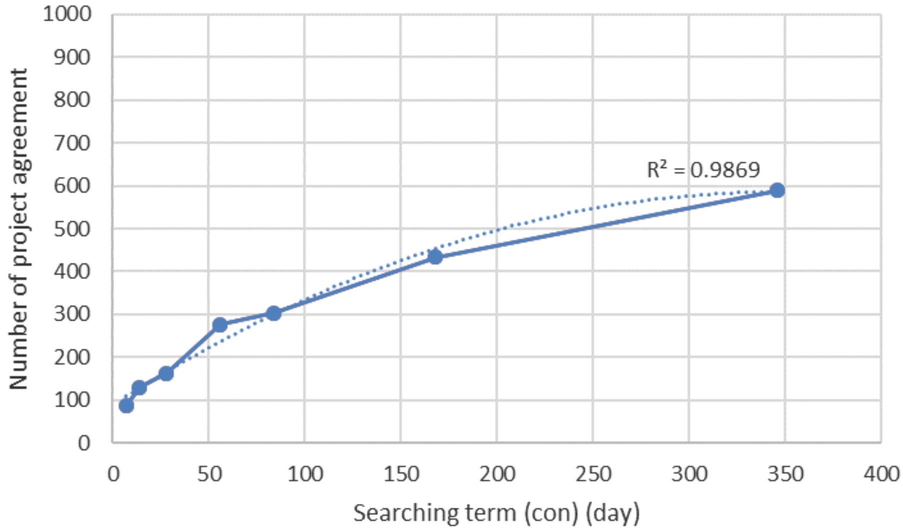


Figure 109 Number of project agreement change with searching term of construction teams

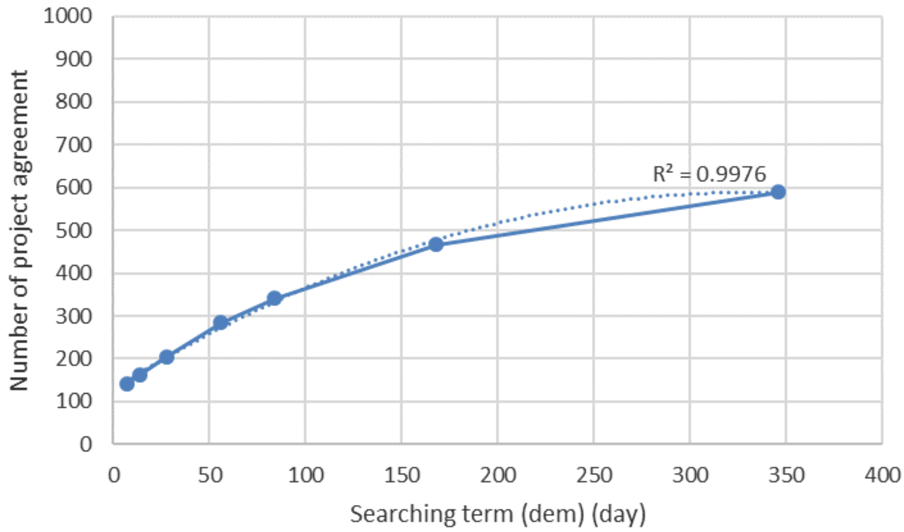


Figure 110 Number of project agreement change with searching term of demolition teams

9.3.1.2. Properties of demolition project team

Compared to construction teams, demolition teams had only one step in the process of agreement. This was based on the assumption that the suggestion which had already been scrutinized by the construction teams is similarly acceptable to them. To adopt the other factors for disagreement in a simple way, the agreement rate was set as the only complex function.

Agreement rate

The number of project agreement is the product of agreeable project number and the agreement rate, which is the last factor to be rejected by a demolisher due to other reasons. Relation between agreement rate and number creates a curve which is almost as a straight line as shown in Figure 111. There was no significant effect from other properties. Only if the project density is high enough to give multiple chances to find candidates more than two or three, even 50 % agreement rate will give 100 % possibility to find agreeable project. In this case, the plot will be a combination of a straight slope in the lower agreement rate value, while it will be saturated beyond 50 % of agreement rate.

Since it could be regarded as proportional, statistical data for the agreement rate would be very helpful to set the minimum requirement offer for the system to maintain.

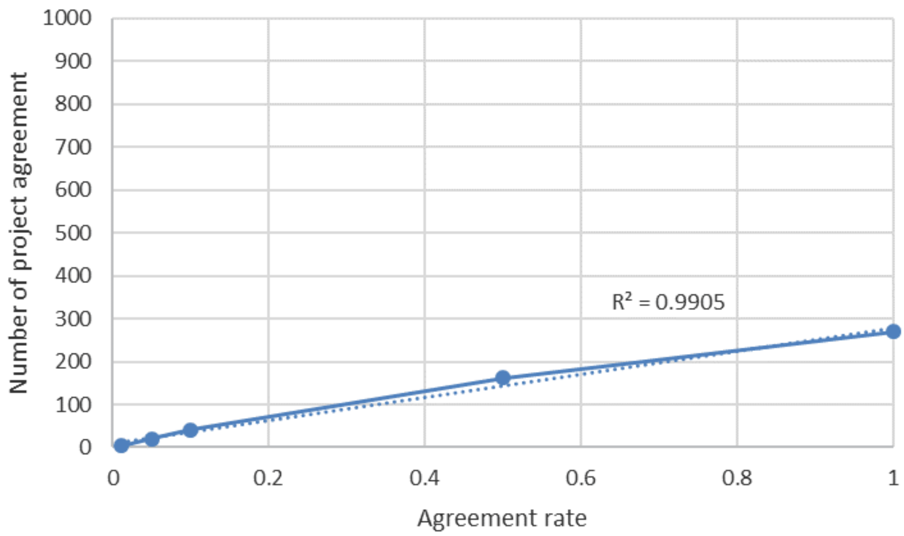


Figure 111 Number of project agreement change with agreement rate

9.3.1.3. DPM use coefficient

In general, as the fraction of DPM users and DPM up-loaders increases, the possibility of agreement between constructors and demolishers will increase. This tendency is always true if the numbers of construction and demolition projects are the same. In this section, imbalance of the number of users for each team is taken into account.

DPM user rate of demolition team (α1·α2)

Relation between demolition DPM user and number of agreement results in a linear line(blue) as seen in Figure 112. Number of agreements achieves 3000 with typical parameters summarized in Table 5, if all projects are full DPM users. Compared to the number of construction teams, 4361, the number of demolition teams used to be less than 1000 (when α1·α2=0.05) but it became more than 18,000 for α1·α2 = 1, and showed 3,500 pairs of agreement. It was remarkable that the ratio of agreement share of demolition projects (red) was almost constant, while the one of construction (green) constantly increased as shown with broken lines. This was explained by the different viewpoints of each. For the construction team, surrounding demolition project density was spontaneously increased as the α1·α2 rate increased. On the other hand, from demolition teams' view, although their own number density increased significantly, the possibilities to find construction project arising at the proper place and timing were constant in Figure 16. This implied the increase of one type of stakeholder would only increase the other type's agreement share. It may result in two spiral scenarios; a negative spiral where the loss of one type cause a loss for the others repeatedly, and vice versa (as a positive spiral). In this situation, increase of DPM users from 4000 to 18,000 about factor of four larger did enhance the number of project agreement. However, the agreement fraction of demolishers was free from the increase of α1·α2.

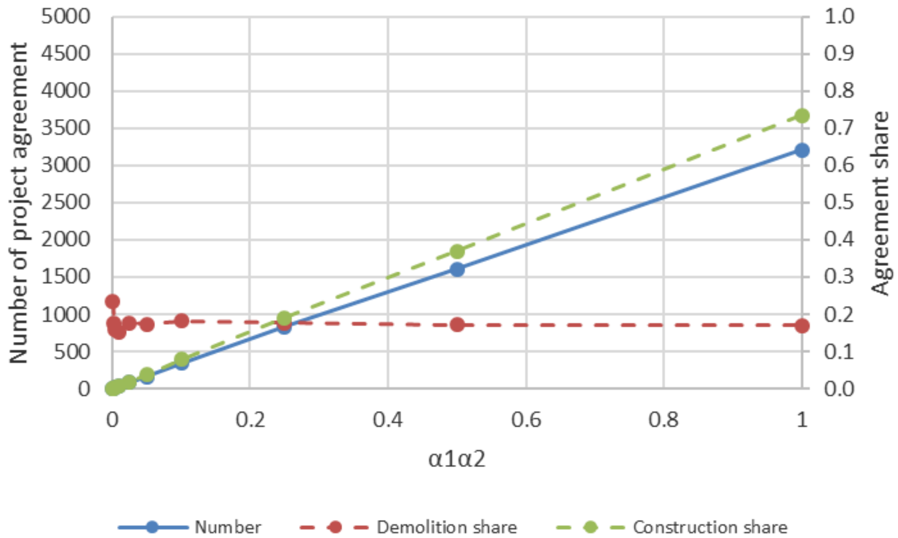


Figure 112 Number of project agreement change with DPM user rate of demolition team (β1·β2=0.025)

DPM user rate of construction team (β1·β2)

Relation between construction user rate and number of project agreement seemed to be a polynomial curve as shown in Figure 113. Increment rate of number of project agreement (blue) declined as the construction user rate was set larger, while it was constant in the demolition user's case in Figure 16. It was attributed to the ratio of two stakeholder types. In this case, the construction sites are about 20 times more than demolition ones. This caused a severe competiton of perchase among construction teams, because demolishers preferable for a constructor could be already contracted by another contracter. Therefore, it resulted in the lower increment rate of number of project agreement. Two broken lines described the decline of construction agreement share and the rapid growth of demolition agreement share which was strongly demanded. The deceleration of demolition share became significant at a high rate. This was thought to be caused by construction demand drastically exceeding demolition supply in urban areas and isolated projects were left at the end. Due to the scale gap between populations of construction and demolition (170,000 vs 20,000), demolition users must be incorporated to balance the number of participants from both the demolition and construction sides.

Just for a record, the numbers of projects handled in this section are summarized based on the statitical values surveyed in Chapter7. Total number of demolishers and constructers are set as 20,000, and 170,000, respectively. By adopting tentative values to the DPM application rate for both demolishers (α1·α2=5%) and contracters (β1·β2=2.5%), the contact agreement rate for users becomes 18% (α3) and 39% (β3), respectively.

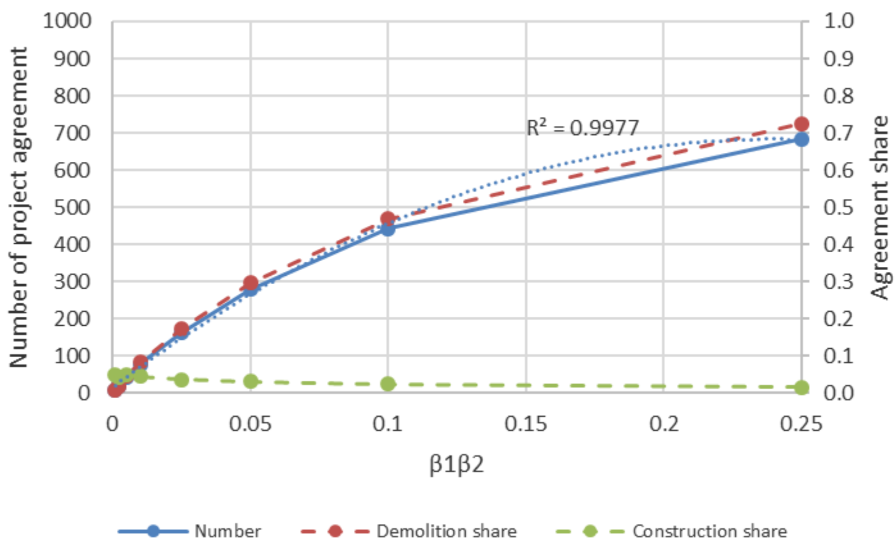


Figure 113 Number of project agreement change with DPM user rate of construction team (α1·α2=0.05)

9.3.2. Influential factors for the material flow II (transportation distance)

Following the DPM agreement rate, related properties were analysed especially for transportation distance. It is because the distance between agreed groups is determined by several trials with various the facility selection rules. At the same time, the transportation distance also affects the total cost and impact. There were two patterns that influenced the facility selection in this model. Construction teams, had the opportunity to decide the source of recovered material (i.e. from reclamation yards and recycling facilities) so they might skip the closest facility, which action was recreated by the satisfaction rate. Another factor was the excess supply compared to the facility capabilities. The influence of the refusal of waste due to the capacity was investigated through the comparison of capability setting and waste recovery rate explained below.

9.3.2.1. Properties of construction project team

Facility distances between construction site and reclamation yard or recycling facilities were decided by the simulation of selection algorithm which repeatedly examined the recovery products from the closest stakeholders. If satisfaction rate was set as 0.1, it would decide in 10% of cases to choose the stakeholder as a material source, so roughly 10^{th} closest candidate would be chosen in average. The result of this simulation was evaluated with different satisfaction rates as shown in Figure 114 with logarithmic scale for both axes. Except the distance to a Pb (Lead) facility data, all drawn linear lines, which implied the relation between distance and satisfaction can be represented by the following formula:

$$distance = k \cdot (satisfaction\ rate)^n$$

where k, n: natural number

This was explained by the decision method the result of which could be calculated from the sum of geometric series as below.

$$\sum_{k=1}^{n} ar^{k-1} = \frac{a(1-r^n)}{1-r} \ (r \neq 1)$$

where a, r: actual number, k , n: natural number

According to the figure, the value would be half increased even if it passed over the closest facility just once. Because of the trade-off between the product satisfaction and the extra transportation burden, it does not seem this value would be lower than 0.1 which requires three times larger transportation distance than the closest option.

Beside the satisfaction rate, the number of construction teams which has higher awareness for application of recovery material, was changed to check its influence to the distance. There was, however, no difference for the scarce opportunity (12.5 % of total) for waste recovery in construction, which has been recommended by Wrap for 10-15% of recovery material application onsite (Wrap, 2015). As a result, there were no competition for the securement of recovery resource between construction teams. This influence would be necessarily a concern when the application of recovered material will be drastically increased by such as the legal enforcement on new construction in the future.

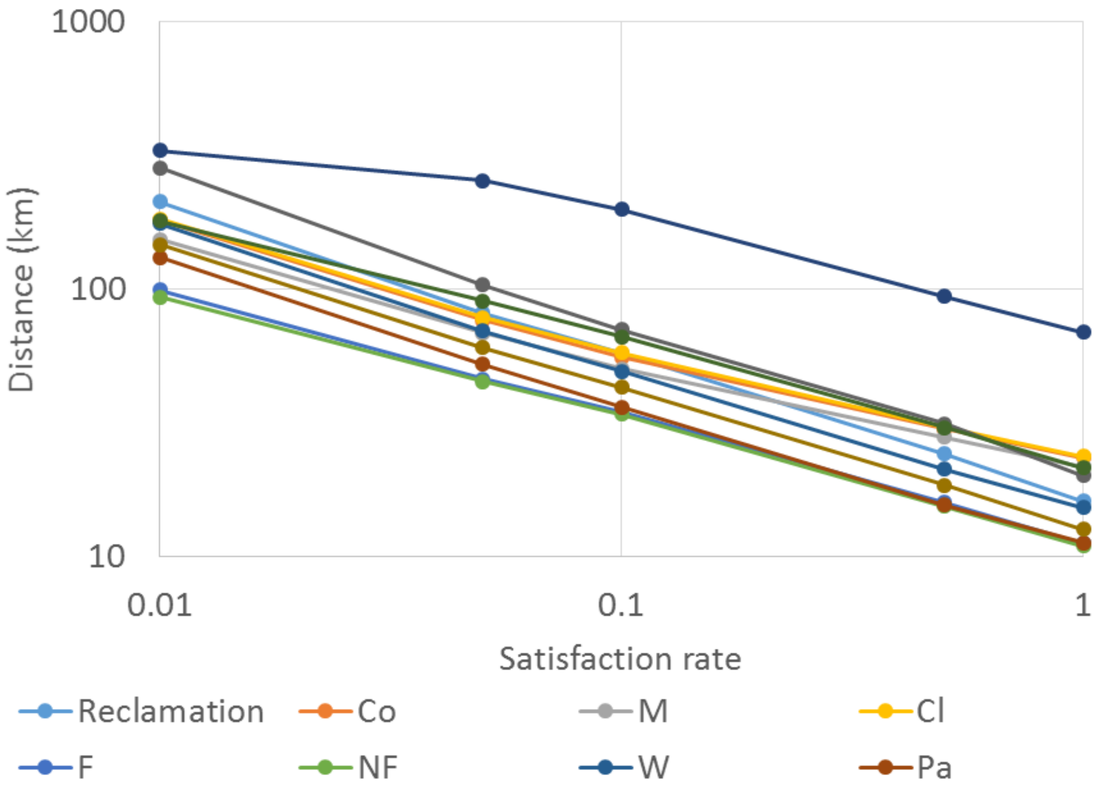


Figure 114 Distance change with satisfaction rate of construction team

9.3.2.2. Properties of treatment facilities

The capability of sorting plant and recycling facilities were set to identify the impact on the transportation distance. Based on the treatment facilities' algorithm, waste acceptance was not permitted if it would exceed the facility capability. Due to the small number of treatment plants for minor waste types such as glass and lead, some extreme cases forced the extension of the transportation distance in large scale. Here, the capacity and the recovery rate, from two aspects, transportation distance was evaluated.

Capability setting

In this analysis, the facility capability was set for recycling and sorting facilities to treat demolition waste. These facilities could not accept more demolition waste if the volume of current waste stock to be treated exceeded the daily capability. When a day was lapsed in the model, the waste stock was subtracted from the capability volume as the treatment. Therefore, if the facility got an offer from one construction site whose volume corresponded to 10 days' treatability, that facility would stop accepting any offer from other sites. Here, landfilling facilities had no treatment ability due to the large capacity assumed not to be filled within the near future. In the research of Mercante et al. (2012), the treatment ability of sorting facilities was estimated as 3750 tons per day and this value was applied to this model. Each type of recycling plant was set as Table 57 assuming the recycling facility treats constant fraction (%) of the demolition waste generated by a project per day. 10 % means all waste can be accepted but that facility is occupied for ten days. The value was calculated by the mass of recycled material with conventional onsite sorting rate. The proportions were set as 100, 80, 60, 40, 20, 10 and 1% of original waste volume from a single project, respectively. The detail explanation of 'facility capability' in social impact model can be found in Chapter2.3.3.

Table 57 Facility capability for recycling facilities

(ton/day)

	C1	C2	C3	C4	C5	C6	C7
	100(%)	80(%)	60(%)	40(%)	20(%)	10(%)	1(%)
Co	1048.07	838.45	628.84	419.23	209.61	104.81	10.48
M	518.12	414.49	310.87	207.25	103.62	51.81	5.18
Cl	28.76	23.01	17.26	11.50	5.75	2.88	0.29
F	34.55	27.64	20.73	13.82	6.91	3.46	0.35
NF	7.81	6.25	4.69	3.12	1.56	0.78	0.08
W	89.78	71.82	53.87	35.91	17.96	8.98	0.90
Pa	0.48	0.39	0.29	0.19	0.10	0.05	0.00
G	10.57	8.46	6.34	4.23	2.11	1.06	0.11
Pl	16.08	12.86	9.65	6.43	3.22	1.61	0.16
Pb	26.23	20.98	15.74	10.49	5.25	2.62	0.26
O	37.05	29.64	22.23	14.82	7.41	3.70	0.37

First of all, the distance results from demolition sites to recycling facilities was shown as Figure 115 with logarithmic scale on the horizontal axis. This describes the large distance increase with the facility capability which is equivalent to the 1% (c7 with the dark blue line) of the waste generation from single project. As explained above, if the treatment volume corresponded to n days' treatment volume that facility service would have been suspended for n days. In this case, a maximum of four projects could send waste to each facility per year. Specifically, the majority of the Pb (lead) waste could not be treated by 20 facilities which were full of waste. Therefore, the ghost facilities were alternatively applied, with the distance set as 1000km for simulation convergence. Similar to this, G (Glass) waste with 130 facilities (less than half of other waste type) showed large extension of distance. In other words, demolishers tend to send G or Pb waste to facilities in farther distance, for example, since treatment is possible in limited number of facilities.

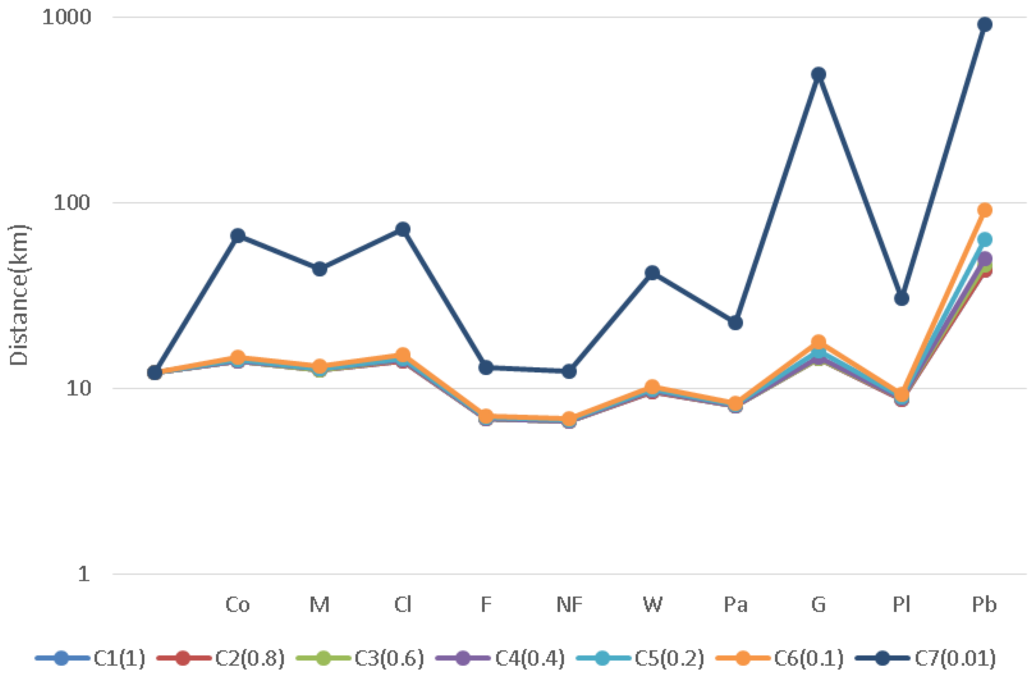


Figure 115 Distance change between demolition sites to recycling facilities with capability

Following this, the data for C1 (1), C6(0.1) and C7 (0.01) were re-plotted with the facility number in UK as shown in Figure 116 with logarithmic scale for both axes. The number of recycling facilities is different from item to item. For example, there are only about 20 plaster board recycling facility, while there are more than 150 glass recycling facilities quoted from public data. To find recycling sites for G or Pb, a demolisher haa to search much farther distance. The same as the satisfaction rate, it showed the negative power relationship with distance due to the risk of not being accepted as waste by facilities. The facility capability which reduced the refusal rate showed more influence on facility number when they had higher risks of being overloaded for lower capability (like C7), which could be seen from the proportion value of trend line for C1 to C7. The same phenomenon was displayed in the distance change between sorting and recycling facilities as Figure 117. Although sorting facilities were usually located at a close place because of transportation, it did not show any advantage especially if the low capability was given. The small gap between C1 and C6 implied the capability influence was negligible if facilities had a treatability within ten days. However, at least 100 facilities would be ideal to maintain the transportation in UK.

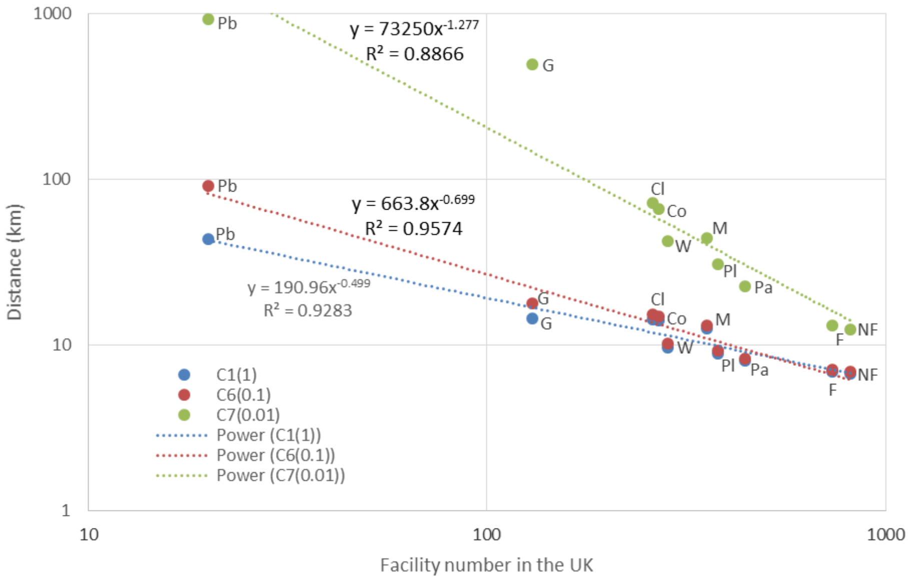


Figure 116 Distance change between demolition sites to recycling facilities with inverse value of facility number in UK (for C1(1), C6(0.1) and C7(0.01))

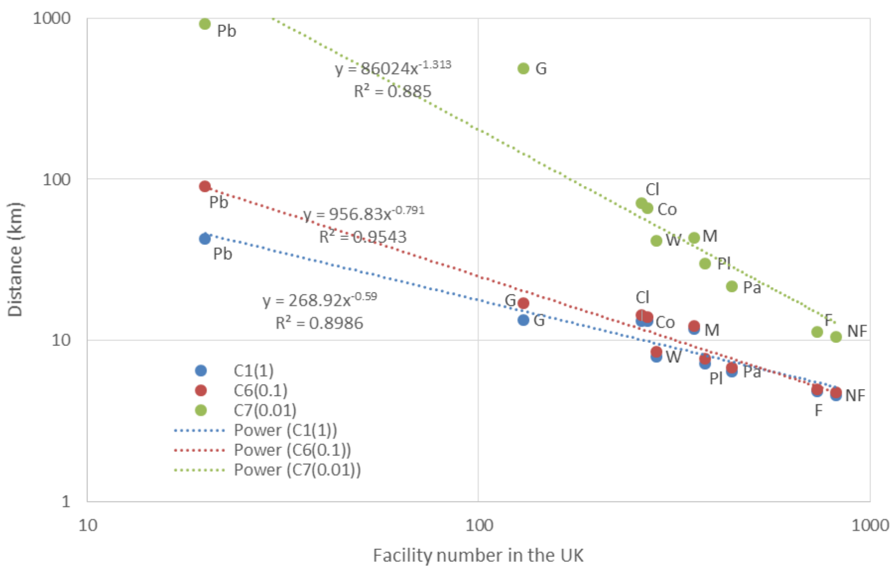


Figure 117 Distance change between sorting facilities to recycling facilities with inverse value of facility number in UK (for C1(1), C6(0.1) and C7(0.01))

Recovery rate setting

Recovery rate was set as Table 58 which was suggested in the author's previous research based on the onsite sorting progress as explained below. Volume of waste stream was changed with the sets of recovery rate so that the distances among facilities for C1, C6 and C7 were analysed for the significance of impact with different capability.

Case1. Complete landfill

All demolition waste except that diverted through basic recovery of reinforcement was sent to a landfilling facility for disposal. No additional sorting was conducted on-site.

Case2. Conventional demolition

Demolition waste was sorted according to the conventional sorting rate as the benchmark. The gap of environmental impact from this was assumed as a relative improvement to the current situation.

Case3. Complete sorting

Demolition waste was completely separated on site. Whole waste component was directly sent to recycling facilities.

Case 4 to 7. Intermediate sorting

Intermediate sorting conditions between Case 1 to 3 were set as 1, 4, 6 and 8 days onsite sorting. The inert disposal rate was assumed the same as Case 2.

Case 8 to 10. Intermediate disposal

While onsite sorting was assumed the same as the conventional demolition case, the disposal rates for inert waste were set as 0.4, 0.7 and 1.0. This was expected to reveal the influence on environmental impact during the transition between complete landfilling and complete recycling for demolition treatment.

Table 58 Sorting rate coefficient and recycling rate for each case

	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
R_B	0.0	0.4	1.0	0.3	0.6	0.7	0.9	0.4	0.4	0.4
R_E	0.0	0.3	1.0	0.2	0.5	0.7	0.8	0.3	0.3	0.3
R_I	0.0	0.8	1.0	0.6	0.9	1.0	1.0	0.8	0.8	0.8
R_R	0.8	0.8	1.0	0.8	0.9	0.9	1.0	0.8	0.8	0.8
R_M	0.0	0.8	1.0	0.6	0.9	1.0	1.0	0.8	0.8	0.8
R_D	1.0	0.1	0.0	0.1	0.1	0.1	0.1	0.4	0.7	1.0
Co	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
M	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cl	0.00	0.40	1.00	0.25	0.55	0.70	0.85	0.40	0.40	0.40
F	0.66	0.72	1.00	0.70	0.79	0.86	0.92	0.72	0.72	0.72
NF	0.00	0.80	1.00	0.60	0.90	0.95	0.95	0.80	0.80	0.80
W	0.00	0.30	1.00	0.20	0.50	0.65	0.80	0.30	0.30	0.30
Pa	0.00	0.80	1.00	0.60	0.90	0.95	0.95	0.80	0.80	0.80
G	0.00	0.30	1.00	0.20	0.50	0.65	0.80	0.30	0.30	0.30
Pl	0.00	0.80	1.00	0.60	0.90	0.95	0.95	0.80	0.80	0.80
Pb	0.00	0.80	1.00	0.60	0.90	0.95	0.95	0.80	0.80	0.80
O	0.00	0.80	1.00	0.60	0.90	0.95	0.95	0.80	0.80	0.80

Distance change for each case was described as following for three different capability conditions C1(1), C6(0.1) and C7(0.01) (see Figure 118, Figure 119 and Figure 120). There were few difference among cases for C1 and C6, which was similar to the result of capability changes in the previous section (see Figure 19). On the other hand, C7 showed a huge difference due to the low capability and high risk of facility overflow. The distance change for obvious Cl and G items with the average project number to be treated by each facility per year was shown in Figure 121 for each case. This was calculated by dividing the days of year (360) by the average facility suspension term with one project waste (directly from sites and indirectly via sorting plant). The values were plotted on the power lines so that the distance and the treatable project number had a similar relation to facility number. Increasing the number of facilities or the average treatable number can be regarded as having the same effect so that the enhancement of facility capability or minimization of waste flow especially for immature material recycling (e.g. Pb, Cl, G) would prevent the extension of transportation distance.

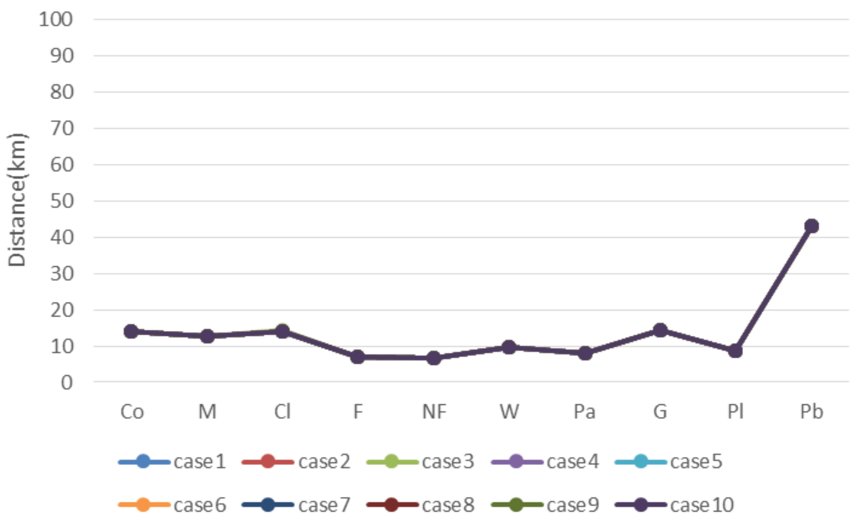


Figure 118 Distance change between demolition sites to recycling facilities (C1)

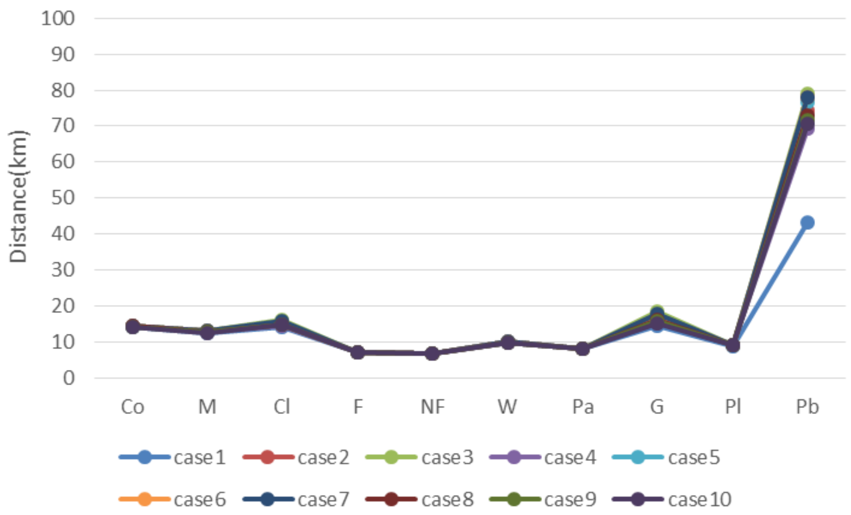


Figure 119 Distance change between demolition sites to recycling facilities (C6)

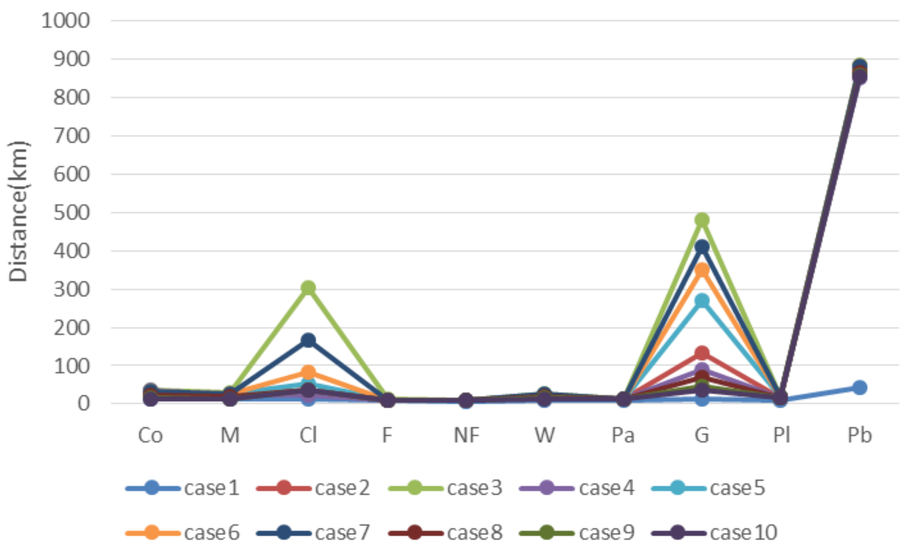


Figure 120 Distance change between demolition sites to recycling facilities (C7)

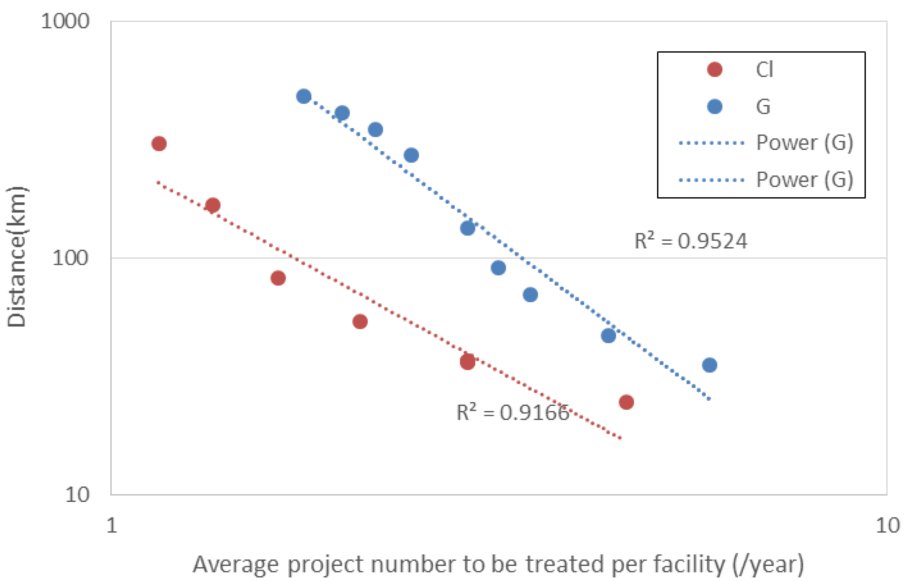


Figure 121 Distance change between demolition sites to recycling facilities (C7)

9.3.3 Scenario analysis and environmental impact scale analysis

As in the previous section, the impact evaluation was explained as the unified calculation process for the three main values; i) group sorting rate (G or α1, α2 and α3), ii) impact value (I(D), R(D) and T(D)) and iii) impact improvement coefficient (ki, kr, kt). Therefore, each impact generation and estimated environmental impact for three scenarios were separately calculated and its individual influence was analysed. The following property values in Table 59 were set as the bench mark scenario when altering the values. This resulted in Table 60 and Table 61 for the total impact of absolute value and ratio for scenario 1. For scenario 2, three DPM application rates were set to compare the total demolition impact; 1, 10 and 100% of application. The result showed a proportional improvement for the result of scenario 2. As it increased α_1 value ten times, the relative improvement against scenario 1 became approximately ten times better than before. Comparing scenario 2 with scenario 3 in the same α_1 value, the improvement efficiency was less than half the improvement. Application of the DPM showed more efficiency than the increase of DPM uploading rate based on this result. This hypothesis would be verified to see if it works in all cases in following sections.

Discussing the content of environmental impact caused by demolition, scenario 1 and the most improve scenario, scenario2 (α1=1), could be visualized as Figure 122 and Figure 123. Here, ‘waste disposal’, ‘mineral extraction’ and ‘climate change’ which is followed by ‘fossil fuel depletion’ showed their significance and those factors apart from ‘mineral extraction’ seemed to be mainly improved by DPM application when comparing the two scenarios. In other words, the improvement of total environmental impact in demolition was definitely achieved by the above three factors. Originally the high volume of mineral waste recovery from landfilling (less than 10%) even in scenario 1 could be the main reason for the low contribution of ‘mineral extraction’ here, the raw impact of which showed a 2% of improvement at best. On the other hand, the contribution of ‘total energy use’ improvement for ‘fossil fuel depletion’ which had a high improvement rate (-21% in scenario2) became less influential in total (-6%) due to the relatively small scale of impact factor.

Table 59 Property values of control scenarios

Case setting	
Case number	2
Capacity	1(100%)
Demolition project number per year	18838
Construction satisfaction rate	1
Demolition group coefficient (α)	
PDM user(α1)	0.1
PDM uploader(α2)	0.5
matching (α3)	0.1726
Construction group rate	
sustainability awareness (β1)	0.25
PDM user (β2)	0.1
matching (β3)	0.2828
Improvement rate	
Onsite impact improvement (ki)	0.2
recovery rate improvement (kr1,rc)	0.2
reuse share (kr1,ru)	0.2
reuse share2 (kr2,ru)	0.2
Onsite application (kr2,on)	0.5

Demolition group share	
without PDM (g1)	0.9
with PDM without agreement (g2)	0.091370634
with PDM with agreement (g3)	0.008629366
Construction group rate	
without PDM	0.975
with PDM without agreement	0.017930955
with PDM with agreement	0.007069045

Recycle rate (Case number2)	
RcB	0.4
RcE	0.3
RcI	0.8
RcR	0.8
RcM	0.8
RcD	0.1

Demolition impact (I(D))	
Main demolition impact (MJ)	29321.51381
Treatment day (446MJ/day)	2
Total (MJ)	30213.51381

Table 60 Impact value for the control scenarios (absolute value)

		Unit	Project emission					UK impact per citizen	Normarisation					Weighting factors	Eco point				
			Scenario1	Scenario2			Scenario3		Scenario1	Scenario2			Scenario3		Scenario1	Scenario2			Scenario3
				α1=0.01	α1=0.1	α1=1				α1=0.01	α1=0.1	α1=1				α1=0.01	α1=0.1	α1=1	
Climate change		kg CO2eq	-5.8E+09	-5.8E+09	-5.8E+09	-6.2E+09	-5.8E+09	12269	-4.7E+05	-4.7E+05	-4.7E+05	-5.1E+05	-4.7E+05	35	-1.6E+05	-1.6E+05	-1.7E+05	-1.8E+05	-1.7E+05
Acid deposition		kg SO2eq	2.5E+06	2.4E+06	2.4E+06	2.1E+06	2.4E+06	58.9	4.2E+04	4.2E+04	4.1E+04	3.6E+04	4.1E+04	5	2.1E+03	2.1E+03	2.1E+03	1.8E+03	2.0E+03
Ozon deletion		kg CFC11eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.3	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	8	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Polution to air	Human	kg tox	4.3E+05	4.3E+05	4.3E+05	4.2E+05	4.3E+05	90.7	4.7E+03	4.7E+03	4.7E+03	4.6E+03	4.7E+03	6.5	3.0E+02	3.0E+02	3.0E+02	3.0E+02	3.0E+02
	Low-level ozone creation	kg ethene eq	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	32.2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	3.5	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Fossil fuel depletion		toe	-1.8E+06	-1.8E+06	-1.8E+06	-2.2E+06	-1.8E+06	4.09	-4.4E+05	-4.4E+05	-4.5E+05	-5.3E+05	-4.5E+05	11	-4.8E+04	-4.9E+04	-4.9E+04	-5.9E+04	-5.0E+04
Polution to water	Human	kg tox	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.01	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	2	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	Ecotoxicity	kg tox	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	177948	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00	4	0.0E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
	Eutrophication	kg PO4eq	4.6E+05	4.5E+05	4.5E+05	4.0E+05	4.5E+05	8	5.7E+04	5.7E+04	5.6E+04	5.0E+04	5.6E+04	4	2.3E+03	2.3E+03	2.2E+03	2.0E+03	2.2E+03
Minerals extraction		tonne	-3.0E+07	-3.0E+07	-3.0E+07	-3.0E+07	-3.0E+07	5	-6.0E+06	-6.0E+06	-6.0E+06	-6.1E+06	-6.0E+06	3	-1.8E+05	-1.8E+05	-1.8E+05	-1.8E+05	-1.8E+05
Water extraction		litres	-4.5E+07	-4.5E+07	-4.6E+07	-5.0E+07	-4.6E+07	417583	-1.1E+02	-1.1E+02	-1.1E+02	-1.2E+02	-1.1E+02	5	-5.4E+00	-5.4E+00	-5.5E+00	-6.0E+00	-5.5E+00
Waste disposal		tonne	-3.2E+07	-3.2E+07	-3.2E+07	-3.3E+07	-3.2E+07	7.2	-4.5E+06	-4.5E+06	-4.5E+06	-4.6E+06	-4.5E+06	6	-2.7E+05	-2.7E+05	-2.7E+05	-2.8E+05	-2.7E+05
Freight		tonne km	1.3E+09	1.3E+09	1.3E+09	1.3E+09	1.3E+09	4141	3.3E+05	3.3E+05	3.2E+05	3.1E+05	3.2E+05	7	2.3E+04	2.3E+04	2.3E+04	2.2E+04	2.2E+04
	Landfilled volume	ton	3.4E+06	3.4E+06	3.4E+06	2.7E+06	3.3E+06							Total	-6.3E+05	-6.3E+05	-6.4E+05	-6.7E+05	-6.4E+05
	Demolition	MJ	5.7E+08	5.7E+08	5.6E+08	4.6E+08	5.6E+08												
	Transportation	MJ	1.1E+09	1.1E+09	1.1E+09	1.1E+09	1.1E+09												
	Reclamation	MJ	0.0E+00	-2.2E+08	-2.2E+09	-2.2E+10	-3.0E+09												
	Recycling	MJ	-7.8E+10	-7.8E+10	-7.8E+10	-7.1E+10	-7.7E+10												
	Off-site Sorting	MJ	1.2E+09	1.2E+09	1.1E+09	9.2E+08	1.1E+09												
	Landfilling	MJ	2.2E+07	2.2E+07	2.2E+07	1.8E+07	2.2E+07												
	Total Energy use	MJ	-7.5E+10	-7.6E+10	-7.7E+10	-9.1E+10	-7.7E+10												
	Total Recovery	ton	3.4E+07	3.4E+07	3.4E+07	3.5E+07	3.4E+07												

Table 61 Impact value for the control scenarios (relative ratio against Scenario1)

		Unit	Project emission					UK impact per citizen	Normarisation					Weighting factors	Eco point				
			Scenario1	Scenario2			Scenario3		Scenario1	Scenario2			Scenario3		Scenario1	Scenario2			Scenario3
				α1=0.01	α1=0.1	α1=1				α1=0.01	α1=0.1	α1=1				α1=0.01	α1=0.1	α1=1	
Climate change		kg CO2eq (100 years)	0.00	0.00	-0.01	-0.08	-0.01	12269	0.00	0.00	-0.01	-0.08	-0.01	35	0.00	0.00	-0.01	-0.08	-0.01
Acid deposition		kg SO2eq	0.00	0.00	-0.01	-0.13	-0.02	58.9	0.00	0.00	-0.01	-0.13	-0.02	5	0.00	0.00	-0.01	-0.13	-0.02
Ozon deletion		kg CFC11eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.3	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	8	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Polution to air	Human toxicity	kg tox	0.00	0.00	0.00	-0.01	0.00	90.7	0.00	0.00	0.00	-0.01	0.00	6.5	0.00	0.00	0.00	-0.01	0.00
	Low-level ozone creation	kg ethene eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	32.2	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	3.5	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Fossil fuel depletion		toe	0.00	0.00	-0.02	-0.21	-0.03	4.09	0.00	0.00	-0.02	-0.21	-0.03	11	0.00	0.00	-0.02	-0.21	-0.03
Polution to water	Human toxicity	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	0.01	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	2	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Ecotoxicity	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	177948	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	4	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Eutrophication	kg PO4eq	0.00	0.00	-0.01	-0.13	-0.02	8	0.00	0.00	-0.01	-0.13	-0.02	4	0.00	0.00	-0.01	-0.13	-0.02
Minerals extraction		tonne	0.00	0.00	0.00	-0.01	0.00	5	0.00	0.00	0.00	-0.01	0.00	3	0.00	0.00	0.00	-0.01	0.00
Water extraction		litres	0.00	0.00	-0.01	-0.11	-0.01	417583	0.00	0.00	-0.01	-0.11	-0.01	5	0.00	0.00	-0.01	-0.11	-0.01
Waste disposal		tonne	0.00	0.00	0.00	-0.04	-0.01	7.2	0.00	0.00	0.00	-0.04	-0.01	6	0.00	0.00	0.00	-0.04	-0.01
Freight		tonne km	0.00	0.00	0.00	-0.04	-0.01	4141	0.00	0.00	0.00	-0.04	-0.01	7	0.00	0.00	0.00	-0.04	-0.01
	Landfilled volume	ton	0.00	0.00	-0.02	-0.20	-0.03							Total	0.00	0.00	-0.01	-0.06	-0.01
	Demolition	MJ	0.00	0.00	-0.02	-0.19	-0.02												
	Transportation	MJ	0.00	0.00	0.00	-0.04	-0.01												
	Reclamation	MJ	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!												
	Recycling	MJ	0.00	0.00	0.01	0.09	0.01												
	Off-site Sorting	MJ	0.00	0.00	-0.02	-0.20	-0.03												
	Landfilling	MJ	0.00	0.00	-0.02	-0.20	-0.03												
	Total Energy use	MJ	0.00	0.00	-0.02	-0.21	-0.03												
	Total Recovery	ton	0.00	0.00	0.00	0.02	0.00												

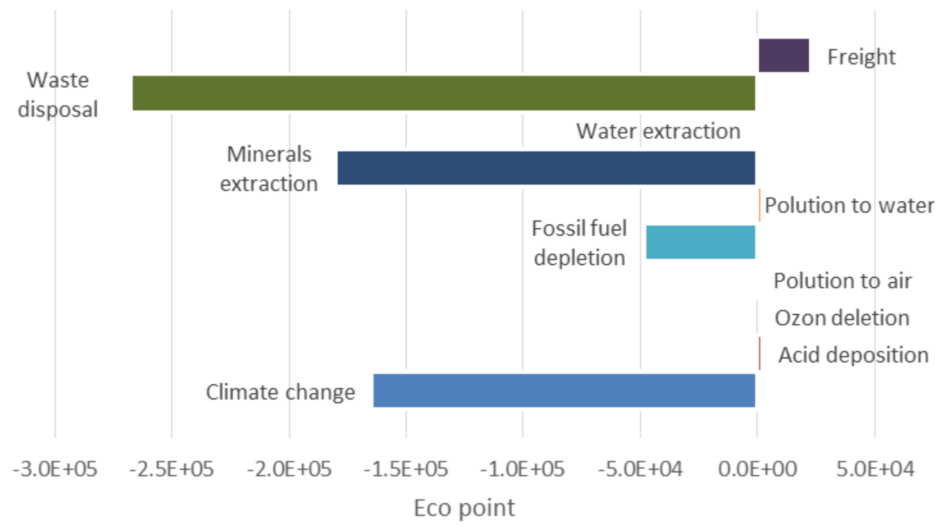


Figure 122 Environmental impact breakdown of scenario1

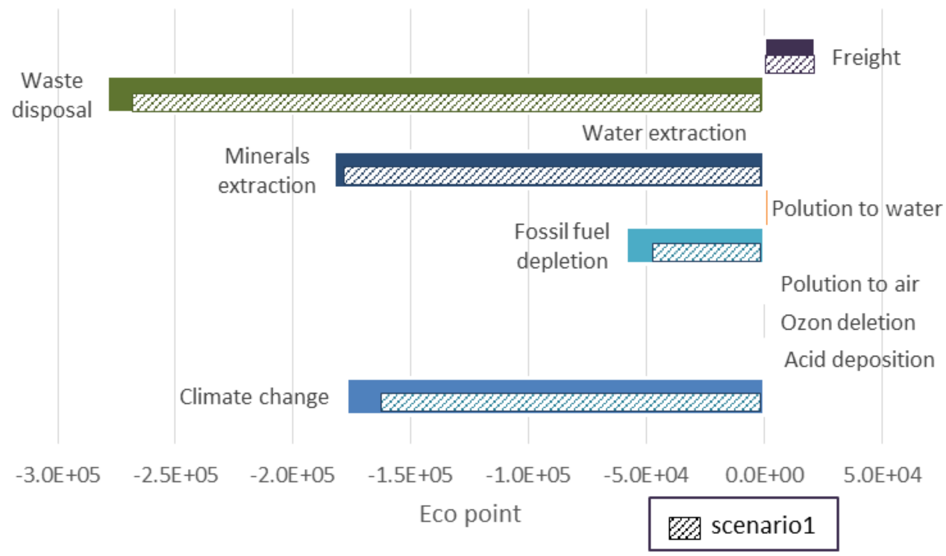


Figure 123 Environmental impact breakdown of scenario2 (α1=1)

9.3.3.1. Group sorting rate

In the sensitivity analysis, the correlation between application rate and agreement rate was calculated. For the third scenario, the values in Table 62 and Table 63 were used to recreate the DPM application condition for maximizing α1 and α2 respectively. Although both ways of value settings had the same level of agreement as group 3, the share of group 2 was largely changed by α1 which caused a huge effect on impact.

Table 62 Application and agreement rate for scenario3 (when α1=1)

case name	α1-1	α1-2	α1-3	α1-4	α1-5	α1-6	α1-7	α1-8	α1-9	α1-10	α1-11
β1·β2	0.025				0.25				0.05	0.1	0.25
α1·α2	0.05	0.25	0.5	1	0.05	0.25	0.5	1	0.05		
α1	1	1	1	1	1	1	1	1	1	1	1
α2	0.05	0.25	0.5	1	0.05	0.25	0.5	1	0.05	0.05	0.05
α3	0.173	0.177	0.171	0.17	0.683	0.653	0.65	0.655	0.296	0.47	0.683
agreement number	162.56	832.12	1610.6	3205	643.37	3075.48	6124.43	12330.3	278.9	442.35	643.37
g1=1-α1	0	0	0	0	0	0	0	0	0	0	0
g2=α1(1-α2·α3)	0.99135	0.95575	0.9145	0.83	0.96585	0.83675	0.675	0.345	0.9852	0.9765	0.96585
g3=α1·α2·α3	0.00865	0.04425	0.0855	0.17	0.03415	0.16325	0.325	0.655	0.0148	0.0235	0.03415

Table 63 Application and agreement rate for scenario3 (when α2=1)

case name	α2-1	α2-2	α2-3	α2-4	α2-5	α2-6	α2-7	α2-8	α2-9	α2-10	α2-11
β1·β2	0.025				0.25				0.05	0.1	0.25
α1·α2	0.05	0.25	0.5	1	0.05	0.25	0.5	1	0.05		
α1	0.05	0.25	0.5	1	0.05	0.25	0.5	1	0.05	0.05	0.05
α2	1	1	1	1	1	1	1	1	1	1	1
α3	0.173	0.177	0.171	0.17	0.683	0.653	0.65	0.655	0.296	0.47	0.683
agreement number	162.56	832.12	1610.6	3205	643.37	3075.48	6124.43	12330.3	278.9	442.35	643.37
g1=1-α1	0.95	0.75	0.5	0	0.95	0.75	0.5	0	0.95	0.95	0.95
g2=α1(1-α2·α3)	0.04135	0.20575	0.4145	0.83	0.01585	0.08675	0.175	0.345	0.0352	0.0265	0.01585
g3=α1·α2·α3	0.00865	0.04425	0.0855	0.17	0.03415	0.16325	0.325	0.655	0.0148	0.0235	0.03415

Scenario analysis

The reduction of demolition impact compared to scenario 1 is shown in Table 64 and Table 65, which are summarised in Figure 124. Here, reclamation values showed error because of no reclamation process in scenario 1. The results showed the huge gap in energy consumption and landfilling between the cases maximizing α1 and α2 for the lower values of α1· α2. This was explained by the large impact improvement with DPM application (i.e. reduction of g1) regardless of uploading to DPM. On the other hand, the increase of g3 with same β1· β2 such as α1-1 to α1-4 and α1-5 to α1-8 showed the impact reduction. However, it required certain scale of share to make the impact significant. Even g3 increased value for approximately 16 to 17% (e.g. between α1-1 and α1-4, α1-6 to α1-7) only 10% of improvement could be expected (e.g. -0.21 to -0.23 of improvement from scenario1 in Total Energy use). In order to expect significant impact reduction, DPM needs to be applied to at least 25% of demolition projects (i.e. β1· β2≥0.25). It can be also said that if DPM application and uploading became legally compulsory (α1 and α2=1 such as α1-4 and α1-8) 20 to 30% of landfilling and total energy use reduction could be achieved. Encouragement of DPM application to construction teams is also a pivotal factor to enhance its significance.

Table 64 Impact comparison with scenario1 (when α1=1)

case name	α1-1	α1-2	α1-3	α1-4	α1-5	α1-6	α1-7	α1-8	α1-9	α1-10	α1-11
Landfilled volume	-0.20	-0.21	-0.22	-0.23	-0.21	-0.23	-0.26	-0.32	-0.20	-0.21	-0.21
Demolition	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19	-0.19
Transportation	-0.04	-0.05	-0.06	-0.09	-0.05	-0.09	-0.14	-0.24	-0.04	-0.04	-0.05
Reclamation	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Recycling	0.09	0.10	0.10	0.12	0.09	0.12	0.14	0.20	0.09	0.09	0.09
Off-site Sorting	-0.20	-0.21	-0.22	-0.23	-0.21	-0.23	-0.26	-0.32	-0.20	-0.21	-0.21
Landfilling	-0.20	-0.21	-0.22	-0.23	-0.21	-0.23	-0.26	-0.32	-0.20	-0.21	-0.21
Total Energy use	-0.21	-0.22	-0.22	-0.23	-0.21	-0.23	-0.25	-0.29	-0.21	-0.21	-0.21
Total Recovery	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.02	0.02

Table 65 Impact comparison with scenario1 (when α2=1)

case name	α2-1	α2-2	α2-3	α2-4	α2-5	α2-6	α2-7	α2-8	α2-9	α2-10	α2-11
Landfilled volume	-0.01	-0.06	-0.12	-0.23	-0.02	-0.08	-0.16	-0.32	-0.01	-0.01	-0.02
Demolition	-0.01	-0.05	-0.10	-0.19	-0.01	-0.05	-0.10	-0.19	-0.01	-0.01	-0.01
Transportation	0.00	-0.02	-0.05	-0.09	-0.01	-0.06	-0.12	-0.24	-0.01	-0.01	-0.01
Reclamation	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Recycling	0.01	0.03	0.06	0.12	0.01	0.05	0.10	0.20	0.01	0.01	0.01
Off-site Sorting	-0.01	-0.06	-0.12	-0.23	-0.02	-0.08	-0.16	-0.32	-0.01	-0.01	-0.02
Landfilling	-0.01	-0.06	-0.12	-0.23	-0.02	-0.08	-0.16	-0.32	-0.01	-0.01	-0.02
Total Energy use	-0.01	-0.06	-0.12	-0.23	-0.01	-0.07	-0.15	-0.29	-0.01	-0.01	-0.01
Total Recovery	0.00	0.01	0.01	0.02	0.00	0.01	0.02	0.03	0.00	0.00	0.00

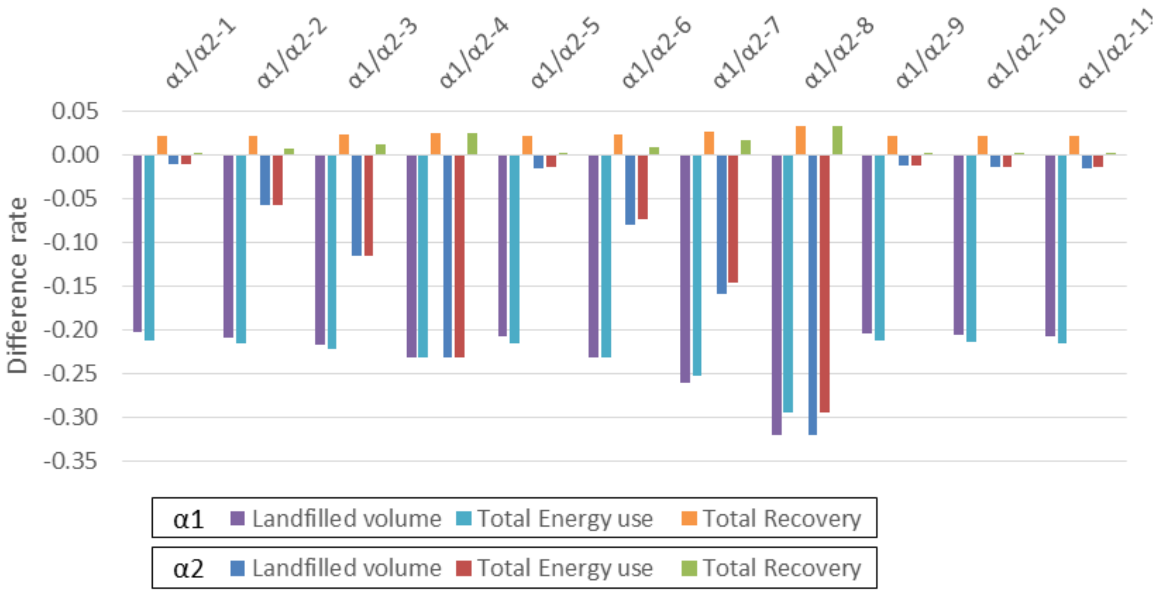


Figure 124 Impact comparison with scenario1*

*Different rate implies the gap with the result of scenario1. If it is -0.15, the impact value was 0.85 times as the impact of scenario1.

Environmental impact analysis

The environmental impact converted from the above raw impact data is summarised as Table 66 and Table 67. It showed a similar value change as the raw impact in the previous section. Main impact improvement was derived from DPM application, and a certain number of DPM users were necessary to make a large improvement from the increase of DPM uploading rate. Considering the share of environmental impact as shown in Figure 125 for α1/α2-8, it showed a similar result to the base line scenarios such as scenario2 (α1=1). Due to the increase of DPM uploading rate (α2) to 1, it resulted in further improvement in each factor. Onsite recovery from the contract agreement in DPM diminished the impact of transportation in terms of 'freight' impact and offsite-sorting as 'fossil fuel depletion' impact. Although it showed the increase of waste disposal as uploading rate increased, a greater amount of waste was reused onsite and offsite so that it succeeded in cutting the energy consumption during the recycling process.

Table 66 Environmental impact comparison with scenario1 (when α1=1)

Impact factor		Unit	α1-1	α1-2	α1-3	α1-4	α1-5	α1-6	α1-7	α1-8	α1-9	α1-10	α1-11
Climate change		kg CO2eq (100 years)	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.08	-0.09	-0.08	-0.08	-0.08
Acid deposition		kg SO2eq	-0.13	-0.14	-0.14	-0.16	-0.14	-0.16	-0.18	-0.23	-0.13	-0.13	-0.14
Ozon deletion		kg CFC11eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Polution to air	Human toxicity	kg tox	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01
	Low-level ozone creation	kg ethene eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Fossil fuel depletion		toe	-0.21	-0.22	-0.22	-0.23	-0.21	-0.23	-0.25	-0.29	-0.21	-0.21	-0.21
Polution to water	Human toxicity	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Ecotoxicity	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Eutrophication	kg PO4eq	-0.13	-0.14	-0.14	-0.16	-0.14	-0.16	-0.18	-0.23	-0.13	-0.13	-0.14
Minerals extraction		tonne	-0.01	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.03	-0.01	-0.01	-0.02
Water extraction		litres	-0.11	-0.12	-0.12	-0.12	-0.12	-0.12	-0.13	-0.15	-0.11	-0.12	-0.12
Waste disposal		tonne	-0.04	-0.04	-0.05	-0.05	-0.04	-0.05	-0.06	-0.07	-0.04	-0.04	-0.04
Freight		tonne km	-0.04	-0.05	-0.06	-0.09	-0.05	-0.09	-0.14	-0.24	-0.04	-0.04	-0.05
		Total	-0.06	-0.06	-0.06	-0.07	-0.06	-0.07	-0.08	-0.09	-0.06	-0.06	-0.06

Table 67 Environmental impact comparison with scenario1 (when α2=1)

Impact factor		Unit	α2-1	α2-2	α2-3	α2-4	α2-5	α2-6	α2-7	α2-8	α2-9	α2-10	α2-11
Climate change		kg CO2eq (100 years)	0.00	-0.02	-0.04	-0.08	0.00	-0.02	-0.04	-0.09	0.00	0.00	0.00
Acid deposition		kg SO2eq	-0.01	-0.04	-0.08	-0.16	-0.01	-0.06	-0.12	-0.23	-0.01	-0.01	-0.01
Ozon deletion		kg CFC11eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Polution to air	Human	kg tox	0.00	0.00	-0.01	-0.01	0.00	0.00	-0.01	-0.01	0.00	0.00	0.00
	Low-level	kg ethene eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Fossil fuel depletion		toe	-0.01	-0.06	-0.12	-0.23	-0.01	-0.07	-0.15	-0.29	-0.01	-0.01	-0.01
Polution to water	Human	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Ecotoxicity	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Eutrophication	kg PO4eq	-0.01	-0.04	-0.08	-0.16	-0.01	-0.06	-0.12	-0.23	-0.01	-0.01	-0.01
Minerals extraction		tonne	0.00	0.00	-0.01	-0.02	0.00	-0.01	-0.01	-0.03	0.00	0.00	0.00
Water extraction		litres	-0.01	-0.03	-0.06	-0.12	-0.01	-0.04	-0.07	-0.15	-0.01	-0.01	-0.01
Waste disposal		tonne	0.00	-0.01	-0.02	-0.05	0.00	-0.02	-0.03	-0.07	0.00	0.00	0.00
Freight		tonne km	0.00	-0.02	-0.05	-0.09	-0.01	-0.06	-0.12	-0.24	-0.01	-0.01	-0.01
		Total	0.00	-0.02	-0.03	-0.07	0.00	-0.02	-0.05	-0.09	0.00	0.00	0.00

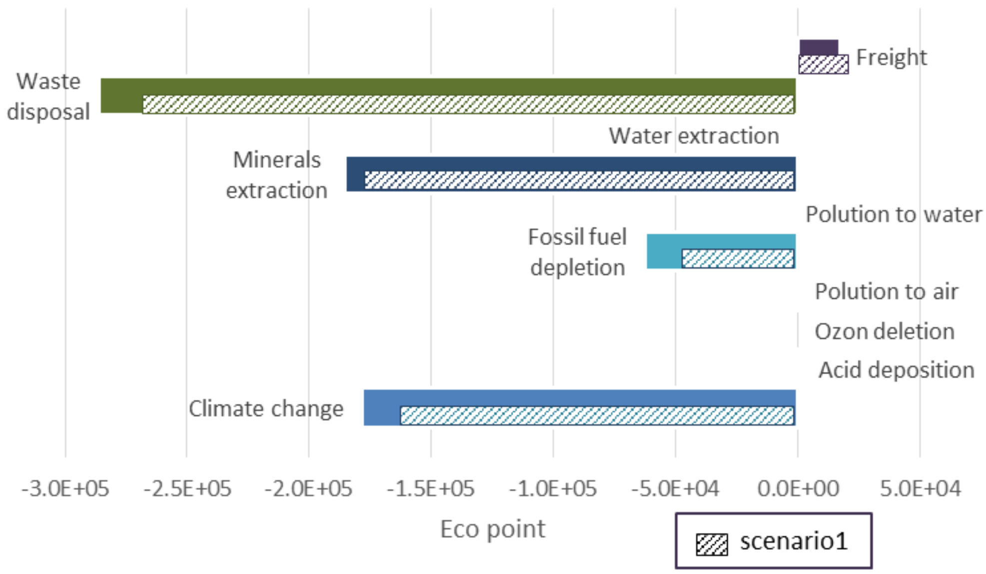


Figure 125 Environmental impact breakdown of scenario3 (α1/ α2-8)

9.3.3.2. Impact value

Impact value consisted of three variables, I(D), R(D) and T(D). For the control value, I(D) value was set by referring to the research of Sara et al (2001) which surveyed the demolition project impact in Italy. Based on the waste generation volume, the impact for the control building demolition in this research was calculated as the main demolition impact in MJ (mega joule). Considering the differences between Italy and UK and the uniqueness of the studied case, two other demolition impact value was tested, half and double as the original impact, which caused the difference as shown in Table 68 and Table 69. Here, some factors not directly related to demolition procerss are filled with error messages such as 'ozon deletion'. It only changed the value of energy use of 'demolition' in raw impact and related factors of environmental impact; 'climate change', 'acid deposition', 'pollution to air (Human toxicity)', 'Fossil depletion' and 'Pollution to water (Eutrophic)'. Gas emission from the application of demolition machines (here excavator property was applied to estimate the gas emission) triggered the above phenomena. Here, the impact improved by material recovery through reuse and recycling was translated into CO_2 emission. Therefore, the CO_2-related impact change for 'climate change' and 'fossil depletion' remained at less than 1% improvement. 'Pollution to air (Human toxicity)' also showed less influence due to the large impact from the waste recovery of metal rather than gas emission. Because those factors occupied a large share of environmental impact, the impact change of main demolition did not exceed 1% in total.

Comparing the scenarios, there were some demolition impact reductions as the increase of DPM application rate (α1) (seen among three scenario2). It was derived from lower impact of main demolition under the assumption that demolition project design would be learned by DPM application. The result also showed proportional change such as scenario 1 with half main demolition impact of -0.19% and with double of +0.38%. The proportion of DPM application rate and the increase of total impact improvement were maintained regardless of the scale of main demolition impact.

Table 68 Environmental impact comparison with baseline scenario (half)

		Eco point				
		Scenario1	Scenario2			Scenario3
			α1=0.01	α1=0.1	α1=1	
Climate change		-0.0033	-0.0033	-0.0032	-0.0025	-0.0032
Acid deposition		-0.1103	-0.1103	-0.1096	-0.1015	-0.1103
Ozon deletion		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Polution to air	Human toxicity	-0.0104	-0.0104	-0.0102	-0.0084	-0.0102
	Low-level ozone creation	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Fossil fuel depletion		-0.0037	-0.0036	-0.0035	-0.0024	-0.0035
Polution to water	Human	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Ecotoxicit	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Eutrophic	-0.1103	-0.1103	-0.1096	-0.1015	-0.1103
Minerals extraction		0.0000	0.0000	0.0000	0.0000	0.0000
Water extraction		0.0000	0.0000	0.0000	0.0000	0.0000
Waste disposal		0.0000	0.0000	0.0000	0.0000	0.0000
Freight		0.0000	0.0000	0.0000	0.0000	0.0000
		-0.0019	-0.0019	-0.0019	-0.0014	-0.0019

Table 69 Environmental impact comparison with baseline scenario (double)

		Eco point				
		Scenario1	Scenario2			Scenario3
			α1=0.01	α1=0.1	α1=1	
Climate change		0.0067	0.0066	0.0065	0.0049	0.0065
Acid deposition		0.2207	0.2205	0.2191	0.2030	0.2205
Ozon deletion		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Polution to air	Human toxicity	0.0207	0.0207	0.0203	0.0167	0.0204
	Low-level ozone creation	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Fossil fuel depletion		0.0073	0.0073	0.0070	0.0048	0.0070
Polution to water	Human	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Ecotoxicit	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Eutrophic	0.2207	0.2205	0.2191	0.2030	0.2205
Minerals extraction		0.0000	0.0000	0.0000	0.0000	0.0000
Water extraction		0.0000	0.0000	0.0000	0.0000	0.0000
Waste disposal		0.0000	0.0000	0.0000	0.0000	0.0000
Freight		0.0000	0.0000	0.0000	0.0000	0.0000
		0.0038	0.0038	0.0037	0.0029	0.0037

R(D) and T(D) were discussed together since R(D) value largely affected T(D) when the facility capability was considered as seen in the sensitivity analysis. Following that, the change of R(D) and T(D) was analysed by the recycling value setting with ten onsite sorting cases and by the treatment facility capability with seven cases which were discussed in the above recovery rate setting sections (see Table 57.).

For the recycling value setting, values were compared in two ways: i) among the same scenarios in different cases and ii) between scenario 1 and 3 in the same cases. The environmental impact breakdown of scenario 1 for each case resulted in Figure 126. While case 2 to 9 showed negative impact values due to the waste recovery, case 1 and 10 which set the disposal rate (RcD) to 1(100%) caused positive impacts. Further onsite sorting (from case4 < 2 < 5 < 6 <7) showed similar impact breakdown share, and there were small improvements overall. The most sustainable case was case 3 which directly sent whole wastes including inert wastes (Co, M, Cl) to recycling facilities. This figure also showed the improvement of scenario 3 compared to scenario 1 for each case with red points. According to this, it was found that DPM application showed more efficiency of impact minimization as the disposal waste volume increased in scenario 1. This could be seen from the raw impact and the converted environmental impact data (seen in Table 70). It also showed the large improvement in cases 1, 8, 9, and 10 having high disposal rates (RcD). Since the most demolition waste was originally planned to be sent to the landfilling site, reuse and recycling from the application of DPM relieved the huge burden of 'mineral extraction' and 'waste disposal'. In case 1, 'climate change' and 'water extraction', which were mainly composed of waste recovery, showed very large value due to the complete waste disposal. However, the total improvement was not that great. This was a resulted of the modest improvement of dominant factors such as 'waste disposal' (i.e. 3% of improvement in landfilling). Those tendencies of impact change were similarly seen in the results of scenario 2 as shown in Figure 127. When α1=1, the scale of improvement was more than five times as scenario 3. Nevertheless, scenario3 showed better results compared to the one of scenario 2 with same value of α1. It implied further impact cuts would be achieved once a high contract agreement rate would be fulfilled.

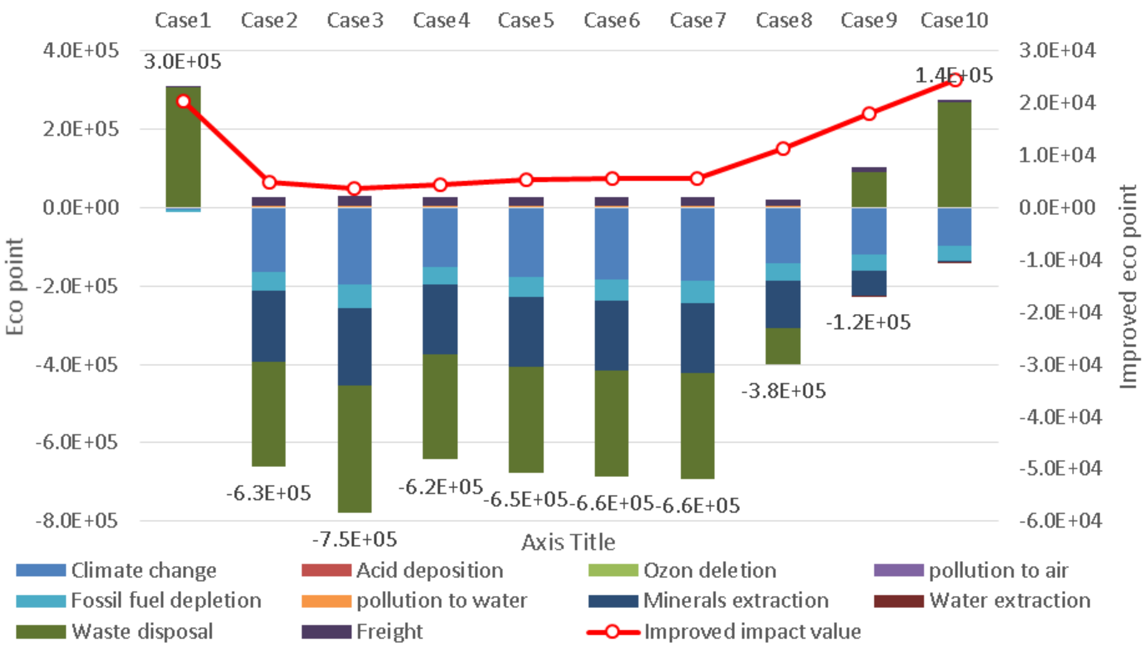


Figure 126 Environmental impact breakdown of scenario1 for different recycling cases

Table 70 Environmental impact comparison of scenario 1 and 3 with different recycling rate

		Unit	Case1	Case2	Case3	Case4	Case5	Case6	Case7	Case8	Case9	Case10
Climate change		kg CO2eq (100 years)	-0.16	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.03
Acid deposition		kg SO2eq	-0.01	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01
Ozon deletion		kg CFC11eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
pollution to air	Human toxicity	kg tox	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Low-level ozone creation	kg ethene eq	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Fossil fuel depletion		toe	-0.04	-0.03	-0.03	-0.02	-0.03	-0.03	-0.03	-0.03	-0.03	-0.04
pollution to water	Human toxicity	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Ecotoxicity	kg tox	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Eutrophication	kg PO4eq	-0.01	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.01
Minerals extraction		tonne	#DIV/0!	0.00	0.00	0.00	0.00	0.00	0.00	-0.02	-0.06	-1.55
Water extraction		litres	-0.76	-0.01	-0.01	-0.01	-0.01	-0.01	-0.01	-0.02	-0.04	-0.07
Waste disposal		tonne	-0.05	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.07	-0.12	-0.06
Freight		tonne km	0.02	-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.01
		Total	-0.07	-0.01	0.00	-0.01	-0.01	-0.01	-0.01	-0.03	-0.15	-0.18
	Landfilled volume	ton	-0.02	-0.03	#DIV/0!	-0.02	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Demolition	MJ	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02	-0.02
	Transportation	MJ	0.02	-0.01	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.01
	Reclamation	MJ	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
	Recycling	MJ	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.01	0.01	0.01
	Off-site Sorting	MJ	#DIV/0!	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03	#DIV/0!
	Landfilling	MJ	-0.02	-0.03	#DIV/0!	-0.02	-0.03	-0.03	-0.03	-0.03	-0.03	-0.03
	Total Energy use	MJ	-0.04	-0.03	-0.03	-0.02	-0.03	-0.03	-0.03	-0.03	-0.03	-0.04
	Total Recovery	ton	1.64	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.05	0.28

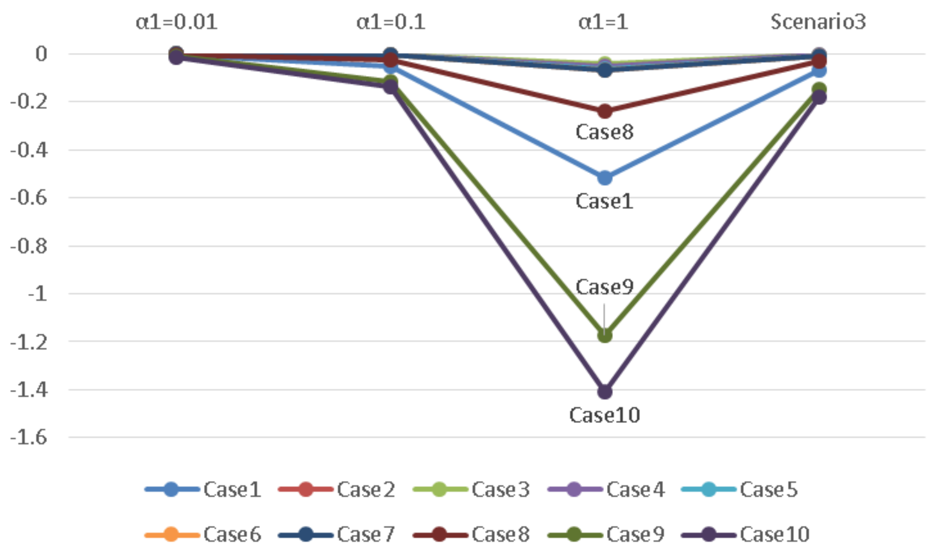


Figure 127 Environmental impact change of scenario2 for different recycling cases

Concerning the capability of treatment facilities, the seven capability values which were used in the above sensitivity analysis were applied to comprehend the change in result impact. Figure 128 showed the breakdown of environmental impact of scenario 1 (case 2). The facility capability only affected the transportation distance and related impacts which were mainly 'fuel fossil fuel depletion' and 'freight'. As seen in the sensitivity analysis of facility capability, there was a huge distance extension in C7, in which facilities could only handle waste caused by less than five projects per year. It resulted in approximately 5% of the impact increase in total, and scenario 3 achieved more impact improvement by DPM application as the 'freight' value increased. However, the significance of improvement was relatively small compared to total impact. It implied improvement of waste recovery which could drastically diminish 'mineral extraction' and 'waste disposal' should be more realistic to show a large improvement with DPM application.

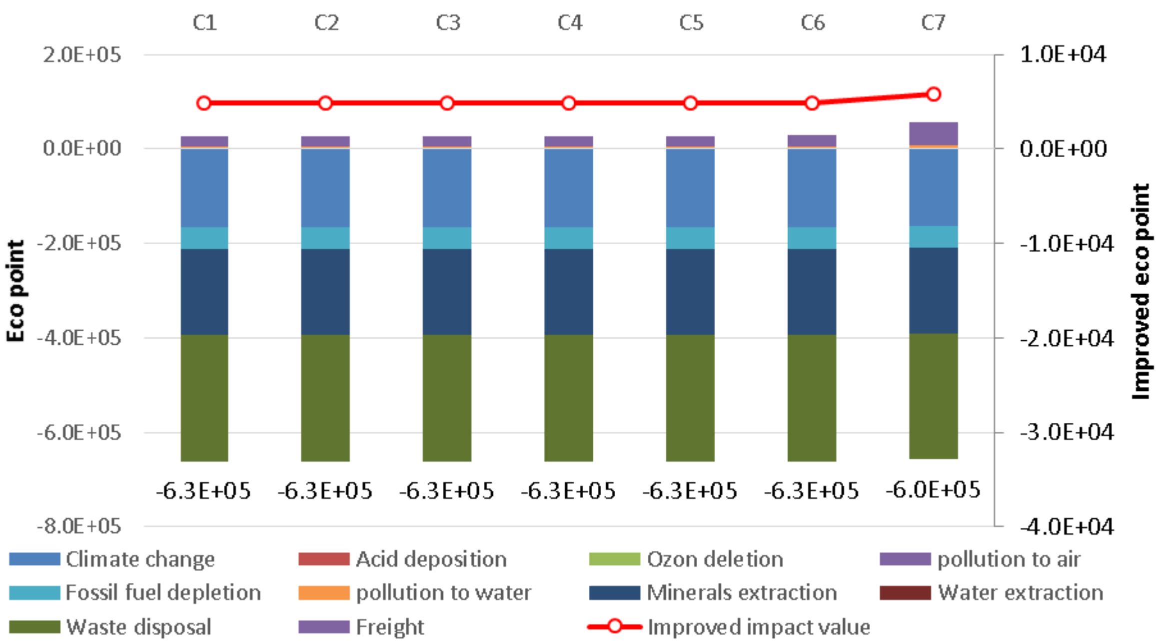


Figure 128 Environmental impact change of scenario1 (Case2) with different facility capabilities

9.3.3.3. Impact improvement coefficient

The impact improvement coefficients (ki, kr, kt) were applied to recreate how much contribution could be created by the application of the DPM system in this model. According to the improvement result from the pilot study of actual project application in Chapter4, each value was set as Table 71. Similar to the previous section, 'Group sorting rate', scenario 3 set four different α1α2 values with maximizing α1 or α2 which differed in the rate of DPM application (g1) and caused the huge change of impact in the sensitivity analysis. The significance of each coefficient was analysed by the gap from the base line result. For instance, the significance of ki was calculated by dividing the improvement gap between scenario 3 of base line and ki (ki=0) with 0.2. It implied the significance of impact reduction with DPM application when the onsite impact would be improved by 100% (i.e. causing no demolition impact). Environmental impact results of Scenario 3 with each group sorting rate and impact improvement coefficient value set were plotted with α1α2 values in Figure 129 and Figure 130. Those were separated as datasets of α1=1 and α2=1. In Figure 129, the first three coefficients (ki, kr1-rc and kr1-ru), which described the improvement from DPM application (i.e. mainly ruled by α1), showed constant values while the other two coefficients (kr2-ru and kt) ruled by α3 proportionally increased. Even though Kt showed a proportional increase, it was negligible. Since kt improved the distance of waste transportation by onsite application, the improvement could only contribute in relatively small factors, 'freight' and 'fossil fuel depletion'. On the other hand, the improvement of recovery rate with kr1 and kr2 showed significance due to its contribution to relatively large factors, 'waste disposal', 'mineral extraction' and 'climate change'. It is, however, to be added that the total impact improvement from them may be confined by the improvement limit, especially for kr1-rc. Considering the significance change with α1α2 in Figure 130, it showed a linear correlation for each coefficient. As mentioned above, the first three factors were influenced by α1 and it resulted in α3 increase and improvement of other factors. It implied further impact significance of other two factors with α3 increase from current value (about 0.17) with other factors analysed in 'sensitivity analysis' session. The application rate of construction teams (β1β2) may raise α3 to about 0.65 so that a four times larger scale of significance would be expected. Given the improvement limit, the environmental impact from demolition could be mainly prevented by large scale of onsite reuse (i.e. increase of kr2-ru) at demolition-construction integrated projects in DPM system rather than simple recovery improvement (i.e. increase of kr1-rc).

Table 71 Impact improvement coefficient for scenario3

	α1α2=0.05, 0.25. 0.5. 1 (α1=1)						α1α2=0.05, 0.25. 0.5. 1 (α2=1)						improvement limit
	base	ki	kr1-rc	kr1-ru	kr2-ru	kt	base	ki	kr1-rc	kr1-ru	kr2-ru	kt	
Onsite impact improvement (ki)	0.2	0	0.2	0.2	0.2	0.2	0.2	0	0.2	0.2	0.2	0.2	1
recovery rate improvement (kr1,rc)	0.2	0.2	0	0.2	0.2	0.2	0.2	0.2	0	0.2	0.2	0.2	0.125
reuse share (kr1,ru)	0.2	0.2	0.2	0	0.2	0.2	0.2	0.2	0.2	0	0.2	0.2	1 (sum)
reuse share2 (kr2,ru)	0.2	0.2	0.2	0.2	0	0.2	0.2	0.2	0.2	0.2	0	0.2	
Onsite application (kr2,on)	0.5	0.5	0.5	0.5	0.5	0	0.5	0.5	0.5	0.5	0.5	0	1

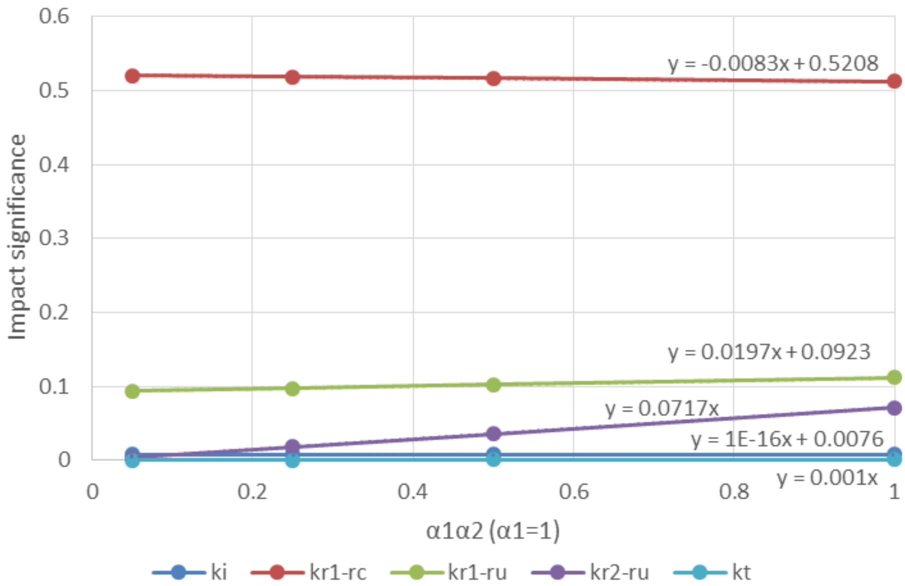


Figure 129 Impact significance for each coefficient in Scenario3 (α1=1)

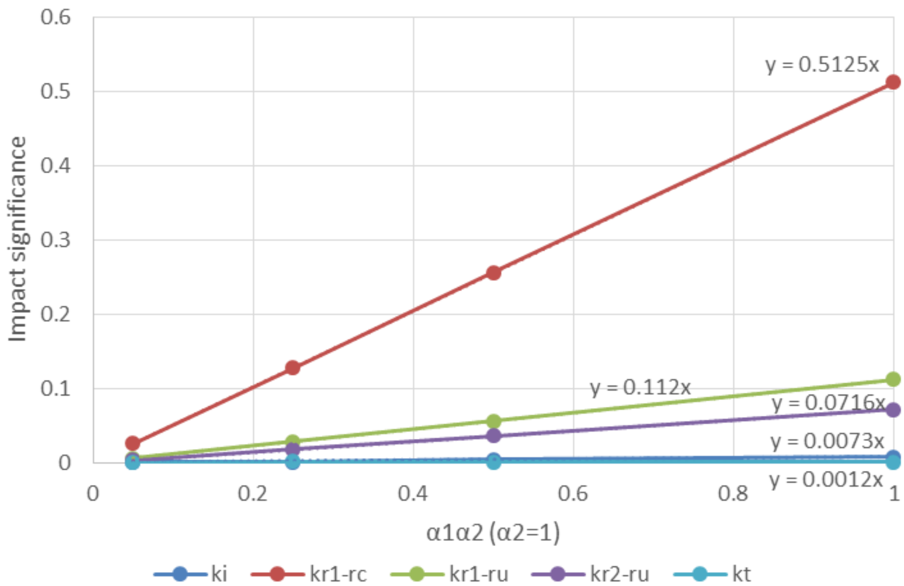


Figure 130 Impact significance for each coefficient in Scenario3 (α2=1)

9.4. Summary

In this chapter, the social impact caused by demolition and waste treatment is evaluated by the suggested model to discuss the significance of the impact cause by the DPM system application to the UK society. After evaluating the total impact in the current society, demolishers and constructers are classified into the groups according to the DPM system application in the model. In this model, the algorithms are set for individual stakeholders to make them decide with own rules as in reality. In order to analyse the sensitivity of individual algorithm settings, they are separately discussed from the two point of views; i) DPM agreement rate and ii) transportation distance to be affected. For the DPM agreement rate, the change of number of project agreement from the requirement of each stakeholder and the number of the DPM users in stakeholders are investigated. On the other hand, the transportation distance between stakeholders is examined to correlate with the stakeholder's requirement or the waste generation and treatment volume in the society. Both results are summarised as Table 72. As seen in the table, many factors in the DPM agreement rate show the exponential trend with the number of project agreement. This is because the target value is dominant by the exponential of constant as below. Thus, the increase of target would be less as the factor value becomes larger. It implies the general improvement of stakeholders' property is more suitable than focusing on the specific factor. For the number of DPM users, the number of agreement will be increased with linear correlation if the number of demolishers and constructers are balanced. After the balance is disrupted, the severe competition of recyclked material securement has happened and it declines the increment rate of the number of project agreement. Due to the original project number ratio, the increase of demolisher involvement should be prioritised to enhance the system efficiency.

e.g. the relation between the number of project agreement and the searching days

$$P(day) = 1 - (1 - \mathrm{p})^{day}$$

On the other hand, power trend is usually seen between decision factors and the transportation distance. This is explained by the decision method the result of which could be calculated from the sum of geometric series as below. Accordingly, the distance can be drastically increased by factors. Considering the distance to the recycling facilities, the material types which have less than 100 facilities in UK are possibly overflowed by waste acceptance. As a result, the transportation distance becomes one of difficulties to recycle those materials rather than landfilled.

e.g. the relation between the constructers satisfaction rate (with recovery source) and the distance

$$distance = k \cdot (satisfaction\ rate)^{n}$$

Table 72 Summary of the sensitivity analysis of the social impact model

Factor	factor value			Target	target value			trend of relation
	unit	min	max		unit	min	max	
1. DPM agreement rate								
Properties of construction team								
Distance limit	km	0	1000	Agreement number		0	900	sigmoid
Floor area gap	%	0	100	Agreement number		0	500	exponential
Searching term(C)	day	0	350	Agreement number		100	600	exponential
Properties of demolition team								
Searching term(D)	day	0	350	Agreement number		150	600	exponential
DPM use coefficient								
Agreement rate		0	1	Agreement number		0	300	exponential
DPM user rate(D)		0	1	Agreement number		0	3200	linear
				Agreement rate(D)		0.25	0.18	unique
				Agreement rate(C)		0	0.72	linear
DPM user rate(C)		0	0.25	Agreement number		0	700	exponential
				Agreement rate(D)		0.00	0.72	exponential
				Agreement rate(C)		0.5	0.1	unique
2. Transportation distance								
Properties of construction team								
satisfaction rate		0	1	distance for recovery	km	See Figure.114		power
Properties of treatment facilities								
capability	%	100	1	distance to facilities	km	See Figure.115		unique
facility number		20	800	distance to facilities	km	See Figure.116,117		power
Recovery rate setting								
sorting rate	Case1-10			distance to facilities	km	See Figure.118,119		unique
treated project number	/year	1	10	distance to facilities	km	See Figure.120,121		power

where C: construction team and D: demolition team

Following the sensitivity analysis, the scenario and environmental impact resulted from the system application is discussed. The impact evaluation is examined for the three main factors; i) group sorting rate, ii) impact value and iii) impact improvement coefficient. For the group sorting rate, the application of model simulation to demolition projects as the first step can make a large improvement regardless the agreement with constructers. If the model application is compulsory for demolishers to apply, about 5% of the total environmental impact can be improved. In addition, if the 25% of constructer joined this system about 10% of improvement can be expected. These are mainly attributed to the reduction of impact at ‘waste disposal’, ‘mineral extraction’, ‘fossil fuel depletion’ and ‘climate change’. For the impact value, ten different waste treatment strategies are assumed to evaluate the improvement of DPM application in each case. According to the result, the DPM application shows more efficiency of impact minimization as the disposal waste volume increased. If the whole waste is landfilled in the strategy, about 20% of improvement can be achieved with the application. For the impact improvement by the model application, demolition impact, recovery rate and treatment impact are considered the impact significance. The result shows the largest contribution of recovery rate improvement at the DPM application. In particular, the waste recyclability improvement reaches half of the contribution in this system. Since the onsite impact reduction is significantly small, the waste recovery should be more prioritised than the reduction of machine operation time which tends to be prioritised in benefit-oriented planning.

Chapter10

<Chapter Abstract>

In this chapter, the quantitative methods are applied to collecting a feedback from practitioners to validate the final hypothesis that “The development of a collaboration support system between demolishers and constructers with a 4DCAD simulation tool can contribute to sustainable demolition waste treatment”. The alternative application of practitioners’ feedback for validation is justified by the infeasibility of the actual impact estimation caused by the DPM system application. The hypothesis is considered its correctness, and the further development of this approach is discussed based on the result.

Chapter10. Validation

The feedback from stakeholders involved in demolition projects to the suggested DPM system and impact evaluation model is discussed in this chapter as the model validation. Questionnaires were used mainly to evaluate the usability of models quantitatively. Then, the open questions which asked for the recommendations of future developments were conducted by individual interviews with the author. In order to achieve the set objectives of the two approach as shown in Table 73, the authors set different targets to collect answers. For the questionnaire, participants were set to the IDE* members who joined the IDE Scottish seminar which was held on 8th of July in 2016. This was because the questionnaire was conducted after the presentation as feedback on the introduced model application. Since the IDE members are not confined to certain job positions, this style was appropriate to collect feedback from different types of workers in demolition. On the other hand, the interviews were also held with the demolition consultants who are the members of IDE. This aimed to get further feedback from the most relevant stakeholders to the project planning as the assumed users of the suggested model.

Table 73 Feature of two quantitative approaches; questionnaire and interview

	Questionnaire	Interview
objectives	1. To assess the ability of the model as a decision support tool 2. To evaluate the fitness of the model to the demand of demolition stakeholders 3. To scale the quality of suggestions (e.g. research concept, DPM system, model) 4. To identify the advantage and the shortcomings of model development for the further improvement	1. To identify the issues in the demolition industry (asked to demolition consultants) 2. Same as Questionnaires' 1 to 4 3. To discuss the further development of the model for the application to society
target	Participants of the IDE Scottish Seminar (IDE members)	Demolition consultant (IDE members)

269 *IDE was established to advance the science of demolition engineering and it has a long experience to encourage demolition practitioners to exchange their knowledge and expertise (IDE, 2016). As the group of the experienced demolition practitioners, they tends to be chosen for the respondents of validation in conventional demolition researches (Qu, 2010 and Quarmby, 2011).

10.1. Questionnaire

The Questionnaires were held at the IDE Scottish seminar on 8th of July in 2016. It was separated into three stages, i) introduction of research and suggestion of DPM system, ii) showing a simulation model application movie, and iii) answering questionnaires. The first two process were done by the author as a 30 minutes' presentation. Before showing the model application movie, the DPM system was suggested with the research background. The movie contained a brief description of model structure and explained the whole impact estimation process from the project modelling to the impact conversion. The impact results saved in Microsoft Excel explained how to interpret and compare with each other to suggest the optimal strategy in the pilot study. After describing the further application of the model such as impurity mapping, observers were asked to complete the form. While the ability and applicability of the model were evaluated by ratings in the questionnaire, the model shortcoming for the social application was identified by the feedback from the open questions.

10.1.1. Questionnaire design

The questionnaire was designed to achieve four objectives which are shown in Table 73 above. The design is based on the study of Abdullah (2003), who developed a decision support tool for the demolition technique selection. Due to the similar research content and the target (he also chose the IDE members in his validation process), some of his questions were included in this questionnaire, and the results were compared with Abdullah's in the discussion below. The detail of Abdullah's research can be seen in the Appendix3.

As shown in Table 74, the first part of questionnaire consists of three different types of rating scale questions. As highlighted in red, questions 4 to 10 were the same as the Abdullah's questions. Following this, the open questions were set to get the feedback on the merits and the demerits of the suggested model application in the respondents' own words. Each question and the corresponded aims of each type of questions can be summarised as follows:

1. **Model performance…**

Q1. for the project recreation

Q2. for the demolition impact evaluation

Q3. for the model usability

- Objectives1: To assess the model ability

2. **Model applicability…**

Q4. to the impact evaluation process

Q5. for the industry professionals

Q6. to the decision making (for speed improvement)

Q7. to the decision making (for process improvement)

Q8. to the selection of optimal demolition method

- Objectives2: To evaluate the model fitness

3. **General evaluation…**

Q9. for the model integrity

Q10. for the overall model

Q11. for the personal interest in the model application

Q12. for the importance of impact evaluation

Q13. for the DPM system

- Objectives3: To scale the suggestion quality

4. **Open question…**

Q14. for the benefit of model application

Q15. for the shortcoming of model development

- Objectives4: To identify the advantage and the shortcoming of model development

Table 74 Questionnaire content at the IDE Scottish seminar

	Questions	Rating				
		Poor (1)	Fair (2)	Satisfactory (3)	Good (4)	Excellent (5)
Performance of model						
1	Recreation of project: How well are following realistically recreated?					
	onsite objects (building, machines)					
	demolition method (pattern of order)					
	demolition behaviour in simulation					
2	Evaluation of demolition impact: How well are following realistically evaluated?					
	machine productivity					
	waste property (distribution, purity)					
	total cost (time, labour, sustainability)					
	onsite safety from animation					
3	Usability of model: How well is this model usable in terms of following?					
	user-friendliness					
	flexibility of project designing					
	decision support for planning					
	communication among stakeholders					
Applicability to demolition industry						
4	How effective is the model at the evaluation of demolition impact?					
5	How convinced are you that demolition industry professionals will accept (or use) the system?					
6	How effectively will the system increase the speed of decision making process?					
7	To what extent does it represent an improvement in the decision making process?					
8	To what extent is the system flexible in choosing the most appropriate demolition method?					
General						
9	How well integrated the overall process in model?					
10	What is your overall rating of the suggested model?					
11	To what extent do you want to apply this model to your projects?					
12	How convinced are you that the impact evaluation is useful for the improvement of demolition project planning?					
13	How convinced are you that the suggested collaboration system between demolition and construction teams are beneficial for stakeholders?					
Open question						
14	What do you consider the main benefit of this model?					
15	In what ways can the system be improved?					
16	Further comment					

10.1.2. Result and discussion

10.1.2.1. Breakdown down of respondents

As a result of the presentation and the questionnaire at the IDE Scottish seminar, 16 participants answered the interviews. Since the seminar had about 30 observers when the presentation was given, approximately half of them helped to give feedback. The respondents can be classified by two factors; i) job position and ii) working career of respondent as seen in Figure 131. Working career is set here as the barometer of conservatism. 15 years are set to separate them into two which is the closest value to the first quantile (the second quantile value is 25 years). To analyse the change in attitude of industry people to the innovative suggestion based on their experience, it seems beneficial to compare the results between them. It needs to be noted that one engineer only answered the open questions so the results of rating questions reflects 15 people.

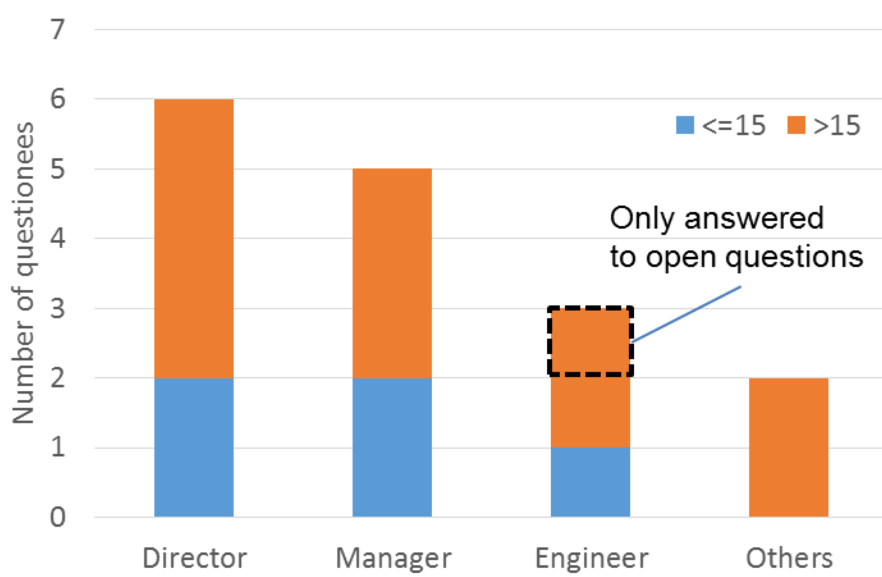


Figure 131 Breakdown of respondents

10.1.2.2. Result based on job position

The average score for each respondent is plotted for each question type as shown in Figure 132 in which the less experienced respondents are described with hollow circles. For directors, all the directors except one gave a higher rating for each type compared to managers. This might be attributed to the role of managers which includes project planning. Since they tend to decide the project planning based on their own experience, a suggestion which requires more operations (e.g. BIM data collection, software use) does not seem feasible for them. On the other hand, directors who have more opportunities to collaborate with clients or who organize the whole project (i.e. having opportunities to work with other stakeholders) show similar high expectations of the applicability as the model performance or general evaluation. Engineers might be the first stakeholders who feel the potential of the model to improve current practice. Since their work is more specific than other stakeholders, the visualization or multiple impact estimation might be more attractive to comprehend the planning or communicating with other stakeholders. Others (a committee member of IDE and a senior lecturer) show higher rating on applicability than other question types which tendency was also seen in the study of Abdullah (2003). In his study, the IDE members and the researchers of Loughborough University were compared in their evaluation of his intellectual tool. Results showed the academics were more tolerant of his theoretical approach than practitioners. Despite the increase of implementation process, they may appreciate the theoretical advantage of impact evaluation with the suggested model.

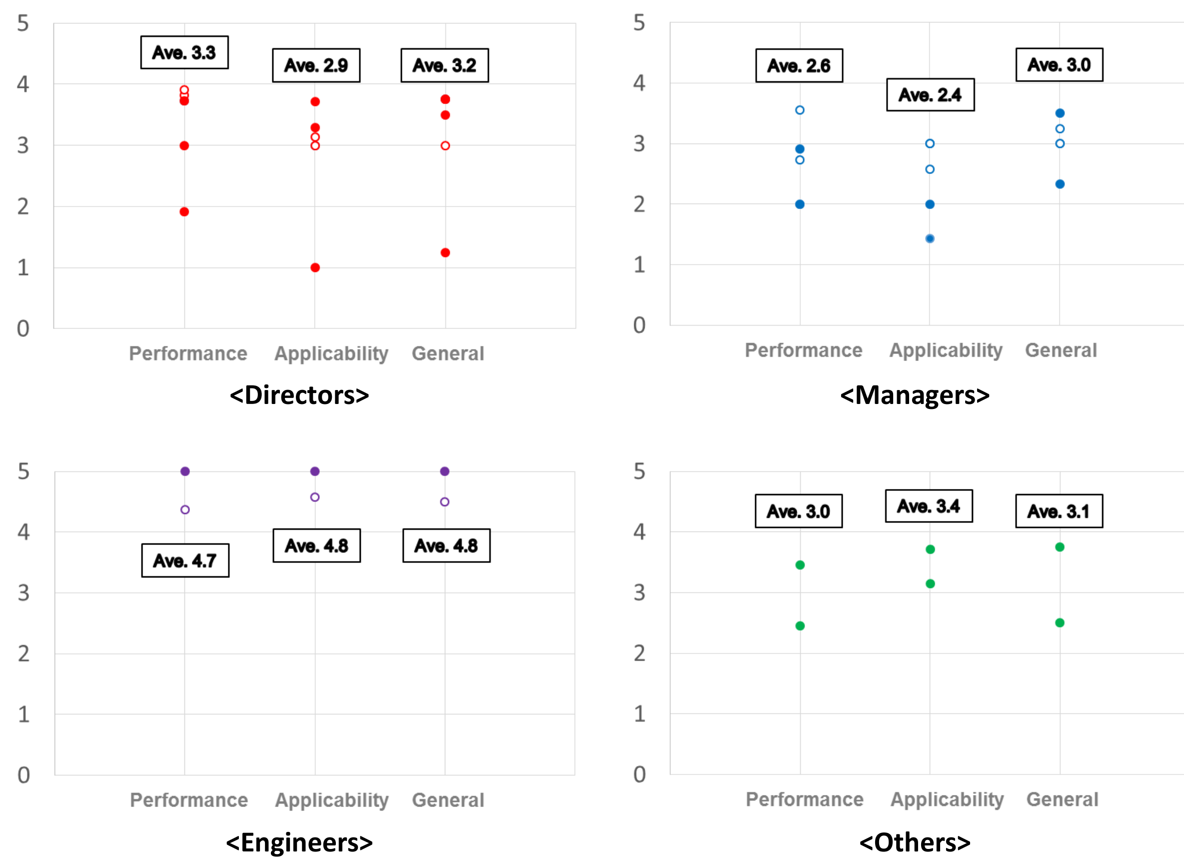


Figure 132 Rating results of each question type for different job positions

10.1.2.3. Result based on working career

In the former section, it was not clear the difference of respondent attitude with working experience for each job positions. In order to clarify the relation between work experience and tolerance of new suggestions, the whole results are individually plotted with respondents' working career as depicted in Figure 133. Although the line indicates a downward trend, due to the large dispersions especially around 20-30 years of career, the R-squared values become quite low to indicate a correlation with working career. Those values are, however, drastically improved once the target is set to the respondents up to 15 years' experience as shown in Figure 134. Since the number of values are reduced with this treatment, the adjusted R Square also need to be calculated. As the result of the recognition analysis, they become 0.54, 0.79 and 0.63 respectively. It implies at least in the first 15years of work, there is a strong relation to a positive attitude toward innovative suggestions especially for the model application. Compared to this, the rating after 15years does not describe the influence of career duration.

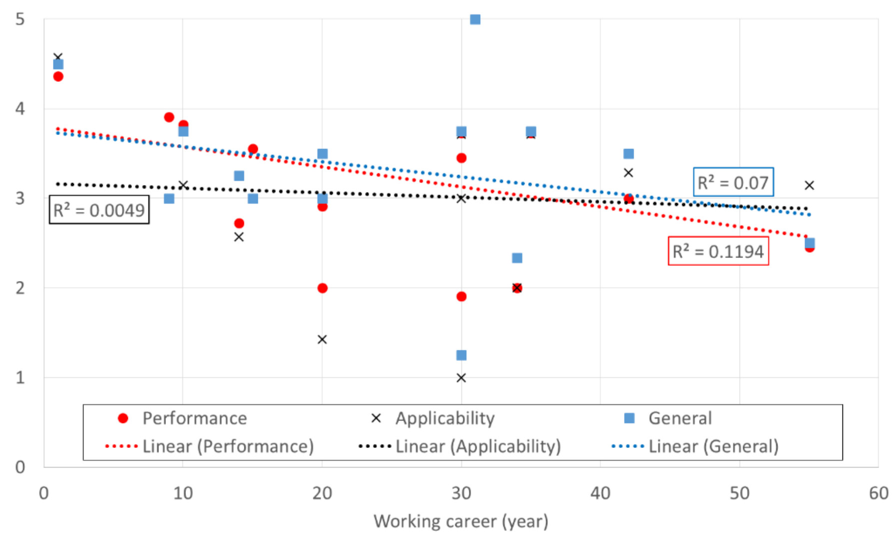


Figure 133 Rating results of each question type with working career

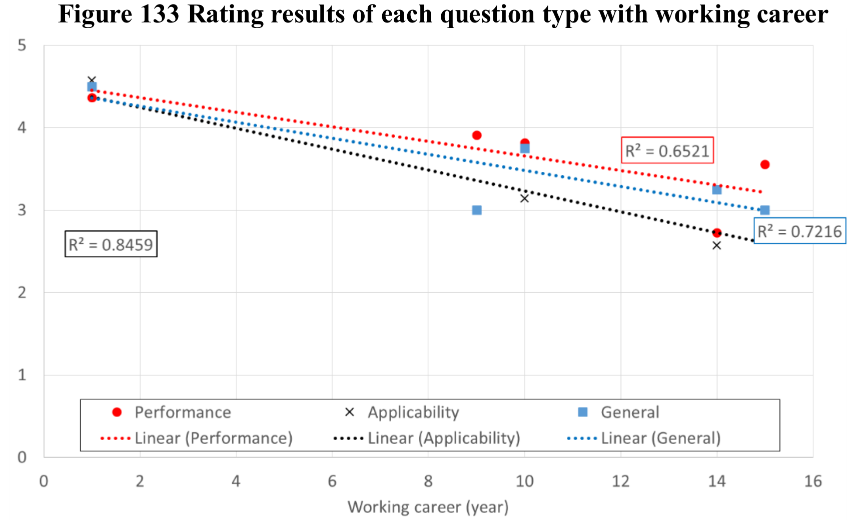


Figure 134 Rating results of each question type with working career (up to 15 years)

10.1.2.4. Results for individual questions

The result of each question is summarised as Table 75. It also contains the results of Abdullah (2003) to compare with the current research. For the questions related to the model performance, the ratings of factors in the same question mostly show a similar evaluation. However, in the impact evaluation questions, respondents find the model's advantage for evaluating the machine productivity which can be described by both an animation and impact values (e.g. time, cost, waste generation). On the other hand, the animation is not regarded as convincing enough to support the safety analysis. This result is derived from the shortcoming of structural analysis function in the software and the occasional awkwardness of machine movement in simulation. Therefore, the questionnaire result for the model expectation as a communication tool between stakeholders is also relatively lower than other usability evaluations.

In the model applicability part, the expectations of the process improvement for 'impact evaluation' and 'method decision' are evaluated. Similar to the former positive feedback, the impact evaluation process is expected to be improved by the dynamic and diverse feature of innovative impact evaluation in the suggested model. This affirmative attitude can also be seen in the results of 'method decision' in which process and result quality are expected to be advanced. The further resources for decision making are perceived as beneficial in those processes. Nevertheless, the model application is also regarded as a demerit once the operation burden is considered. As seen in questions 5 and 6, the feasibility of the model being adopted by practitioners and the contribution to reducing the operation time shows the lowest rating, especially without BIM data. This implies the difficulty of application in the near future due to the low penetration rate of BIM design, especially for old buildings which will end their service life soon. Since clients need to invest extra budget for the BIM data securement, many respondents are not convinced of the improvement of speed of operation including the extra process. They suppose practitioners would reach to the same conclusion as them and keep operating with the traditional approach. The hesitation of practitioners to install the modelling approach may explain the still low evaluation in spite of the existence of BIM data. As shown in the 'result based on working career', the conservativeness of practitioners tends to increase as their career becomes longer and longer up to first 15 years. It will be challenging to convince people 15 years in the job, and it may take several decades until today's understanding young stakeholders replace the majority in this industry.

Regarding the feedback of general evaluation of the model suggestion, it is generally satisfactory but relatively worse than the result of Abdullah's proposal. The overall process is not as appreciated as Abdullah's static approach for the optimal demolition technique selection. Besides the precise and robust description of demolition process for each demolition technique, the detailed description of model process seems necessary in order for respondents to understand properly. Since the explanation of the suggested model was done in the presentation with the assumption that the observers acknowledge BIM, the preparation process or the basic knowledge of BIM was not described there. Regarding that, further development of the model should be explained to the practitioners to remove their fear of unknown methodology. Most of the respondents agree with the importance of our two objectives, the impact evaluation for project planning and the tighter cooperation between demolishers and constructors. Accordingly, it must be the quality and structure of the model which requires further development to lead them to achieve those objectives.

Table 75 Result of questionnaire with the result of Abdullah's (2003) study

	Questions		Rating					Answered		Score	
			1	2	3	4	5	total	rate(%)	Ave.	Abdullah
Performance of model											
1	Recreation of project: How well are followings realistically recreated?										
	onsite objects (building, machines)			3	6	5	1	15	93.75	3.3	
	demolition method (pattern of order)			3	6	4	1	14	87.5	3.2	
	demolition behavior in simulation		1	3	5	5		14	87.5	3	
2	Evaluation of demolition impact: How well are followings realistically evaluated?										
	machine productivity			2	3	9	1	15	93.75	3.6	
	waste property (destribution, purity)		2	2	2	7	1	14	87.5	3.2	
	total cost (time, labour, sustainability)		1	3	2	6	1	13	81.25	3.2	
	onsite safety from animation		2	5	2	5		14	87.5	2.7	
3	Usability of model: How well is this model usable in terms of followings?										
	user-frendliness		1	5	2	5	2	15	93.75	3.1	
	flexibility of project designing			4	5	5	1	15	93.75	3.2	
	decision support for planning			3	6	5	1	15	93.75	3.3	
	communication among stakeholders		1	4	3	5		13	81.25	2.9	
Applicability to demolition industry											
4	How effective is the model at the evaluation of deomlition impact?		1	2	1	9	1	14	87.5	3.5	3
5	How convinced are you that demolition industry professionals will accept (or use) the system?	without BIM	5	2	5	1	2	15	93.75	2.5	3.2
		with BIM	2	1	6	3	1	13	81.25	3	
6	How effectively will the system increase the speed of decision making process?	without BIM	2	6	4	1	1	14	87.5	2.5	3.6
		with BIM	2		6	5		13	81.25	3.1	
7	To what extent does it represent an improvement in the decision making process?		2	1	4	5	3	15	93.75	3.4	3.2
8	To what extent is the system flexible in choosing the most appropriate demoliiton method?		2	1	5	5	2	15	93.75	3.3	3.4
General											
9	How well integrated the overall process in model?			4	6	4	1	15	93.75	3.1	3.8
10	What is your overall rating of the suggested model?		1	3	3	6	2	15	93.75	3.3	3.6
12	How convinced are you that the impact evaluation is useful for the improvement of demolition project planning?		1	2	5	4	3	15	93.75	3.4	
13	How convinced are you that the suggested collaboration system between demolition and construction teams are beneficial for stakeholders?		1		4	5	3	13	81.25	3.7	

10.1.2.5. Result of open questions

Table 76 summarises the result of open questions which correspond to questions 14-16 in the questionnaire. Job position is used to sort the answers for a better understanding of the relation of responses with the respondent’s role. From the director’s point of view, many respondents mention the applicability of simulation results as a resource for presenting to clients. This shows the strong connection with clients in their roles. They also insist on the advantage of the swift evaluation of resource volumes as a person in charge of the total project and the business planning. This model ability is, however, not regarded to be high quality enough to discuss the project planning with managers or operators at this stage. They are not satisfied with the quality of machine operation or visualization especially when considering the model application to health & safety analysis. At the same time, the further requirement of input for running a simulation is considered to hinder the operation. Although comments do not mention the BIM existence in the current project, this anxiety may be mitigated once BIM data is more general at the construction phase or the technology of BIM extraction becomes more cost-effective.

For managers, who are closer to the implementation phase than directors, the model function to project the waste generation is appreciated. There are some respondents who find the merits of this model from evaluation of the extensive factors. Those factors such as the environmental impact are assumed to be of importance at decision making in the near future. Similar to the directors, they are also concerned about two aspects, the insufficiency of model accuracy and the extra burden for the data input, an attitude which was also seen in the rating questions. The managers suggest the application of structural analysis to reflect the onsite safety. Including the extra burden which needs to be justified to clients for further investment, there are some huge barriers to accepting the theoretical approach in this industry. Due to the huge gap between the as-designed and the as-built at the demolition phase, stakeholders of demolition projects have often been required to manage some unexpected issues in the process (e.g. asbestos treatment, recovery of valuable bricks). Accordingly, the project planning with a pre-design such as BIM does not seem realistic or beneficial for them. That might be the reason why the one of managers points out the necessity of drastic change in the industry to accept informative approaches.

As seen in the results of the ratings questions, both engineers regarded the current research quite positively (rating 4.6 out of 5 on average across all the questions). They found this model is suitable to comprehend the impact generation in demolition especially for inexperienced users. This might be similar to the position of directors who suggested its use for the presentation to clients. They regarded the projection of cost and other impact analysis is advantageous to decide the strategy. However, one of them also advises simplification of the data entry; he is the only person mentioning this. Since the model has been redeveloped to minimize the users' burden including the data input, this feedback was unexpected. It would be better to hold a workshop to identify the perceived usability through the actual experience of model application, and get more feedback of usability before further development.

The people who are not currently involved in practice also find the superiority of the model in further consideration at project planning. The positive stance to the visual risk assessment beside the environmental impact analysis shows a good introduction here. The closer to the onsite implementation the stakeholders stand, the higher the requirement of the simulation quality. As seen in the rating results, the requirement of the model quality for the application becomes less strong in the order of managers, directors and others.

Table 76 Result of open questions in questionnaire

Job position	Advantage of the model	Model shortcoming and suggestions	Other comments
Directors	● Useful for presentation to clients ● Beneficial for quick comprehension of require resources and generated waste	● Insufficient quality of machine operation and visualization for onsite health & safety analysis ● Not precise enough ● Further requirement of input	
Managers	● Prospective to improve the waste recovery efficiency ● Scalable to consider the extensive factors (e.g. CO_2 emission)	● Further requirement of input and related budget increase (clients to be convinced) ● Need to consider structural engineering and machine accessibility	● Adoption of this suggestion may require industrial revolution
Engineers	● Suitable for inexperienced users to comprehend diverted impacts from visual ● Prospective for strategy and financial projection	● Data entry is to be more ease	
Others	● Beneficial for risk assessment ● Prospective for project planning with sustainability	● Further time is required to be developed for application	● Planning is 80% and designing is 20% in the project

10.2. Interview

The validation process was almost same as the questionnaire, i) introduction of research and suggestion of DPM system, ii) showing a simulation model application movie, and iii) answering interview questions. The same slides and movies as the IDE seminar were used to introduce the research in the first phase. It contained the brief description of model structure and whole impact estimation process from the project modelling to the impact conversion. To show the model versatility, the different types of demolition methods were applied to the simple building model, the results of which could be compared to suggest the optimal strategy in the pilot study. Then, the designed questions were asked to comprehend the feedback from three different points of view, i) issues in practice, ii) model evaluation and iii) application advice. In order to understand the feedback from the most likely stakeholders for the future model users at the project planning process, demolition consultants (IDE member) were chosen as the respondents.

10.2.1. Interview design

The design of the interview is shown in Table 77 and it is summarised into three main parts as below. By taking advantage of an interview, the issues in the industry perceived by respondents were asked about before the evaluation of research suggestions. It aimed to survey the current gap in the demolition industry and confirm the fitness of the suggestions to their demands. After similar questions to the questionnaire were asked, advice for the further model development was asked.

1. **<u>Issues in practice…</u>**

   Q1. to comprehend the engaging process of respondents

   Q2. to identify the issues

   Q3. to identify the person in charge of issues

   - Objectives1: To identify the issues of the industry

2. **<u>Evaluation of model…</u>**

   Q4. for the applicability to practice

   Q5. for the model usability

Q6. for the simulation result

Q7. as the solution of conflicting issues

- Objectives2: To get feedback for the suggested system and model

3. <u>Advice of application…</u>

Q9. to identify the advantage of the model

Q10. to identify the shortcomings of the model

Q11. to identify the key point of application

- Objectives3: To identify the challenges before the model application

Table 77 Content of questions asked in interviews

Issues in practice		
1	In which process of demolition project are you mainly engaged?	
2	At that process, what kind of issues do you think hinder the project progress or make a huge loss?	
3	Which stakeholder is or stakeholders are responsible for this issues?	
Evaluation of model		
4	Through the workshop, were you convinced by the idea of C&D collaboration system?	
5	How do you feel about the usage of model?	
6	How do you think about the result of model (e.g. machine usage, waste generation, impact estimation)? Do you think those are helpful in your process?	
7	Do you think this model can support to prevent or solve the issues which you tend to conflict in practice?	
Advice of application		
8	What do you consider the main benefit of this model?	
9	In what ways can the system be improved?	
10	Assuming the application to practice, what do you think is the most important for this model?	

10.2.2. Results and discussion

Two demolition consultants who belong to IDE agreed to have an interview. Both of them are working at the same demolition consultant company in England as demolition consultants. In terms of working career, one is classified as more experienced, the other has less than 15 years' experience. The answers from the two consultants for each question is summarised as Table 78. For the issues in practice, they found more issues in the implementation process especially management of the resource to achieve their planned goal. Although it seems far from the aims of this research, the visualization and the communication, in particular, with operatives for conveying the project planning is originally considered as the advantage of the suggestion.

At the evaluation of the model, the main point of argument was the necessity of BIM data as the model input. Due to the current situation of BIM equipment for existing buildings (can be said to be zero), they pointed out how the clients and also project planners (including themselves) would be resistant to extra operations and investment. Accordingly, they were asked to just evaluate the model ability assuming BIM data is ready. Similar to the feedback from the directors and the managers in questionnaire, visualization and waste property analysis were appreciated with the request for further accuracy in the model. Since they knew the huge loss from onsite accidents, they expressed reservations about the application of a theoretical approach to health and safety analysis. They preferred to apply the model to the data administration such as waste volume and its origin. However, they did not accept the advantage of impact evaluation with the model simulation. This was because of the belief that the project planning decision taken from their accumulated experience and knowledge would never been replaced by automated tools. Compared to the outcome from the simulation which asked for extra process (not only BIM data but the acquisition of the model operation skills), they supposed the benefit resulting from the model application would not exceed the extra investment from their point of view. Even though the advantage of quantification of demolition impact was pointed out by the author, they explained there was no need for over engineered technologies when convincing clients. For this reason, they were also suspicious of the BIM application in demolition industry in near future. Since they were suffering from the difficulty of supervision and resource management daily using whiteboards and handwritten plans, the benefit produced by the computation (e.g. visualization, data administration) should be more appealing to them. Accordingly, further development which quality is sufficient to apply to the safety analysis may be necessary to change their mind. In addition to this, the experienced consultant wanted to know if this model is assumed to operate machines automatically. Although he repeatedly mentioned the importance of simulation accuracy, the improvement of machine operation in terms of reduction in labour and operation time were also regarded as potentials of model application.

Table 78 Summary of interview answers from demolition consultants

Issues in practice		
1	In which process of demolition project are you mainly engaged?	● project planning to implementation process
2	At that process, what kind of issues do you think hinder the project progress or make a huge loss?	● quality of labour ● deliveries ● supervison and management
3	Which stakeholder is or stakeholders are responsible for this issues?	● managers ● general operative
Evaluation of model		
4	Through the workshop, were you convinced by the idea of C&D collaboration system?	● not convinced for the current BIM application in practice
5	How do you feel about the usage of model?	● attractive for... modeling in short time estimation of wastre generation project recreation in 4D
6	How do you think about the result of model (e.g. machine usage, waste generation, impact estimation)? Do you think those are helpful in your process?	● attractive for visualuization if more accurate and waste property analysis ● not convinced that the model replace experienced project planners for waste generation and method decision ● attractive if BIM is ready
7	Do you think this model can support to prevent or solve the issues which you tend to conflict in practice?	● infeasible to investiment more to BIM data ● attractive to comprehd the material and waste volume immediately in the model
Advice of application		
8	What do you consider the main benefit of this model?	● short time (at modeling) and clarity ● visualization if accurate ● identification of waste origin
9	In what ways can the system be improved?	● BIM application in practice (own ability with long experience as consultant exceeds the model for project planning) ● graphics and render
10	Assuming the application to practice, what do you think is the most important for this model?	● belief of stakeholders in the practitioners' experience rather than theoretical approach ● timing of BIM to be standard in demolition (few more decades later) ● necessity of extra input, and production of more benefit

10.3. Summary

The suggested collaboration system and the impact evaluation model were evaluated from the feedback of the demolition stakeholders in IDE through two steps of validation, i) questionnaire and ii) interview. In the questionnaire, the general feedback on the model and the different ideas of stakeholders according to career and role were clarified. Through the survey, the suggested impact evaluation by visualization and quantification of multiple impacts were admired by most of stakeholders. However, the model requirements, especially for the simulation accuracy of the structural engineering, was asked about by more stakeholders as their role became closer to the whole project planning (e.g. managers > directors > engineers). In addition to this, the suggestion of the application of BIM and the data treatment processes were negatively regarded by many stakeholders. This was mainly attributed to the infeasibility of extra investment from the clients and the characteristic of demolition industry. The respondents judged the value produced by the model application would not be enough to convince the clients to spend more time and money. In addition to this, some stakeholders mentioned the culture of the demolition industry. As seen in the huge delay of the BIM application by the construction industry, the stakeholders in this industry are prudent about adopting new methods. Therefore, many stakeholders believed in the necessity of the BIM adoption to the demolition industry as the first step which may take more time. The rating result also showed a change in the stakeholders' conservatism regarding the innovative suggestion based on length of career. It may take a long time to replace the main stakeholders who are negative about changing their traditional style in demolition.

In comparison with the questionnaire results of Abdullah (2003)'s study which suggested the optimal demolition planning with a static approach, the results were generally lower. This implies the importance of the detailed description of model process for the respondents (assuming model users). In terms of the precision of the description of the demolition process, static modelling was perceived as more understandable than the suggested dynamic and automated model which is somehow black boxed by algorithm application. Since the significance of both suggested concepts, 'collaboration between demolishers and constructers' and 'impact evaluation of demolition project' were strongly agreed by respondents, the quality of simulation and the clarity of the model structure must be more important to embody those ideas.

After the interview with the two demolition consultants in IDE, the fundamental cause of negativity against the model was identified at the belief of practitioners about their accumulated experience and knowhow. For the impact estimation of demolition planning, they were quite suspicious that the benefit resulting from the model application would exceed their own performance. The quality of simulation needs to be raised at least to sufficient level to apply to the health and safety analysis with structural engineering analysis. In addition, it seems more effective to change their point of view from the project planning to the implementation process where they recognize issues. The advantage of the model application in terms of impact visualization and data administration must be more featured to appeal to the efficiency of the onsite resource management compared to the current whiteboard and handwritten project plans. As represented by the automated operation of machines which attracted the practitioners, those advantages which can be only created by a computational approach should be more emphasised to convince practitioners to consider the project planning with a quantitative approach.

The correctness of the hypotheses suggested in Chapter1.3 can be analysed from the above validation results. The importance of the collaboration between demolition and construction practitioners and the further information of demolition waste generation have been by practitioners. However, the advantages derived dynamic information have not been well appreciated yet by project planners, for example. It results from two main reasons, the infeasibility of BIM application and the inaccuracy of model simulation for the safety analysis. Accordingly, the 4DCAD simulation tool must be more improved in both the model ability and the application burrier in practice to convince practitioners. The detail suggestion for further approach will be discussed in next chapter and to be concluded in Chapter12.5.

Chapter11

<Chapter Abstract>

In this chapter, the results shown in Chapter 8 to 10 are discussed how the research objectives have been accomplished. Two impact evaluation tools for the individual project (in micro level) and the whole society (in macro level) are firstly analysed from the simulation results. According to the results of macro tool and the practitioners' feedbacks, the validation of DPM system application is finally discussed. It can be regarded as the analysis of the final hypothesis validity introduced in Chapter1.3.

Chapter11. Discussion

In this chapter, the three main objectives suggested in Chapter1 are discussed for the significance of the present approach and the future prospects based on the results of pilot studies and validation from Chapters 8 to 10 i) Project impact estimation, ii) Social impact estimation and iii) DPM application.

11.1. Project impact estimation

11.1.1. Contribution

The uniqueness of the present project impact estimation model for the demolition planning can be seen in three major areas; i) comprehensive impact evaluation (covering the whole demolition process), ii) dynamic evaluation and iii) automation of the demolition process. In the following sections, the validated abilities of the present model are discussed in comparison with previous works in the literature.

11.1.1.1. Comprehensive (whole demolition) evaluation

With the present model, demolition projects can be evaluated for the whole process (from the soft-stripping to the waste treatment process). Apart from the soft-stripping process, the demolition impact can be calculated in terms of time, by the automated simulation of machine operation, and waste generation. Accordingly, the planning can be analysed by the five different impact factors, i) cost, ii) duration, iii) environmental impact, iv) labour burden and v) waste generation, which enable us to quantitatively decide the optimal planning with multiple factors. In the case of most of the conventional research aimed at waste estimation (e.g. volume, type, purity, treatment cost), the impact estimation at each demolition process is relatively little. For instance, Akbarnezhad et al. (2014) applied BIM data to identify the joint of elements and calculated the cost and the environmental impact from the total disassembly. However, it could only be estimated from the number and the type of connection. Without considering the applied methods or machine properties, project planning cannot evaluate the change of impact of alternative methods. Abdullah (2003) suggests a selection tool of the optimal demolition method which estimates the total impact of the target case by scaling previous data with the number of building elements and a cost database of demolition methods. Nevertheless, this is still based on the number or volume of the element objects so that the method of implementation is not considered. Therefore, the influence of applied machine, demolition method and strategy on the demolition project impact can be addressed with this model only. The validity of the simulation accuracy must be validated from comparing the result in onsite survey in the further research.

11.1.1.2. Dynamic evaluation

In the present model, the progress of a project can be recreated in 4D (3D with time axis) by applying a 4DCAD, which provides us with several advantages in the project description and the impact estimation. In terms of description, the visualization in 3D/4D is beneficial for stakeholders as a communication tool. In addition, the application to the onsite safety analysis also makes it possible to identify hazardous wastes although further improvement in accuracy is inevitable for practical use. At the same time, the material component or purity of the collected wastes can be identified along time axis based on the original elements when the mixing behaviour of debris is simulated in 4D. The waste property can be analysed through the mapping of the waste distribution and the purity of recovered waste. In particular for the hazardous waste, the waste distribution and the exposure risk can be depicted by tracking contaminated elements in 4D space. Demolition project for the buildings with asbestos or the radio isotopes from nuclear power plants can be involved in the model target. Although previous research also applies 4DCAD to the risk analysis of asbestos exposure, the hazardous area can be only identified at the element level on the intermittent schedule. Accordingly, this research is innovative in identifying the hazardous waste collection path and the mixed risk of hazardous waste in recovery. Although the idea of project simulation in 4D is not new in the construction industry, most approaches in practice aim at visually recreating the progress for the site management. In our simulation, a dynamic estimation is more likely in the optimization approach for the onsite crane location. In the Zhou et al. (2015)'s research, based on the elements to be transported, the optimal crane location can be identified by the duration of whole lift work in 4D. By adding the idea of conflict between two objects (e.g. excavator vs element) to these approach, this research innovatively extends the evaluation target to the demolition.

11.1.1.3. Automation of process recreation

In order to reduce the users' burden, the impact estimation model is developed to automate the process recreation in simulation. By applying the algorithms to the machine operation in the model, the self-running simulator is successfully developed which is examined in the pilot study in Chapter8.1. It allows users to recreate the whole project planning process and to estimate the resulting impact with the simple selection of the demolition methods and machines. Algorithms give several options of machine operation pattern and demolition order to compare, and the cost impact and the environmental impact are actually reduced from 19 to 28 % among several scenarios in Chapter8.2. The pilot study in Chapter8.3. also shows the comparability between different demolition methods. Therefore, the model can be applied to evaluate state-of-the-art demolition methods for quantitatively analysing the superiority of suggestions. This wide applicability including new methods is superior to the conventional approaches which require the previous research data as the basis of estimation.

11.1.2. Issues and mitigations

After the pilot studies and validations in the previous chapters, two issues are identified for the demolition project impact estimation model. The model accuracy is mostly found to be improved for the actual application especially for the safety analysis. As the practitioners opinion, the structural analysis must be added to the model, and more precise location of machine operation from the target structure should be considered for the safe operation. For the structural analysis, the objects' data can be constantly exported to the external structural analysis tool and the results of destruction can be imported to the model to update in Blender. Since this data transaction may consume considerable computational time, the simple method of structural analysis in Blender should be studied as the compromise solution which maintains the speed of the model simulation.

In addition to the accuracy, the optimization approach for the project planning needs to be improved. The current model can only evaluate the impact for the model as the decision support tool in which the best suggestion can be only chosen among the input options. The final goal is to suggest the optimal demolition planning automatically from the target building design as suggested in the study of Abdullah (2003) with cost performance as the users' criteria. Similar to his approach, in this research the optimal planning can be suggested from the past project database based on the target structure property and the actual demolition impact. The supervised machine learning method seems suitable to sort the prospective options from the numerous types of planning so that only a few simulations are required to complete the optimization. On the other hand, if the suggestion is so innovative that there is no reference in old projects, each factor of project's property (e.g. applied machine type, number, layout) can be decided from other optimization methods such as GA which is frequently applied to estimate the optimal location of the onsite crane in the conventional research. As the users repeatedly apply the model to the new methods, more data can be accumulated as knowledge in the database. As a result, subsequent users can apply this to their own project design (i.e. the accuracy and the calculation time for optimization would be improved by its use). The users can select the factors to be prioritized, and a suitable suggestion would be produced considering those features.

11.2. Social impact estimation

11.2.1. Contribution

The uniqueness of the present social impact estimation model for demolition planning can be seen in two major areas; i) impact quantification of demolition waste flow with AB model and ii) environmental impact estimation with 'Eco point'. The validated abilities of the present model are discussed in the following sections with comparison to the previous research.

11.2.1.1. Impact quantification with AB model

Conventional research applying the AB model is referred to recreate the demolition waste flow. In the suggested model, the agents represent the stakeholders, and their whole behaviour produce the total impact of demolition waste treatment in UK. The geographical data of each facility allows for the estimation of the transportation burden so that the whole waste flow process can be covered to evaluate the total environmental impact of demolition projects in UK. By adding demolishers and constructers to the target agents with decision algorithms, it is possible to properly design different scenarios for the share of DPM application between them. The result will show the prospective environmental impact change from the previous DPM users in UK. In addition, the sensitivity analysis is held for each factor of model simulation such as the property of the waste sorting plants (e.g. the treatment ability or the waste acceptance criteria). The result of this analysis shows the scale of the impact on the final result for each impact factor. The optimal demolition plans at the national level can be suggested from this comprehensive analysis of the demolition waste flow. Although currently there is no actual data estimating the total environmental impact from demolition to constructrion, the comparison with the actual impact data should be achieved to validate the accuracy of this model

11.2.1.2. Eco point application

The 'Eco point' suggested by BRE is applied to unify the environmental impacts in both demolition and the waste treatment process. Accordingly, different demolition planning can be compared. Following the components of the 'Eco point' in which more than ten different types of weighted environmental factors, such as fuel consumption, waste disposal, are included, each process illustrates the impact of individual factors in this model. The dominant factors in the process can be identified from those individual values. In comparison with the above scenarios for the DPM application, this information can support the government to decide policy in application of current systems.

11.2.2. Issues and mitigations

After the pilot studies and validations of the impact estimation of social demolition impact, two issues are identified; i) status update of agents and ii) estimation of the initial application investment. For the agent status, there is some gap between the stakeholders' behaviour in reality and the decision with fixed status algorithms. Based on the suggestion of Kitagaki's (2011) study, which applies the GA for the agent status update, decision making is supposed to reflect the social demand of boundary conditions (e.g. decision of the concrete waste acceptance from the social demand of recycled aggregate). Then, the agents can behave according to surrounding conditions, and the model results will be closer to the reality. In order to achieve this, the data from the stakeholders must be obtained by interviews and questionnaires at the same time.

It is suggested that the initial application investment be added to the social impact estimation model considering the actual model application. This aims to evaluate the risk of the social system change from the amount of investment at the initial instalment stage (such as the establishment of the new facilities and the refurbishment of the existing facilities). It can create a considerable benefit for the government to decide the actual application with regard to the financial reality. In detail, the investment involves both the online server or computers to establish the online DPM service and the human labour cost to maintain the online service. In addition to this, the possible conversion method for the existing facilities is also key to prevent a big impact from the system replacement. It is also emphasised here that the current suggestion is not expected to require a drastic change and related burden as it is for software rather than hardware.

11.3. DPM application

11.3.1. Contribution

The uniqueness of the proposed DPM system can be seen in two major areas; i) demolisher-constructer collaboration system and ii) computation of demolition planning. The validated abilities of the present model are discussed in the following sections with comparison to the previous works in literature.

11.3.1.1. Demolisher-constructer collaboration system

To achieve a sustainable society by optimizing the demolition waste and its treatment, the DPM system encourages demolishers and constructers to attempt to utilise the demolition waste at the next construction in the same or a nearby site. The project impact is now visualized in 4D and the demolition impact can be quantitatively estimated with the present model. Even though the selected planning is not the best suggestion in terms of the environmental impact, the cost-oriented optimal suggestions tend to show a reduction of environmental impact due to the common factors; the reduction of machine use and the better purity of recovery waste. According to the uploaded results online with visualization, the application of demolition waste as building material can be more realistic for constructors. It is expected to increase the volume of demolition waste to be recovered onsite. The total impact reduction from this improvement can be estimated by the suggested social impact evaluation tool. In the pilot study using this impact tool, the improvement of the total demolition impact in UK can be 20 % at maximum, when the government enforces the DPM application for any demolition and construction projects. In the validation process, the suggested system seems to be accepted from most of the respondents. Since all of the stakeholders can reduce the cost from the model application when the BIM data is accessible, there seems less obstacle to applying this system in the future with BIM.

11.3.1.2. Computation of demolition planning

In the tradition of the demolition industry, the whole estimation process requires the domain knowledge and experience of the project planner and clients have always accepted such a situation (Fox, 1994). This culture tends to keep the construction project out from the computational approach application such as BIM or several of the new project management methods. In order to depart from the traditional hand-writing and whiteboard onsite communication, computation technology is applied for describing the advantage of the demolition information management for demolishers. Administration of the project progress information can be achieved with the present model, and it enables us to visualize the progress in 4D and to quantify the demolition impact with multiple factors (e.g. waste generation volume and type, machine use). The suggestions for demolition method and strategy can be discovered by comparing different types of options with these simulated results with impacts. Besides this, the objects' location data is relatively easy to find out by computation. Using this tracking function to the hazardous objects, the path and the resulted waste component can be simulated for the onsite safety. After the validation, the stakeholders are also curious about the model applicability to the auto machine operation. Including the advantage of project management with computation, which they are concerned with in practice, there are many merits of computation for the demolition project planning. This should be more appealed to convince demolishers to shift the paradigm.

11.3.2. Issues and suggested solutions

After the pilot studies and validations, two issues are identified for the DPM system application; i) extra process of model application (BIM data creation and model skill acquisition for workers) and ii) simulation accuracy. For the process of model application, BIM data is necessary to recreate the target building with the material and structural data. In reality, it would be at least few decades later that the buildings having BIM data from the construction process can be demolished. (i.e. the model application does not require any further process and additional cost). Even in the validation, however, the respondents are sceptical that the stakeholders will accept the additional cost of further process for model application due to the time and cost consumption. Beside the extra burden of the model adoption for stakeholders, the traditional project planning approach is currently regarded as efficient. In order to persuade them, the prospective cost reduction needs to be quantitatively demonstrated by the optimization of planning with our model. As shown in Chapter8.3., the application can reduce up to 28 % of cost at the project.Although the application of BIM data to demolition project is inefiesible for the cost, once the technology is generalized and the cost drops, this approach should be more convincing for the practitioners (especially managers and clients).

To enhance the benefit of the model application, the quality of simulation for the health and safety analysis need to be upgraded. To be more precise, the model needs to include the structural analysis to make the suggestion more convincing for both site safety and machine operation. Since the impact estimation can be evaluated with the boundary condition of projects, the optimization can be achieved for each circumstance. This allows for cost savings at the project planning phase and safety can be included as a factor in the project decision. Accordingly, this project planning model produces further benefits at other related phases for those stakeholders (e.g. constructers and government). For instance, the government can decide the approval of project planning according to the safety values quantified by the present model. Constructers can also connect the simulation data to their own BIM project design for identifying the origin of recovered materials. Consequently, the values which can be produced outside the demolition industry are also important when discussing the advantage of the present simulation system. Further validation for those external stakeholders should be performed to clarify the pros and cons of the current model.

Chapter12

<Chapter Abstract>

In this chapter, the conclusion is drawn from the findings through the whole research. Since the content of research is briefly summarised at the first section, readers can revise the whole flow of research. Then, the evaluation of the suggested DPM system is summarised from the benefit and the limitation aspects. These can be regarded as the validated and not validated aspects in the final hypothesis which assumes the advantage of DPM system in society. Based on this, the conclusions which the author reached in the present research are introduced. The further works to be achieved are instructed by authors aiming the practice application of DPM system in the future.

Chapter12. Conclusion

The aim of this research is to suggest the improvement of environmental impact from the demolition industry in the UK. A system of the collaboration is suggested between demolishers and constructers to encourage the use of demolition waste in new construction projects. In order to achieve this, the impact estimation tools for a demolition project and the total social impact in the UK are developed. In this chapter, the findings from these developments are firstly summarised along with the stated objectives in Chapter1. Following this, the future prospects for the practical application are outlined to conclude the current research.

12.1. Summary

1. **Understanding of the conventional demolition process and the waste material flow**

According to the references and collected data in Chapter2, the waste flow from the demolition to the new construction phase is summarised from three point of views; i) demolition waste, ii) demolition planning and iii) academic approach. In terms of demolition waste, the current definition and position of demolition waste and the appropriate treatment methods are reviewed. For the demolition planning, the applicable demolition system and the methods involved are summarised to know how to apply them in practice. Finally, the academic approaches to the optimization of demolition waste treatment are surveyed to comprehend the applicable suggestions for demolition waste flow, which is the rationale for the suggested methodology in Chapter3.

2. **Suggestion of the DPM system**

The current demolition waste flow is mainly controlled by demolishers and salvage companies according to Addis (2006). To enhance the waste flow between demolition and construction projects, the collaboration system for the both stakeholders is suggested in Chapter 5.2. It was decided to develop a 4D impact evaluation tool for the online service based on the practical tool SMARTWaste. This suggestion aims to recreate the demolition planning from the input of target building data and to quantify the resulting impact. The social impact evaluation tool for estimating the social effect of the DPM application to society is also developed. The system development is analysed by the practitioners' feedback at the validation process in Chapter10 The challenges for the actual application of the model are identified by the requests of respondents for further development.

3. **Development of a 4D-CAD evaluation model for demolition projects**

An impact evaluation model using BIM data is developed in a 4D-CAD software, Blender, as a decision support tool for demolishers in the DPM system (in Chapter4). The demolition process is generalized into patterns by adapting algorithms to the machines and the building elements with a programming language, Python. This concept enables the creation of demolition systems and methods in the 4D simulation. Progress can be visualized and the waste demolition and the machine application are quantified in this approach. It allows the users to analyse the onsite safety, to understand the waste generation and to evaluate the demolition impact (e.g. cost, time) respectively. The impact results of different planning with algorithms are compared in the pilot study in Chapter4.2. According to the impact value, the optimal method of the machine operation and the demolition order setting are identified. By adopting this quantitative comparison, the feasibility of the impact reduction is examined with the actual project design in Chapter4.3. At the validation process in Chapter10, the structural analysis is suggested as an addition to the model simulation so that the simulation quality can maintain the enough feedback level to suggest to the onsite safety. In addition to this, the feedback requested the automated machine operation with the model algorithms.

4. Development of a demolition algorithm for the impact optimization

As explained in the previous section, the algorithms in the operation machines enables the visualization of progress and quantification of the waste generation and machine application impact as the total impact. The suggested algorithms are compared to identify the optimal choice using this function in Chapter5.2 The algorithms can be mainly classified into two groups, 'machine operation' and 'demolition order'. In 'machine operation', the 'individual' movement examines the algorithm efficiency of the single transportation and destruction while the 'tandem' movement considered the productivity resulting from the algorithms of machine interactions. For 'demolition order', the influence of demolition order with algorithms is examined by cost resulting from the main two factors; 'duration of machine operation' and 'recovered waste purity'. In Chapter8.3., three prospective demolition plannings with algorithms are applied to the actual building design based on this algorithms survey. As a result, the model ability to reduce the project impact is validated at the actual project BIM data. In other words, the current buildings designed with BIM can quantitatively suggest the optimal demolition planning with this model, which can save the project total cost from 19 to 28 %. Since this is only optimised among the input options, the optimization function should be, in the future, developed to create an optimal plan from the target building without planning input.

5. Application of the project evaluation model to pilot studies

After the above developments, the model applicability and the model ability in simulation to the actual building design is validated in Chapter8.3. According to the result, there main challenges are identified for the model adoptability; i) modelling of complicated structure elements, ii) increase of treatment time with data volume and iii) adoption of different data accuracy. Besides the improvement of the algorithm designs of object modelling and machine operation, the material conversion table should be developed to adopt a different accuracy level of BIM data. By unifying the criteria of the impact evaluation for planning, the cost and the environmental burden can be considered as the single factor of project impact to compare. Moreover, for the model ability, the advantage of the planning optimization through the project impact comparison is shown by the model simulation with three different scenarios. In addition, the tracking ability of hazardous objects is simultaneously evaluated in the scenario. The object locations keep being updated through the whole demolition processes, and their paths are consequently identified. By applying this function to the object units which are composed of the hazardous elements, all of the possible paths of the hazardous debris can be analysed, and the resulting waste component can be calculated. This makes it possible to quantify the safety risk for both the onsite labours and the waste operators.

6. Development of a social demolition impact model

The waste material flow from the demolition to the new construction in the UK can be recreated with the suggested AB model in Chapter9. The geographical information is described in the spreadsheet and the decision making of each agent (corresponding to stakeholders) is done by algorithms. The scenarios for the different DPM application rates can be designed by adding demolishers and constructers to those agents. Consequently, the significance of each factor in the social system can be identified for the multiple factors such as the user rate of DPM.

7. Validation of suggested models by practitioners

Questionnaires and interviews were held to collect feedback from the practitioners in order to validate the suggested models and system. As summarised in Chapter10 the questionnaires were held after the author's presentation in the IDE Scottish seminar, and the interviews were conducted with the demolition consultants in IDE who are assumed to be the most probable future model users. At the IDE seminar, feedback is received from 16 respondents from four different job categories; i) manager, ii) director, iii) engineer and iv) others. Suggestions were analysed for each respondents'' status as well as the length of their career in the demolition industry. Additionally, interviews were held with the two demolition consultants to discover their ideas about the necessity of BIM in the model and the application of the computational approach to demolition practice. The issues of the current suggested model and the challenges for the actual application of the system are clarified. Those are summarised in the following section to show the direction of further development of this research.

12.2. Benefits

The advantages of the application of the suggested impact evaluation model for the demolition project are summarised as following through the pilot study:

- Demolition project planning can be recreated in 4D with simple operation so that the project can be automatically simulated and the impacts of the process is estimated.
- The simulation enables users to visualize the progress in 4D (as animation) and it can be utilized as the visual aid for the project management and the safety analysis.
- With this simulation, the waste generation is understood from multiple points of view; generation location, time, volume and material component. According to these results, the onsite distribution can be visualized on a map and the total waste treatment cost can be estimated. A waste collection strategy can be analysed with this information.
- The simulation allows users to understand the duration of machine operation and their productivity. The efficient algorithms of machine operation can be assessed.
- The volume of elements treated in the soft-stripping process can be evaluated by the simulation. The users' designation of material type and application method are only required to assess the generated impacts in this process (e.g. time, cost, labour burden, environmental impact).
- The hazardous waste can be tracked in the simulation by recording the locational information of component units. This information can be utilised to visualize the path of hazardous wastes and to quantify the exposure risks of the onsite workers and the waste operators for the onsite safety analysis.
- The optimal algorithms can be suggested from the impact comparison between different planning. The model applicability to the demolition planning in an actual project BIM data is validated, in which up to 28 % of the cost and considerable amount of the environmental impact can be reduced.
- Approximately 20 % of the total environmental impact from the UK demolition can be ideally diminished by the DPM system application at the most. This is caused by the two main improvements; the demolition impact reduction with the impact estimation tool and the increase of the onsite waste application by constructers with a help of the DPM system.

12.3. Limitations

The limitations of the suggested model are summarised as following.

- The preparation of BIM data was requested to recreate the project planning in pilot studies. However, as shown in Chapter4.1., the 3D-CAD data and the attached material type information is actually needed for the model creation.
- The destruction simulation is not considered with the structural engineering but only the objects collision between the machine parts and the elements. Accordingly, there are some gaps with the debris behaviour in reality, in other words, the simulation accuracy of demolition methods, in particular the ones with the structural collapses, is not high enough for the safety analysis. For estimating those methods such as the implosion or the structure demolition with grapples, interactive analysis should be suggested with the external software of structural analysis in the future works.
- The machines are automatically operated in the simulation with the ideal operational conditions which results in a large gap with practice. The practical operation result should be reflected on the simulation result based on the ratio between the ideal and the actual operation time (i.e. necessity of a mock-up experiment). It also means the operational shift from the manual to automated has great potential to reduce the labour and the machine operation time. Further cost reductions can be achieved by the automated operation.
- The evaluation of the demolition processes which cannot be described with a simple destruction is compromised by the traditional static approach (multiplying a unit cost by time). As represented by the process of water sprinkling or site supervising, the labour working nearby the operating machines are to be simulated as well as the machine behaviour when the onsite safety is discussed. The model needs to be extended to simulate the labours' behaviour with algorithms.

12.4. Conclusion

The followings are the conclusions which the author reached in the present research.

- Reuse and recycle of demolition waste mainly relies on demolishers and salvage industry, and demolition planning is benefit-oriented in general. Following this, the DPM system and the demolition impact evaluation tool are suggested to enhance the material flow from demolishers to constructers. It can increase the information exchange of the waste recovery for new construction, which raises the market value of waste.
- The visualization function of the project planning and the impact evaluation can provide us with the time axis in the planning and impact estimation. The main demolition impacts can be assessed both from the machine operation and the waste generation properties, and it is accumulated with soft-stripping process to analyse the total project impact.
- The applicability of this tool is validated to the BIM data in the actual construction project in a pilot study as well as the ability of impact estimation. The tracking ability is simultaneously examined and its significance is regarded after visualizing the pathway of hazardous waste and calculating the component rate in the collected waste.
- By adopting algorithms into the machines in the simulation to automate their operation, the significance of project impact can be compared between different methods and strategies. According to this, the project planning can be optimized, and approximately 28 % of the cost and considerable amount of the environmental impact are reduced.
- The optimization can be decided from both the boundary condition (e.g. applicable machine number and scale) and the optimization condition (e.g. cost, project duration, sustainability). More flexibility is offered to the users at the project planning phase.
- Validation is held to collect feedback on the system from the practitioners. It reveals the users' demand for the high accuracy of the model simulation considering the structural analysis, and concern about the extra burden of the BIM data preparation. Meanwhile, the site management and the automated machine operations are expected to make large contribution in practice from respondents' feedback.
- An AB model is applied to develop a social impact evaluation tool for demolition. By setting algorithms to the agents (assumed as stakeholders), the change of total impact of demolition and subsequent waste treatment from agents' decision can be quantified.
- Using this social impact tool, the potential of the DPM system in terms of sustainability improvement in the UK society can be evaluated. Through a pilot study, up to approximately 20 % of the environmental impact can be theoretically improved by this system application at the most.

12.5. Future work

Regarding the further development of the current present research, three fundamental directions are of importance; i) resolution of the model shortcoming, ii) improvement of the model ability and iii) model extension of the practical application.

12.5.1. Resolution of the model shortcoming

- In the current demolition practice, the model requirement for the BIM data becomes a great obstacle. In addition to waiting for the cost reduction of the innovative BIM creation technologies (e.g. 3D scanning with UAV) for general use, the automated level1 BIM data creation tool should be developed. In order to minimize the users' burden, the conversion from 2D design to 3D one needs to be automatically accomplished by the computational elements identification suggested by Gimenez et. al (2016). The identified elements information in this technique can be attached to recreate the component material so that the minimum requirement level of BIM can be automatically created.
- Simulation accuracy is key to the model's application to health and safety analysis in which structural engineering must be involved. The interactive method with an external tool of structural analysis is suggested first. However, the simulation accuracy is expected to be more than required, and the data exchange may prolong the computation time significantly. In order to prevent such a case, the target project types can be confined to a restricted amount of data exchange such as the implosive demolition. Apart from that, the demolition projects need to be recreated in Blender including a structural analysis. Simple modelling and selection of the related objects are suggested to minimize the burden so that the current speed of simulation will not be affected.
- The tasks containing the labourers' work are currently evaluated with static approach in the model. It is, however, difficult to fulfil the health and safety analysis in the model where the interaction between machines and labours need to be considered. Accordingly, the labourers' behaviour and the layout of surrounding machines should be assessed by adding labour units in the simulation. Using the same concept as the machine algorithms, the units can be automated with decision making algorithms.

12.5.2. Improvement of the model ability

- The present optimization of the project planning can only select the best solution from the input of users' planning, so that the tool can be regarded as the decision support tool. In order to convert this tool to the self-suggesting optimization tool, the prospective project planning is to be equipped with learning algorithms from the database. The supervised machine learning method is suggested, which is an optimization method classifying results according to the previous decision. According to the existing planning with higher evaluation (e.g. cost against treated floor area), the promising demolition planning can be suggested based on the target building properties (e.g. floor area, construction type, demolition period). After narrowing down to several plans, the impact estimations for each planning can be simulated in the model to decide an optimal suggestion. In case of the innovative planning without any references in the database, optimization methods such as GA can be applied to decide the project setting (e.g. applied machine number, type, scale). Although the suggestion may converge at the local solution at the beginning of this approach, the suggestion should reach to the global solution as the tool is continuously applied and enriches the database.
- The application of the simulation result to achieve the automated operation of machines onsite is expected by practitioners to be advantageous, which results in the enhancement of the model application in practice. Compared to the existing application technology suggested by Kajima Corp (2015) for the individual machine operation, the control of multiple machines based on the whole project planning must produce better productivity overall. The most important benefit of automation is not the productivity but the non-attendance of labours onsite. As mentioned at the discussion of hazardous waste tracking, the risk of labours being involved in any accidents can be prevented by the separation of workers from the site. Further research is to be achieved through the mock-up experiments for the application in practice. For example, the influence of onsite circumstance to the machine operation is examined, and the possible solution for the accidental collision with unexpected intruders or misplaced items are also investigate for the safety operation.

12.5.3. Model extension for the practical application

- In the present research, the model development and the effect of system application are investigated through several pilot studies. To realize the practical application of the system, a service and a way of providing it should be suggested more precisely. This requires the establishment of the online service for demolishers and constructers to allow them to simulate the project planning and to survey the published project data. Before the application, the bulk data treatment and the resulting computational burden should be accommodated by the server and the computer performance. In addition, the issues associated with the agreement between stakeholders and the contract between the system administer and the users should be legally clarified. In other words, the structure of service must be decided from the two main options. The government-driven service which aims to reduce the environmental impact can be offered for free to the users while the company-driven service which is more benefit-oriented can be offered with a contract fee similar to the SMARTWaste.
- Regarding the practical application, the initial cost for the system establishment is suggested as the valuable investment to decide the system application. The risk of such investment should be evaluated from the calculation of the gap between the current and the planned facility distributions. Therefore, the suggested social impact evaluation model can be extended to quantify those gaps. Since the service can decide a prospective service driver and a service structure according to the result (e.g. government-driven with high expectation of sustainability improvement or company-driven with high expectation of business), this factor is expected to make a vision of application more concrete.

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Appendix

Appendix1. Legislations and assessment tools

A1.1. Drivers of sustainability development at C&D process

As mentioned in the previous section, sustainability of demolition and construction has been encouraged from two main aspects. While government and local authority legally set more demanding requirements for disposal at the demolition phase, assessment tools for environmental impact give incentives to new constructions which utilize reused and recycled materials. All related current regulations, standards and assessment tools are discussed in this chapter to comprehend the effect on the flow of demolition waste between demolition and the next construction phase. This is expected to be pivotal for making a simulation model more realistic.

A1.2. Legal restriction

Legal restriction can be separated into four types, directives, acts, regulations and standards. Directives are defined by European Union (EU) as the goal that member countries need to achieve. According to the requirement, national authorities can set their own laws, based on countries circumstances to fulfil within deadline. This gives a common point on different national laws so that the operation of a single market would be globally comparable (European Commission, 2013). On the other hand, acts treated here are the legislation set by UK Parliament to create a new law or change an existing law. This is implemented on the whole or specific parts of the UK by the relative government department. Following acts, which are in a primary position of legislation, regulations are set by the administrative agencies to empower them. Though regulations do not have a direct influence on laws, the sentences to implement laws depend on agencies, and the actual content of law differs in every area.

While the first three have legal power, standards do not have it themselves but they tend to be applied to those regulations for establishing detail without blurring policy objectives. It, however, infers the compliance with standards does not necessarily mean being compliant with legislation (BSI , 2013). Accordingly, this study limits standards which have a certain description in the above legislations or have been admitted applications by government or local authority, regarding as compulsory requirements. On the other hand, the other standards suggested for proper implementations are referred at the design of simulation model in following chapters.

A1.2.1. Act, regulation, directive and Standards

Waste and Resources Action Programme (WRAP) (2011), a not-for-profit company established in 2000 focussing on waste reduction and resource utilization, introduces the legislation applied in the UK for demolition waste treatment and sustainable construction practices. WRAP has been tackling the aggregate program funded by the Department for Environment, Food and Rural Affairs (DEFRA) since 2002 to improve aggregate sustainability from dual aspect, the use reduction of natural aggregate and increase of waste aggregate. Accordingly, these legislations chosen by WRAP can be regarded as related to the waste stream. In addition, it is also considered to be important to refer the *Guidance Note3: Construction, Demolition and Excavation of Waste Materials* (Department of Finance and Personnel, 2010) which explains the relating legislations to be applied on demolition in the UK. The whole legislations mentioned in both references and relevant ones are summarised in Table 79 and Table 80 for demolition waste treatment and new construction phases, respectively. Looking back to the waste treatment flow as shown in the previous chapter, it can be summarised as Figure 135. According to this definition of each phase, the timing for application of the legislations is introduced step by step.

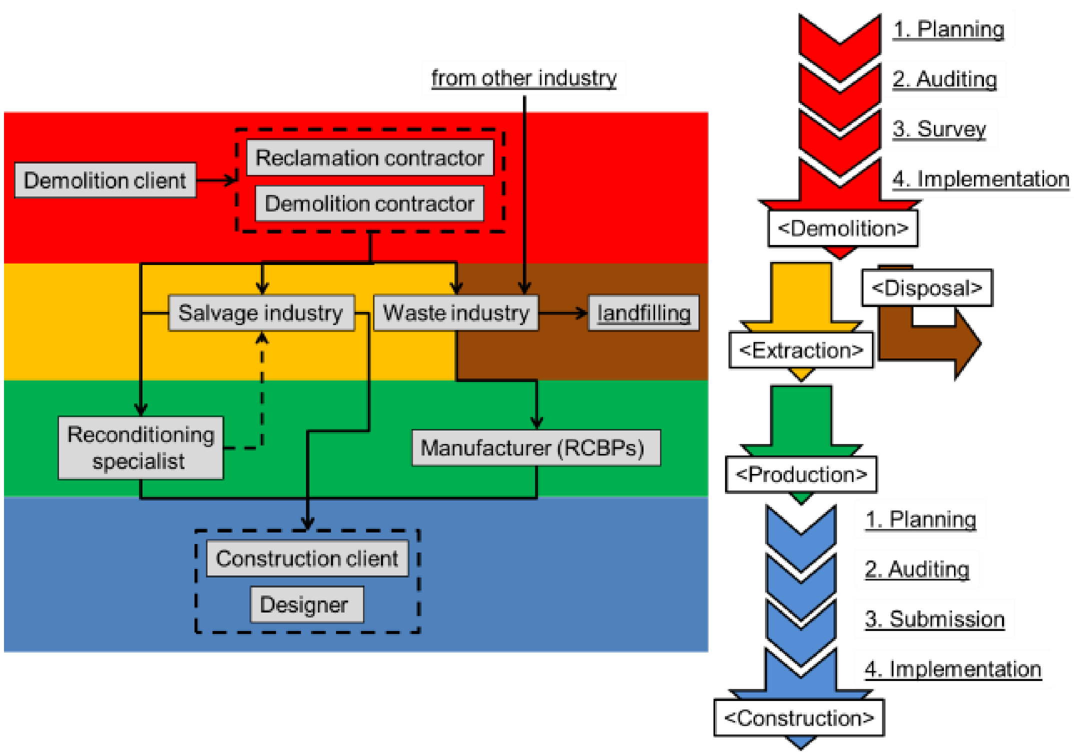


Figure 135 Abstract of Waste treatment flow

<Demolition Phase>

At the planning phase, legislation requirements are considered after the pre-survey of the demolition target, including hazardous components. There are mainly two parts that the demolition team needs to plan. Firstly, the demolition activity needs to be in accordance with the prevailing legislation. Here, health and safety of the demolition process is to be planned and implemented with the Construction (Design and Management) Regulations (CDMR). In addition to this, the Site Waste Management Plan (SWMP) needs to be submitted for construction or demolition projects over 300k pound in England according to the SWMP Regulations. This aims to improve resource efficiency and prevent illegal waste activities by ensuring stakeholders assess the optimal treatment of waste material and waste. This is achieved by the comprehension of building component and prospective waste generation through the audit process.

Following the planning of the demolition process, accordance with waste management regulation needs to be the next step. Fundamentally, stakeholders for the waste stream need to take responsibility of sustainable waste management according to the Environmental Protection (Duty of Care) Regulation (DCR). The operation of waste treatment activities was separated from where they need to be certified (Environmental Agency or local authorities) by the Pollution Prevention and Control (England and Wales) Regulations (PPCR), and it set the exemption for specific operations. For the certification of stakeholders, the Waste Management Licensing Regulations (WMLR) established the 'waste management licence system' according to the Environmental Protection Act (EPA) Part II. This set the requirement of authorization for waste treatment operation to treat waste by competent specialists. Those two have been revoked by Environmental Permitting (England and Wales) Regulations (EPR) since 2007, which also implements other European Directives and national policy (e.g. IPPCD, WFD and LD) through the authorization called permitting system. Similar to this, Waste (England and Wales) Regulations (WR) has revoked those two regulations and askes stakeholders to treat waste at high hierarchy method to reduce environmental impact. For the proper treatment for each waste component, here, the Controlled Waste Regulations (CWR) categorizes wastes and sets the required collection and disposal charge. Following this, each waste is treated in own ways such as the Waste Electrical and Electronic Equipment Regulations (WEEER) legalizes the responsibility of producers not to send WEEE containing chlorofluorocarbon (CFC) and other hazardous substances to landfill. For the treatment of hazardous waste, waste is categorized by the List of Waste Regulations (LWR) and its movement is required to be controlled and monitored for both cases of recovered and disposed by Hazardous Waste Regulations (HWR). This is actually surveyed at soft-stripping process. Main demolishment is implemented under the project plan responding to the above regulation, and the generated waste is transported to following phases.

<Extraction and Production Phase>

As mentioned above, there are several regulations requiring the sustainable waste treatment by stakeholders. In detail, EPR decides the necessity of permit for extraction and production operation; DCR sets the requirement for safety handling and WR makes stakeholders use high hierarchy method to treat wastes. It is worth noting that the consideration of legal limitation for the use of recycling material is not discussed here but at the section on the construction phase.

<Disposal Phase>

In addition to the requirement mentioned above, as landfilling causes only negative impact compared to extraction processes, the government and local authorities set a tax to discourage this flow in waste stream in the Landfill Tax Regulation (LTR). Moreover, the waste components had been categorized by Landfill (England and Wales) Regulations (LR) since 1991, and some of the considered harmful components had been banned from landfill. From 2007, a revoking legislation, EPR, includes the requirement of pre-treatment for the reduction of landfilling.

Table 79 Legislation for demolition waste treatment

Directive
Waste Framework Directive (WFD) / (1975),1991, 2008*
It makes member countries to set the obligation to prevent an environmental damage through waste treatment including stakeholders such as holder, collector and transporter.
EPA implements this in the UK.
Hazardous Waste Directive (HWD) / 1991*
It sets the hazard waste treatment formwork. This clarifies the requirements at each treatment process (identification, handling, storing, treatment and disposal).
This works with WFD. HWR implements this in the UK.
Landfill Directive (LD) / 1999*
It classifies the waste type and the site acceptance of landfilling. It also requires the pre-treatment to divert waste from landfilling to recycling.
LR implements this in the UK.

Integrated Pollution Prevention and Control Directive (IPPCD) / 1996, 2003', 2008, 2010*
It makes the system to protect the environment as well as human health with integrated method for pollutants control. The procedure to get an operation permit and minimal requirements are described.
PPCR implements this in the UK.
Waste Electrical and Electronic Equipment Directive (WEEED) / 2002, 2006', 2009', 2012'*
This aims to set the proper treatment for WEEE possibly containing hazardous substances. It sets the requirement for registration of product and treatment processes (collecting and treating).
WEEE regulations are set in the UK to implement.
Act
*Environmental Protection Act 1990, Part II (EPA)** / 1990*
To prevent the waste treatment process from damaging environment, it provides the principle of licencing controls and other provisions. It also defines the responsibility of stakeholders to handle wastes adequately.
DCR cites large part from this.
*Environment Act (EA) *** / 1995*
It established Environment Agency in England and the equivalents for the other regions such as the Scottish Environment Protection Agency (SEPA) to achieve regulatory function for sustainable development in the UK.
Pollution Prevention and Control Act (PPCA) / 1999
It is set to implement IPPCD in the UK.
PPCR reflects this.
Regulations
Construction (Design and Management) Regulations (CDMR) / 1994, 2000', 2007
It requires the planning of safe implementation of construction activity including demolition. Besides the responsibility of each stakeholder, it requires the proper communication between them.

*Site Waste Management Plan Regulations (SWMPR)**** / 2008*
It requires the submission of SWMP before demolition to clarify the demolition project detail and certify it accords regulations.
*Environmental Protection (Duty of Care) Regulations (DCR)** / 1991, 2003**
It declares duties for the safe waste handling and the accordance with laws on stakeholders of waste industry.
LTR follows this.
*Pollution Prevention and Control (England and Wales) Regulations (PPCR)*** / 2000, 2001', 2002', 2003', 2004', 2005', 2007'*
According to the IPPCD, it defines the integrated pollution control by environmental agency and local authority for installations or mobile plant operation under section2 of the PPCA 1999.
It is revoked by EPR.
*Waste Management Licensing Regulations (WMLR)*** / 1994, 1995', 1996', 1997', 1998', 2002', 2003', 2006'*
It aims to provide formwork of a 'waste management licence system' according to the EPA 1990 (Part II) besides the setting of regulations for waste management to implement WFD.
It is revoked by EPR which also transposes IPPC Directives.
*Environmental Permitting (England and Wales) Regulations (EPR)** / 2007, 2009', 2010, 2011', 2012', 2013'*
This was originally set to combine PPCR and WMLR. It aims to fulfil sustainability with minimal regulatory burden for stakeholders.
It contains IPPC, WFD and LD at Schedule 7-10.
*Waste (England and Wales) Regulations (WR)**** / 2011, 2012'*
It askes stakeholders to treat waste at high hierarchy method to prevent environmental impact from demolition.
Controlled Waste Regulations(CWR) / 1992, 1993', 2012
This categorizes wastes and sets the required collection and disposal charge.

*Hazardous Waste Regulations (HWR)**** / 2005, 2009'*
To implement HWD, it sets the guideline how to control the hazardous waste movement.
List of Waste Regulations (LWR) / 2005
It distinguishes wastes from hazardous or not, and codes those hazardous materials.
*Waste Electrical and Electronic Equipment Regulations (WEEER)**** / 2006, 2007', 2009', 2010'*
According to the WEEED, it put the responsibility not to send WEE to landfill to producers.
*Landfill (England and Wales) Regulations (LR)** / 2002, 2004*, 2005**
To prevent the landfilling from damaging environment, it provides the definition of classification and the acceptance criteria.
It is revoked by EPR which also imposes LD.
Landfill Tax Regulations (LTR) / 1996, 1998'~2013'*
It sets the required procedure for landfilling of material including tax payment. The revenue of tax is used for the support of reduction and recycling of waste scheme called LTCS.
It is amended from the Finance Act 1996.

(source: *Edinburgh University, 2008, **WRAP, 2010a, ***Defra, 2013, ****Environmental Agency, 2013)

<Construction Phase>

To think about the legislation relating to the waste stream at the construction phase, the regulation for reuse and recycling and for the management of construction waste are regarded as important. There is some concern for the influence of reuse and recycling products on the building performance. Because of this, as the first group, the legislations cover the building ability and construction procedure need to be studied. This group is represented by the Building Act (BA) and Building Regulations (BR), Sustainable and Secure Buildings Act (SSBA) and Regulations (SSBR) and CDMR.

In addition, as the second group, some focus to develop the sustainability of the building project. This is mainly induced to the official stakeholders (e.g. social project promoter, Secretary of State and local government) to implement the sustainable development on whole construction projects or significant social projects, which is regulated in the Planning Act (PA) and Sustainable and Secure Buildings Act (SSBA).

Following this, as the third group, the assessment tools and standards which evaluate the sustainability of construction project is included since the intensive of high rank certification with them increases the asset value. Otherwise, some social projects are required to satisfy some certain level of requirement in the law. This group is represented by the Code for Sustainable Homes (CSH), EcoHomes and BREEAM.

Finally, the legislations which require the proper waste management at construction phase are expected to affect the construction plan in practice. This aims to minimize the generation of construction waste with the decent project design at pre-construction phase, and it includes Clean Neighbourhoods and Environment Act (CNEA). This aspect of sustainability in the construction plan is also included in the evaluation target of assessment tools, introduced above. In accordance with each feature of four groups, the necessities to consider legislations at the process of construction projects are described step by step.

The planning phase can be separated into four steps; setting, designing, audit and programming step. As the first part of setting, project goal is set according to the requirements suggested by regulations and standards. There are two types of concept here, to achieve the high certification of building assessment for enhancement of asset values and to satisfy the mandatory baseline in regulations. BREEAM and other assessment tools introduced at following sections are included for the first aim, while EcoHomes*[1] and CSH can be included for both aims. Though EcoHomes was replaced by CSH and the BREEAM Domestic Refurbishment for the application of new construction and refurbish project, it

*[1] EcoHomes was launched in 2000 and set as the mandatory assessing for social building in 2003. This can be applicable to the new and existing building, private and social housing and flat/apartments and houses. The application of new building has been replaced by CSH in 2007 so that it was expired at April 2012. In addition, the application to refurbishment plan was also replaced by the BREEAM Domestic Refurbishment in 2012 so that in 2014 it will be expired as well. (BRE, 2013b))

was mandatory for social housing to be certified by EcoHomes (BRE, 2013b). In addition, the compulsory application of CSH to new homes under the consultation document from DCLG was confirmed in 2008 (though it has not implemented yet) (WRAP, 2010a). In the project team organized to achieve this goal, the approval person should be added from beginning of project to flexibly reflect the consideration of above requirements on plan. Besides the approval person for assessment tools and standards such as BREEAM and CSH, BR also suggests the choice of certification by approval person to verify the project satisfaction with 14 types of techniqueal requirements in BR. In addition, CDMR requires the organization of proper project team to achieve healthy and safety site in the construction process. As the approval person from outside, besides the necessity of a CDM co-ordinator for notified projects, a planning supervisor is to be appointed by clients to produce a pre-tender health and safety plan (Griffin and Howarth, 2001).

Health and safety is also considered at the designing step. Designers are obliged to design for safety, combat risk at the source and include adequate information in design (Griffin and Howarth, 2001). Moreover, the ability of energy consumption is also necessary to design in accordance with the requirement of Energy Performance of Building Regulations (EPBR), which is also included in BR from 2010. As they only consider the energy consumption, the reduction of embodied CO_2 from reuse and recycling is not evaluated here. After the decision of final design to achieve above abilities, the materials and products to apply are designated in accordance with the Construction Products Regulations (CPR). This originally aimed to certificate the material and product quality which is applied in European area with the standards of Committee European Normalization (CEN). After the change from Construction Products Acts (CPA) to CPR in 2011, it has covered the reused and recycled materials and products, and has required the CE mark certifications (Construction Production Association, 2013). It is also necessary to consider whether the applied materials are excluded from the 'short-lived material' or 'unsuitable material for permanent building' which are mentioned in BR. This is evaluated by the local government in accordance with BR, and their use results in the rejection or modification of project or the reduction of building service life (Uff, 2009). On the other hand, the application of waste materials also gives an advantage for the evaluation with assessment tools and standards. For instance, in the chapter of CSH, 'Material 1: Environmental Impact of Materials', the element achievement with materials evaluated as 'A+' to 'D' in the Green Guide for Housing Specification for at least three elements gives credits according to the reduction of environmental impact (CSH, 2010). The equivalent chapters can be found in many other BRE's tools such as EcoHomes and BREEAM.

At the auditing step or it can be said the cost planning step, the extra financial burden from the application of assessment tools should be a concern. This derives from the extra tasks to satisfy the requirements and achieve high evaluation score. Abdalla et al. (2011) compare the project budget with and without BREEAM assessment, and report the possibly higher budget or the risk of cost overrun for the satisfaction of BREEAM requirements. They also point out no reflection on the score for a project management prospective in BREEAM evaluation, especially from financial view. Accordingly, the project team needs to be concerned with project feasibility while achieving the set level of evaluation.

At the programming step, the appropriate management of material stream can contribute not only to improve the project efficiency but also the sustainability of material use. The sustainable use and treatment for the waste generated at the construction process is required to treat with SWMP in the Clean Neighbourhoods and Environment Act (CNEA). In the chapter of CSH, 'Waste 2: Construction Site Waste Management', it evaluates whether project focuses on minimization of construction waste and diversion of waste from landfill, basically referring to the SWMP content of project (CSH, 2010). Additionally, CDMR compels a primary contractor to produce the construction health and safety plan according to the pre-tender health and safety plan. This aims to ensure the health and safety of people to be affected by the project before the project commences.

After the whole process of planning, under the BR, firstly people need to submit a 'building notice' (or full project plan in some specific case) as a self-certification or a certification from 'approved person'. Then, the plans are to be judged by local authority and it might result in some parts of modification or a rejection of plan.

As the implementation phase, the project program is implemented onsite with the approval of the local authority to commerce construction. Here, the inspection of local authority for BR and the evaluation at pre-construction stage of assessment tools and standards are to be held. The site record and inspection are used to verify the project held in proper way which can achieve the prospective result assessed at the design phase.

Table 80 Relating legislation for new construction

Directive
Construction Products Directive (and Regulations (EU)) (CPD and CPR) / 1989, (2011)
It adopts standards of Committee European Normalization (CEN) to put the required level of construction materials. It also specifies reused and recycled material for the application to new construction.
Regulations affect the English BR, especially on Regulation7 (Materials and workmanship).
Energy Performance of Buildings Directive (EPBD) / 2002, 2010, 2013
It aims to improve the building energy performance from four parts; establishment of calculation

measure, setting of minimum requirement, enforcement of certification and inspection of boiler and air-conditioning.
Act
Planning Act (PA) / 2008
It aims to achieve significant infrastructure planning with system enhancement. It sets Infrastructure Planning Commission (IPC) to authorize nationally significant projects. The government is empowered to put National Policy Statements (NPSs). Project promoters are required to consult with parties relating to a project.
It amends Town and Country Planning 1990 and Planning and Compulsory Purchase Act 2004 applied for town and country development before.
Clean Neighbourhoods and Environment Act (CNEA) / 2005
It aims to maintain the environment of site and its neighbour from the impact of activity onsite. At the Part5: Waste, it mentioned the necessity of regulation for site waste management plans (current SWMPR).
PPCR reflects this.
Sustainable and Secure Buildings Act (SSBA) / 2004
It aims to add the sustainable concern to the building regulations. The suggestion to concern sustainability covers the whole lifecycle under the Building Act 1984.
Building Act (BA) / 1984
It aims to achieve three main goals; securing the health, safety, welfare and convenience of in and about of building, the energy saving and reduction of material cycle (wasting and using). Secretary of State is empowered to make regulations to achieve this targeting building owners and occupants.
Regulations
Construction Products Regulations (UK) (CPR) / 1991, 2013
It requires the construction material to satisfy the suggesting requirement. The certification of conformity to CE marking and other equivalences is required for manufacturers or agents and held by a certification body.

Energy Performance of Buildings Regulations (EPBR) / 2007, 2008~2013**
It requires the comprehension of building energy certificate by stakeholders so that it mandates for a relevant person to offer the energy certificate, to building owner after construction and to prospective owner if they sell or rent a building.
The evaluation of building performance needs to be done by the approved person under Building Regulations 2000.

Building Regulations (BR) / 1985, 1989*, 1991, 1992*, 1994*, 1995*, 1997*, 1998*, 1999*, 2000*, 2010, 2012*, 2013*
According to the BA, it describes the procedure of building project and the power of local government. It uses approved documents to clarify the requirement in practice.
Standards
Code for Sustainable Homes (CSH) / 2006
It aims to be a common standard for all construction industry to give the initiative by government to improve the sustainability of building and its activities. . This mainly requires energy saving, efficient material use and the comfort of residents.
EcoHomes scheme suggested by BRE Global is the base to evaluate and certify the new building sustainability.

(source: WRAP, 2010b, and own documents of CPR, 1991, PA, 2008, CNEA, 2005, SSBA, 2004, BA, 1984, EPBR, 2007, BR, 1991, 2010, CSH, 2010)

A1.2.2. Prospective effect of legal restriction on waste flow

Regarding to the legal restriction, waste flow is mainly organized to suit demolition phase regulations and construction regulations; and the interim phases, extraction, production and disposal phase, can be regarded as an extension of waste control from the demolition phase. At the demolition phase, the regulations have three main functions; to establish the framework of waste treatment system in the UK, to ensure safe waste treatment, and to achieve a sustainable waste treatment.

The framework of the system is started from the categorization and identification of waste under CWR and LWR. Then, the responsibility of waste treatment and necessary act for each stakeholder is specified by EPR (which revokes PPCR and WMLR). The stakeholder, waste component and its flow in the UK treatment system can be identified here.

Safety of waste treatment implies both the safety during demolition project and the proper treatment of hazardous or other substances having a risk. CDMR aims to maintain the site health and safety for all people who can be exposed to the influence of the demolition project. It requires not only the identification of hazardous components in building members and its proper treatment, but also the project design to minimize the human risk during the demolition process. This may hinder the application of certain demolition method such as using explosives, regardless of the environmental impact.

To develop the sustainability of waste treatment, SWMPR and WR are regulated to force stakeholders to treat waste with the most sustainable methods or strategies onsite and offsite. As this research suggests that in order to treat waste in the most feasibly sustainable way, the limitation from those regulations seems less influential than safety concerns.

Though the most part of regulations at the interim phases are covered by the waste treatment policy mentioned from demolition phase, landfill should be noted here in terms of the influence to decide optimal waste treatment method. LTR sets the landfill tax to be paid according to the type of waste. The price and the type of material which is accepted by landfill site are assumed to influence the project design in terms of budget including transportation.

At the new construction phase, the basic function types of regulations are similar to the demolition ones. It has CDMR and SWMP application from CNEA to achieve the health and safety and sustainability of construction project. Following this, there is BR which establishes the procedure of construction project. As the other feature of BR, this requires the building ability as EPBR for the building energy use ability. Including the content of its reference act, BA, the application of reused and recycled material can be regarded as the 'short-lived material' or 'unsuitable material for permanent building'. Since there are some possibilities to be modified or designated a certain material treatment, reused and recycled material should refer CPR which certifies the construction material to assure the practical application onsite. In addition to this, the existence of assessment standard, CSH, for project sustainability differs the construction phase from demolition. Due to the incentives given from the high evaluation from assessment standard, the application of reused and recycled materials can be justified as the implementation of sustainable treatment of construction waste. However, as mentioned above, the implementation of those strategies tends to cost more than conventional project so that the financial aspect should not be ignored when assessing the project feasibility.

To sum up the influence from the legislation, the regulations for treatment sustainability seems less influential to the optimal suggestion from this research than other regulations. This is because their final goal is, as this research, to achieve the most feasibly sustainable treatment through the imposition of each role on the stakeholders and its implementation. On the other hand, the regulations of health and safety and tax add the other factors to be concerned at the project design stage. It is necessary to achieve the most sustainable treatment satisfying the safety and financial aspect of projects at the same time.

A1.3. Assessment tools for environmental impact

The increase of awareness against sustainability development can be seen in the business reports to government in Europa. Commencing with 'Bruntland report' (1987, UK), 'Stern report' (2005, UK) and 'Garnaut report' (2007, Australia) showed the predictions that 'business as usual' approach from Green gas emission lead global economy in long span. With IPCC prediction of climate change, it stimulated the adoption of sustainability to reduce climate change from green gas emission. In the UK, Sustainable Development Educational Panel decided to include this criterion in all course accreditation requirements for profession and leading bodies in 2010. As a result of official movement, early studies focus on 'business case' which needs to concern about environmental risk in the real estate sector. There were approximately 600 tools in 2004 to evaluate the sustainability on social, environmental and economic aspects regarding to the use and management of local resources (Reed et al., 2009). This can be seen in Figure 136 that following to BREEAM in the UK many assessment tools are globally suggested.

While there is diversity of assessment tools as mentioned above, most of them derive from few main tools such as BREEAM and LEED as shown in Figure 137. They have own assessment systems to adopt locality. Thus, it is important to categorize them from the purposes, the way of measurement or assessment and the influence on a sustainable development from practice and procedure change. Fowler and Rauch (2006) also summarize the origin of tools as shown in Table 81, and compare their feasibility to apply to buildings administrated by the U.S General Services Administration (GSA). In their research, as described in Table 82, they find four prospective tools satisfying four required aspects for practical application; BREEAM, CASBEE, GB Tool (today it changes a name to SBTool), Green Globes and LEED. According to this, those tools except Green Globes which is regarded as modified BREEAM for Canada are regarded as the main assessment tools applicable in worldwide in this study. Thus, in this session, the features of four tools are discussed first through the comprehension of background and evaluation system. The comparison of their features is expected to suggest future possibility of assessment tools globally applied. This also gives a suitable method to evaluate the effect of evaluation with assessment tools on waste stream to make a social system model.

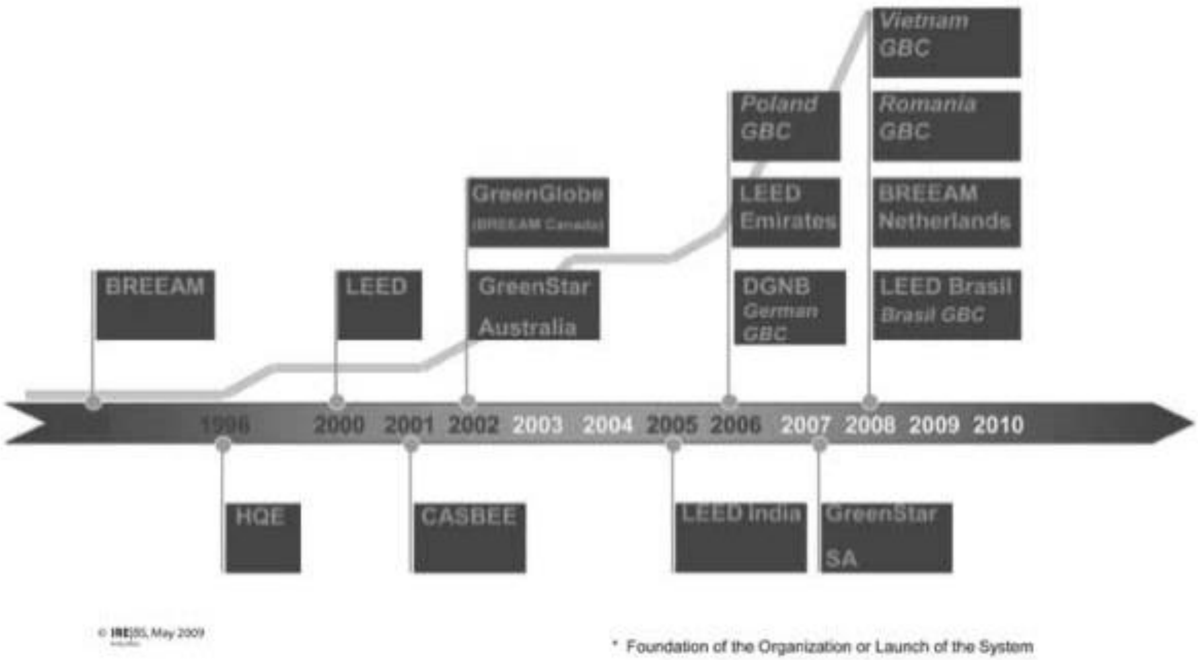


Figure 136 Timeline of global development of rating system

(source: Reed et al., 2009)

Figure 137 Distribution of LEED and BREEAM based assessment tools

(source: Reed et al., 2009)

Table 81 Development Basis of rating systems

Sustainable Building Rating Systems	Development Basis
BREEAM (Building Research Establishment's Environmental Assessment Method)	Original
BREEAM Canada	BREEAM
BREEAM Green Leaf	BREEAM, Green Leaf™
Calabasas LEED	LEED®
CASBEE (Comprehensive Assessment System for Building Environmental Efficiency)	Original
CEPAS (Comprehensive Environmental Performance Assessment Scheme)	LEED®, BREEAM, HK-BEAM, IBI
Earth Advantage Commercial Buildings (Oregon)	Undisclosed
EkoProfile (Norway)	Undisclosed
ESCALE	Undisclosed
GBTool	Original
GEM (Global Environmental Method) For Existing Buildings (Green Globes) – UK	Green Globes Canada
GOBAS (Green Olympic Building Assessment System)	CASBEE, LEED®
Green Building Rating System – Korea	BREEAM, LEED®, BEPAC
Green Globes Canada	BREEAM Green Leaf
Green Globes™ US	Green Globes Canada
Green Leaf Eco-Rating Program	Original
Green Star Australia	BREEAM, LEED®
HK BEAM (Hong Kong Building Environmental Assessment Method)	BREEAM
HQE (High Environmental Quality)	Undisclosed
iDP (Integrated Design Process)	Original
Labs21	Original
LEED® (Leadership in Energy and Environmental Design)	Original
LEED Canada	LEED®
LEED India	LEED®
LEED Mexico	LEED®
MSBG (The State of Minnesota Sustainable Building Guidelines)	LEED®, Green Building Challenge '98, and BREEAM
NABERS (National Australian Built Environment Rating System)	Undisclosed
PromisE	Undisclosed
Protocol ITACA	GBTool
SBAT (Sustainable Buildings Assessment Tool)	Original
Scottsdale's Green Building Program	Undisclosed
SPiRiT (Sustainable Project Rating Tool)	LEED®
TERI Green Rating for Integrated Habitat Assessment	Original
TQ Building Assessment System (Total Quality Building Assessment System)	Original

(source: Fowler and Rauch, 2006)

Table 82 Satisfaction of rating system for screening criteria

Rating System Name	Relevance	Measurable	Applicability	Availability
BREEAM	✓	✓	✓	✓
CASBEE	✓	✓	✓	✓
CEPAS	✓	✓	✓	-
Earth Advantage Commercial Buildings	✓		-	✓
EkoProfile	✓	✓	-	-
ESCALE	✓	✓		-
GBTool	✓	✓	✓	✓
GOBAS	✓	✓	-	-
Green Building Rating System	✓		-	-
Green Globes™ US	✓	✓	✓	✓
Green Leaf™	✓		-	✓
Green Star	✓	✓	-	✓
HQE	✓		✓	-
iDP	✓	-	✓	✓
Labs21	✓	✓	-	✓
LEED®	✓	✓	✓	✓
MSBG	✓		✓	✓
NABERS	✓	✓	-	✓
PromisE	✓	-	-	-
SBAT	✓	✓	-	-
Scottsdale's Green Building Program	✓	✓	✓	-
TERI	✓	✓	✓	-
TQ Building Assessment System	✓		✓	-

(source: Fowler and Rauch, 2006)

A1.3.1. BREEAM

Here, BREEAM new construction 2011 and Green Guide to Specification (4th) 2009 is discussed. Though BRE has already published a standard for existing building in 2012 and introduced at their official webpage, it is not possible to discuss it because its standard only mentions about the framework and not the detail of these single requirement today. Thus, the concept and discipline of BREEAM is discussed based on it for new building and the applied material selection guide which is also made by BRE group.

< BREEAM new construction 2011>

Background

An independent third party approvals body, BRE Global Limited (included in BRE Group) suggests BREEAM to offer certification of sustainability product and services. Those tests are held by world renowned testing laboratories, and it becomes world's leading environmental assessment method for building. BRE Global Limited is accredited by United Kingdom Accreditation Service (UKAS) to BS EN ISO 17024 (Conformity assessment –General requirements for bodies operating certification of persons) for BREEAM assessors ability, and to BS EN 45011 (General requirements for bodies operating product certification product) for complete process. As the framework of European Standards CEN/TC 350 which mainly focuses on environmental performance assessment of building, CEN (the European Committee for Standardization) contains BREEAM 2011 for majority part with other social performance and economic measures (BRE, 2011).

BREEAM targets on the environmental, social and economic impact from building through four phases: design, management, evaluation and certification. This is decided from whether it complies with set requirement and principle. Therefore, the scheme document of BREEAM is updated on time. In detail, BREEAM has four aims, (i) to mitigate the life cycle environmental impacts of building, (ii) to be recognized environmental benefits, (iii) to provide environmental label for building and (iv) to stimulate sustainable demand. To make BREEAM possible to apply for diverse types of building, it has a several standard category of non-domestic building. This allows fairly evaluation for most types of buildings. Otherwise, tailored evaluation can be applied by BREEAM assessors. The small size of building is not applicable of BREEAM 2011, and needs to wait extension (BRE, 2011).

Evaluation system and target

BREEAM is scored by the accumulation of credits for nine basic sessions. Each session has defined number of requirements, and building gets credits if it complies with these requirements. The total score can be calculated by credits and weighting of sessions. In addition, there is one specific session, 'Innovation'. This session is awarded for the technologies which have not been assumed by conventional requirement set by BREEAM (those are separated from unexpected degree of improvement and methods). Accordingly, 10% of addition can be possibly added from the application of Innovation technology.

There are two phases for the introduction of BREEAM to building lifecycle; design stage and post-construction stage. At design stage, it assesses the performance of design and confirms the appropriate communication between stakeholders such as designer, client and BREEAM assessor for sustainability request and principle. This is reviewed at a post-construction stage whether it has been completed as planned. This stage also includes the asset for post-construction and, as well as designing, this would be reviewed after completion of the building works.

As mentioned above, BREEAM score is calculated by credits and weighting of each section. This weighting as shown in Table 83 is decided by explicit weighting system from consensus based on a panel of experts, which results are also applied to BRE Green Guide and BRE Environmental Profiling Method for construction material. This score is rated according to benchmark shown in Table 84 to allow people to compare the building ability. Here, unclassified implies a building does not comply with the minimum requirements of BREEAM. Although BREEAM admits an off-set (which is called 'balanced score-card') from one area to the other, it has minimum requirement for each and needs to clear for each rating level. In addition, the certification of BREEAM evaluation is only verified if the assessor complies with BS EN ISO 17024 (Conformity assessment –General requirements for bodies operating certification of persons) (BRE, 2011).

Table 83 Weighting of BREEAM evaluation (2011)

Environmental section	Weighting
Management	12%
Health & Wellbeing	15%
Energy	19%
Transport	8%
Water	6%
Materials	12.5%
Waste	7.5%
Land Use & Ecology	10%
Pollution	10%
Total	100%
Innovation (additional)	10%

(source: BRE, 2011)

Table 84 BREEAM Rating (2011)

BREEAM Rating	% score
OUTSTANDING	85
EXCELLENT	70
VERY GOOD	55
GOOD	45
PASS	30
UNCLASSIFIED	<30

(source: BRE, 2011)

Feature of tool

As one of the positive features of *BREEAM new construction 2011* as an assessment tool, the evaluation of each session is quantitatively defined so that it is easy to distinguish whether a building satisfies requirements. As these requirements tend to include several checking points, only the highly oriented building can be awarded credits. The necessity of assessor for evaluation also helps to establish the fairly evaluation system. Besides, the setting of Section 'Innovation' as the extra score and the acceptance of setting off between individual sessions accepts a flexible and new environmental approach to sustainable building design.

On the other hand, the weighting is only applied to the sectional level but not to the sub-sectional level. Although the weighting seems to be reflected from the set point for each session, this is thought to be rough evaluation compared to CASBEE's weighting. In addition, although it aims to cover the new buildings' life-cycle impact on environment, it can only cover first several years whether the assessed performance is properly working in New Building standard. Therefore, the application of 'In Use Asset Scheme assessment' is needed to cover this, and standard for existing buildings is just suggested in 2012, which has not shown the detail of standard requirement yet. In other word, the good evaluation by *BREEAM new construction 2011* only implies the better performance until construction phase. Similarly, it prioritizes the optimization to reduce the life-cycle environmental impact of building before demolition because it assumes the environmental impact at demolition phase depends on demolition method and it is difficult to evaluate. Accordingly, the ability of recycle for next generation is not adequately considered in the evaluation with BREEAM.

< Green Guide to Specification (4th) 2009>

Background

Part of the BRE Group, BRE Global published first edition of *Green Guide to Specification* (GGS) in 1996 to aim to provide construction material index for environmental impact based on numerical data. To certify the material evaluation, not only BRE but also cooperated sponsors (called project steering group (PSG)) and other relating organizations such as WRAP join and offer relevant data (Anderson et al., 2011).

GGS aims to provide a guide for material selection from an environmental aspect with two fundamental points. Firstly, it needs to be easy to understand for users rather than previous specific papers and reports. Secondly, it bases on numerical data to quantify the environmental impact from material selection. To achieve this, GGS adopt BRE's 'Environmental Profile Methodology' (EPM) which contains the methodology and supporting data for building material sustainability evaluation. In detail, EPM has the database for material properties and life-cycle flow based on the partner trade associations. This makes it possible to calculate the environmental impact of material, and it can extent to the calculation of impact from building element.

It would be used at the evaluation of material use sustainability in BREEAM. Therefore, designers and specifiers would utilize this at design phase, and the implementation needs to be checked at construction phase (Anderson et al., 2011).

Evaluation system and target

As mentioned above, GGS evaluation adopts EPM evaluation method. With its database and own material life-cycle model, it can calculate environmental impact for each component material. It contains three processes to evaluate from material properties and life-cycle flow: characterization, normalization and weighting. Characterization aims to identify the influence of each material component on 13 environmental issues (e.g. climate change, water extraction etc.). This describes the environmental impact of material as a whole, individually. It is followed by normalization which translates these raw impact values to equivalent amount of burden emitted by European civilians. Through weighting (to be given later) and accumulation, summary of environmental impact from material or element is calculated (Anderson et al., 2011).

Referring this methodology, GGS organizes an evaluation framework constituted by three steps. At first, element categories needed to concern and building type are specified. Following this, the profile for each element for specified building type is evaluated from database. Here, (i) net quantity of component material, (ii) replacement interval (assuming 60years for service life), (iii) embodied environmental impact for component material (based on EPM), (iv) generation of construction, refurbishment and demolition waste and (v) required transportation are included. Finally, summary rating for each element is calculated as Eco-point as well as EPM evaluation. In addition to Eco-point evaluation, the following information as shown in Table 85 is added to comprehend the environmental properties of material (Anderson et al., 2011).

Table 85 Other information in GGS (2009)

Additional data	Scoring
Typical replacement interval	Years (for key component)
Embodied CO_2	kg CO_2 per m^2
Recycled input	Recycled content by mass (kg per m^2)
	Recycled content by mass (% per m^2)
Recycled currently	Mass of element which is currently recycled at demolition, as % of total mass installed per m^2

(source: Anderson et al., 2011)

It must be mentioned here that the evaluation for element is based on the environmental impact for one elemental unit. It targets for an element function so that the volume or mass of element differs to each type (e.g. concrete wall would be larger than wooden wall). The potential energy saving from the use of element during service life is intentionally not included in this evaluation to prevent a double count of benefit with BREEAM which rewards for minimization of operational.

According to the ten panels of experts, 13 categories of environmental issues mentioned above are weighted as Table 86 to calculate summary rating of element. In detail, two individual issues are compared each by experts, and it results in the importance of issues. The total score calculated based on that weighting is rated by 6 classes ("A+" to "E" for good to bad) for each element specification (including building and element type) as shown in Figure 138, to make it simple and easy to understand. These classes are evenly separated from the lowest to highest identified impact on environment. In other words, the maximum value of "E" implies the requirement for materials to comply with GGS credit. GGS covers 8 types of element basis (ground floor, upper floor, roof, external wall, window, internal wall, insulation and landscaping) for 6 types of building specification (commercial, educational, healthcare, retail, residential and industrial) as bellow. Otherwise, designer or specifier needs to ask BRE Global about the suitable evaluation for element (Anderson et al., 2011).

Feature of tool

GGS evaluates material and component for building element not only total but individual categories of environmental impact. This allows users such as designer or specifier to utilize those data for their own targets. In addition, this evaluation of material choice for whole life-cycle uses numerical data of recyclability after demolition. Although this refers current data and it might be different from future situation, it can be considered as the best evaluation method for material LCA today. However, due to the feature of evaluation, the numerical data for generic material use or component for building element are necessary to comply with GGS. While it is established for European countries, the other areas, especially in Asia, need to certify own materials complying with GGS. As a result, it is quite challenging to apply BREEAM using GGS to outside of Europe and this can be seen statistically. This makes the situation that certified buildings concentrate on Europe.

Table 86 Weighting of the impact categories in GGS (2009)

Environmental impact category	Weighting (%)
Climate change	21.6
Water extraction	11.7
Mineral resource extraction	9.8
Stratospheric ozone depletion	9.1
Human toxicity	8.6
Ecotoxicity to freshwater	8.6
Nuclear waste (higher level)	8.2
Ecotoxicity to land	8.0
Waste disposal	7.7
Fossil fuel depletion	3.3
Eutrophication	3.0
Photochemical ozone creation	0.20
Acidification	0.05

(source: Anderson et al., 2011)

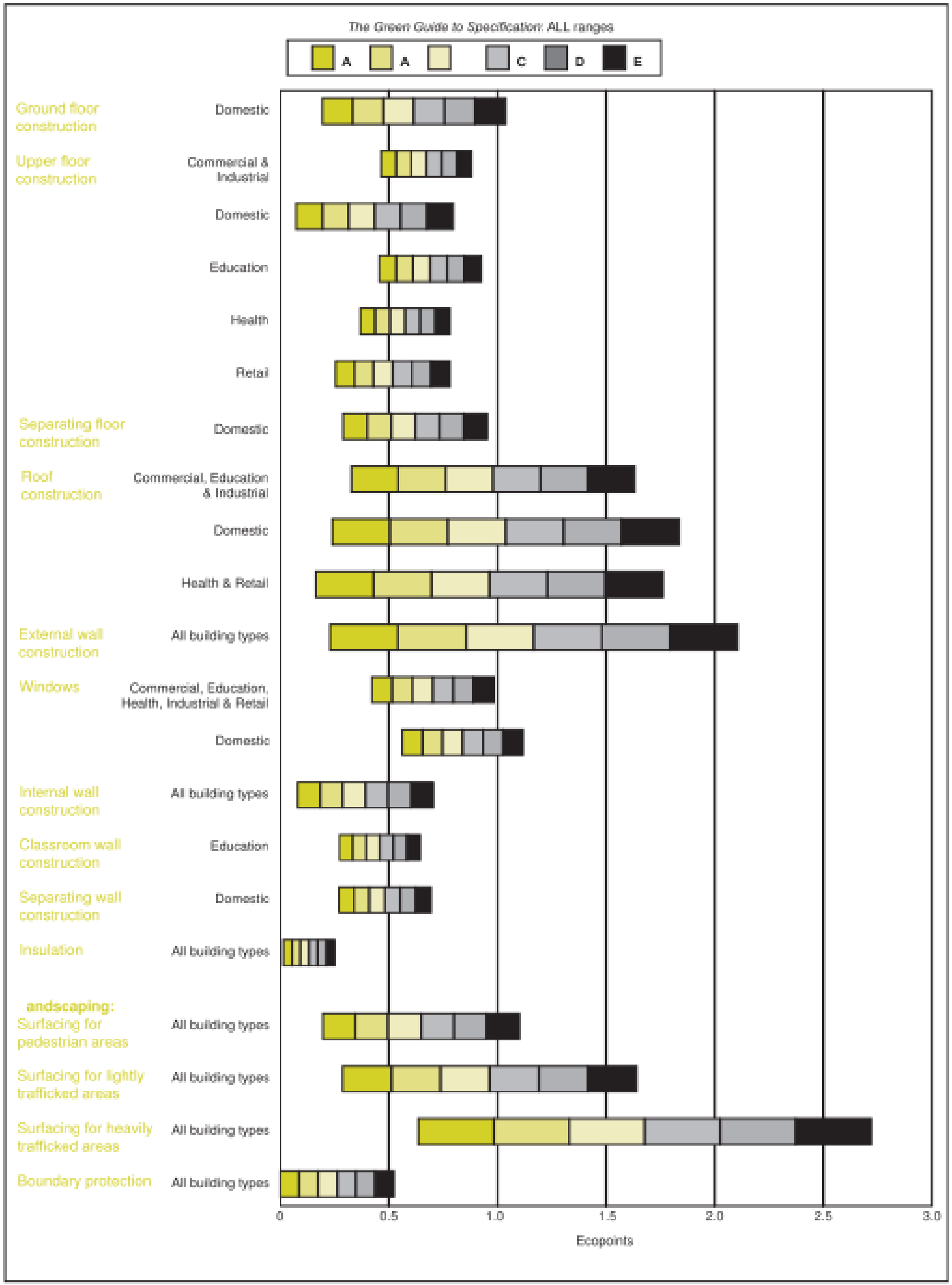


Figure 138 Rating of each element in GGS (2009)

(source: Anderson et al., 2011)

A1.3.2. LEED

LEED evaluation covers not only the normal commercial new building but also operating building and other new buildings for specific purpose. This allows an inclusive application of LEED tools for building. In this session, *LEED 2009 for new construction and major renovations* and *LEED 2009 for existing buildings (operation and maintenance)* are discussed as the mainstream to comprehend the concept and discipline of LEED for building sustainability.

< LEED 2009 for new construction and major renovations>

Background

A non-profit organization, US Green Building Council (USGBC) suggests LEED to offer certification of sustainability product and services for building. Those credentials and certifications for each requirement relating to green building are applied to Green Building Certification Institution (GBCI).

LEED is identified as the voluntary and market-driven evaluation tools for building sustainability. For LEED of new building it is composed by two phases, design and construction. The evaluation is held by whether a building project complies to set requirements and principles. Therefore, the scheme document of LEED is updated on time. LEED set the minimum requirement before evaluation according to three aims; (i) to guide customers clearly, (ii) to remain integrity of LEED and (iii) to reduce the burden of certification process (LEED, 2009a).

Evaluation system and target

LEED is scored by the accumulation of 5 basic sessions' credits. Each session has defined number of requirements, and building gets one credits for each if it complies with these requirements. The total score can be calculated by credits and weighting of sessions. In addition, there are two specific session, 'Innovation' and 'Regional Priority'. 'Innovation' session is awarded for the technologies which have not been assumed by conventional requirement set by LEED (those are separated from unexpected degree of improvement and methods). On the other hand, 'Regional Priority' reflects the consideration of local condition on project to improve sustainability. Accordingly, 10% of addition can be possibly added from the application of Innovation technology and utilization of locality.

The score from LEED is rated according to the benchmark as shown in Table 87 to allow people to compare the ability of building. Here, uncertified implies the building does not comply with the minimum requirements of LEED. As mentioned above, since LEED has prerequisites for each environmental category, the buildings which cannot satisfy these also cannot be certificated.

For LEED score, as shown above, it is shown by points out of a possible 110 including bonus for innovation and regional priority. The score is calculated from the accumulation of individual points, and these points are decided from the products of three factors; (i) impact category, (ii) activity group and (iii) association between individual credits. For the impact categories, it is defined by TRACI (used by U.S. Environmental Protection Agency) and weighted according to National Institution of Standard and Technology (NIST) which aims to assess LCA impact. From this, each credit is categorized by main influence on environmental impact and identifies its largeness of impact. This weighting is assigned to the relating activity groups, and it decides the points for individual activity. The association of credits inside each activity finally decides the individual point of credits. As a reference, NIST applies an analytical hierarchy process (AHP) for weighting of individual categories, and it adjusts the sum to 100% (LEED, 2009a).

Table 87 LEED rating (2009)

Certified	40–49 points
Silver	50–59 points
Gold	60–79 points
Platinum	80 points and above

GBCI will recognize buildings that achieve 1 of these rating levels with a formal letter of certification.

(source: LEED, 2009a)

There are two phases for LEED introduction to building lifecycle; design stage and construction stage. While the documentation of construction plan should satisfy the requirement at design phase, the site situation on the construction phase also needs to be reviewed if it complies with LEED requirement.

The certification of LEED evaluation is conducted after the registration of project by project team on GBCI website. This allows them to utilize LEED evaluation software and the GBCI staff would offer critical information and necessary communication. Besides this, GBCI certifies some professionals as accredited professionals (AP). It is recommended to include them to the project team and it would get a point for building rating (LEED, 2009a).

Feature of tool

As one of positive features of *LEED 2009 for new construction and major renovations*, it considers the importance of locality to achieve better performance for building sustainability with the environmental category, 'Regional Priority'. Therefore, the extra score can be added to the building's base score as a regional bonus. It also considers waste generation at construction, operating and demolition phase, though it does not mention about a concrete requirement for demolition recycling plan on the chapter. It infers theoretically LEED thoroughly covers life-cycle waste generation. In addition, it has a various LEED for its specific functions so that the viability is high to evaluate several types of building. In addition, LEED for existing building enables the evaluation of operational building as well.

On the other hand, the certification process is not clear and transparent enough. Since it proclaims they would not take any responsibility for certification, the reliability of LEED certification seems lower than other evaluation tools complied with regulations or governmental approval such as BREEAM and CASBEE.

< LEED 2009 for existing buildings (operation and maintenance)>

Background

As the evaluation of building at the existing phase, it is mainly based on the measured or achieved data to evaluate the contemporary ability of building. It assumes building needs to be certified every 5 years so that the recertification is set within 5 years to maintain LEED certification (LEED, 2009b).

Point of difference and in common with LEED for new construction

As well as *LEED 2009 for new construction and major renovations*, the building is evaluated from the environmental categories and their individual chapters. On the other hand, as mentioned above, LEED for existing building aims to certify operation and management ability from an actual operational data. Therefore, the requisite data verifying required ability is necessary for registration of LEED for existing building. The evaluation using the operational data allows it to be quantitative. As a result, some of the individual chapters in LEED for new construction are integrated. Alternatively, multi points are given to the evaluated buildings according to the degree of improvement calculated from data.

In addition, this tool focuses on the commissioning of operation plan and whether it works properly. According to this, some new chapters are found relating to commissioning which are not included in LEED for new construction.

While LEED for new construction requires comparing with the previous site condition for such as habitat preservation, LEED for existing building requires comparing with baselines or requirements of external standards.

Feature of tool

The section of framework is almost same as LEED for new building. However, it does not completely accord with each other while CASBEE use the same framework between new and existing building standards. This reduces its interchangeability although it rewards some credits for buildings if it is previously certificated under other LEED.

A1.3.3. CASBEE

Compared to above two assessment tools, CASBEE has a tool for renovation phase besides for new construction and existing phases. Including that aspect, the concept and discipline of CASBEE for building sustainability is discussed here.

< CASBEE for new construction 2010>

Background

In 2001, the Minister of Land, Infrastructure, Transport and Tourism set the committee inside of Institute for Building Environment and Energy Conservation (IBEC) to establish the environmental impact evaluation system for buildings to achieve sustainable construction following foreign evaluation tools such as BREEAM and LEED. Besides CASBEE aims to encourage the effective energy saving, the use of ecological material and durable construction, it is also expected to be used as the labelling tool for ZEB (Zero Energy Building), ZEH (Zero Energy House) and LCCM (Life Cycle Cost Minus) house.

CASBEE evaluates not only the building impact on environment but also analyses the building environment quality. The comparison between the achieved quality and environmental impact decides the fifth-grade labelling with the calculation of $LCCO_2$ (Life Cycle CO_2) to evaluate the increase of environmental impact reduction. In detail, CASBEE has three concepts, (i) to evaluate building through the whole life cycle, (ii) to evaluate from two sides: the building environmental quality (Q) and the environmental impact (L), and (iii) to accommodate the index of building environmental efficiency called BEE (Built Environment Efficiency) (CASBEE, 2010a).

Evaluation system and target

As mentioned above, in CASBEE, the building is evaluated from the unique index, BEE based on the comparison of the building environmental quality (Q) and the environmental impact (L). Both of them have three breakdown chapters to evaluate building with set criterion, and each score is weighted and accumulated to calculate total score as BREEAM evaluation. $LCCO_2$ calculation is applied to the evaluation of Q's chapter3: treatment for environmental impact. This is separated into as following three phases, and this can be simply calculated if the relating questions in chapters are answered and basic building data is input. However, own $LCCO_2$ calculation result is also applicable to directly input if it complies with equivalent policy using accurate data.

CASBEE score is calculated by credits and weighting of each section. This weighting as shown in Table 88 is decided by explicit weighting system using AHP (Analytic Hierarchy Process) based on the questionnaire results answered by CASBEE using designer, client, administer and government workers. The score is finally rated according to the benchmark in Table 89 and visualized as the Figure 139 for the building environmental efficiency. In addition to this, the individual rate for each chapter and also the result of $LCCO_2$ calculation is shown at score sheet.

The evaluation with CASBEE New Building standard (simple version) is designed for self-evaluation of environmental impact. Thus, the question is simply designed whether its design satisfies each requirement. However, the assessment by the credited assessor must be needed to be officially certified (CASBEE, 2010a).

Table 88 Weighting of evaluation of CASBEE for new construction (2010)

Assessment Categories		
Q1 Indoor Environment	Non-factory	Factory
	0.40	0.30
Q2 Quality of Service	0.30	0.30
Q3 Outdoor Environment on Site	0.30	0.40
LR1 Energy	0.40	
LR2 Resources & Materials	0.30	
LR3 Off-site Environment	0.30	

(source: CASBEE, 2010a)

Table 89 CASBEE rating (2010)

Ranks	Assessment	BEE value, etc.	Expression
S	Excellent	BEE = 3.0 or more and Q = 50 or more	★★★★★
A	Very Good	BEE = 1.5-3.0 BEE = 3.0 or more and Q is less than 50	★★★★
B^+	Good	BEE = 1.0-1.5	★★★
B^-	Fairy Poor	BEE = 0.5-1.0	★★
C	Poor	BEE = less than 0.5	★

(source: CASBEE, 2010a)

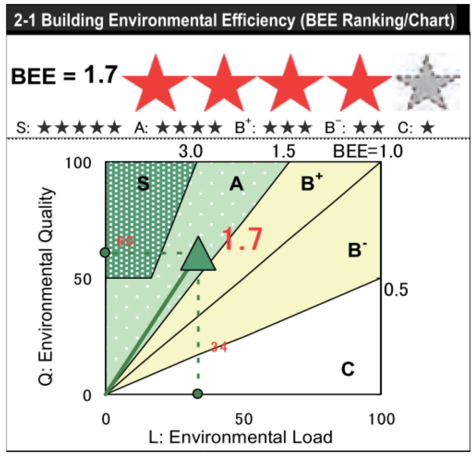


Figure 139 Rating of building in CASBEE for new construction (2010)

(source: CASBEE, 2010a)

According to the first concept, to cover the whole life cycle of building, CASBEE has four types for each phase: design, new-built, existing and renovation. Including the other specific CASBEE for heat island effect and town planning, those are called CASBEE family. For CASBEE for new construction manual, the whole building type is covered excluding individual house which has own manual can be applicable. For the building types including residential function, building needs to be separately evaluated as 'residential area' and 'common area'. The multi-functional building can also use CASBEE to evaluate. The share of floor area is used to average the score of building (CASBEE, 2010a).

Feature of tool

As one of positive features of *CASBEE for new construction 2010*, it accommodates the ability value such as $LCCO_2$ and ERR (evaluation for skin ability) for the evaluation of building ability and environmental influence. This evaluation process allows us to comprehend building from multiple aspects. In addition, CASBEE contains future sustainability in many parts. This is represented by that it considers renewability at design phase from the room physically and functionally, and it also considers the recyclability of materials at demolition phase. With the other phases of building life-cycle, CASBEE allows LCA based on actual performance.

Conversely, the definition of satisfaction for building ability seems quite ambiguous. To allow designers flexible suggestion for requirement, it decides the score for single chapter from the number of satisfaction for several requirements. It results in difficult to decide whether the buildings having same score have the practically same sustainability. Moreover, it has not been widely applied yet compared to BREEAM or LEED.

< CASBEE existing buildings 2010>

Background

As the evaluation of building at the existing phase, it is mainly based on the measured or achieved data to evaluate the contemporary ability of building (not at design phase). Designing specifications are also utilized if it can make these calculations more accurate and simple. Especially, CASBEE for new building has a high interchangeability with this tool (CASBEE, 2010b).

Point of difference and in common with CASBEE for new construction

As well as CASBEE for new construction, the building is evaluated from the unique index, BEE based on the comparison of the building environmental quality (Q) and the environmental impact (L). Both of them have three breakdown chapters to evaluate building with set criterion, and each score is weighted and accumulated to calculate total score as BREEAM evaluation. $LCCO_2$ calculation is applied to the evaluation of Q's chapter3: treatment for environmental impact. So that framework of chapter and score weightings are the same as the other CASBEE families. The only different part is that it sets up criterion for the score addition and subtraction for each chapter to modify the evaluation for current ability based on actual data. According to this, the gap of building ability from design is reflected on the score for existing buildings. It also allows people to reevaluate the building under the renewed environmental requirement for building.

Feature of tool

Since CASBEE tools are designed to cover whole life phase of building, it is easy to finish the evaluation of existing building ability with CASBEE for new construction. This can be also said to compare the abilities of different phases with these tools.

At the same time, this tool uses the energy consuming results as the indicator for the gap of energy ability from its design. However, this result is decided from the comparison with the average energy use for the buildings of the same area and building function. This can accept low ability buildings if it is surrounded by buildings having similar low ability.

< CASBEE for renovation 2010>

Background

As the evaluation of building at the renovation phase, it focuses on the improvement of BEE between before and after of building. To achieve this, each evaluation is calculated by CASBEE for existing and new building, respectively. As the renovation of building tends to be held partially, the evaluation needs to be categorized according to renovation plan. In addition, the building function also needs to be considered if the renovation changes function. For the application of CASBEE for existing building, it is mainly based on the measured or achieved data to evaluate the contemporary ability of building (not at design phase) (CASBEE, 2010c).

Point of difference and in common with CASBEE for new construction

As well as the other CASBEE tools, the building is evaluated from the unique index, BEE based on the comparison of the building environmental quality (Q) and the environmental impact (L) with $LCCO_2$ calculation. The framework of chapter and score weightings are also the same as well. On the other hand, the main focus for each tools are completely different.

While CASBEEs for new construction and existing buildings aim to evaluate the absolute score of the building sustainability at that phase, this tool aims to evaluate the relative score to describe the contribution of renovation for sustainability with BEE.

Feature of tool

Since this tool utilizes the comparison of before and after building ability, the evaluations with CASBEE for new construction and existing buildings allow this easily. This comes from the highly designed interchangiability between CASBEE tools as mentioned in the summary of CASBEE for existing building. As a result, it is easy to compare the abilities at different phases in whole life cycle.

However, the environmental impact from the renovation process such as the recyclability of generated waste and energy consumption for process is confined by the mention for the report, and not evaluated quantitatively. This is also said to the both evaluation at construction and renovated phase. Since they use the assumed constant service lifespan for $LCCO_2$ calculation, it does not reflect the actual service lifespan by renovation. Besides this, it might be difficult to collect the data at construction phase which tends to be more than 30 years before. Even though the target building has been evaluated by CASBEE for new construction before, it is required to be reevaluated by latest version of CASBEE.

A1.3.4. Others

< SBTool >

An international non-profit organization, iiSBE suggested to encourage the movement of a global sustainability and built environment. iiSB mainly focus to adopt policy, methods and tool in worldwide so that it constantly holds international conferences.

As the feature of SBTool, it orients to be used by local organization and third authorization to apply for their region or buildings rather than private evaluation. Therefore, the adoption of locality is originally assumed, and it was actually applied to the project of the Principality of Monaco to extend the downtown area into sea. For example, SBTool considers region and site specification for sustainable evaluation. Accordingly, the weighting of building requirement which uses local criteria is modified.

Since iiSBE insists the importance of international network to achieve global sustainability, SBTool inserts local language and the data base 'Sustainable Building Information System' (SBIS) is also a multi-language (iiSBE, 2013).

< BCA-GM>

The Building and Construction Authority (BCA) which belongs to the Ministry of National Development, suggests BCA-GM to encourage the excellent inside and outside environment of building in Singapore. This tool only aims to evaluate private sector so that the public constructions are not applied under the recognition that is a government issue.

As the features of BCA-GM, it covers the evaluations for new, operating and refurbished building. As well as BREEAM, it separates the evaluation in two steps, designing and implementation, and each credit would be certified with both satisfaction (Building and Construction Authority, 2010).

< ESGB >

Evaluation Standard for Green Building is the standard suggested by Ministry of Construction and Quality Supervision, Inspection and Quarantine of the People's Republic of China issued in 2006. As the feature of standard, it sets the evaluation phase at one year after construction, extension or reconstruction, besides the design, planning and construction phases, to ensure the process control implemented properly (ESGB, 2006).

< Green Star>

A non-profit organization, Green Building Council of Australia (GBCA) suggested to encourage the movement of a building sustainability and built environment in Australian. As the unique part, GBCA is supported not only by government but also industry.

As the feature of Green Star, it aims to evaluate the building in Australia and these are separated into building functions. For the certification and rating of building, it has two steps of submission for documents. This allows the reflection of feedback from Assessment Panel to first submission, and it can confirm the requirement is achieved properly. It can be said the system and framework are quite similar to BREEAM which has two phase certification at designing and construction phase (Green Building Council Australia, 2013).

A1.3.5. Comparison of main tools

There are many studies to compare the assessment tools to comprehend the characteristic of each tool and find the possibility to make tools applicable to whole world as a common evaluation method of building sustainability. Through the studies, many authors find its commonality of assessing system among main tools and the difference of priority caused by locality. For instance, Saunders (2008) points out the lack of horizontal connections between tools. As most of the tools were originally developed in one country and affected by the locality of referred standards and regulations, it is not assumed to corroborate with other tools. He insists that ‘transparency’ and ‘comparability’ are necessary to improve this. ‘Transparency’ is expected to make the comparison of each requirement and allows them to share best practice. ‘Comparability’ not only with other green building but also other functional assessment tools allow ‘licensing’, ‘cross certification’ and ‘multiple labelling’. This makes clients comprehend building with their familiar assessment such as local brand. Additionally, the business model employed by scheme operators to utilize these tools seems to be shared.

Mao et al. (2009) compares the characteristic of tools from three aspects, East or West, origin country is developed or developing, and target of application (dominant or global). He points out, (i) while Western tools (LEED, SBTool and BREEAM) are suggested by non-profit third party, Eastern tools (CASBEE, BCA-GM, ESGB) comes from government or its subsidy, (ii) developed countries have higher awareness for market-orientation for assessment tools, and (iii) while SBTool has higher flexibility which assumes to be applied in worldwide, BCA-GM and ESGB suggested in developing countries have no afford to concern about their application for outside. Though Mao et al. (2009) explains this based on the three different aspects, it seems to derive from the single fact that many tools were established in early age at Western countries, not Eastern. Because of that those Western tools have already established high status of their brands as building incentive in construction market. This made it infeasible to develop new assessment tools for market-orientation so that Asian governments needed to lead domestic construction industry to more sustainable by own legal-orient assessment tools. This can be supported by the truth that CASBEE has only applied to less than 150 buildings for certification today while it has been adopted as mandatory policy by many local authorities represented by government-decreed cities such as Nagoya, Sapporo and Osaka.

Through the comparison between BREEAM and LEED, Sleeuw (2011) analyses both of them are not worth to applying to foreign area covered by own assessment tools. In his opinion, to improve the efficiency of global application, they have to develop against changing regulatory standards and distribution of best practice globally, and the most important key is the agreement of common metric and performance standards. Actually, BREEAM, LEED and Green Star decided to develop common metrics to measure CO_2 emissions to improve their comparability in 2009. However, it is not mentioned in his paper written in 2011. This implies that it takes long time or it is difficult to distinguish the effect of unification for global application.

When the future possibility for evaluation of building sustainability in the UK is considered, there seem mainly three types; following global assessment tool, certain foreign tool and domestic tool. SBTool can be said the most possible tool chosen for the global rating because of its fundamental tool concept and its system and large worldwide accomplishment as mentioned above including the established network. As discussed above, the major requirement for tools to become global is the adoption of locality and common measurement method to compare each other. SBTool uses dual evaluation system from relative and absolute aspect. According to the local third party, SBTool for certain region is tailored reflecting local regulation and policy besides weighting of each factor are set concerning locality. It allows two types for benchmark, qualitative and quantitative. Relating regulations, experimental result or consensus of experts is referred to put the requirement for each score. Since the general requirement and weighting is originally suggested following a common structure and terminology, at the same time, the absolute evaluation of building is able to be calculated and compared to the others at different region. Otherwise, there is one possibility that main tools are integrated or share large parts and enhanced their changeability following the unification of CO_2 emotion measurement above mentioned. In first possible type of future, it is expected that SBTool would be tailored as BREEAM which is standards embraced in the UK regulation (especially for public construction). The second type is also expected to adopt BREEAM as the base tool for the evaluation in the UK. As far as the baseline of requirement goes, there would not differ from what is defined in BREEAM.

When it is assumed the certain foreign tool is chosen to evaluate UK buildings, LEED is most possible. Similar to GBTool, LEED has a worldwide network of World Green Building Council. In addition, Mark (2013) attributes two main factors to the large number of application of LEED outside of the US. As the first factor, since many decision maker in Middle East learn from the US education system so that they are familiar with LEED besides eager training diffusion of LEED which clue-up practices. In addition to this, BREEAM becomes not enough attractive as the choice for foreign stake holders. Besides the large charging fee of evaluation after privatisation, they are uncooperative to share the building ability data while LEED which offers a large amount of certified data through the pipeline of WGBC.

However, it is also said by Mark (2013) as far as the evaluation in the UK, BREEAM is the most suitable. This derives from the establishment of its position as a standard which is required to apply to all public building. Compared to LEED, its baseline is severer and matches to UK climates and context. This is statistically supported by that while 2365 projects were certified by BREEAM, LEED did for 134 buildings. Therefore, although it is numerically shown that LEED has increased the application of tools in worldwide, as far as UK dominant, BREEAM has a significant influence on rating of building sustainability.

To summarise, there are three possible change of rating system from global aspect. However, as far as UK dominant, assessment tool seems not to be changed from BREEAM to be applied or the newly tailored would be made as similar content. Thus, it is the currently best option to refer the assessment system of BREEAM as the main effect caused by assessment tool for waste flow to make a social system model.

A1.3.6. Prospective effect of assessment tool on waste flow

As mentioned at beginning of this chapter, the main focus here is to clarify the influence of assessment tool on waste flow from demolition to next construction. According to the summary of previous session, it seems practical to focus on BREEAM as the prospective assessment tool used in the future UK. Therefore, the prospective effect from BREEAM on waste flow is discussed from the relating chapter in BREEAM new construction 2011. The other approaches taken by other assessment tools introduced above are also important to point out the insufficiency of BREEAM suggestion. This is expected to be a good suggestion for BREEAM modification in new version, as well as the consideration of some possibility that the other tools would be used in the future UK.

Approach to waste flow in BREEAM (new construction 2011)

The approach to evaluate the sustainability of building project at waste flow in BREEAM can be separated into two main types.

On one hand, the waste utilization from previous demolition to new construction is evaluated at following chapters; 'Management 03: Construction site impacts', 'Waste 01: Construction waste management' and 'Waste 02: Recycled aggregates'. The specific discipline of BREEAM for the waste utilization onsite is described as resource efficiency. Just as the term indicates, it focuses on how resource is properly utilized at both phases: for construction and after demolition. In other words, new building materials are expected to produce less construction waste, and demolition wastes are expected to be treated in high utilized way (e.g. reusing, recycling) as possible.

To evaluate the resource efficiency of project, chapter of Management 03 put the credit of proper monitor of construction and demolition wastes to comprehend their amount, component and transported distance. Then, firstly the rate of generated waste is compared to baseline set at chapter of Waste 01 from the hundreds of real project data using BRE's SMARTWaste system in accordance with Site Waste Management Plan (SWMP). As mentioned above, to improve resource efficiency and prevent illegal waste activities by ensuring stakeholders assess the optimal treatment of waste material and waste, submission of SWMP is required by the 'Site Waste Management Plan Regulations 2008'. The web-based tool developed by BRE, SMARTWaste Plan, helps to complete SWMPs in full compliance with this regulation. In addition, this tool can measure generated waste, energy and water consumption and procurement of certified timber onsite. Accordingly, carbon emission and economic assessment for waste treatment can be calculated with this tool (BRE, 2011).

BREEAM excludes demolition and excavation (D&E) waste from the generated waste. This is because, though BREEAM admits the importance to avoid demolition (i.e. to encourage reusing of existing building), it insists there are some inevitable amount of D&E waste produced. It is afraid of relatively large amount of D&E waste would reduce the impact of construction waste treatment, and that balance depends on each site. Secondly, the diversion of construction and demolition wastes from landfilling gets awarded according to its volume rate. At this time, those materials need to be sorted into individual waste group onsite and offsite. Following this, the applications of recycled aggregates which occupy large share of material consumption are evaluated at Waste 02. It evaluates the amount of recycled and secondary aggregates which substitutes high-grade aggregates. It sets baseline of component not only for total amount but also for each application such as 100% substitution for gravel landscaping.

On the other hand, BREEAM uses Life Cycle Analysis (LCA) for CO_2 emission called Life Cycle CO_2 ($LCCO_2$) to evaluate a building sustainability. This $LCCO_2$ is composed by initial and operational CO_2, and initial CO_2 includes embodied CO_2 of construction materials. It infers the advantage of reusing and recycling waste as construction material because they do not need to put extraction and refinement energy but recovery energy which tends to be relatively small. However, this is not discussed in the chapter of Energy where operational CO_2 emission is mainly focused for building ability as mentioned at 'Energy 01: Reduction of CO_2 emissions' that '….focuses only on energy and carbon dioxide emissions resulting from the operational stage of the building life cycle. It does not take in to account the embodied carbon …. (these impacts/benefits are dealt with in BREEAM issue Mat 01 Life Cycle Impacts).' At the chapter of Material 01, it evaluates the reduction of environmental impact from the use of low impact materials through LCA. The available credits are decided by the number of satisfied element and building type. $LCCO_2$ is fundamentally used for each element to compare with requirement. It uses Green Guide which is the database of $LCCO_2$ for many building elements to make calculation easier and simpler. BREEAM defines an environmental profile methodology as 'a measure of all key environmental impacts, during extraction, processing / manufacture, use (including maintenance and refurbishment) and disposal, over a 60-year study period.'

To summarize, BREEAM aims to encourage stakeholders to utilize resource onsite from the designing of SWMP. This is expected to maintain high level treatment of resource at the reconstruction phase containing demolition and construction in short term. This reduces the loss at closed loop of material flow. Then, the advantage of using low environmental impact material certified by Green Guide can be regarded as the other momentum to connect the flow from demolition to next construction.

Approach to waste flow in other main assessment tools

In LEED (New Building 2009), similar to BREEAM, the effect of sustainability on waste flow is discussed at the chapters relating to material and energy (‘Material and Resources (MR)’ and ‘Energy and Atmosphere (EA)’). For material utilization, it also mentions about the diversion of construction and demolition waste from landfilling at ‘MR Credit 2: Construction waste management’. However, LEED does not require stakeholders to submit SWMP but it tries to comprehend the waste flow quantitatively from three credits; MR Credit 1: Building reuse, MR Credit 3: Material reuse and MR Credit4: Recycled content. Compared to BREEAM, LEED sets certain baseline for the share of existing building (both structure and non-structural elements) reused for next construction. On the other hand, the evaluation of sustainability from the applications of reused and recycled materials is only based on the component share from cost and volume, respectively. Though the advantage of using low $LCCO_2$ materials in construction can be described at ‘EA Credit 1: Optimize energy performance’ which compare the total energy cost for building project with baseline building, it mainly focuses on the energy efficiency of building. Therefore, the evaluation of material $LCCO_2$ seems less accurate than with Green Guide in BREEEAM.

In CASBEE, similar to LEED, there is one chapter, ‘Load Reduction (LR) 2.2: Reducing usage of non-renewable resources’, focussing on the continuous use of existing building and the use of recycled material as construction material. Nevertheless, the definition of reused and recycled share is quite ambiguous such as ‘except extremely limited’ or defining by the number of non-structural application using recycled material. Moreover, it does not concern about the disposal of construction and demolition waste. But CASBEE, at the same chapter, sets the session to evaluate the consideration of demolition at construction design phase. There are three factors to be regarded to consider demolition; the use of separable finishing materials, internal finishes and equipment and reusable unit material. Though CASBEE only shows some example of construction method which can be regarded as being ‘separated easily’, this has never been covered in BREEAM and LEED. It seems worth noting the feature of Green Star to discuss about the consideration of environmental impact at demolition phase. As CASBEE, it rewards the project designing more than 50% of the structural frame (including roof) or 95% of facade for deconstruction to utilize demolished material without damage (Tingley and Davison, 2011). In addition to this, CASBEE holds a $LCCO_2$ analysis with reference building applications at ‘LR 3.1: Consideration of global warming’. Compared to others, it focuses the reduction of embodied CO_2 from the reusing of existing building and the use of recycled material evaluated as well as building energy efficiency. This helps to compare the influence of CO_2 emission at different phases much easier.

According to above summary, it can be said that the evaluation way of waste flow differs from assessment tools. As shown in Figure 140, there are mainly seven parts of waste flow to be evaluated. While LEED and CASBEE try to evaluate or somehow encourage the application of reused and recycled material (① and ③ in Figure 140) with certain baseline, BREEAM integrates ①～④ into SWMP and gives some flexibility for site situation in particular for demolition waste treatment. Though this sounds BREEAM less strict against other tools for reusing of existing building for next construction, the truth is different. Tingley and Davison (2011) studied the earning rate for every single credit in LEED new construction 2009. They showed there were less than 20% of projects earning a minimum Building Reuse credit, and Material Reuse credit is not achieved more than 30%. This result justifies the infeasibility to compel stakeholders to reuse existing building besides the large task to increase a material reuse rate.

Regarding to the embodied CO_2 of building material, BREEAM evaluates ⑤ from two aspects, material-based and building energy efficiency-based due to the application of Green Guide. Since CASBEE is designed to compare the reduction of embodied CO_2 with other factors, it is easy to distinguish its significance of effect. The unified LCA method based on Green Guide seems preferable to satisfy both merits.

As the final part, BREEAM does not consider the environmental impact at next demolition and construction phase. This seems to derive from SWMP-based solution in BREEAM. However, this is just a supportive measure for unplanned demolition. As a result, the separation of each material from comingled waste can cause large damage or include impurity. It naturally needs to rely on low level treatment such as cascade recycling and landfilling. Tingley and Davison (2011) gives the following factors as barriers to material reuse and design for deconstruction: the negative stereotype for reused material, economic aspect, absence of recertification system for reused materials and absence of incentive. It is possible to solve the last burrier with modification of assessment tools. Actually, the design for deconstruction is under discussion in the Environmental Protection Agency (EPA) and USGBC, and proposed 2011 BREEAM update for LEED and BREEAM, respectively (Tingley and Davison, 2011). Thus, it would be included in the future version of them. As the other possible choice they suggest, these designs would be set as a prerequisite for certain share at beginning and it would be extends as developed. Otherwise, point-deduction system for the lack of consideration of reuse and destruction design is prospective to improve with assessment tools.

To think about the waste flow model from demolition to next construction, at this moment, last two parts of sustainable factors (⑥ and ⑦) for next construction seems negligible in BREEAM application. Nevertheless, the indirect influence on waste flow derived from the adoption of those factors in the future should be considered to allow own model to flexibly fit in future change of BREEAM.

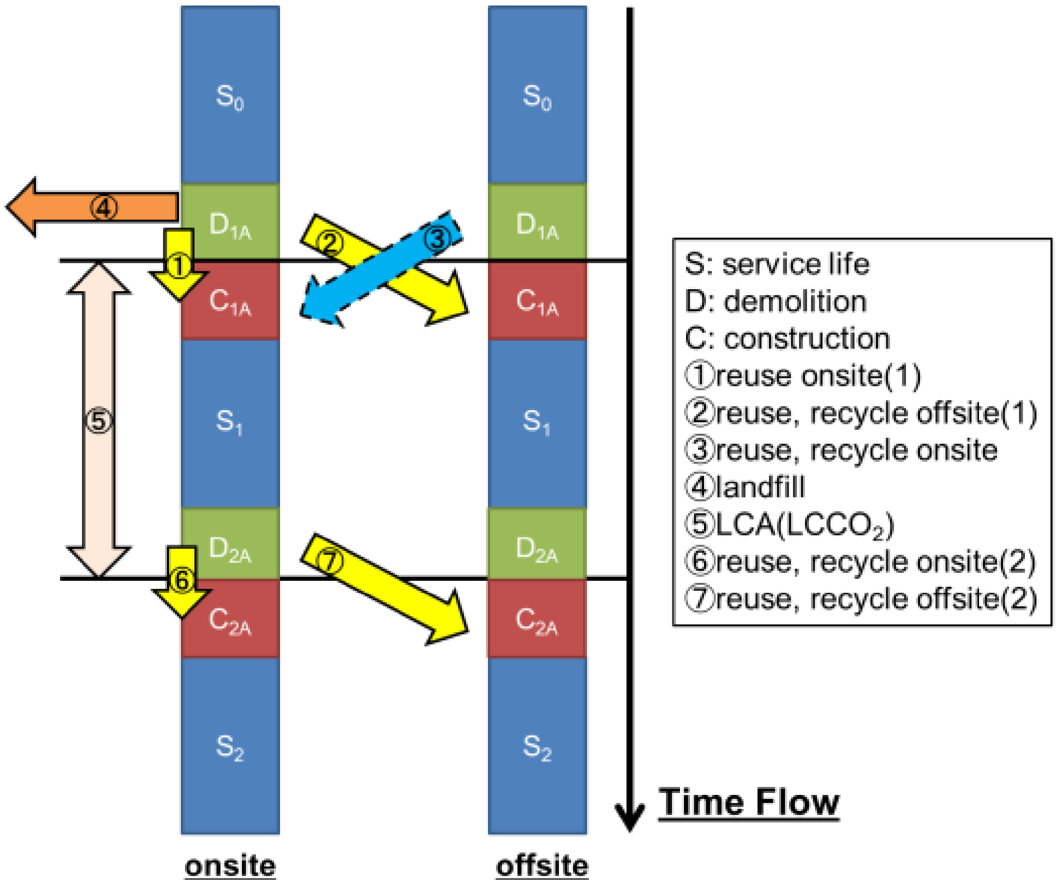


Figure 140 Waste flow overview in building life cycle

A1.4. Summary

Through the study of legislation, the main regulations were identified which directly relate to the suggestion of optimal waste treatment in this research. Those are separated from their objectives to achieve the sustainable treatment or other factors. The legal requirements from other aspects, such as the health and safety of project or project budget, ask for the multidirectional approach for decision making. This will be investigated through the data collection phase to try and establish the practical use of legislations. In addition, at the legislation approach, the existence of CSH as the evaluation standard of sustainable waste treatment has a great importance to the design of the construction project. This is also true at the application of assessment tools such as BREEAM. As touched above, the sustainable project strategy can be justified by the incentives from the high evaluation of those assessments. Thus, those incentives have to be numerically evaluated to compare the influence with other factor units such as CO_2 emission or pounds for project budget. It implies the necessity to calculate the prospective impact generated from the assessment application including the extra investment to achieve certain requirement. Yet, it seems difficult to assess the impact at next demolition phase as the attitude against this phase differs for each assessment tools. At least in the UK, or it can be said BRE assessment tools (CSH, BREEAM series), it is regarded efficient to focus only on the impact at the construction phase rather than concerning future demolition. However, this is on arguing and it would be possibly included in future version of tools. It would appear that it could be rational to choose CSH and BREEAM as the applicable tools to the future construction projects in the UK with certain consideration for possible amendment. Accordingly, the waste treatment model developed in this research is going to be developed with this fundamental concept.

Appendix2. Conventional demolition methods

A2.1. Preparation method

A2.1.1. Drilling with abrasion

As the main drilling methods with abrasion, Kasai (1988a) introduce three devices; a) hand hammer drill, b) large size hammer drill and c) diamond boring machine. Besides the application for the insertion of chemical expansive demolition agents or explosives into elements, it is used to extract core pieces as the actual specimen for comprehension of the current status.

A2.1.1.1. Hand hammer drill

This device aims to bore into the concretes. In addition to the rotating system, the percussion function is incorporated to improve the drilling efficiency (Chen, 1998). The efficiency of the drill has almost doubled today compared to the one from 1980s.The current model is shown in Figure 141, which made by Makita Gulf FZE has hitting speed of 1650 to 3000 times and turning speed of 315 to 630 rotations per minute, respectively. With normal and core bit, it allows boring size of 35mm and 90mm in concrete.

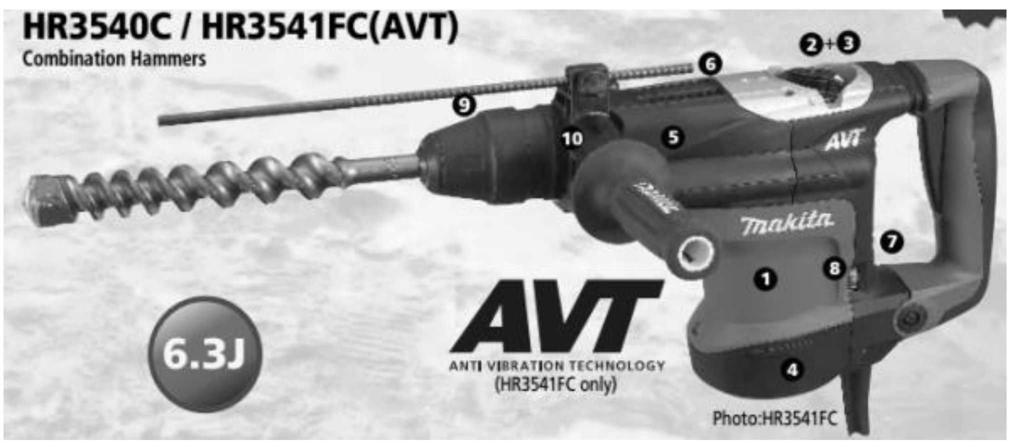


Figure 141 Hand hammer drill unit

(source: Makita Gulf FZE, unknown)

However, at the same time the side effect on the labour health from the use of a hand hammer drill needs to be concerned. 'Hyposthenia Hammer syndrome' named by Conn et. al in 1970 is the occupational disease happening for workers exposed to the vibration routinely. This is generally caused by the transformation of the hamate bones in the wrist by the frequent trauma as shown in Figure 142. This makes the ulnar artery fixed to surrounding structure for 2 to 3cm, which results in stenosis or occlusion. Therefore, the workers exposed to the vibration by the use of a hand drill would be recognized an episodic blanching affecting especially the little fingers well known as ‘white finger’ (Cooke, 2003).

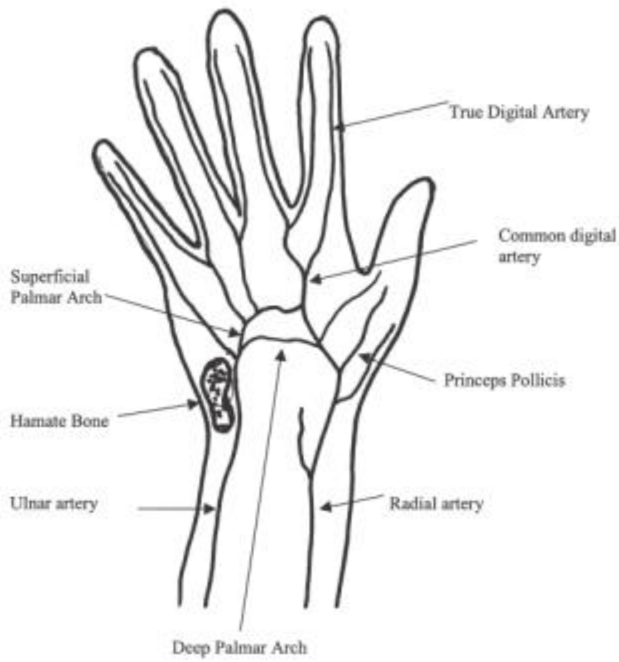


Figure 142 A diagrammatic representation of the main blood vessels in the hand

(source: Cooke, 2003)

The introduction of suspension has been suggested by many researchers to prevent the effect of the vibration on the labours (Saggin, 2011 and Oddo, 2004). Saggin (2011) models the system of vibration transmission as shown in Figure 143 and included the vibration exposure into the equation. With a gradient-based algorithm, the optimal suspension properties are suggested as the nonlinear constrained optimization problem, and the empirical result shows approximately three times smaller mean value of exposed vibration. On the other hand, Oddo (2004) suggests adding a prevention system not only to the suspension mechanism but also to the hand-arm part. This can be described as shown in Figure 144 and he reports 30% and 50% of vibration attenuation at between 35Hz and 45Hz which is the frequency range the vibration tools such as a pneumatic drill induces. The product introduced above also contains this suspension function in the two parts as shown in Figure 145. The movement of the piston moves the balancer to the opposite direction so that the conducted vibration is offset. The spring between the main structure and the grip also weaken the conductivity of vibration to labours as well.

The main side effects of the hand hammer drilling are the noise and vibrations which are caused by the large impact between the elements and the drill. Thus, labours need the ear defenders and the vibration proof globe during a drill operation (Kasai, 1988a). In addition, the dust proof mask is also required onsite for the sub-product dust.

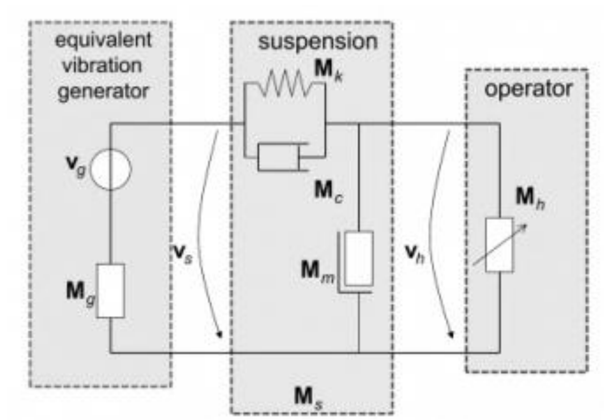


Figure 143 Impedance scheme of the interaction between vibration and operator
(source: Saggin, 2011)

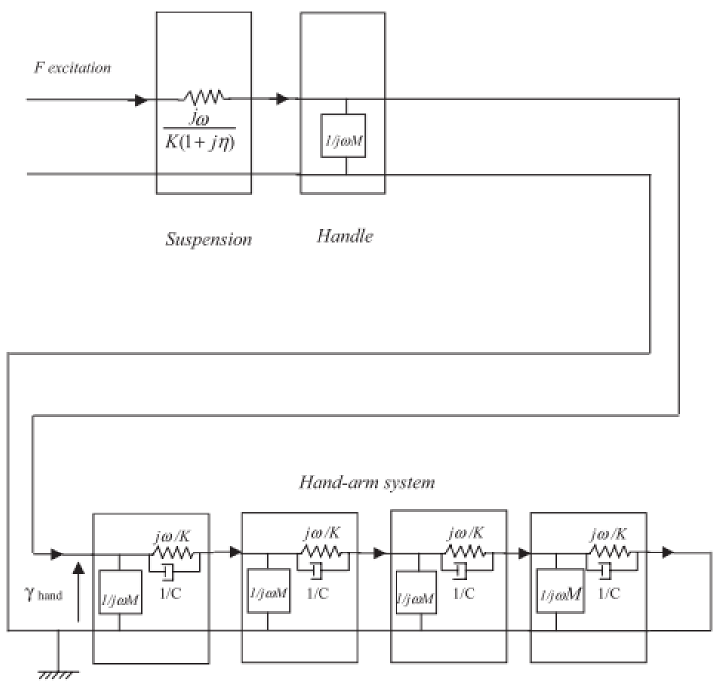


Figure 144 Impedance scheme of the suspended handle and the hand-arm system
(source: Oddo, 2004)

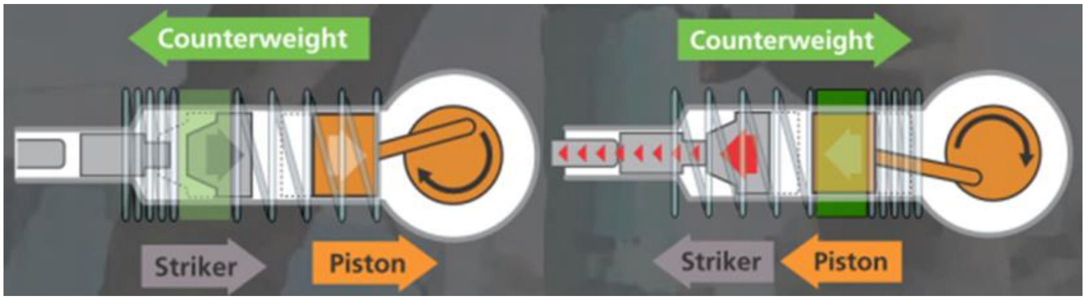


Figure 145 Concept figure of suspension function

(source: Makita Gulf FZE, unknown)

A2.1.1.2. Large size hammer drill

Compared to the hand hammer drilling, the drill is mounted on a self-propelled machine and applied to bore a massive or mat concrete (Kasai, 1988a). This device tends to be applied to a civil project such as the rock drilling. Bruce (2003) classifies the rock drilling methods into three types; ‘rotary’, ’rotary percussive’ and ’rotary vibratory’. The last two types of methods are equipped with percussion and vibration device respectively to improve the drilling ability with simple rotation. The ‘Rotary percussive’ type is extensively used and it includes ‘top hammer’ and ’down-the-hole hammer’ methods. As shown in Figure 146, ‘top hammer’ generates percussion force at the top of drill and feed it to the bit of drill (Kahraman, 2003). On the other hand, as described in Figure 147, ‘down-the-hole hammer’ generates the percussive force by the pneumatic power piston at the head of drill, so that the bit can bore a straight hole (Chiang, 2000).

Those methods tend to cause large noises and dusts, as similar principle as hand hammer drilling causes. Due to the large scale of drilling, the insulation fence is required onsite (Kasai, 1988a).

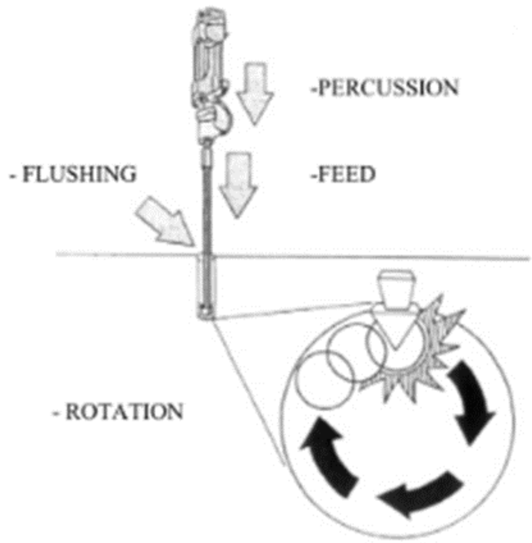


Figure 146 Concept figure of top hammer drilling

(source: Kahraman, 2003)

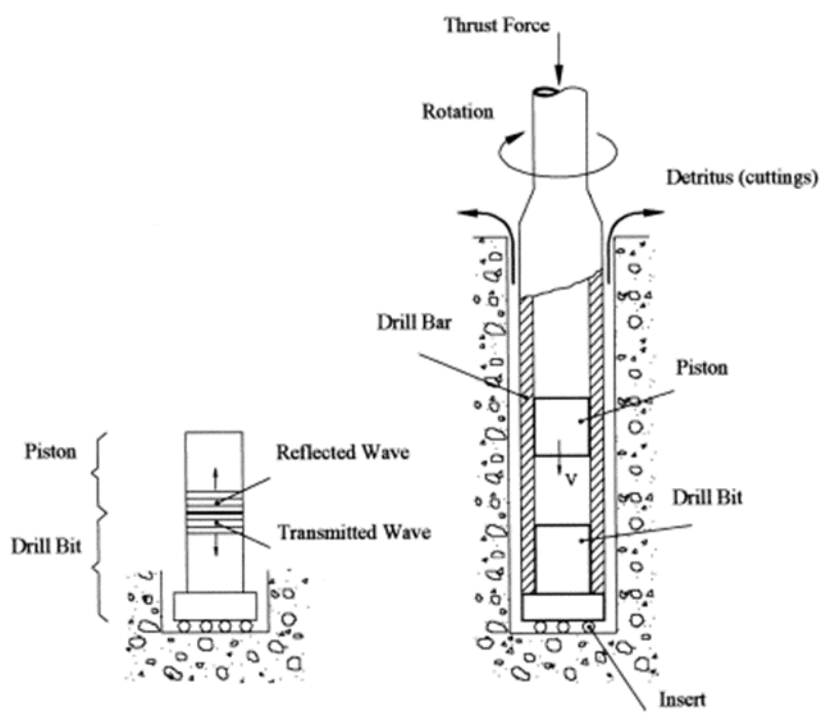


Figure 147 Concept figure of down-the-hole drilling

(source: Chiang, 2000)

Takeda (1988) introduces the actual application of 'top hammer' drilling machine called 'Silent Drill' to the Japanese demolition site as shown in Figure 148. He states that the advantages of the 'Silent Drill' is that it can automatically control the drilling speed according to the drilling materials. This allows safer and quieter drilling process compared to the hand hammer drilling process.

Figure 148 Silent Drill and bored hall

(source: Takeda, 1988)

A2.1.1.3. Diamond boring machine

A diamond boring drill is mounted on the propelled machine as well as large size hammer drill. Due to the diamond's high hardness, wear resistance and thermal conductivity of diamond film coating, the diamond boring machine shows good a cutting ability against both concrete and steel reinforcement (Chen et al., 2002). Accordingly, it has been applied mainly to the following two purposes. Firstly, it is used to bore holes of 100 to 150mm in diameter for the extraction of the core sample. As shown in Figure 149, the hollow bit is set on the machine of handy type as a hammer drill or the fixed type on the element according to the location, safety and size of core. In addition, the boring in the line allows cutting the element (Kasai, 1988a). This can be applied to both horizontal and vertical elements as described in Figure 150.

In terms of the vicinity impact, this method generates negligible amount of noise and dust due to the high cutting ability of the diamond coating blades. In addition, the operation without the large vibration prevents damage on the structure compared to the hitting methods as introduced in the section of 'a) Hand hammer drill'. The vibration effect on the labour can be reduced as well when the machine is held in a cramp (HSE, 1997). However, the high generation of heat on cutting requires water supply between 1 to 4 L per min so that the adequate treatment for the waste water must be considered. A dry cutting method is capable with the polycrystalline diamond (PCD) cutter which has a high energy efficiency and it has the advantage for the application to the nuclear facility (Moseley, 2009). Since the bit price is about four times higher than the conventional bits (Halliburton, 2006), it is limited to be applied where the cutting ability and the drying method shows a large advantage.

Figure 149 Diamond boring drill equipment and application to core extraction
(source: first two from Toolstop, 2013 and the others from China Flying Technology Ltd., 2013)

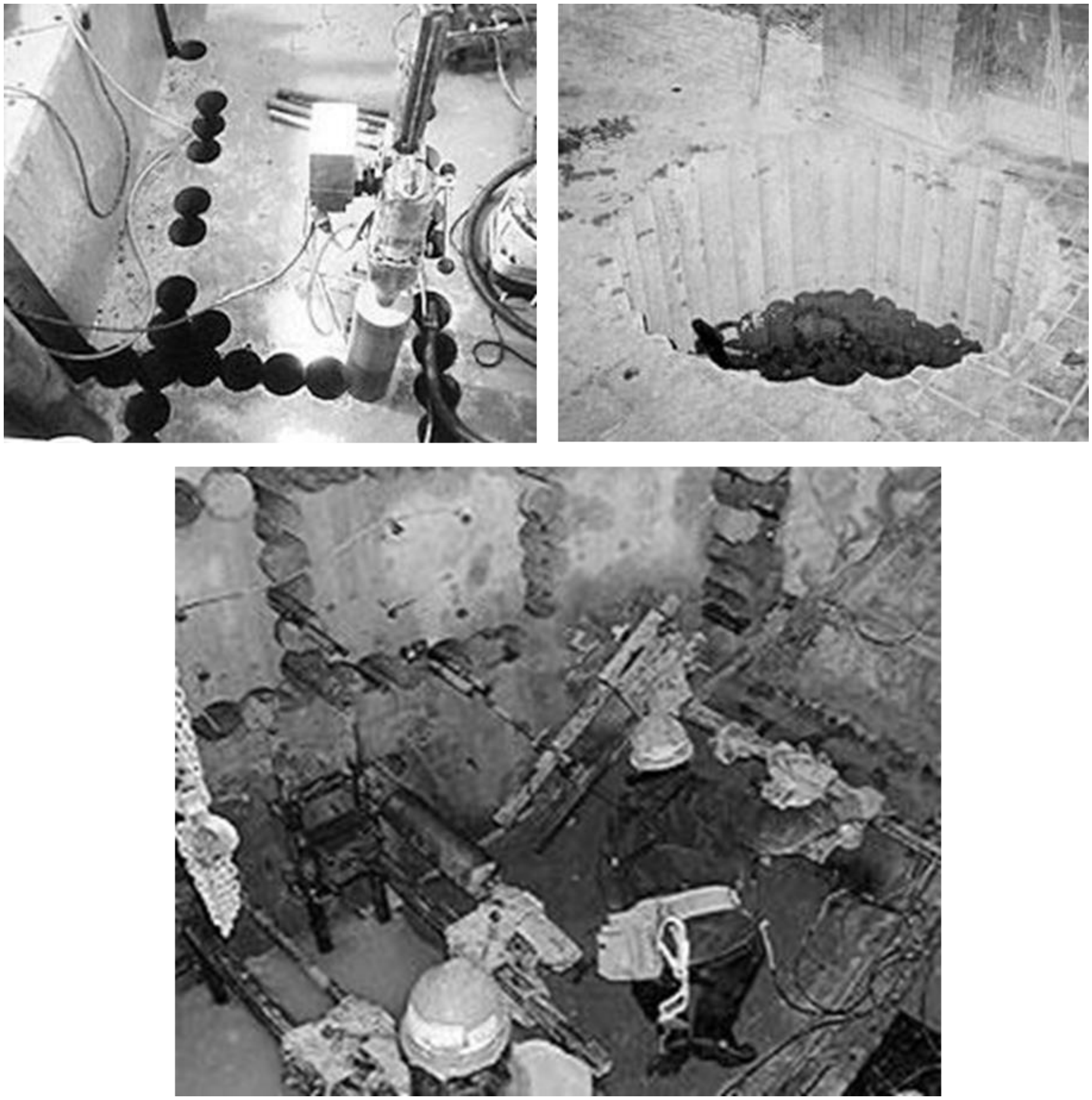


Figure 150 Diamond boring drill application to element cutting

(source: Japan Concrete Cutting Industry Osaka Ltd., 2013)

A2.2. Partial demolition method

A2.2.1. Crushing

Crushing aims to demolish the construction into concrete and reinforcement while dismantling treats the construction to separate into individual elements. Due to the simplicity of the concept, the working speed is faster and cost tends to be lower than dissembling. On the other hand, since its demolition mechanism tends to rely on the mechanical destruction it causes a large noise, dust and vibration. Therefore, it is important to confine this method to the location where the vicinity impact can be minimized such as grand level with a sound-proof fence or offsite. In another case, it would be combined with felling or shearing method for the similar purpose as dissembling.

A2.2.2. Hammering

Hammering tends to be used to crack or break concrete with continuous impact. Here, a) hand hammering and b) large size hammer are discussed.

A2.2.2.1. Hand hammer

A hand hammer is usually used to the confined location where large size machine cannot access. The labours manually use it to break the surface of target section with continuously hitting the hardened steel bit at the rate of 1600 times per minute. There are two types of hand hammer according to the source of force. For the pneumatic hammer as shown in Figure 151, it is relatively light so that it can also be applied to ceiling and walls, which is called a chipping hammer. On the other hand, the hydraulic hammer has stronger power so that it tends to be applied to break slab or asphalt (Co-ordination Network on Decommissioning of Nuclear Installations (CND), 2009). In addition to those types, the electric hand hammer, as shown in Figure 152, is often used due to its handiness with only a source of electricity. However, as well as hand hammer drill it causes large vibration to both the operator and target elements. As a result, noise and dust are generated during the operation so that it is required for labours to put dust proof masks, glass ear defenders and vibration proof gloves (Kasai, 1988a).

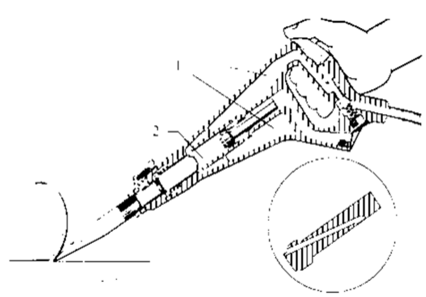


Figure 151 Pneumatic hand hammer

(source: Sokolov, 2007)

Figure 152 Electric hand hammer

(source: Makita Gulf FZE, unknown)

A2.2.2.2 Large size hammer

Compared to a hand hammer, a large size hammer is mounted on a crawler or wheel type machine, as shown in Figure 153, to break the element with a stronger power. A hydraulic type machine tends to be applied due to its higher power and relatively less noise generation during operation (pneumatic machine causes the large exhaust noise and it is quite objective especially in closed area such as in tunnel (Tunçdemir, 2008). As well as the large size drilling, it is also required to set the noise and dust insulation fence onsite. In addition, the ridged support is necessary to support its heavy dead load (Kasai, 1988a). The application in a vertical way is more efficient rather than in horizontal (Enami, 1988).

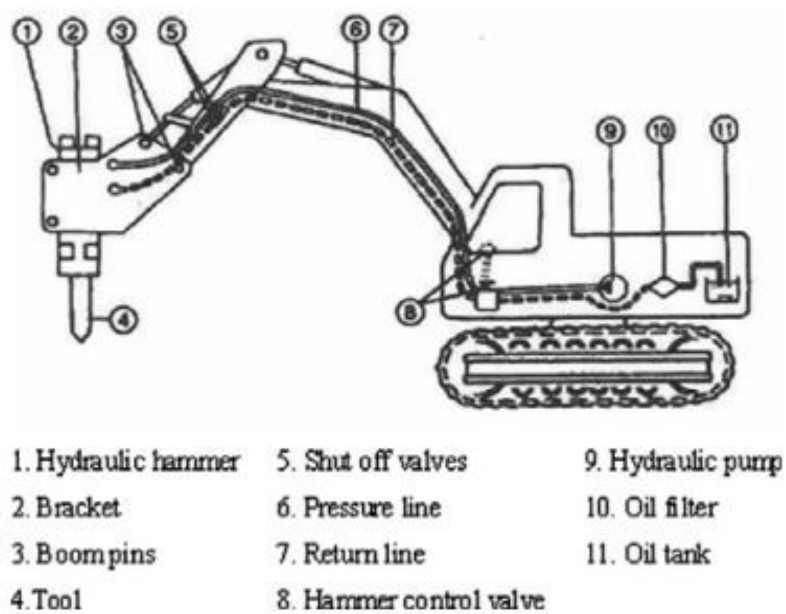


Figure 153 Hydraulic large size hammer drill

(source: Tunçdemir, 2008)

A2.2.3. Bursting with non-explosive>

The bursting method is separated into two types, static and dynamic from the type of bursting force. As the static bursting, a) bursting with wedges and b) chemically expansive agent are used in demolition, On the other hand, c) water and gas power and d) CARDOX are regarded as the dynamic approach with bursting for demolition (Kasai, 1988a). Although the use of explosive is also included to the dynamic bursting category and mild explosive tends to be applied to partial demolition, it is explained in the following section as a separate section, 'a whole demolition method'.

I. Static bursting

A2.2.3.1. Bursting with wedges

The mechanical power is applied to hole with wedge as shown in Figure 154. When the wedge is pressed by the hydraulic force of about 50 MPa and the force is conducted to feathers, the splitting force up to 350 ton is loaded and the crack is developed. This method tends to be used for a plain concrete and masonry (Kasai, 1988a), and often used for rock splitting which names this method as 'rock splitter'. The total term to achieve boring and splitting is about ten minutes and the scale is handy. It is effective to apply to confined area. In addition, the noise and vibration would not occur during operation except the preparation phase. Thus, the contamination control is not necessary for this application (CND, 2009).

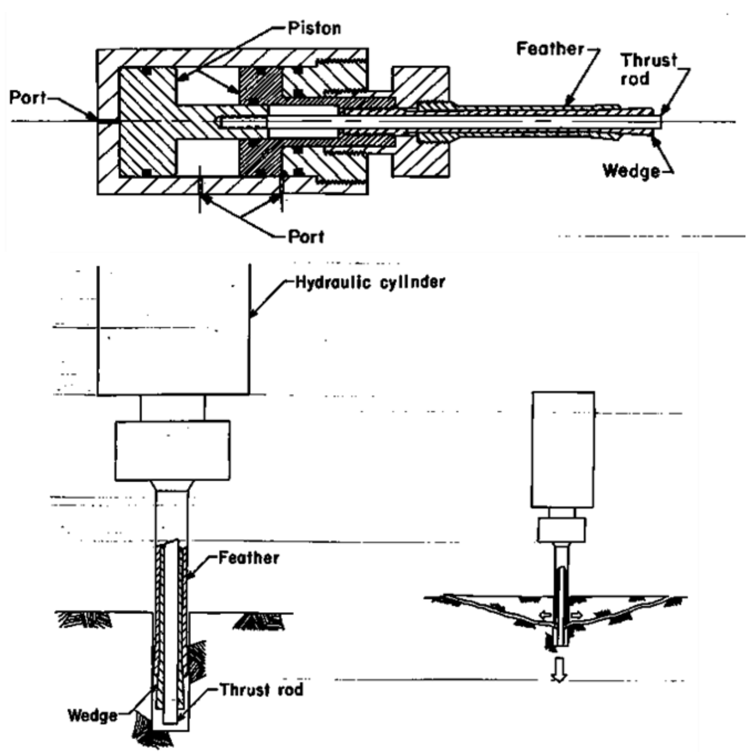


Figure 154 Rock splitter unit and application

(source: Anderson and Swanson, 1987)

A.2.2.3.2. Chemical expansive agent

A chemical expansive agent consists of calcium oxide (CaO) and calcium silicate as its main compounds. The hydration of calcium oxide included about 50%, forms calcium hydrate ($Ca(OH)_2$) which has three times larger bulk than the original when it is unconfined. As a result, the large internal stress caused at a hole casing makes cracks with high expansive pressure when it exceeds the tensile strength of elements as shown in Figure 155 (Soeda, 1988). There are two types of agent, powder and capsule. While the powder type is mixed with water and poured into the hole, the capsule type is soaked into water for several minutes and tampered. Since it is solid, the capsule types is superior in terms of horizontal application (Yamazaki, 1988).

As the efficient application of this method, Ishii and Soeda (1988) suggest the two steps application of this method to reinforced concrete through experimental study. At the first step, the application of agent aims to break covering concrete, which allows cutting reinforcement by shearing. Then, the second expansion can effectively crush remaining concrete.

Compared to other methods, it tends to require a higher cost and a longer term (up to one day) derived from the necessary time for the agent expansion. Therefore, many researchers have tried to improve the agent for quick development and to find the optimal settings of agent e.g. location and diameter of drilling, relation with the ambient temperature and the composition of agent (Soeda, 1988, Goto, 1988, Yansheng, 1988). Although the rapid strength generation has achieved with larger amount and finer agent today, they imply the rapid generation of the reaction heat. As a result, it has a risk to induce the phenomenon called blowing-out that the contained water is vapored by the reaction heat of agent and ejected from the hole. Therefore, the labours are required to wear a pair of eye goggles during the operation. Except that, it does not cause noise, dust, vibration and fly-rock as well as the bursting with wedge (Kasai, 1988a). Accordingly, this method is preferred to apply to urban sites where the large vicinity impact is restrictedly limited regardless of its higher cost which is about twenty times higher than the explosive demolition (Laefer, 2010).

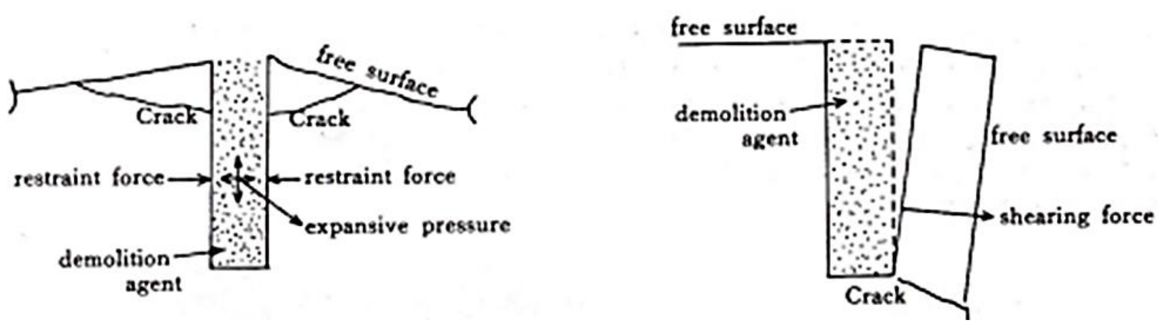


Figure 155 Principle of demolition with chemical expansive agent

(source: Soeda, 1988)

II. Dynamic bursting

A2.2.3.3. Water and gas power

As the same discipline as the other bursting with non-explosive methods, there are several methods to use the high pressure which is generated by the enclosing water or gas into the drilled hole to split concrete or rock from the inside (Kasai, 1988a). A jacking plate with water power is introduced here as the representative method applied to an actual site in Japan today.

Different from the other bursting method with non-explosive, jacking plate with water power method does not use drilled hole but uses a narrow gap cut by a diamond saw. The narrow tube made by welding two metal plates is inserted in the gap, and it is expanded by the poured water. Finally, the pressure split the surrounding material as shown in Figure 157. As shown in that, it can split into line it is easy to demolish massive elements into handling scale without any dusts. It infers the high recyclability at the second demolition phase. Moreover, due to the process, it does not cause a large noise, vibration, and dust except the cutting process with a diamond saw (Climb Ltd., 2013). Although it tends to be applied to civil project e.g. bridge demolition due to its size constraints, it is expected to be applied to the demolition held at urban area taking advantage of less annoyance during the demolition.

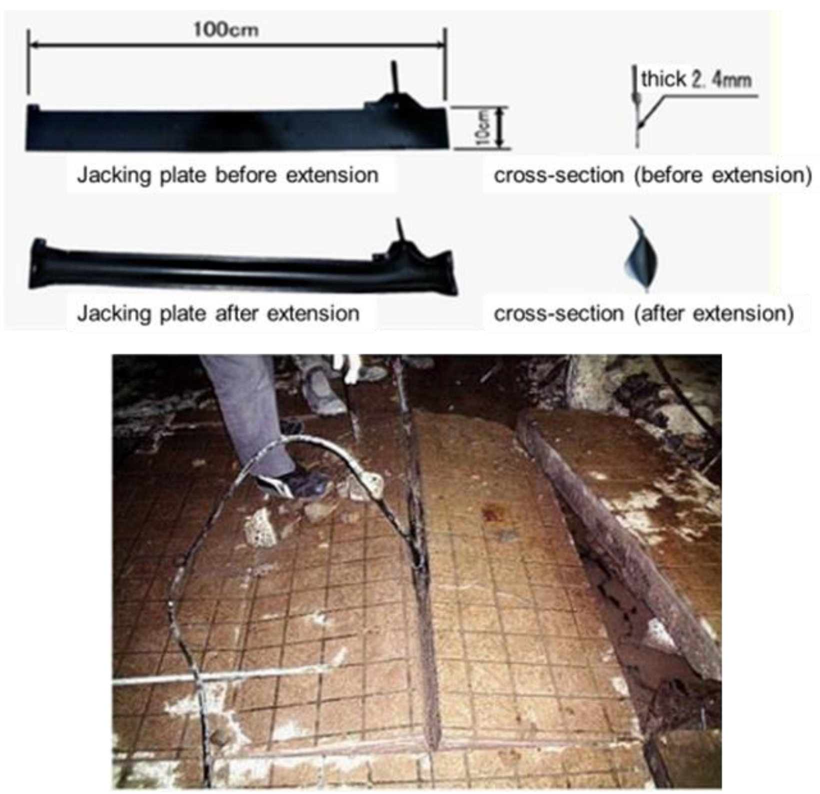


Figure 156 Jacking plate unit and application

(source: Climb Ltd., 2013)

A2.2.3.4.CARDOX

CARDOX is the demolition method which uses the expanding pressure of carbon dioxide (CO_2) gas from liquid. With the electrical filament, the CO_2 liquid charged inside the tube, as shown in Figure 157, starts the gasification. As the volume of the gas increases to 600 times larger than its liquid form, it exceeds the yielding pressure of rupture disc so that CO_2 gas is released from head and breaks surrounding materials. As described in Figure 158, the high pressure of CO_2 gas causes the crack at the target material and that allows making it into pieces. Because of the large demolition energy, labours need to keep some distance from the application place. However, the process takes only one second and it does not cause shockwaves or a damaging vibration and dust. Therefore, the generated waste can be treated easier than the case with explosive demolition. Though the noise at the reaction and drilling for the unit application may concern, it has been applied to the demolition of RC foundation at the site half a mile from the tower of London before (CARDOX International Ltd., unknown). Caldwell (2005) explains the noise and vibration can be supressed when the tube can set properly in the hole without a free face.

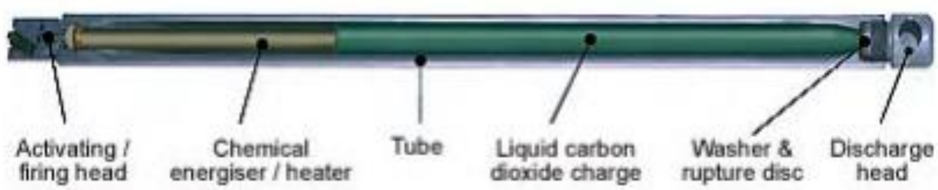


Figure 157 CARDOX tube unit

(source: CARDOX International Ltd., unknown)

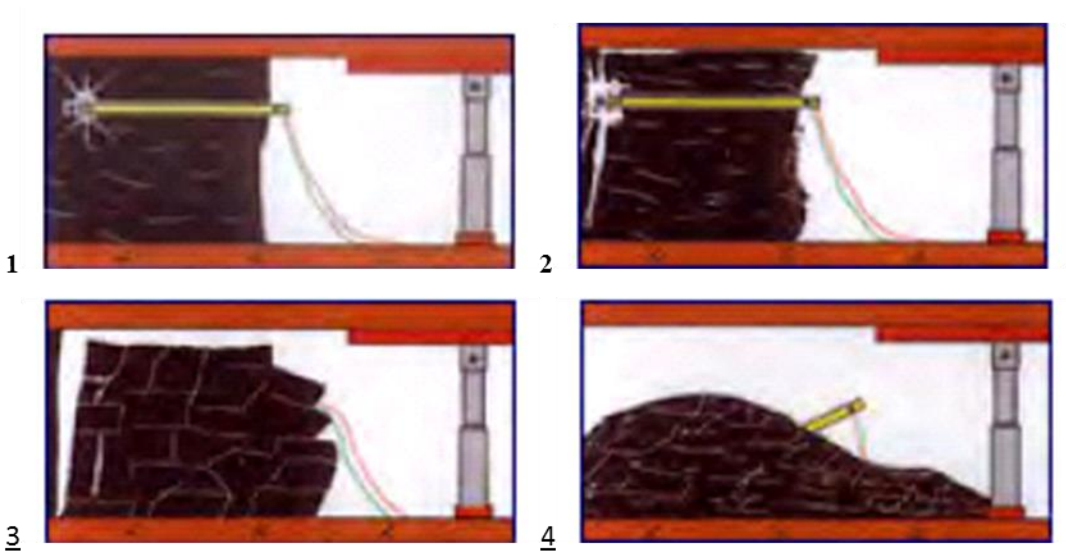


Figure 158 CARDOX demolition process from 1 to 4

(source: CARDOX International Ltd., unknown)

A2.2.4. Heating

There are three main heating methods to demolish the concrete; a) electric current heating, b) induction current heating and c) microwave heating. Though the first two methods aim to heat the steel rebar which has a high electric conductivity compared to the concrete, the third method directly heats elements with microwave regardless of material. Mcfarland (1988) summarizes the main factors of RC deterioration by heating into three types: I) deterioration of cement paste by dehydration, II) distortion of steel reinforcement and III) deterioration of aggregate by transformation with heat. As the temperature of concrete increases, the contained water in various forms is vaporised and that deteriorates internal structure of concrete by the gas pressure or volume reduction with dehydration.

For the thermal behaviour of cement hydrate, at around 300°C, the interlayer water between C-S-H is evaporated and some of the chemically combined water by C-S-H and ettringite (sulfoaluminate hydrate) is lost as well. Around 500°C, the dehydroxylation of calcium hydrate ($Ca(OH)_2$) advances. When the temperature becomes around 900°C, calcium carbonate is decarbonated and C-S-H is decomposed (Mehta, 2006, Alacon-Ruiz, 2005). For the aggregate, at around 573°C, quartz contained in the siliceous aggregates e.g. granite and sandstone transforms from α to β and it brings 0.85% of volume extension. At about 700°C, the carbonate rock causes decarbonation as well as the cement hydrate (Mehta, 2006). Besides the individual volume change of component, the different thermal expansion generates a stress at the interface between cement hydrate and steel reinforcement or aggregates. Once it exceeds the bond strength, the component is segregated easily.

A2.2.4.1. Electric current heating

This method is applied to RC structures to remove the cover concrete and separately treat wastes. As shown in Figure 159, two terminals are connected to form a circulation after removing the cover concrete from the edge of the reinforcement bar. By applying an electric current, the temperature of rebar increases and causes crack from the inside of structure.

Kasai (1988b) verified less dust and flying chips during the operation of electric current heating through mock-up test. He also showed the higher performance of heating with shear reinforcement and insists the suitability of this method for the demolition of the biological shield at a nuclear power plant. Kasai (1988c) also compared the efficiency of demolition with and without the heating before crushing. As shown in Figure 160, the covering concrete can be removed in large pieces with crushing by the hydraulic hammer, which can be crushed into pieces with the simple hand hammer. It was verified that besides the high demolition efficiency, the application of electric current heating allows easier waste separation. In other words, the recyclability of demolition waste with this method is high and it can be treated offsite.

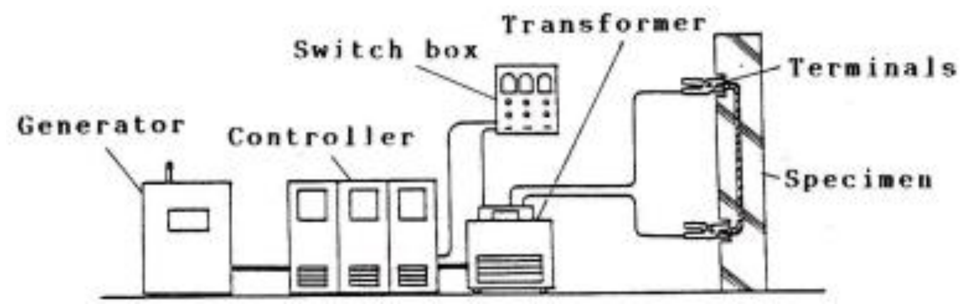


Figure 159 Electric current heating system

(source: Kasai, 1988c)

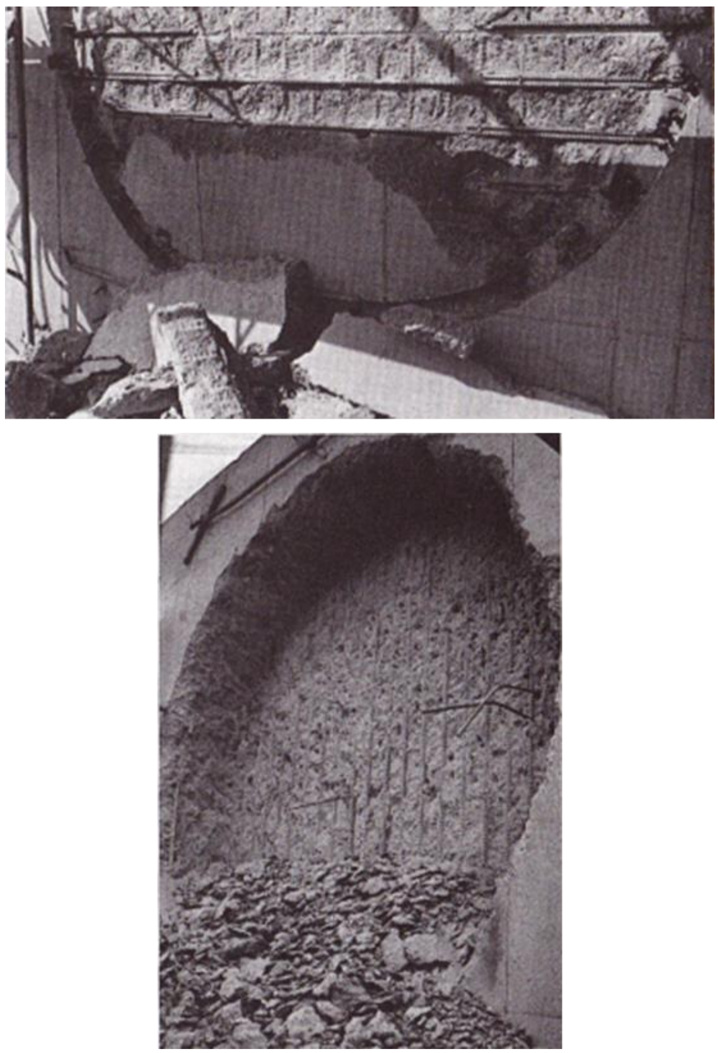


Figure 160 Demolition with and without electric current heating before crushing

(source: Kasai, 1988c)

A2.2.4.2. Induction current heating

This method uses induction current to heat up the reinforcement to remove the covering concrete as the same concept as the electric current heating method. As the metal has the property which generates an opposite electric current against an electromagnetic field, it is possible to induce a current at the reinforcement and heat it without contact as shown in Figure 161. Though it can achieve the removal of concrete without noise, dust and vibration, the efficiency becomes too low to heat the reinforcement as the distance increases. Lim (2010) suggests 30mm from the reinforcement as the maximum distance for an effective heating for 19mm diameter steel bar, which allows the reinforcement to exceed 600°C within one minute. Due to some heating limitations including this, it has not been applied to an actual site yet. Kitagaki et al. (2010) suggest the application of induction current heating to the cementitious joint of elements including steel fibres to exploit the advantages of this technology.

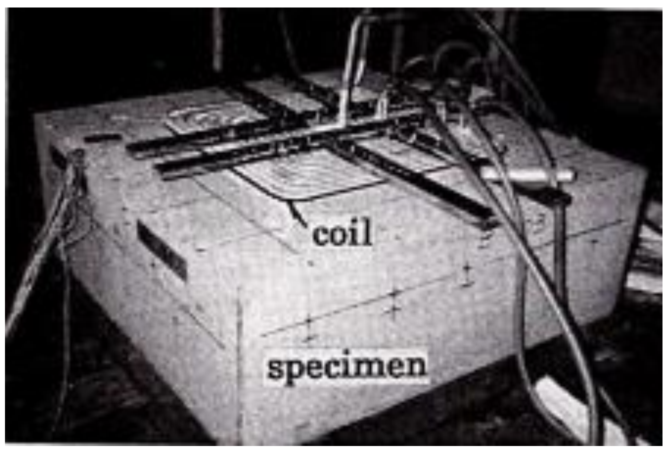


Figure 161 Induction current heating unit

(source: Masimo, 1988)

A2.2.4.3. Microwave heating

Microwave heating breaks concrete by the steam pressure generated by the microwave heating the contained water. A few centimetres of surface concrete absorb energy from microwave and the temperature inside rapidly rises. As a result, the evaporated water therein causes high steam pressure followed by spalling as shown in Figure 162. Though it generates fragment from the spalling, the attachment of vacuum system can suppress the generation to less than 1% which is about 2 mg/m3. In addition, the noise and vibration are very limited during operation. According to these advantages, it is applied to repair asphalt surface in China as shown in Figure 163. The microwave heating immediate melts the surface asphalt and these materials are used to form a new layer. This method is superior to the other methods in terms of the instant heating ability and the impact to ambient environment (Bosisio, 1974).

As another application, Yasunaka (1988) insists the advantages of this method for nuclear facility demolition. Since it was measured in the Japan Power Demonstration Reactor (the first nuclear power plant in Japan) that the surface contamination of nuclear facility was usually limited to 2 cm, the microwave heating method seems to be optimal to remove concrete and minimize the generation of contaminated waste. However, Kakizaki (1988) and White (2009) concluded that the improvement of heating abilities is needed e.g. power and applicable area through the experiments.

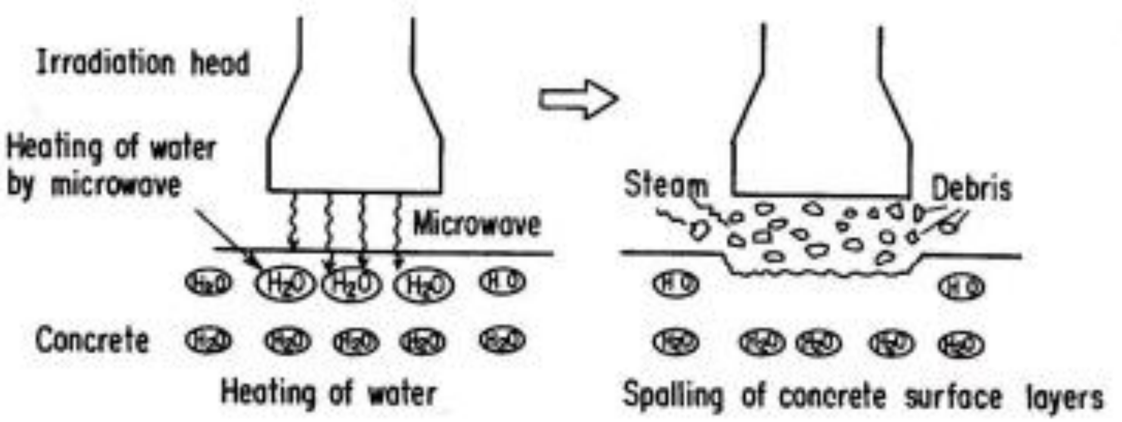


Figure 162 Microwave heating mechanism

(source: Yasunaka, 1988)

Figure 163 Asphalt repair Microwave heating mechanism

(source: New Timehope, 2013)

A2.3. Dismantling method

Dismantling has many advantages in demolition compared to the other types due to its unique treatment which demolishes along elements in opposite order of construction. According to this, the demolition waste is easy to distinguish its component so that it has a high efficiency for recycling at the second demolition phase. In addition, most of the dismantling methods has relatively less noise, dust and vibration. Even though it sometimes needs to apply the demolition methods having a large influence on vicinity as the second demolition, it can be held at the ground area or offsite to minimize its effect. Due to these reasons, all of the five biggest Japanese construction companies (Kajima, Takenaka, Shimizu, Obayashi and Taisei Corp) have competed to invent the combination dismantling methods and applied to demolitions of mega skyscrapers exceeding 50m in urban areas (Research Institute on Building Cost, 2012). This implies the advantages of dismantling method at the high demolition efficiency, less influence on vicinity and environmental impact. In addition to this kind of whole dismantling process, the crushing methods such as hammering can be used to weaken or reveal the joint of members to apply 'shearing' followed by 'felling'. This is still effective to improve the demolition efficiency and suppress the vicinity impact during the operation.

A2.3.1. Cutting with abrasion

As the main cutting methods with abrasion, Kasai (1988a) introduced three devises; a) diamond disc cutter, b) diamond wire saw and c) water jet. While the first two methods exploit the cutting ability of diamond as the diamond boring drill to dismantle elements, water jet using the water pressure.

A2.3.1.1. Diamond disc cutter

The diamond disc cuts construction elements including steel reinforcements. While some of the machines can set the disc having more than 100cm diameter (Kasai, 1988a), disks having 10 to 25 cm of cutting depth tend to be used according to the target elements. As shown in Figure 164, there are manual and mobile types of machines to slide a cutting section with their cutting speed of 2 to 10 and 5 to 25 min/m, respectively (Kemi and Hiraga, 1988). As mentioned in the previous section, dismantling has large superiorities at demolition efficiency, vicinity influence and environment impact, and this is especially suitable for a high-rise building demolition which requires the operation at a high place without minimum impact against vicinity buildings. Kemi and Hiraga (1988) show the demolition flow and the cutting method of elements as Figure 165 and Figure 166, respectively. After cutting out the structure into pieces, the power crane takes them down in order. The systemized method improves the demolition efficiency and decreases the work at high place. Besides the second demolition using the crushing method which tends to cause large noises, vibration and dust can be held in the grand area or offsite. The cut pieces can be reusable or easily separated and recycled for the next construction.

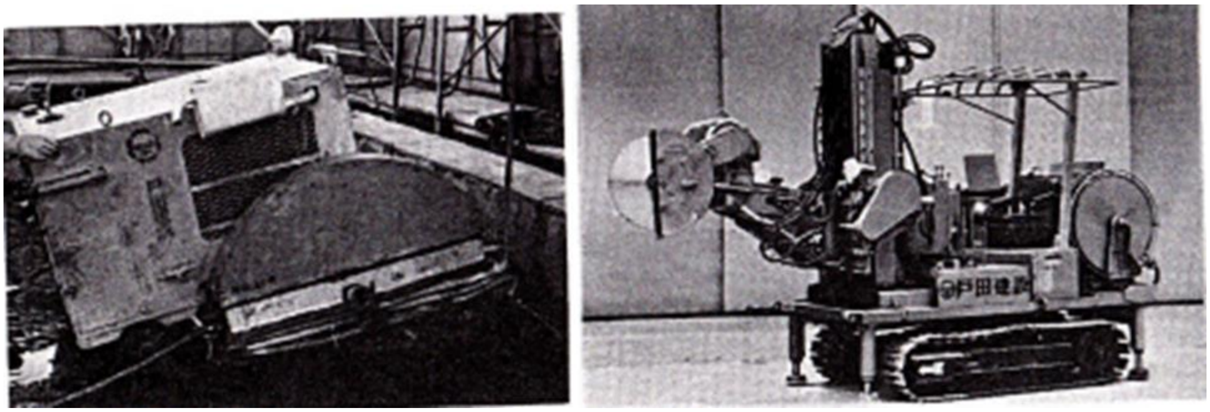


Figure 164 Diamond disc cutting machine (left: slab use only, right: all-round type)

(source: Kemi and Hiraga, 1988)

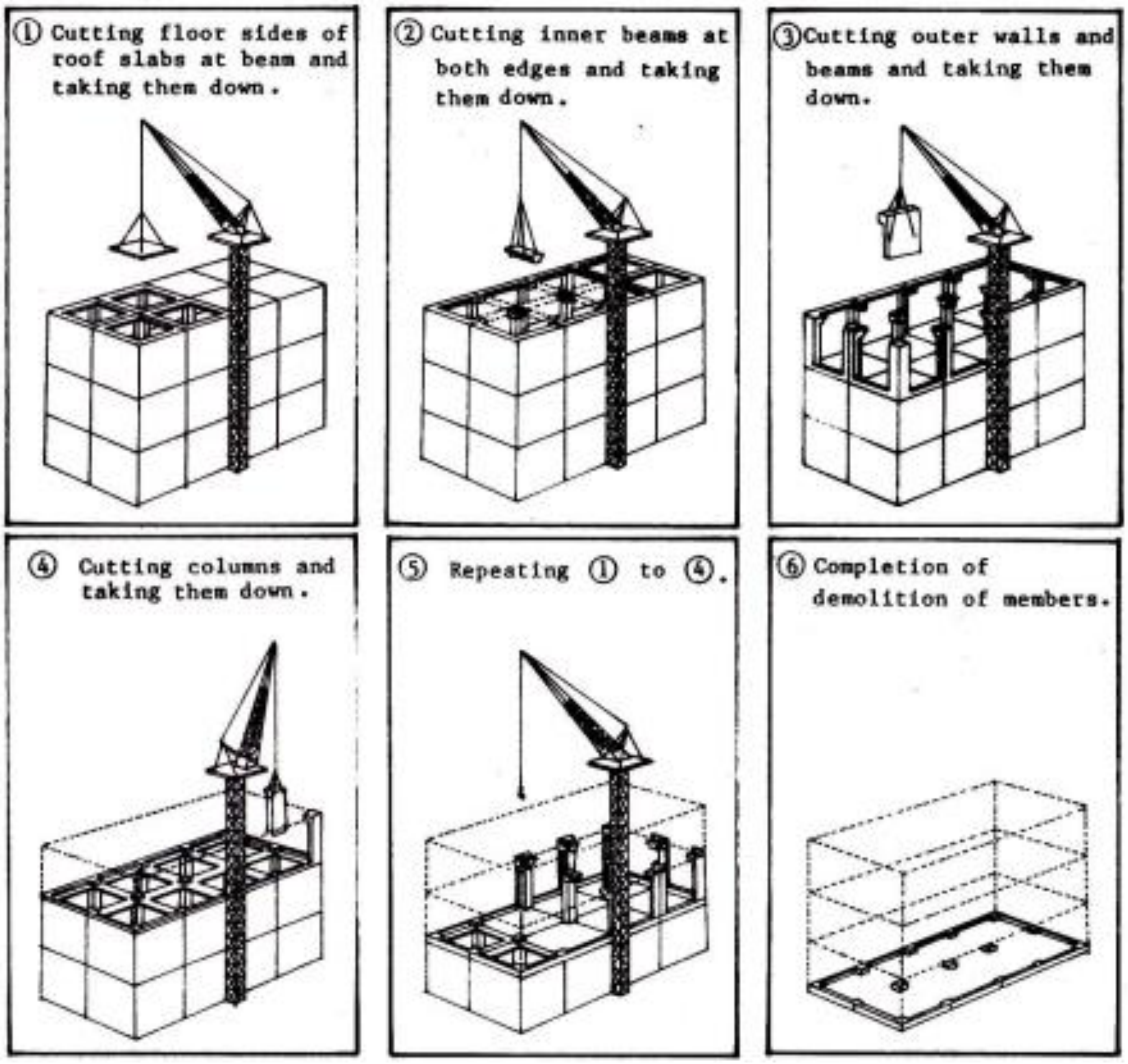


Figure 165 Diamond disc cutting flow

(source: Kemi and Hiraga, 1988)

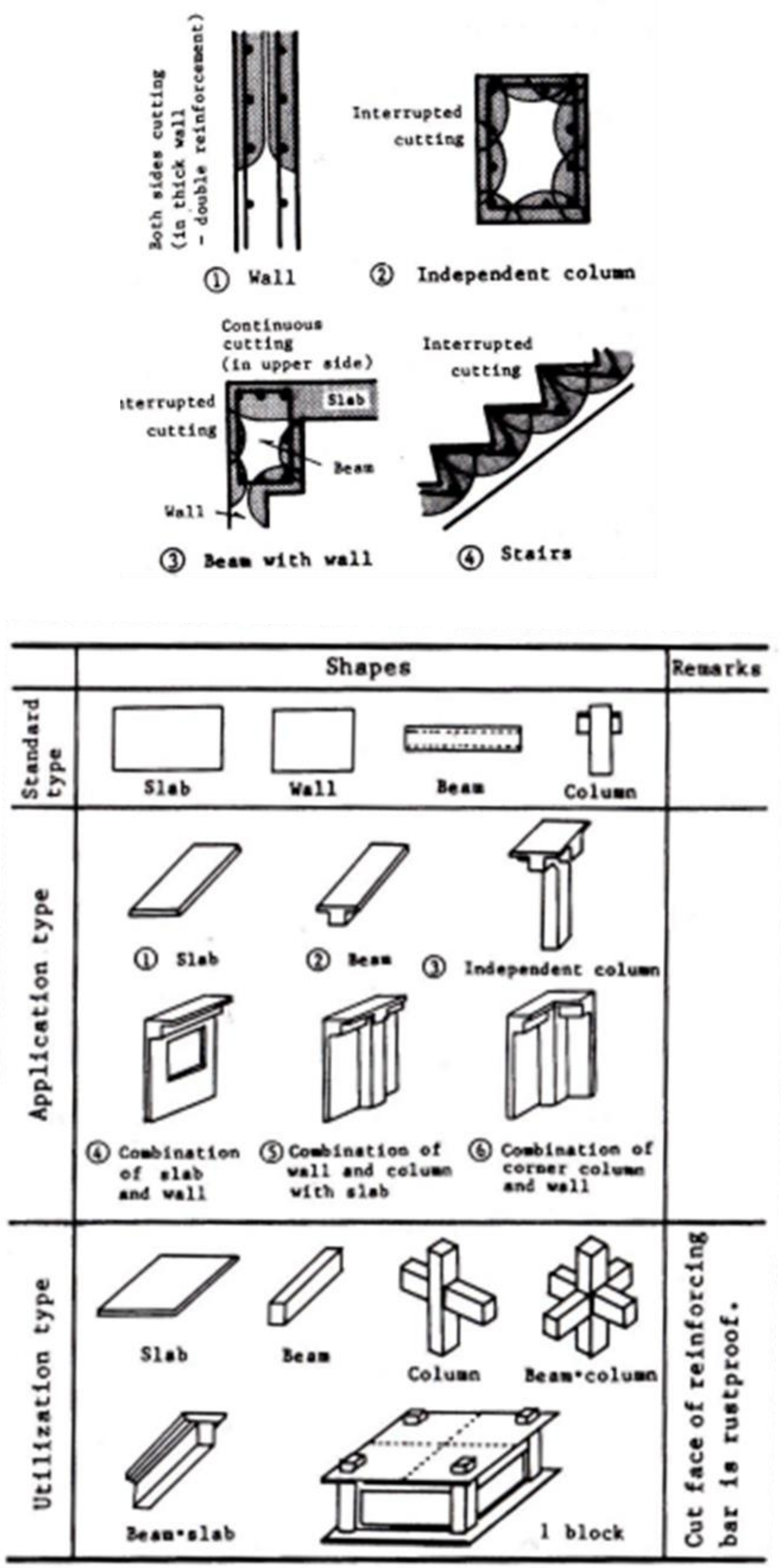


Figure 166 Diamond disc cutting method and shapes of pieces

(source: Kemi and Hiraga, 1988)

A2.3.1.2. Diamond wire saw

This is the method to use the closed loop wire saw with the diamond bits to cut the construction. Due to the high cutting ability of diamond as mentioned in diamond boring machine section, the steel reinforcement can be cut by this saw. While the target needs to be enclosed the wire loop, it can be applied to a large and flexible section. Accordingly, it tends to be used for the dismantling of a massive and foundation concrete (Kasai, 1988). This method is originally used for the quarrying rocks and the advent of diamond bit extent the applicability to reinforced concrete constructions. It has largely three types as shown in Figure 167, according to the way to move the pulley for controlling the tension of the wire loop. While the first two devices need to run or slide the main part, the final device slides only pulley, which allows the application at confined place on site. As the merit of this method, Diamond Wiresaw Structure Society (2013) points out the less vibration, noise and dust and the flexibility of application with semi-remote control such as underwater, high place and narrow area besides the application introduced above. A low cutting temperature and small defectiveness of cutting section is also included as their superiority (Cichosz, 2008).

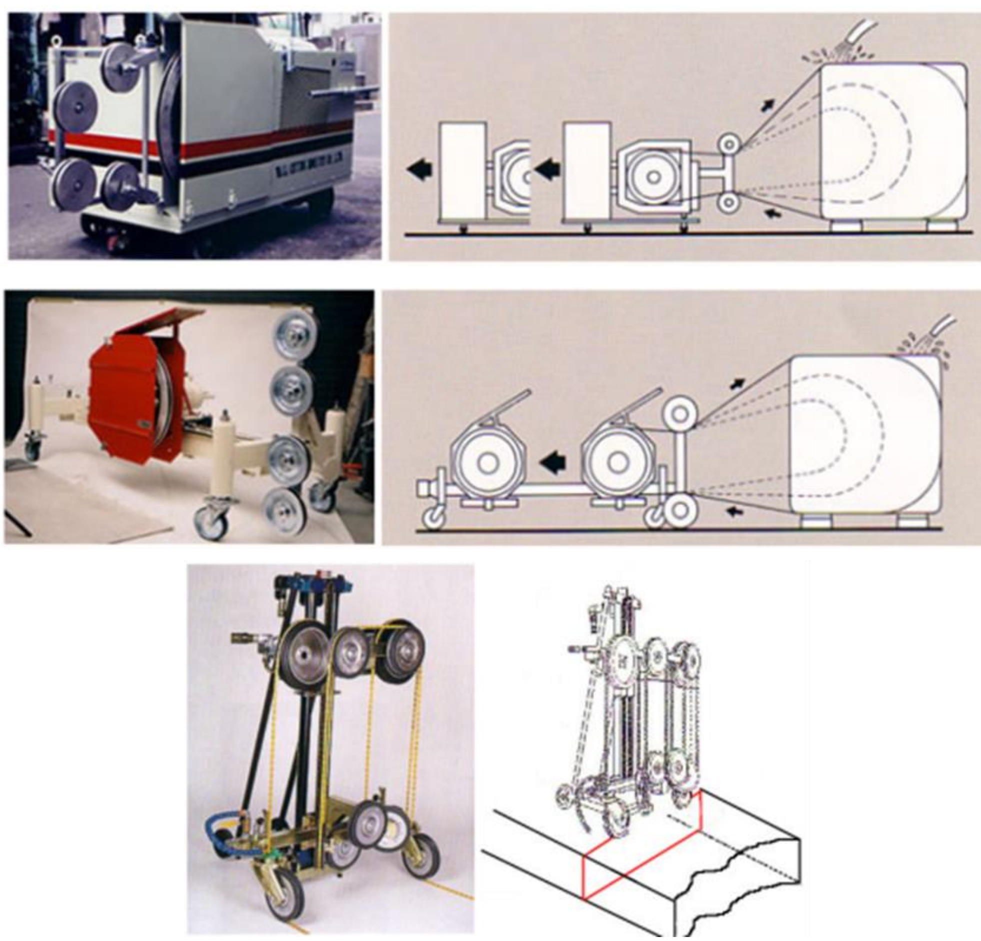


Figure 167 Diamond wire saw devices (self-running, guide beam running and rig type)

(source: Diamond Wiresaw Structure Society, 2013)

In contrast, the relatively high cost can be included as the disadvantage of this method according to the consumption of wire during operation. Thus, many researchers have investigated the relation between cutting circumstance and wearing of wire. For instance, Ozcelik and Yilmazkaya (2011) regarded the cutting efficiency as the combination of unit wear, cutting rate and specific energy, and tested the effect of the strength of the rock and the cutting position on it. Besides, they showed the direct relation of cutting efficiency to rock anisotropy, the high effective cutting position such as the angle of wire were suggested.

As its application, McAnuff and Cyr (2007) introduce its use on demolition of stacks and silo in Toronto. As shown in Figure 168, the sturdy concrete construction was sliced using a diamond wire saw, and the explosion of each foot columns caused the collapse of slice. Owning to the unlimited cutting section of wire saw, the large building having 36m high and 12m wide section could be separated. As a result, the amount of the hole to be drilled was reduced into half with preparation cutting.

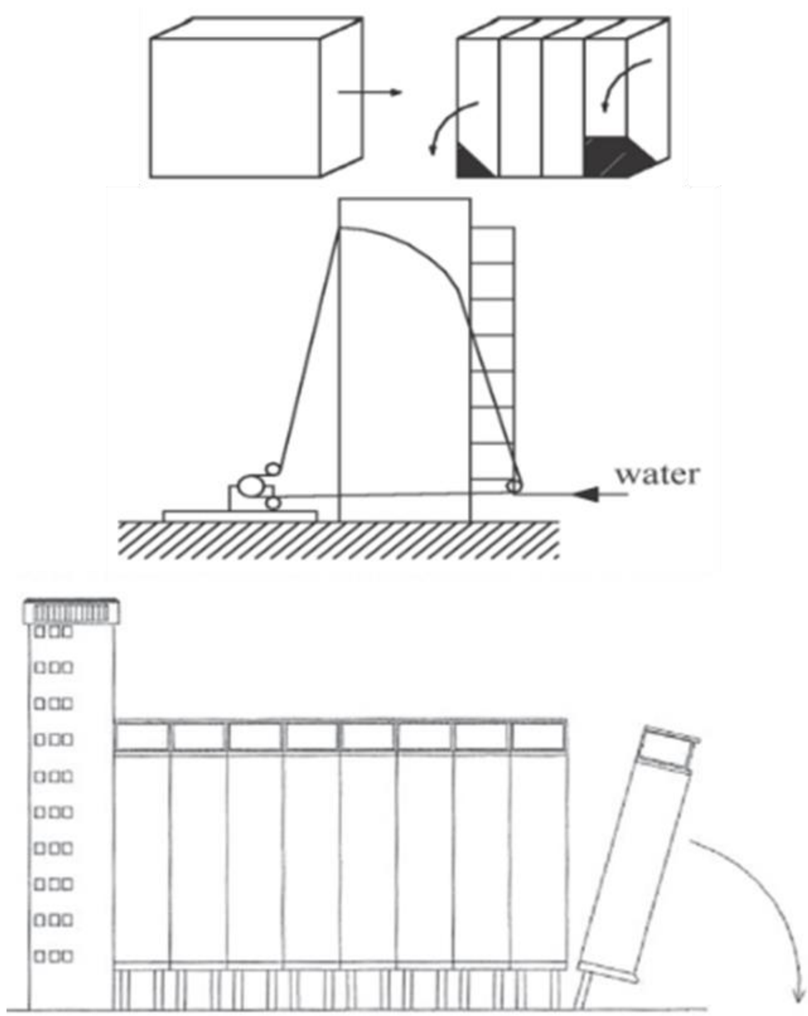


Figure 168 Diamond wire saw method application to stacks and silo in Toronto
(source: McAnuff and Cyr, 2007)

The US Department of Energy (2000) suggests the application of diamond wire saw method as the alternative method to Plasma Arc method for dismantling the nuclear facilities. As mentioned before, the nuclear facilities dismantling needs to concern about the minimization of radioactive explosion of the labours during the operation and the spreading of the contaminated materials. Compared to the Plasma Arc method which requires preparation of cutting inside the facility with a protective suit, diamond wire saw method fills the inside with low weight concrete and cut it from outside. The better cost performance and highly improved safety of labours were verified by the mock-up test. As the other example which shows the wide applicability of this method, Molfino and Zoppi (2012) introduced the mock-up test of application to dismantling the underwater pile as shown in Figure 169. They expect this method as a new dismantling method for offshore structures concerning less quantity of pollutant in the sea during operation besides the high efficiency of cutting underwater. The authors insist the robotic control system enhances the feasibility of application to where the labours are difficult to enter.

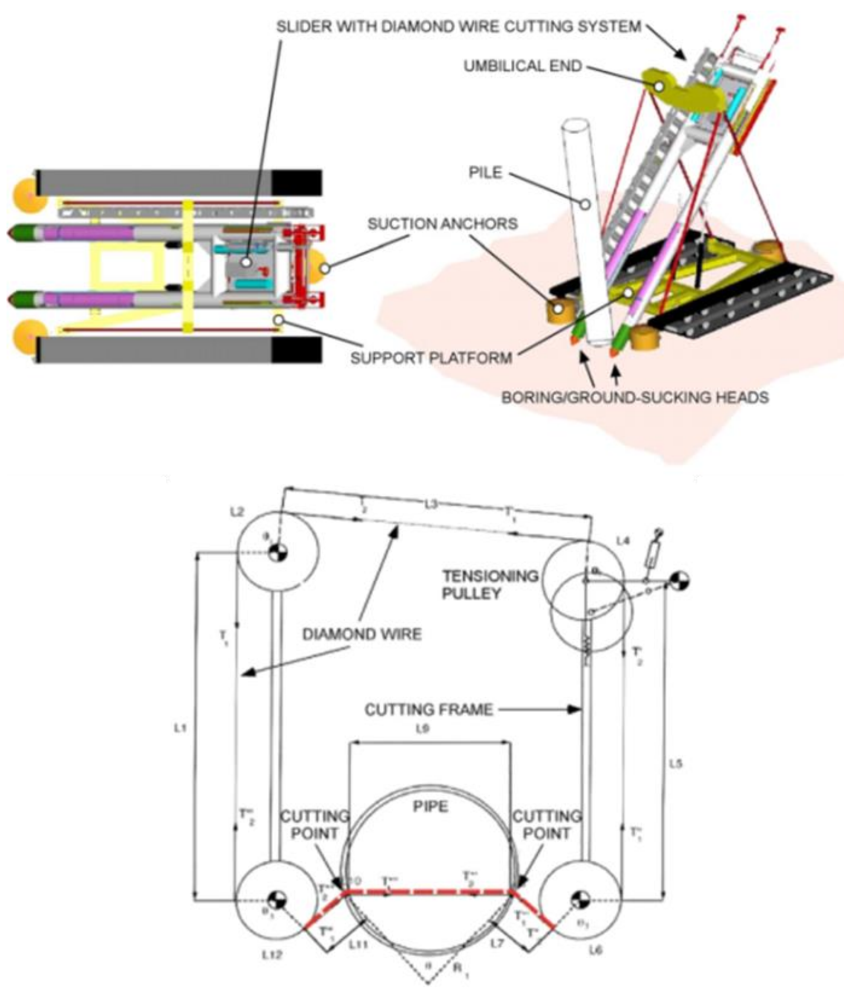


Figure 169 Diamond wire saw method application to underwater pile

(source: McAnuff and Cyr, 2007)

A2.3.1.3. Water jet

Though it is explained that the water jet cuts elements with water pressure, the garnet or steel particles are added to the water to improve cutting ability by abrasion (Kasai, 1988a). As shown in Figure 170, the extra-high-pressure water is mixed with abrasives at the head of the machine and they are released at around 2500 to 4000 kgf/cm2 from the nozzle to cut the concrete and steel reinforcement in the speed of 5 to 10 cm/min (Matsushita, 1988). Due to the strong impact and the use of water, the guard and evacuation hose is needed at the front and back side. Accordingly, the necessity of preparation for setting makes the demolition term longer and relatively costly. The lower durability of equipment such as nozzle and consumable use of abrasive also increases the cost of water jet method. However, Konno (1988) insists the two advantages; less noise and a high applicability even in water or in air and at the confined space due to its light weight and a small stream reaction.

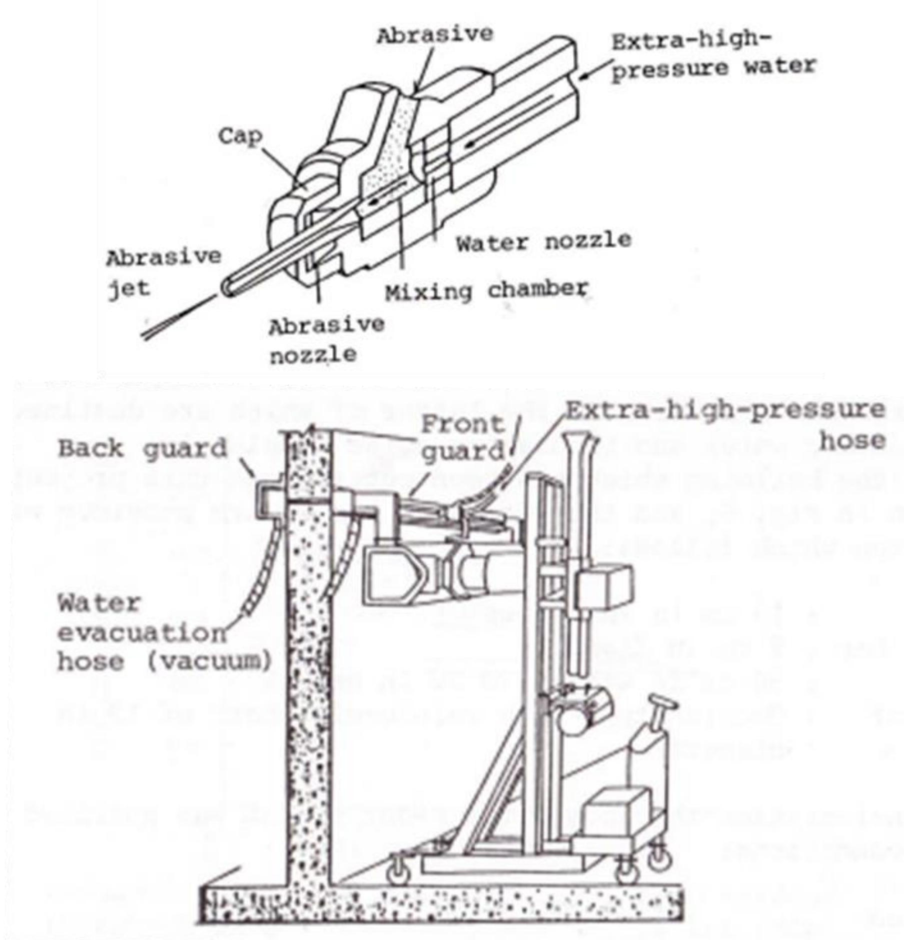


Figure 170 Water jet machine detail

(source: Matsushita, 1988)

Matsushita (1988) introduces the application of this method to the dismantling of a hospital as described in Figure 171, which exploits those advantages. As the hospital was needed to remain function at the existing building during dismantling, it had to be held without any noise, vibration and dust, and it had achieved properly.

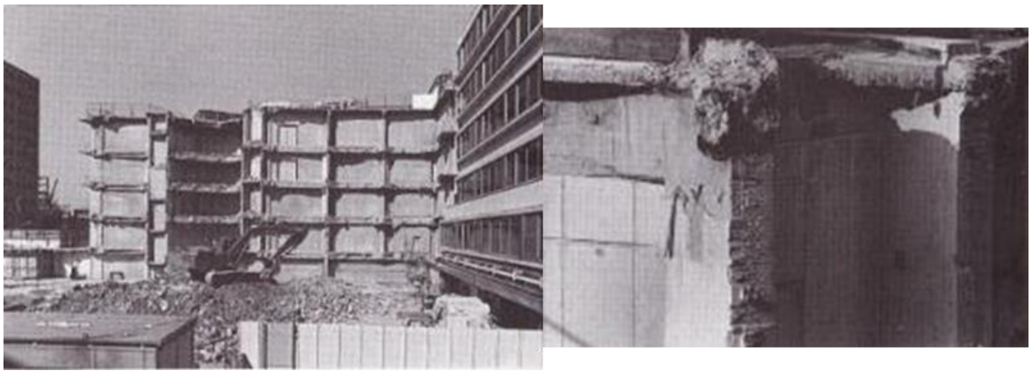


Figure 171 Application of water jet system to partial dismantling of hospital

(source: Matsushita, 1988)

Yokota (1988) suggests the application of this method to the dismantling of reactor biological shield at the nuclear power plant as shown in Figure 172. As the biological reactor shield is exposed to radioactivity, the workers cannot operate in proximity during the operation, and the special measure is required not to spread the radioactive contamination to sustain the environmental impact as low as possible. In addition, it has a massive and strong structure to achieve the safety requirements. Responding to these, Yokota (1988) suggested a remote control water jet system to apply to a practical project through mock-up test.

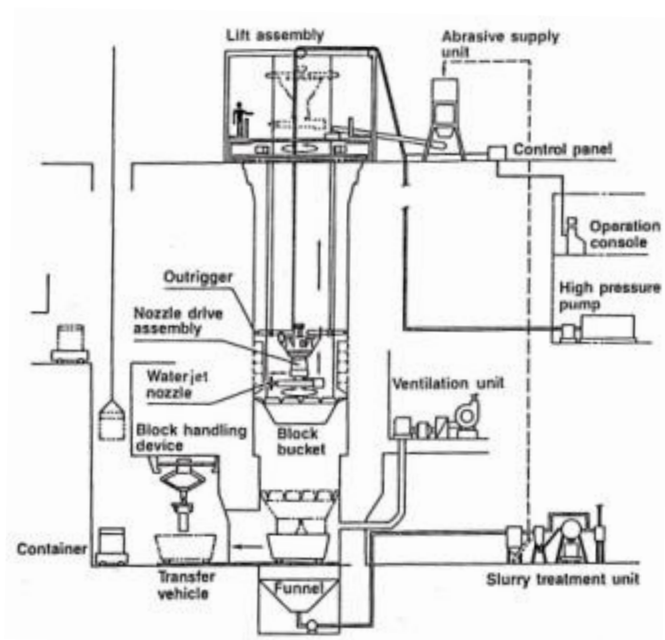


Figure 172 Application of water jet system to dismantling of reactor biological shield

(source: Yokota, 1988)

A2.3.2. Cutting with melting

As the main cutting methods with melting, Kasai (1988a) introduced four methods, a) thermic lance, b) fuel oil flame and c) laser beam and d) plasma. Although the previous section introduces the methods using abrasion for cutting, this method cuts off elements by heat generated in different ways.

A2.3.2.1. Thermic lance

The wires made by the alloy of steel or aluminium are enclosed inside the metal pipe as shown in Figure 173 and the tip is burned by acetylene gas. Once the wire is ignited, the oxygen gas is supplied to maintain burning (Kasai, 1988a) and the wire is fed as the cutting process progress. The resultant reaction heat (2200~5600°C) between alloy and oxidant can decompose concrete and melt the reinforcement bars. Track mounted-lance device normally cut elements for 0.5 to 1m length regardless of reinforcement existence (CND, 2009). However, due to the high reaction heat, it causes a large quantity of heat smoke, toxic gas and slag during the operation so that an efficient disposal and treatment system needs to be applied (Uchikoshi, 1988).

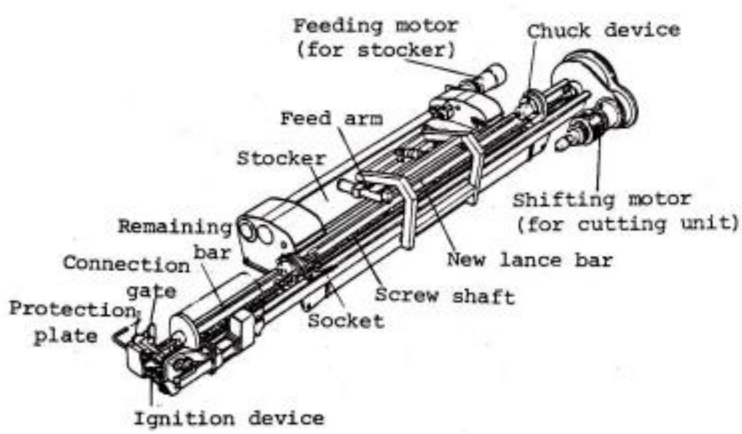


Figure 173 Thermal lance cutting unit

(source: Uchikoshi, 1988)

Through the mock-up experiment, Uchikoshi (1988) shows the feasibility of an automatic cutting with thermic lance as shown in Figure 174. This is expected to be applied to the structures containing many metallic components where labours cannot enter such as biological shielding structures.

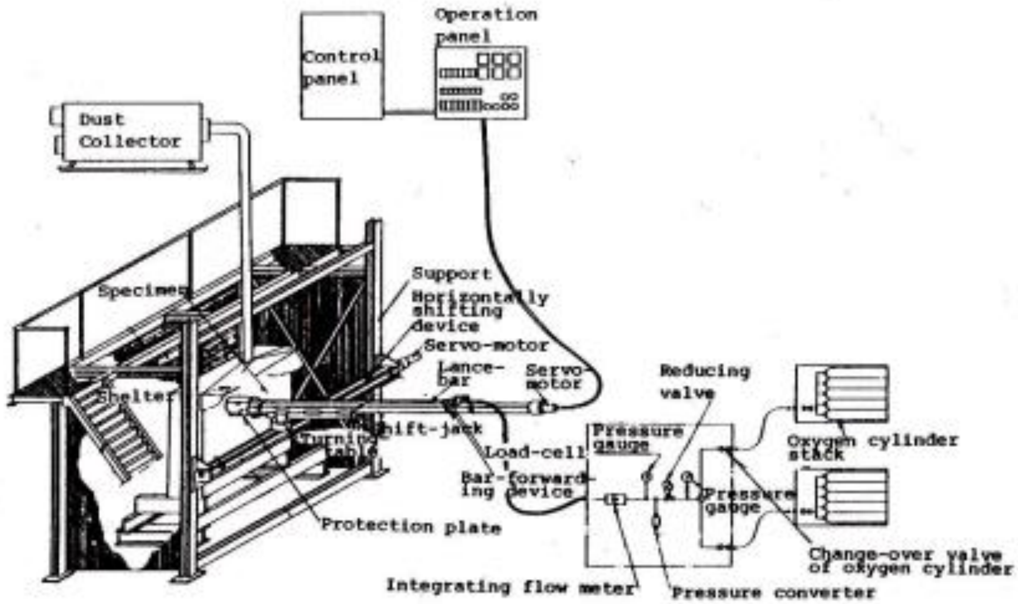


Figure 174 Automatic system of thermal lance cutting

(source: Uchikoshi, 1988)

A2.3.2.2. Fuel oil flame

The heat from the combustion of oxygen and kerosene gas jet melts concrete and reinforcement. As shown in Figure 175 and Figure 176, oxygen and kerosene supplied separately into a combustion chamber are ignited and ejected from the nozzle to generate a flame. Though cutting ability largely depends on the cut material, the supply of kerosene and content of steel element also influence the ability (Nakajima, 1988). Similar to the thermal lance method, the high heat produces fume and toxic gas. In addition, due to the large noise during the operation, it cannot be applied to the demolition of construction in the urban area (Kasai, 1988a). Accordingly, this method tends to be applied to underwater demolition as shown in Figure 177. Besides the noise problem, the dross generated during the operation would not reduce the cutting efficiency underwater.

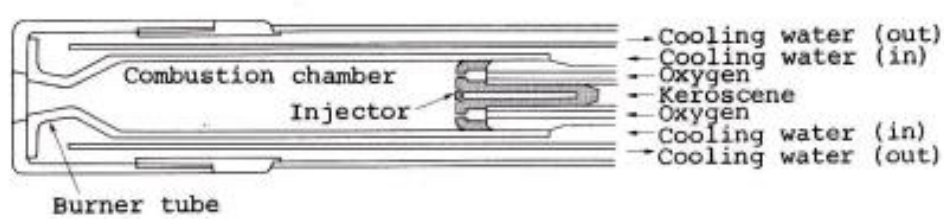


Figure 175 Fuel oil flame cutting unit

(source: Nakajima, 1988)

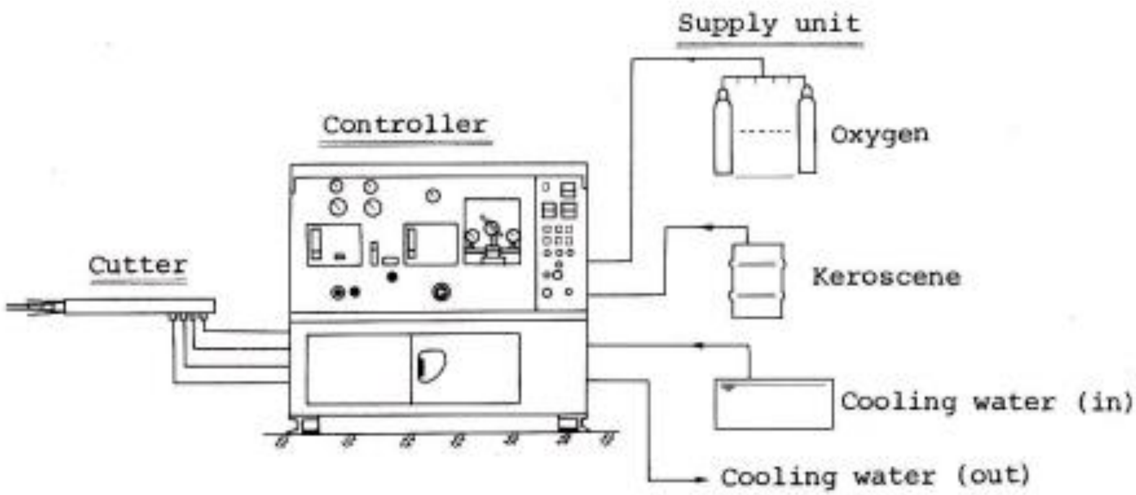


Figure 176 Fuel oil flame cutting system

(source: Nakajima, 1988)

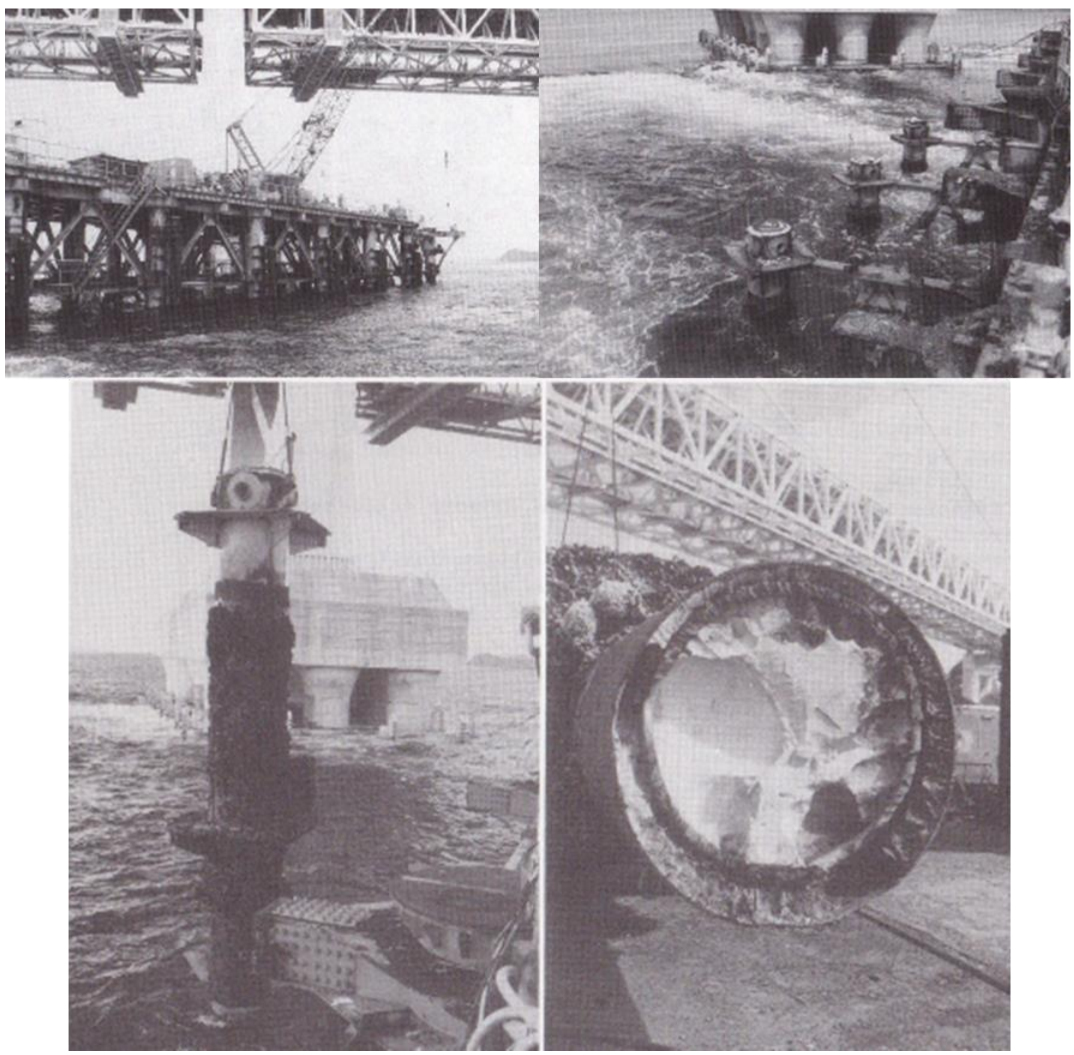


Figure 177 Application of fuel oil flame cutting to underwater temporary structures

(source: Nakajima, 1988)

A2.3.2.3. Laser beam

A laser beam is often applied to metal structures, especially to nuclear power plants rather than general reinforced concrete structures. There are mainly three types of laser beam cutting methods; laser flame cutting, laser fusion cutting and laser sublimation cutting. The laser flame cutting, as shown in Figure 178, uses the exothermal reaction energy between laser and supplied oxygen. Due to the high energy, the cutting speed is faster than the other two types, and the slag becomes fluid, which can be removed with a low gas pressure. On the other hand, the laser fusion cutting tries not to cause an exothermal reaction during the cutting process to prevent the generation of sub-product by supplying shielding gas e.g. Argon or Nitrogen. While the cut edge remains non-oxidised, the slag tends to be so viscos that a high gas pressure is required to prevent the declining of cutting efficiency. For the laser sublimation cutting, just as the name says it transforms the material from solid to vapour directly with an intense laser beam. It also supplies shield gas to prevent the gas burning. Due to the high vapour temperature of metals, it tends to be applied to organic materials (CND, 2009).

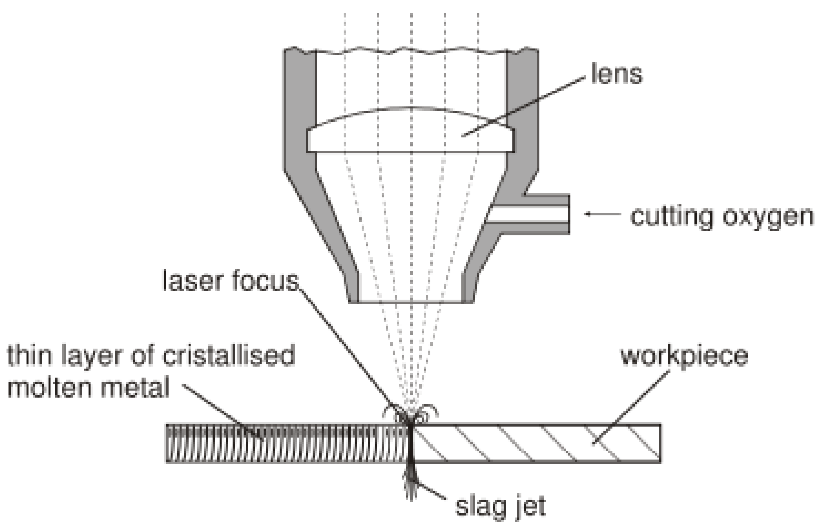


Figure 178 Laser beam cutting unit

(source: Dilthey, 2005)

Mori (1988) insists the suitability of the laser beam method for dismantling nuclear power plants due to the cutting ability of concrete and reinforcement, no use of water, less generation of fume and debris, and compact and controllable torch. Less generation of waste including water is especially pivotal to the concerns about the impact of material contaminated by radioactive.

The laser application also shows superiority of asbestos cutting. By vaporising the asbestos which are originally released to the air as cancerous fibrous aerosols, this method only generates harmless spherical particles. Moreover, the cut edge of elements is covered by the glazed layer and remaining fibres cannot diffuse more (CND, 2009).

A2.3.2.4. Plasma

A plasma cutting uses the high temperature plasma streamed in a high velocity to melt down the material as shown in Figure 179. The electric current between electrode and the material heats the gas until it arrives at the materials. As a result, the temperature of gas raises 5000 to 7000°C and becomes plasma (CND, 2009). However, due to that mechanism, the application to materials having less conductivity shows less cutting ability than conductive materials (Dilthey, 2005).

As well as the laser beam cutting, it also has some types introducing shielding on plasma jet to minimize the sub-products. Figure 180 describes water shielding method which enables to cool torch and reduce the emission during the cutting process at the same time. Otherwise, the use of inert material as shielding can cut objects in a dry condition. Yet, it would cause some harmful substances required to suck and dispose of (Dilthey, 2005). Therefore, thinking about the generation of sub-product such as gas, dust and noise, the cutting in or under water is suitable for this method as shown in Figure 181. Besides this, the precise cutting depth, the high cutting speed and the easiness of remote handling extends the applicability of plasma cutting (CND, 2009).

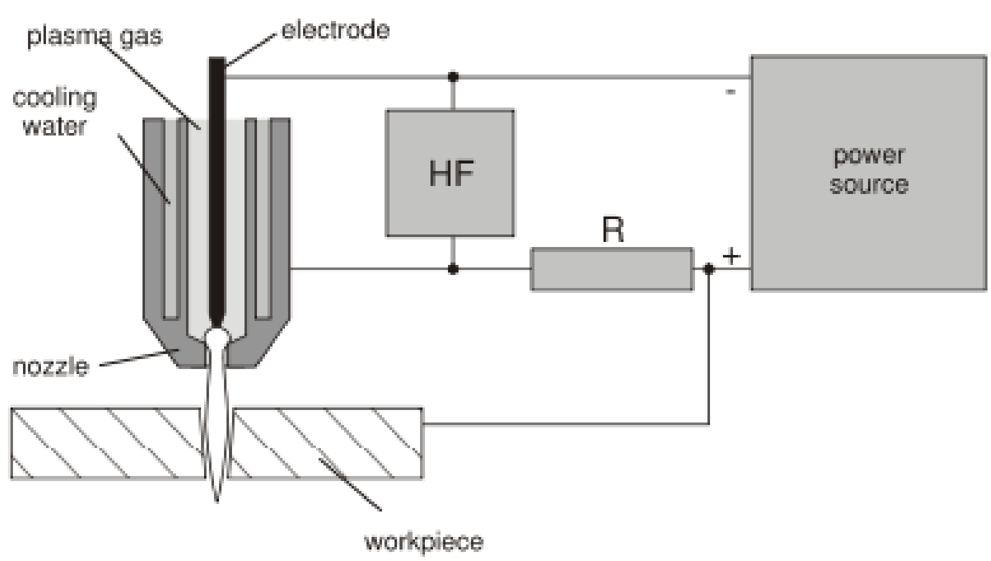


Figure 179 Plasma cutting unit

(source: Dilthey, 2005)

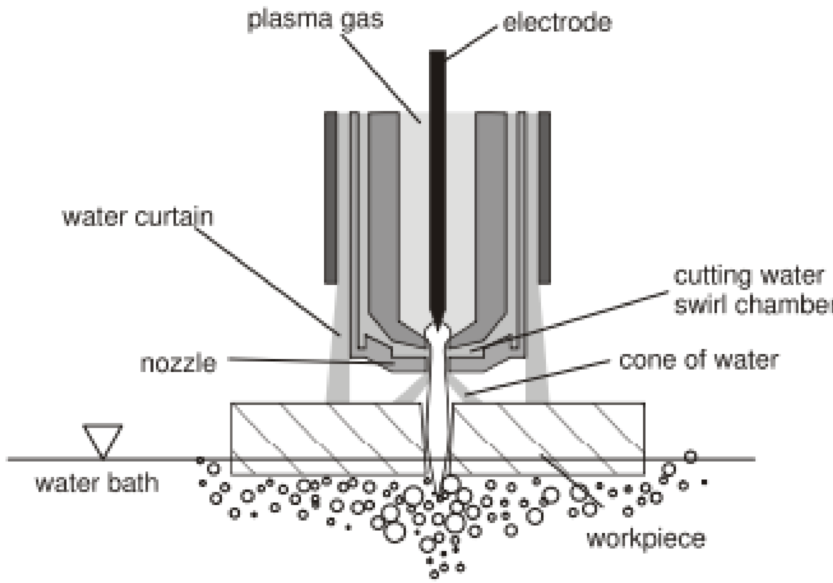


Figure 180 Water injection plasma cutting unit

(source: Dilthey, 2005)

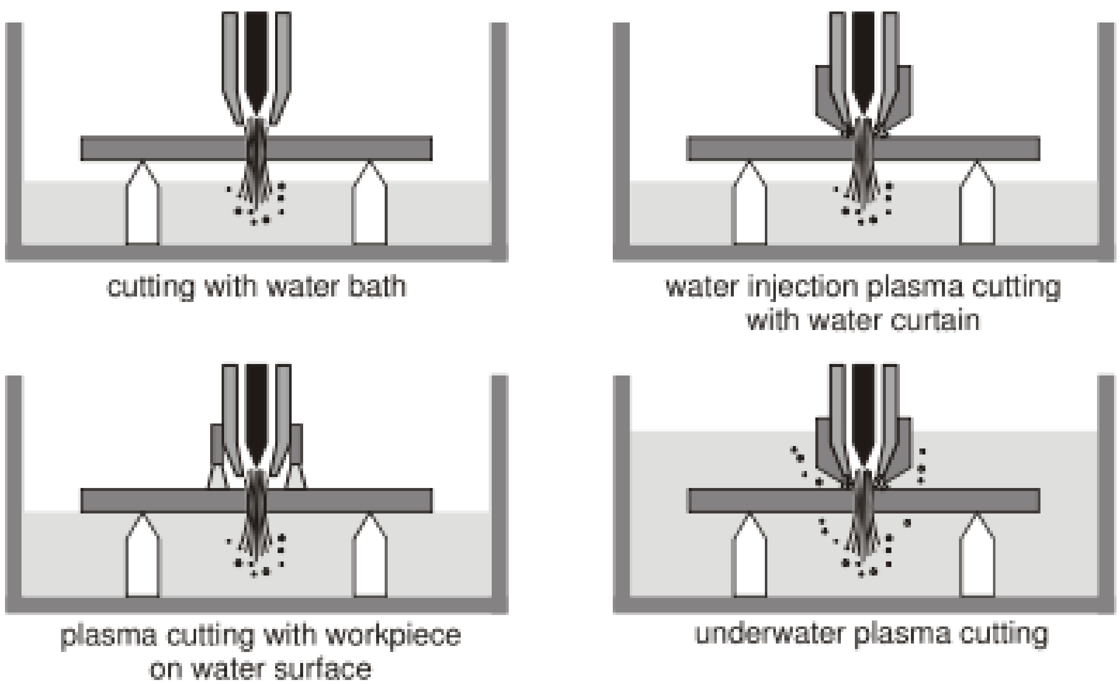


Figure 181 Water bath plasma cutting method

(source: Dilthey, 2005)

A2.3.3. Shearing

Shearing is the method to cut the steel reinforcement and shaped steel after the covered concrete crushed by methods previously introduced. It can be separated into two types according to the size of equipment which is handy or not. Kasai (1988a) named them, a) hand shears and b) hydraulic large size shears, respectively. Since this method aims to cut the reinforcement from the structure, it allows demolisher to separate the waste from the component. Although it is applied to cut the joint between remaining structure and one element such as a wall or a beam, the extraction of element allows the choice of place and method for the second demolition as well as cutting methods mentioned above. The difference is a less noise and dust or the generation of toxic gas or slag on the operation except the removal of covering concrete.

A2.3.3.1. Hand shears

For the hand shears, a manpower type and a small size hydraulic type exist as shown in Figure 182 and Figure 183, respectively. While they have the advantage to be applicable to the confined area, there is a limitation on steel bar diameter they can cut due to the relatively weak shear force compared to the large size equipment.

Figure 182 Manpower hand shears equipment

(source: Shanghai Xinfan Container Fittings Ltd., 2005)

Figure 183 Hydraulic hand shears equipment (arm and power unit)

(source: LUKAS Hydraulic GmbH, 2010)

A2.3.3.2. Hydraulic large size shears

This method uses the large size of hydraulic shear mounted on a self-propelled machine as shown in Figure 184. While it is possible to cut the medium size of steel section such as H-shaped steel section, the rigid support is necessary to support its heavy dead load (Kasai (1988a Compared to the melt-cutting method, It is safer as it does not use flame and Its cutting speed is faster. Therefore, it tends to be applied to the site where it has a risk of fire and does not require too much cutting accuracy (Occupational Safety and Health Service, Dept. of Labour, 1994). The shearing cutting does not produce a large vibration, noise, dust and toxic gas which is probably produced by heat cutting.

Figure 184 Hydraulic large size shear machine

(source: Caterpillar, 2012)

A2.3.4. Felling

There are two types of felling methods according to the main force for felling elements. Firstly, the imbalance of element weight fells the tall elements such as column and smoke stacks. After cutting a section of the element into V-shape, gravity and the pulling force with wirer ropes dismantle construction elements as shown in Figure 10. Otherwise, explosive can be applied to the column foot and the end of the beam to fell. The millisecond delayed ignition allows demolisher to determine the direction to fall it down (Kasai, 1988a). This makes the dissembling the elements so that the second demolition can be easily held at ground level or offsite. As a result, it simultaneously achieves a low vicinity impact onsite and a high recyclability.

A2.4. Whole demolition method

Similar to the concept of the crushing method, the whole demolition method aims to break structures into concrete and steel reinforcement regardless of elements. Since it does not destroy a structure for each floor as the crushing method does, the working speed is faster and the cost tends to be lower than the partial demolition method due to the simplicity of the concept. Moreover, the large scale of crushing such as the use of explosion or steel ball is designed to operate remotely. Therefore, it is secure and allows effective demolition. Contrary, because of the large scale of destruction it causes large noises, dusts and vibrations. Moreover, it is extremely difficult to separate the waste components to recycle from the mixed debris.

A2.4.1. Hitting

As described in Figure 185, the construction is demolished by the hitting impact of a steel ball of around 2 tons controlled by a crane on the ground. In detail, there are three types of technique to hit; vertical drop, swing in line with jib, and slewing jib. Each hitting technique can be regarded as one, two and three dimensions' movement, respectively. As the dimension increases it is possible to hit with stronger energy, but it also increases the difficulty of the ball controlling. As a result, it can cause the turnover of the crane, damaging a boom and a jib or the hazardous scattering of fragments. Accordingly, a skilled operator is necessary to achieve a safe demolition (Hong Kong Building Department, 2004). This method tends to be applied to a high-raised building which cannot be treated by an excavator so that many fragments fall down from high place during operation. This causes large noises, vibrations, flying-rocks and dusts even though it is preliminary wetted. Besides, this method is relatively expensive due to the high price of equipment and the necessity of a skilled operators (CND, 2009). Therefore, its application is limited to sites where the demolition efficiency is the highest priority and there is a sufficient operation area without the concern of the vicinity impact. In addition, the difficulty of separating waste components from the whole demolition must be concerned as well.

Figure 185 Application of wrecking ball

(source: Super Stock, 2013)

A2.4.2. Breaking by hydraulic pressure

The hydraulic C-shape equipment mounted on the crane holds and crushes the structure from outside of the building as shown in Figure 186. It destroys a structure by crunching or felling elements with hydraulic strong force. The C-shape equipment has several types according to their aims and target building types.

Figure 186 Application of hydraulic breaker

(source: Foley Inc., 2013)

The large-scale breaker as shown in Figure 187 is introduced as one of the popular types to be applied. Though there are many different products with subtle different features, it usually generates the thrust force by the single cylinder with two rods so that the machine can operate with a good balance from its symmetry movement and the effective opening mouth can be secured. The shape of the blade depends on the purposes. The flat tip, for instance, is superior in terms of dealing with small pieces. As the second type, the small-scale breaker, as shown in Figure 188, is included to break down the debris generated by the large scale breaking. While the first type aims to nibble off a piece of debris from the structure, this type pulverises those debris in to small size. Thus, the multi-tiered or tick blade is applied rather than a single thin blade as the first type. This has a small disc-shape breaking cutter, which helps to cut the debris by shearing destruction so that less force is required. Since it only moves the front jaw, the demolition can be effectively achieved with less hydraulic circuitry (Yoshino, 1988). The fork attachment is suggested as the final type, as shown in Figure 189. With its fork-shape, it is superior in terms of grabbling. This can also be used to demolish wooden structures or to move debris caused by the other demolition methods. Following this, a selector grab is developed from this fork attachment as shown in Figure 190 to perform precise removal of a single element. This is achieved by 360° rotations and a vertical move of grab and the symmetry control of the jaws by a switch or a foot pedal (Quarmby, 2011).

Figure 187 Large-scale breaker attachments

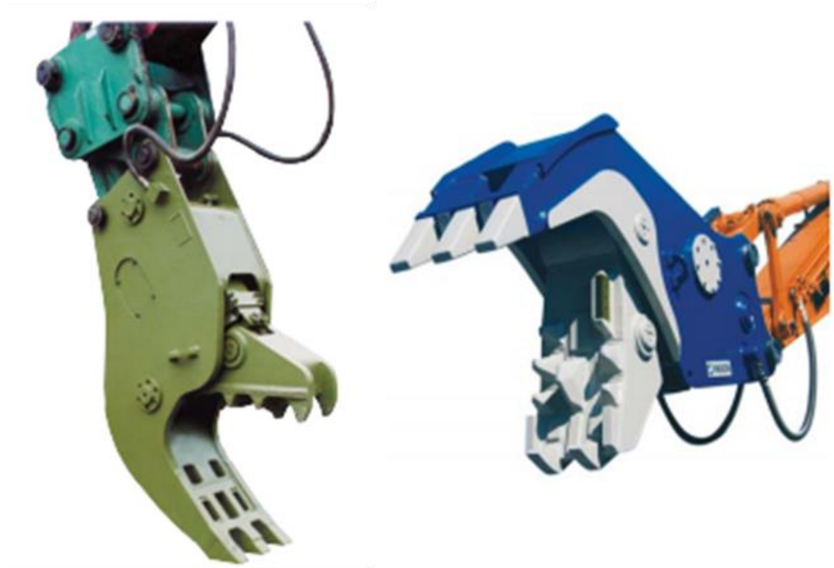


Figure 188 Small-scale breaker attachments

Figure 189 Fork type attachment

(source: Hitachi Construction Machinery Japan Co., Ltd., 2013)

Figure 190 Selector grab attachment

(source: Lynch, 2013)

The mobility and easy applicability to the vertical and high places within the arm distance are the advantages of this method besides the strong breaking force. It also does not cause large noises, vibrations and dusts as well as the demolition method using the hitting force. This, however, requires the rigid and flat footing and a wide space to operate (Occupational Safety and Health Service, Dept. of Labour, 1994), and the falling of debris during operation needs to be concerned for the safety of labours. In addition, the debris, especially when the method is applied to the housing detaching, contains various members in the same pile. This requires the sorting by hands or fork machine onsite before loading the debris on trucks. From the recycling aspect, it is less efficient to sort the waste from the comingled debris than assembling into members or soft-stripping the compound members before demolishing (Poon et al., 2001).

A2.4.3. Simple machine demolition

The bucket or shovel, as shown in Figure 191 and Figure 192, is possible to be applied to the demolition of detached housings like a masonry type. This method used to be the main demolition method with crawler crane and steel ball demolition in 1960's to 1970's; they push over the wall and destroy the structures regardless of the boundary of members (Quarmby, 2011). It can be said that the application of the hydraulic fork type machine to demolish wooden structures is included into this simple demolition method. Due to the simplicity of the demolition process, it is quick and it does not require a large number of labours for demolition. Additionally, as mentioned before, the noise, vibration and dust are not generated compared to the hitting demolition, but the sorting of the debris is necessary before loading except landfilling of them all.

It is worth noting that the machines introduced here also have an important role to move and load the debris onsite after the demolition with other methods. If the demolition waste has already been decided to use as the filler, the continuous operation between demolition, transportation and application processes gives a huge advantageous for the machine productivity.

Figure 191 Application of bucket

(source: Idaho Press-Tribune, 2013)

Figure 192 Application of shovel

(source: Cleveland Live LLC, 2013)

A2.4.4. Bursting with explosive

The bursting of explosive can be applied to partly and completely destroy the structures which is the most significant value compared to the bursting of no-explosives. Although it is categorised as bursting, the mechanism of destruction is completely different from the method with non-explosives. As shown in Figure 193, while the demolition of using non-explosive only forms the tensile breaking zone, the explosive forms the compressive breaking zone inside the tensile one. Because of the mechanical property of concrete and rocks, the tensile rupture needs about ten times less energy as the compressive one. Accordingly, the required energy for explosive demolition can be extremely large and its demolition impact is as well. Moreover, if the reaction energy exceeds the destruction energy of member embracing explosive, it would cause an air overpressure called a sonic wave, which the impact can possibly breaks the vicinity glass. To prevent these subside effects, the controlled bursting has been applied. This is the technique to optimise the use of explosive by the adequate bursting design and divided charging bursting which ignites several charges at a short-time interval (about 20 to 30 ms). The reduction of the charge amount allows minimising the bursting effect on the surrounding members or the remaining structures (Lauritzen, 1988). In addition, the explosive called moderate bursting which causes about 30 m/s of sonic wave (ordinary explosive has 4000 to 7000m/s of sonic wave) is also applied to suppress the impact (Kasai, 1988a). Test bursting before the actual application is recommended to confirm the behaviour of explosive impact.

There are several steps for applying explosive to demolition under BS6187 'Code of practice for full and partial demolition'. It requires the supervision of competent explosive engineer accordance with BS5607. As the unique point of explosive demolition, it is set exclusion zone according to the type, size and distribution of explosive in terms of health and safety including the vicinity area. As a result, the evacuation control from the zone including road closure is required before bursting. In addition, the contingency plan concerning about the failure or impact on the vulnerable services (e.g. ground facilities) is to be submitted to the authority to inform before bursting (BSI, 2011). Due to these necessary processes and the large impact of bursting, bursting with non-explosive is sometimes alternatively applied at the urban area requiring the rigid limitation against demolition effect. Besides, the whole building component is comingled into the generated waste. Without deliberate soft-stripping before bursting, it is inefficient to separate the waste components from the comingled debris. This hinders the application of this method to the whole demolition but to the partial demolition to cut off structures into members. In 2011, Kajima Corp. advertised the partial demolition method with explosive bursting to apply in urban area with less vibration and noise. It also insists the advantages of quickness and applicability to the confined area (e.g. underground) against the demolition with cutting by wire-saw which tends to be applied in the current urban demolition in Japan (Kajima Corp., 2011).

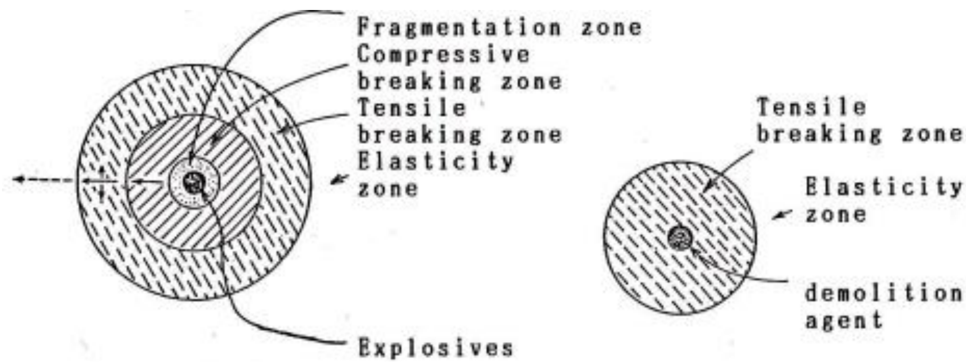


Figure 193 Demolition mechanism of bursting with non-explosive and explosive

(source: Goto, 1988)

Appendix3. Conventional demolition waste treatment methods

A3.1. Metal waste

A3.1.1. Steel

The application of used steel components in a new structure is regard as the most sustainable way to utilize steel if the characteristics of the elements fulfil the requirements. Although this method maintains the element's shape and structure, the function of service tends to change. For instance, an element used for rail has been reclaimed for a framework for a glass roof. Due to the normalization of steel members, it has higher applicability rather than the non-ferrous members. A high safety margin for steel members also accommodates subtle design changes such as bored holes for previous appreciation (Addis, 2006). On the other hand, recycling methods recover steel as scrap and use them as the reinforcement materials. Though steel is known to be 100% recyclable, 80% of the used steel is recycled and reinforcements are almost fully produced from the scraps. This allows a relatively low energy requirement and carbon dioxide emission as seen in Table 90. The result of a project by Langton and Everest supports that the longevity of steel elements enhance its sustainability. Besides this, the lack of contamination makes the recycle process of steel more simple than other components (Coventry et al., 1999).

Table 90 Embodied energy and carbon unit for metal

Metal type	Embodied energy		Embodied carbon	
	Virgin	Recycled	Virgin	Recycled
Steel	35.3	9.5	2.75	0.43
Aluminum	218	28.8	11.46	1.69
Copper	70	17.5 to 50	3.83	0.96 to 2.75
Lead	49	10	2.61	0.53
Zinc	72	9	3.86	0.48

(source: Hammond and Jones, 2008)

A3.1.2. Non-ferrous metals

Compared to steel, most non-ferrous metals are not suitable for reclaiming and recycling as they are used in relatively smaller quantities and hardly have product standards. According to literature, the cost of recovery, handling and storage are not worthwhile except for the architectural component (Addis, 2006). Materials such as zinc which is primarily used for steel coating is one of the few materials which is suitable for recycling. These materials tend to be recycled through a secondly industry as scrap in high rates and most of them are used for construction purpose, except aluminium containing some alloy components (Coventry et al., 1999). Although recycling requires extra processes compared to reclaiming, the reduction of environmental impact is significant as seen in Table 1. In addition, since metals do not degrade by recycling, the quality can be kept the same as virgin materials. However, Dyer (2012) puts an emphasis on the dependence of recycling demand on the location situation and the price of treatments.

A3.2. Organic waste

A3.2.1. Plastic

With the exception of MDPE pipe offcuts which are reclaimed for landfill drainage, plastics are typically recycled due to the higher production energy and their non-biodegradable characteristics. The production energy for plastic is two times larger than the steel (Addis, 2006). For plastics, thermal properties significantly affect the optimal methods. Plastics can be divided into wo categories; thermoplastic and thermosets. While thermoplastics are soft and easily recycled by heating, thermosets become stiffer by the process and pulverizing or chemical treatments are required for their utilization. (Coventry et al., 1999). Because of this disadvantage for material recycling, Coventry et al. (1999) suggested the energy utilization for thermosets and other complex plastic waste materials such as multi-layer, multi-polymer components from economic aspect. In contrast, Dyer (2012) highlights the hazards of combustion of plastic containing inorganic materials such as lead stabilizer. He also suggests the risk of dioxin emissions from PVC.

On the other hand, with respect to thermoplastic Coventry et al. (1999) claim that the separation of each polymer type is crucial to attain a high quality new plastics. Halliwell (1997, cited in Coventry et al., 1999) introduces a European-marking or a coding system as an example to show the importance of the sorting systems. In addition, the mechanical properties of thermoplastics decline with age. Therefore, the addition of 60-70% of virgin materials or the use of stabilizer is inevitable for old plastics to attain the equivalent quality to a virgin material. As a result, the identification of the plastic material is significantly important to decide the correct amount of additions. In summary, a sustainable sorting system is crucial to optimize the thermoplastic recycling (Hendriks and Pietersen, 2000).

A3.2.2. Paper

For papers and paperboards, a careful separation from other materials is required to recycle. Otherwise, they are treated as landfilled or incinerated (Hendriks and Pietersen, 2000). Namjoshi et al. (2010) point out the high bacteria contamination of the recycled paperboard in the US and shows a high correlation between the share of recycled material and the number of inhabiting bacteria. They explain that paperboards which have an exposure history accommodates heat-resistant bacteria which results in high bacteria contents in recycled material. They conclude the heating process during recycling is insufficient to kill some bacteria species such as *Bacillus licheniformis.*

A3.2.3. Timber

Depending on the form of timber recovered from the site, the treatment process can be separated into either reclaimed or recycled. To demolish the timber elements separately before crushing, they are recovered in good condition such as floor, raft and timber units. With the cleaning process, it can be sold at a lower price than the virgin material. A practical application for this is suggested to be mainly as the material of formwork which comprises more than one-third of construction cost (Pallet, P. F., 1994b, cited in Coventry et al., 1999). However, the comprehension of material quality is difficult for reclaiming timber. This is because of diversion of wood materials and its use is influenced by the treatment history. During the service life, it is possibly contaminated by other components like asbestos or pigments. Degradation should be also considered after the demolition, in other words, a proper storage is essential to permit reclamation (Coventry et al., 1999).

Recovered timber of insufficient quality or size is recycled as wood chips. It is also recovered from the separation process of demolished rubble. This chips can be used for the production of boards; chipboard (particle board), MDF, fibre board and OSB. (Dinwoodie, 2000). In addition, wood fibres with plastic and inorganic material like cement and gypsum can produce a new product called ‘wood-fibre plastic composite’. Moreover, wood chunks can be used to produce alternative lightweight aggregates by mixing with sands and cements (Coventry et al., 1999).

The energy utilization is proposed as the other options for wooden materials. Principally, there are two ways to recover energy from them: pyrolysis and gasification. The pyrolysis is a method used to change the organic material into fuel without oxygen. In contrast, gasification uses flammable gas. When heated with wooden materials, the low-calorie gas can be converted into high-calorie gas. Hendriks and Pietersen (2000) notice that this technology is not affected by contamination like nails or paints. However, they conclude that the fuel production from woods has a high cost and needs to find a sufficient market for other industry. In this aspect, it can be said the chipboard technology is the most viable recycling method, which is currently so demanded that partly virgin timbers are imported and applied to satisfy the social material demand (Dinwoodie, 2000). It is thought to be a viable method for the wood material recycling and should be suggested as the optimal recycling system nationwide. of the establishment of the distribution of plants and the process flow would enhance the recycling efficiency of timber material in UK.

A3.3. Mineral waste

A3.3.1. Road pavement

Road pavements have a lot of potentials to be recycled. This is especially true when the old material is recycled for a new road, thus creating a closed recycling loop. The conventional method depends on the location and the absence or the existence of a hot processing as shown in Table 91 (Coventry et al., 1999). Each process flow can be summarised as Figure 194.

Table 91 Conventional asphalt recycling methods

Location	Hot	Cold
In-situ- Shallow	Remix and/or repave	Retread
depth around 20mm		
In-situ- Deep		Deep
depth up to 350mm		In-situ
Off site	Central plant hot recycling	Central plant cold recycling
	(CPHR)	(CPCR)

(Source: Coventry et al., 1999)

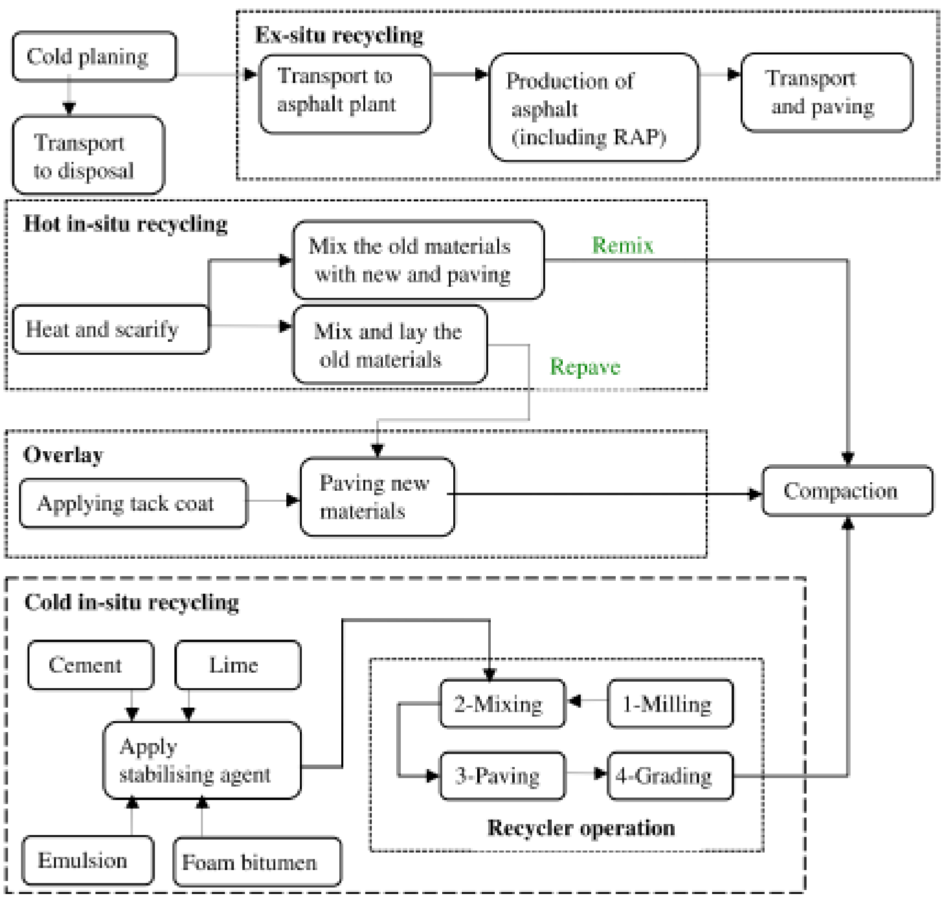


Figure 194 Treatment of pavement surface and placement of asphalt

(source: Huang et al., 2009)

Repaving and/or remix method

These techniques are applied for the road that has a damaged surface and does not meet requirement. The difference between repaving and remix is whether to use the old surface or not. For repaving, a new layer is formed after treating the surface to bond tightly with new surface layer by heating, plaining and scratching. On the other hand, for remix method, the old layer is dug and mixed with new materials to utilize. It is also possible that both methods are used at the same time. Besides the use of new materials can be reduced, the flue and clacks of old layer can be cured through these methods. However, the use of the exclusive machine has high cost. Thus, practically certain scale of wore road should be treated to be worthwhile (Coventry et al., 1999).

Retread method

This method does not need heating process. As similar to repaving method, firstly the worn old surface is dug and levelled. After that, spraying and rolling alternate the producing of new layer. Because it is not required the use of heavy machine or new material, the whole process is faster and cheaper than other road recycling method. This method does not modify or enhance the mechanical property of old layer as repaving or produce low durability bitumen-rich layer. Consequently, the apply for light traffic road is prohibited (Coventry et al., 1999).

Deep in-situ method

Compared to retread method applied for shallow treatment, this treatment can be applied up to 350mm depth. The old surface layer is grained by rototilling machine to utilize filler bound with cement or foamed bitumen, and covered with surface coating or wearing course. Since it requires compacting to gain the required strength and durability, the noise needs to be monitored. However, this process is so fast due to no use of new material that allows long distance project within short term. The rapid construction is reported in the pilot study by Energy Technology Support Unit (1992, cited in Coventry et al., 1999) with high durability performance. It also points out the tolerance to use waste material as another merit. In addition, the height of road is close to the untreated and no affect to verge. Although larger than 5000m2 scale is required from financial aspect, these merits mentioned above allow large scale of application regardless of heavy traffic. such as A24 London Road in Ewell which carries 18000 vehicles/day (Coventry et al., 1999).

Central plant hot recycling (CPHR)

This is the method to use the planed material for heating asphalt production with low amount of bitumen at plant. Since the application of asphalt is to another site, transportation impact becomes bigger than other in-situ methods. Conversely, in the view of material use, besides the recycle of used material and saving of new bitumen, the plant waste can also be used if it complied with the regulations (Coventry et al., 1999).

Central plant cold recycling (CPCR)

This is also the method to use the recycled material to produce asphalt at the offsite plant. The fundamental concept is to utilize the bituminous and cement material planed with bituminous liquid by grinding. Especially, when the bituminous is recycled, the use of rejuvenator as bituminous addition makes it activate. It allows saving procuring asphalt from the production area and it is significantly beneficial for south-east part of England. However, there is uncertainty about the effect of activation with rejuvenator. In the case, emulsion or foam bitumen is used as bounding, strength of early age becomes low. Moreover, it is included as the difficulty to keep the quality constant. The storage for material supply is needed to attain this. When the materials derived from different sites are used, petrologic influence should be cared. In addition, due to the small share of bituminous liquid proper mixing is essential to gain required property (Coventry et al., 1999).

There are mainly two types of research in the field of pavement recycling. The first type surveys the effect of the use of reclaimed asphalt pavement (RAP). Doh et al. (2008) shows that the recycled asphalt is stiffer than new asphalt and points out the risk of premature cracking. This is explained by the insufficient rejuvenation of an old bitumen on the RAP surface during the heating process. Shu et al. (2008) also reports the reduction of fatigue resistance of asphalt after recycling. To solve this problem, rejuvenating agents are used. Romera et al. (2006) explains that the reduction of heating temperature contributes towards proper rejuvenation and verifies the effect using thermal experiments.

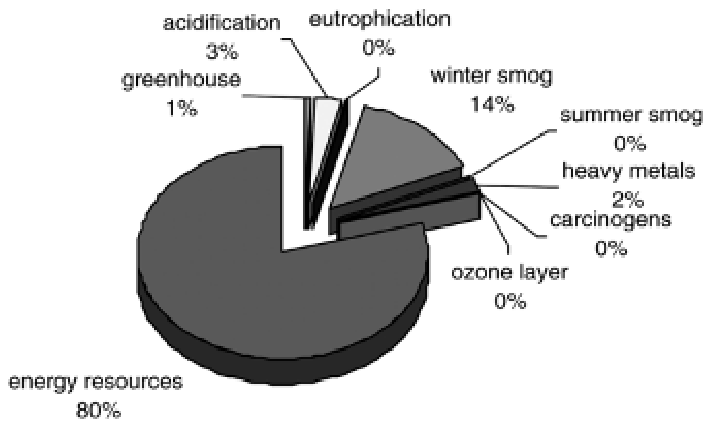
Secondly, the environmental impact is evaluated using the LCA method. Stripple (2001) analyses the energy and the material usage, and the hazardous emission of an asphalt road unit with a detailed inventory, and shows the small difference between the hot and cold process. Following this research, Chiu et al. (2008) extended the function of the LCA method to compare the efficiency of recycled material usage from an environmental impact perspective to verify the environmental benefit from RAP use. Moreover, Huang et al. (2009) also analysed the effect of recycling and emphasized the importance of using weighing system to reflect the aims of construction. They state that it is important to accumulate empirical data relating to the road pavement including the first category of researches, allowing an optimal method to be identified.

A3.3.2. Soil and excavation soil

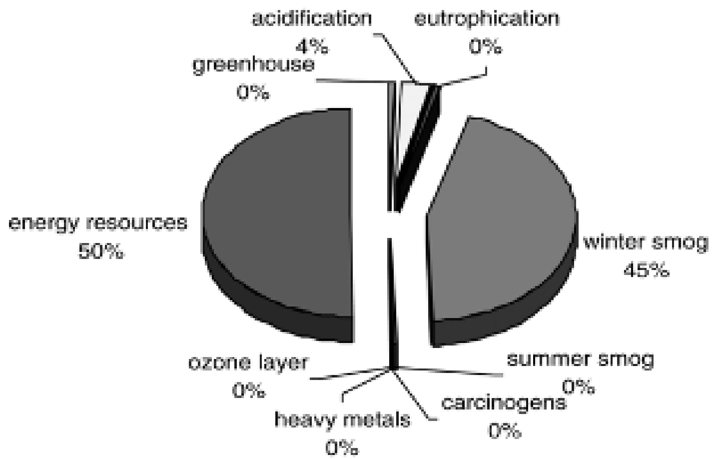
A major part of soil and excavation soil generated during a demolition used to be sent to a landfilling site. However, due to the rise of landfilling tax and legislation, it is now treated as fill or landscaping material onsite. For this application, those materials have to be evaluated from three aspects; i) physical property, ii) water permeability and iii) ecological property. First two aspects are quite important when the next usage of site has already been decided. For instance, the load-carrying capacity has to be concerned for a new construction site. On the other hand, regardless of the next usage, the ecological properties need to be considered to harmonize with the surrounding nature and become habitat for the wild lives. Otherwise, it can be used for a recycled aggregate to mostly produce low quality concretes. In both cases, the largeness of materials' quantity must be kept in mind. It should be utilized at a generation site to prevent a large transportation burden, even though any guidance does not clearly mention about the adequate treatment (Addis, 2006).

A3.3.3. Brick

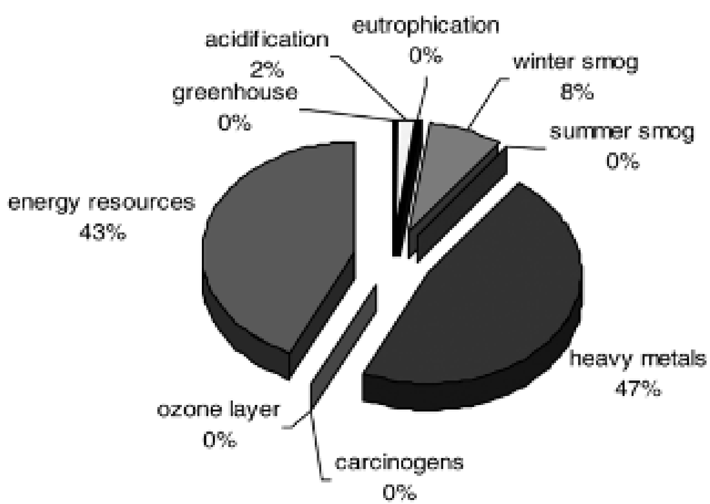
In contrast to other materials, some old bricks have the extra value from an architectural aspect. In such cases, although the separate demolition process is cost intensive, it is commercially valuable and sustainable not to use natural resources and energy (Coventry et al., 1999). However, as Tam and Tam (2005) mention, the share of valuable brick is less than 20% of whole waste bricks and contamination from other material like the mortar attachment makes the reclamation less viable. In addition, there are some suggestion to apply recycling bricks to manufacturing other materials such as an alternative cement (Naceri and Hamina, 2009). However, the recycled aggregate (RA) seems more feasible choice for their application due to the volume of waste generation and material demand. Therefore, reclamation or utilization for the RA is typically more practical. For this, Khairulzan and Halim (2010) use the LCA method and conclude that there is no large difference between the direct disposal, sorting recycle and direct recycle processes. However, they identify a diversity of environmental impact share as shown in Figure 195. It implies the optimal process must be decided considering the site situation.



<Final disposal process>



<Recycling process>



<Sorting recycle process>

Figure 195 Environmental impact breakdown of each treatment process

(source: Khairulzan and Halim, 2010)

A3.3.4. Concrete

Usually, concrete is used for low value applications such as a filler and a road bed on site and sometimes later disposed of. The quality can be improved with sorting, crushing and grading. This allows its application in the road construction as aggregate. Typically, the material has high porosity, low density and displays a deterioration of quality relative to the original (Coventry et al., 1999).

There are three main categories of research into concrete recycling. Firstly, the application for other construction parts like asphalt or bulk filler have been investigated. Here, the main focus is mostly on the quality degrading effects from the replacement by RA. Paranavithana and Mohajerani (2006) report that the absorption of asphalt with RA deteriorates the asphalt quality. Mills-Beale and You (2010) conclude it also causes the reduction of the asphalt stiffness. On the other hand, Aljassar et al. (2005) insist the acceptable property of asphalt using only RA. Therefore, although it is compromisingly recycled, it is viable to use RA as an alternative material. Compared to the conventional on-site recycling method for asphalt, it is less unsustainable for the transportation of material.

The second application of the conventional RA is in new concrete, and the research in this area also compares the quality of concrete with and without RA. While Zega et al. (2010) and Poon et al. (2004) show the effect of the RA property on concrete, Dhir et al. (1999) and Domingo-Cabo et al. (2009) attempt to quantify the change of the concrete property with a replacement level of RA. In addition, the effect of impurity has also a huge interest as a unique problem of RA. For instance, Park et al. (2010) survey the effect of the aluminium content which can cause hydrogen gas and reduce the concrete strength. He also suggests a simple evaluation method for aluminium contents. Moreover, Dhir et al. (2009) show the risk of ASR from the glass contamination. Although McCarthy et al. (2009) also admit the risk, they report the expansion of the concrete specimen with RA is closer or lower than the normal concrete.

Finally, a number of research studies focus on the improvement of RA for a high level application, in other words, construction purpose. This type of research is particularly active in Japan which has suffered from the scarcity of natural aggregate and landfill space. In Japan, 'heating rubbing' and mechanical grinding methods were devised to remove attached mortar from the original aggregate. With this method, Dosho (2007) suggests a system to use recycled aggregate for the construction concrete and verifies its low cost and environmental impact with LCA. In addition, Shima et al. (2005) use an input-output table and analyses the applicability of the heating rubbing method. However, this is the research for the recycled aggregate for Japan and the regulation and the composition are not same for other countries. Thus, Dhir and Paine (2007) suggest three classifications for the proper application of recycled aggregate in UK. Highways Agency et al. (2007) also point out the insufficiency of recycled plant numbers and the importance of recycled material information such as the structure history and the original material usage. These are considered beneficial for the encouragement of a practical regulation.

Furthermore, it is more important to shift the recycling concept from the demolition phase to the construction phase. As Tsujino et al. (2007) suggest, using the material which is easy to demolish in the concrete construction can make a closed-loop recycling system easier with no need for the production of waste.

A3.3.5. Glass

The glass can be recovered by two methods from the construction sites. Firstly, before the whole structure is demolished, the glass units are removed by hand. It can be reclaimed to the next construction with careful handling, storing and transportation. Due to the removal(reduction/elimination) of the production processes, it is ideal for sustainability. Secondly, the glass is separated from the impurity of demolition rubble and recycled. Glass fibre is one of the main recycled materials which imparts heat and solid insulation and can also be used to enhance the concrete strength. In addition, a crushed glass can be used as aggregates for road constructions and concretes. The former use is especially observed in the USA highway as 'Glassphalt'. The properties of this asphalt, such as durability and shear strength, have already been tested by the Clean Washington Centre of Seattle (Coventry et al., 1999). This usage has two benefits. One is because of the grading between cement and aggregate, it improves the fresh properties of concrete. Secondly, its pozzolanic character enhances the durability and the long-term strength. However, since this feature also introduces the risk of Alkali-Silica-Reaction(ASR), the Concrete Society (1998, cited in Coventry et al., 1999) regards this kind of 'man-made glass' as unsuitable aggregate. BRE (1998, cited in Coventry et al., 1999) suggests the addition of lithium to control the alkali level as a countermeasure. Tam and Tam (2006) propose the use of pulverized fly ash to inhibit ASR as another solution and he also mentions its contribution to the concrete quality.

In addition to these usages, a glass cullet can also be used for the brick production as an inert fill. As the result of replacement, it allows low firing temperatures and this implies the saving of fuel. Moreover, no use of flux makes the brick production cleaner without the need for a costly cleaning processes (Coventry et al., 1999).

A3.3.6. Gypsum

A gypsum is mainly used as plasterboard in construction and before the demolition of whole structure, it is sometimes recovered separately. Although the main aim is to avoid the costly landfilling, a recycled plasterboard is used for new product (Yost and Lund, 1997). For a new plasterboard material, the recycled board can be contained 20-25% but less than 3% of contamination is accommodated (Waste and Resources Action Programme, 2006). However, it is difficult to be removed completely and as a result, a proportion is contained within most C & D debris. Through the crushing and the screening process, a small particle of gypsum derived from plasterboard are found in C&D debris and it is about 1% of the total weight (Jang and Townsend, 2001). They tend to be used in undergrounds such as the soil amendment and the roadbed. Due to the risk of leaching of sulphate and its environmental impact from the evolution of hydrogen sulphide, Jang and Townsend (2001) insist the contents of gypsum from a plasterboard object to utilize the fine C&D debris. They also stress that whilst simple screening would eliminate gypsum, it would also cause size reduction and increase in leachability. Yamada et al. (2010) admit the insufficiency of gypsum elimination by sieving and suggests the record of gypsum by a colour distinction of the fine debris by hand pre-sorting. Montero et al. (2010) suggest the separation of gypsum by the difference of density from the fine debris to avoid the risk of hydrogen sulphide emission. They used heavy liquid separation and found 93% of gypsum's density in the range of 1.59-2.28g/cm3. However, they conclude that it is necessary to find the dry alternative methods as there are risks associated with using hazardous materials and the wet processing.

Yost and Lund (1997) introduce the use of waste gypsum as agricultural gypsum to stabilize soil as an alternative recycling solution. It is expected to have three main advantages; it is a source of calcium and sulphur, the soil structure is improved by its use and it provides a solution for the problem caused by sodium. Whilst the Waste and Resources Action Programme(WRAP) (2007) reports on the application to potato fields and its successful result in terms of the contained level of sulphate in soil, the yield of potatoes was reduced compared to a field without gypsum.

Appendix4. Reference of the database

The references of the database applied in the simulation are introduced in this appendix. Sections are separated into four; i) demolition method, ii) machine property, iii) waste component and iv) impact conversion. According to the values shown here, the simulated values such as the duration of machine use can be converted to each impact factor (e.g. cost, CO2 emission).

A4.1. Demolition method

A4.1.1. Top-down

<Algorithm for the demolition order setting>

Option1	Demolition from A_1) upper floor or B_1) lower floor
Option2	Demolition main and sub direction (N to S or S to N, and E to W or W to E)
1	Classification of the elements group according to the vertical level (z-value in the 3D coordinate) (e.g. Roof, 3F vertical, 3F horizontal … GF horizontal)
2	Duplication of the reinforced element objects to recreate reinforcements and classify into reinforcement group
A_1) Upper floor	
3-A_1	Designation of last floor element to stay before the machine descends to the lower level
4-A_1	Set the number on slab and internal beam at highest floor according to the set directions
5-A_1	Set the number on rest of slab, internal beam and column according to the set directions
6-A_1	Set the number on external beam, wall and column according to the set directions
7-A_1	Repeat 3 to 5 until to the last floor level
B_1) Lower floor	
3-B_1	Designation of floor elements to be demolished before the machine descends
4-B_1	Set the number on slab and internal beam elements chosen in 3
5-B_1	Set the number on internal beam and column according to the set directions
6-B_1	Set the number on external beam, wall and column according to the set directions
7-B_1	Repeat 3 to 5 until to the last floor level

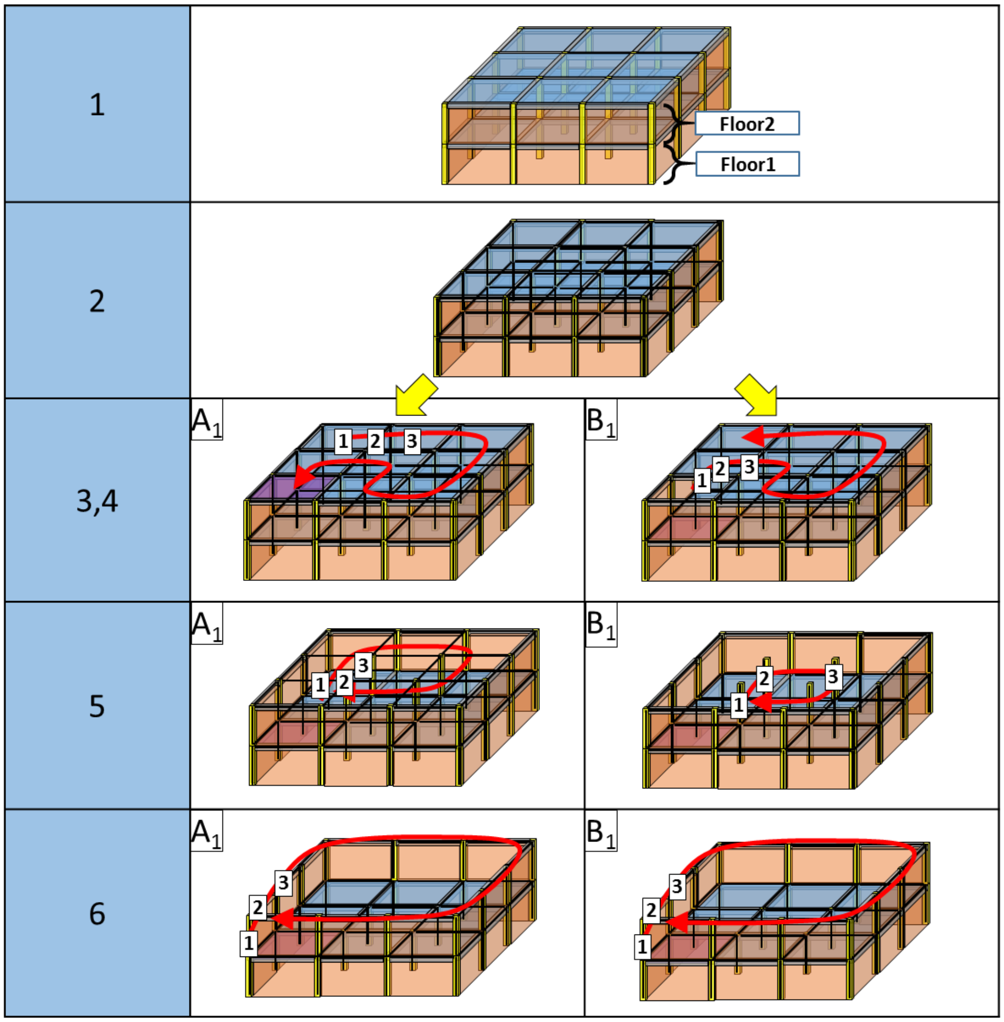


Figure 196 Numbering algorithm for top-down

A4.1.2. Machine demolition

<Algorithm for the demolition order setting>

Option1	Demolition A_1) without or B_1) with considering reinforcement
Option2	Demolition for A_2) whole or B_2) each floor
Option3	Demolition for A_3) whole or B_3) from closer distance
Option4	Demolition main and sub direction (N to S or S to N, and E to W or W to E)
A_1) Without considering reinforcement	
1-A_1	None
B_1) With considering reinforcement	
1-B_1	Duplication of the reinforced element objects to recreate reinforcements and classify into reinforcement group
A_2) Whole floor demolition	
2-A_2	None
B_2) Each floor demolition	
2-B_2	Classification of the elements group into floor level according to the vertical value
A_3) Whole distance demolition	
3-A_3	None
B_3) From closer distance demolition	
3-B_3	Classification of the elements group from set main direction and that axis value
4	Set the number on whole element

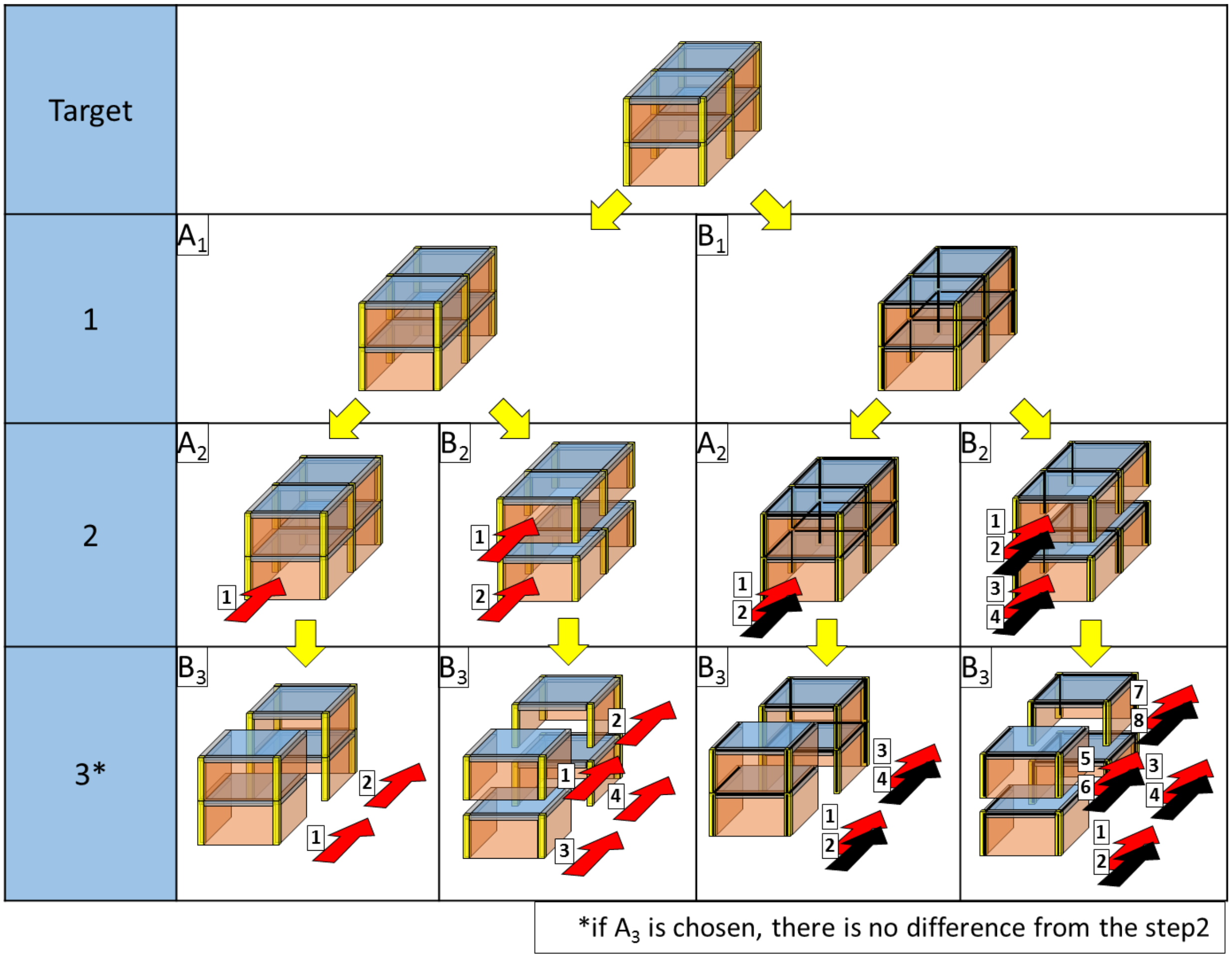


Figure 197 Numbering algorithm for machine demolition

A4.1.3. Implosion demolition

In a future research, implosion force should be applied according to the following formula, and this force should be added to every object based on the distance from the blast centre to recreate the explosive demolition.

$$P = 476.2 * K^{-1.40}$$

$$K = \frac{R}{W^{\frac{1}{3}}}$$

$$F = P * A_{target} = P * \left(\sqrt[3]{V_{target}}\right)^2 = 476.2 * K^{-1.40} * \left(\sqrt[3]{V_{target}}\right)^2$$

where P: blast pressure (kPa), R: distance from the blast centre (m), W: TNT amount (kg), F: blast force (kN), A_{target}: area of target object toward blast wave (m^2) and V_{target}: volume of object(m^3)*

*here is an assumption that object shapes can be regarded as hexahedrons

To reduce the computational burden in the model, the range of implosion can be applied to select the affected objects in the model. Here, the strength threshold can be set to identify the objects to which the implosion force is negligible. According to the table of typical pressure indicators suggested by Atkinson et al (2009), we can set the threshold value. For instance, 17kPa can be set as the pressure strength which would collapse half of the brickwork If we assume the use of 1kg of TNT for the implosion (W=1), the objects located within 10.8m as the blast range would be blown away. The change of blast range with TNT amount and pressure threshold can be described in Figure 198. It shows 1000 times of TNT needs to be applied to extend the range to ten times wider. On the other hand, the setting of pressure threshold would give a huge range gap. Between the pressure with minor structure damage (happened with 4.8kPa) and with rupture of oil tank (with 34kPa), there is approximately a four times gap (26.7m and 6.6m respectively). Since this is for the reduction of the computation burden, users should decide the threshold value based on their priority. Through the threshold setting on several demolition projects, the proper value should be decided by the users from the trade-off between the accuracy and the terms of simulation. Otherwise, the application of external software (e.g. structural analysis model) can be applied to achieve higher accuracy of blast force analysis. The simulation result of implosion force can be adopted to each element so that the distribution of waste and the following impact of collection and treatment can be measured for thorough evaluation.

$$L = R_{P_T} = \left(\frac{P_T}{476.2}\right)^{-\frac{1}{1.4}} * \mathrm{W}^{\frac{1}{3}} = \left(\frac{476.2}{P_T}\right)^{\frac{1}{1.4}} * \mathrm{W}^{\frac{1}{3}}$$

where L: blast range (m), P_T: pressure threshold (kPa)

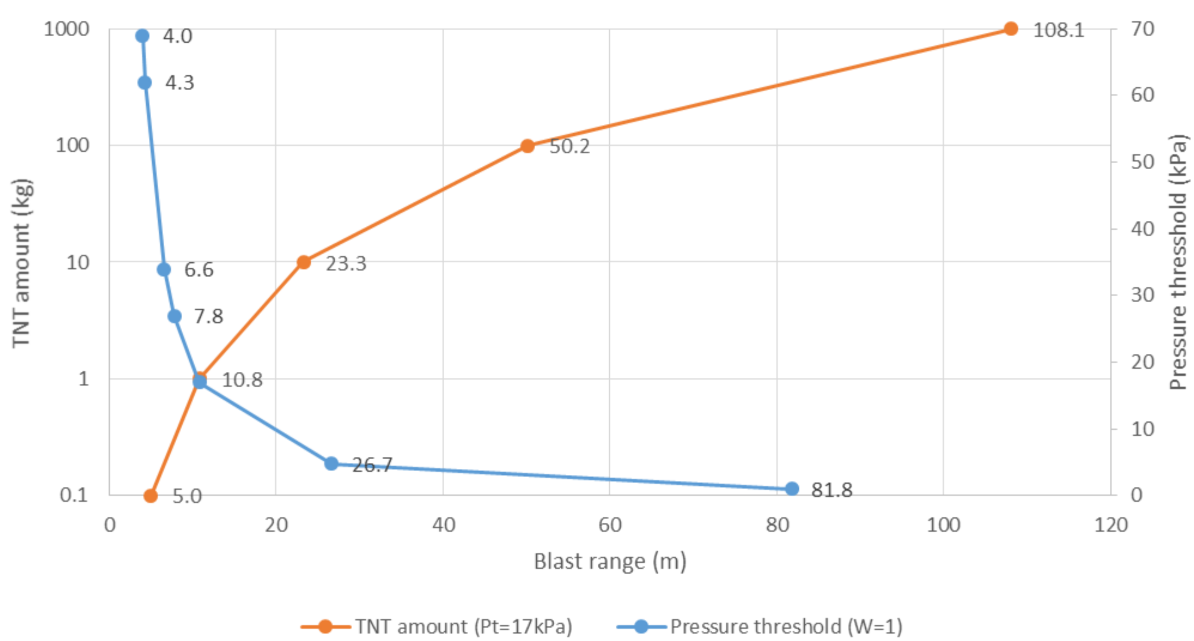


Figure 198 Change of blast range with TNT amount and Pressure threshold

A4.2. Machine property

For the machine property, handbooks and online catalogues of the main machine suppliers (e.g. Caterpillar, Komatsu) are referred to the general machine property table as shown in Table 92 (Caterpillar, 2015, Komatsu, 2011, Liebherr, 2016). According to this table, a machine modelling property table as shown in Table 93 is also developed. This table is consists of three main data extracted from the original; i) unit property, ii) scale spec and iii) mobility spec. For the unit property data, the users can decided the machine type to be applied according to this information. Then, once the type is decided the size is automatically shown on the screen as the default value. If the users can find the difference from the value which they tend to use, it can be manually modified by typing on a keyboard. Once it is confirmed to be added to the project planning, the mobility values are input to the machine model property so that the speed of each action can reflect the machine nobilities in reality.

After the simulation, the duration of machine use is calculated to be converted to the demolition impact. Therefore, the fuel efficiency, the gas emission, and the cost can be evaluated from the general machine property. For the gas emission, the conversion rate for the each class of engines in EU Emission Standards (Directive 97/68/EC) are applied to estimate the environmental impact from the fuel combustion according to the values in Table 94.

Table 92 General machine property table

Machine ID	Maker	Catapillar	Catapillar	Catapillar
	unit	300.9D	301.7D	302.4D
Fuel efficiency*	dissel use (Min)	2.3	2.3	3
	dissel use (Max)	4.1	4.1	5.4
	dissel use (Ave)	3.2	3.2	4.2
	L/h	1.6	1.6	2.1
Ave bucket volume	Min	0.014	0.018	0.035
	Max	0.018	0.056	0.092
	m3	0.016	0.037	0.0635
Engine power	net PS	18	18	18
Machine weight	kg	985	1800	2410
total weight*	kg	1017	1874	2537
power/total weight	PS/kg	0.017699115	0.009605123	0.007094994
total/machine weight	kg/kg	1.03248731	1.041111111	1.052697095
weight/bucket	kg/m3	61562.5	48648.64865	37952.75591
fuel rate	L/M	0.71875	0.71875	0.714285714
	H/M	1.28125	1.28125	1.28571428(
Body length	m	1.22	1.605	1.84
Body width	m	0.73	0.99	1.4
Body height	m	2.276	2.29	2.39
Boom (min)	m	1	1.5	2
Boom (max)	m	2.5	3	3.5
Boom (ave)	m	1.75	2.25	2.75
Dipper(stick)	m	0.89	1.18	1.25
Shovel length	m	0.181267191	0.238241204	0.290205945
Shovel width	m	0.31	0.415	0.48
Shovel height	m	0.362534383	0.476482408	0.580411891
range dimmension	m	3.074	3.7	4.021
travel speed	km/h	1.8	5.6	5.6
swing speed	rpm/m	8	10.5	11.5
Engine category	EU Emission Stn	Tier 4 Final	Tier 4 Final	Tier 4 Final
Engine ID		Yammar 3TNV70	Yammar 3TNV76	Yammar 3TNV77
Engine type(modi)	Referring*	R	R	R
Cost	$/day	150	200	220

Table 93 Machine modelling property table

Excavator	Maker	Catapillar	Catapillar	Catapillar
	unit	300.9D	301.7D	302.4D
Fuel efficiency*	L/h	1.6	1.6	2.1
Ave bucket volume	m3	0.016	0.037	0.0635
Engine power	net PS	18	18	18
Machine weight	kg	985	1800	2410
total weight*	kg	1017	1874	2537
scale spec				
Body length	m	1.22	1.605	1.84
Body width	m	0.73	0.99	1.4
Body height	m	2.276	2.29	2.39
Boom	m	2.5	3	3.5
Dipper	m	0.89	1.18	1.25
Shovel length	m	0.181267191	0.238241204	0.290205945
Shovel width	m	0.31	0.415	0.48
Shovel height	m	0.362534383	0.476482408	0.580411891
mobility spec				
travel speed	km/h	1.8	5.6	5.6
swing speed	rpm/m	8	10.5	11.5

......

Table 94 Gas emission requirement in Directive 97/68/EC

Cat.		Net Power	Date*	CO	HC	NOx	PM	HC+Nox
		kW		g/kWh				
Stage I	A	130 ≤	1999	5	1.3	9.2	0.54	10.5
	B	75 ≤ P < 130	1999	5	1.3	9.2	0.7	10.5
	C	37 ≤ P < 75	1999	6.5	1.3	9.2	0.85	10.5
Stage II	E	130 ≤ P ≤ 560	2002	3.5	1	6	0.2	7
	F	75 ≤ P < 130	2003	5	1	6	0.3	7
	G	37 ≤ P < 75	2004	5	1.3	7	0.4	8.3
	D	18 ≤ P < 37	2001	5.5	1.5	8	0.8	9.5
Stage III A	H	130 ≤ P ≤ 560	2006	3.5	0.52	3.48	0.2	4
	I	75 ≤ P < 130	2007	5	0.52	3.48	0.3	4
	J	37 ≤ P < 75	2008	5	0.62	4.08	0.4	4.7
	K	19 ≤ P < 37	2007	5.5	0.98	6.52	0.6	7.5
Stage III B	L	130 ≤ P ≤ 560	2011	3.5	0.19	2	0.025	2.19
	M	75 ≤ P < 130	2012	5	0.19	3.3	0.025	3.49
	N	56 ≤ P < 75	2012	5	0.19	3.3	0.025	3.49
	P	37 ≤ P < 56	2013	5	0.62	4.08	0.025	4.7
Stage IV	Q	130 ≤ P ≤ 560	2014	3.5	0.19	0.4	0.025	0.59
	R	56 ≤ P < 130	2014.1	5	0.19	0.4	0.025	0.59
Stage V	S	560<P	2019	3.5	0.19	0.67	0.035	0.86

(source: DieselNet, 2016)

A4.3. Waste component

The waste component for each object is supposed to be given by the BIM data. It is, however, currently quite labour and cost intense to collect the accurate data for each object. Accordingly, the waste component is compromisingly decided from the element type if not the component data is attached in the simulation. Since the users need to define the element type for the impact evaluation of the soft-stripping, the material component can be regarded them as the main component of elements. To make the component more accurate, the general component value of each type of elements are suggested based on the previous researches (Jalali, 2007, Chen and Ma, 2013) as shown in Table 95.

Table 95 Material component for each element type without designation

	t	m3	Rate(%)
Foundation*			
Concrete elements		24.0	
reinforcement	1.0	0.1	0.5
concrete part		23.9	99.5
Structure(col,beam)*			
Concrete elements		82.0	
reinforcement	9.0	1.1	1.4
concrete part		80.9	98.6
External wall*			
masonry		285.0	100.0
Interior wall*			
plasterboard		350.0	100.0
Ceiling*			
plasterboard		310.0	100.0
Door**			
Wood			100.0
Window**			
Window elements		179.0	
glass		15.6	8.7
Wood		163.4	91.3

(source: Jalali, 2007 for * and Cheng and Ma, 2013 for **)

A4.4. Impact Conversion

The impact calculation after the simulation is separated into three different phases as shown in Figure 199; i) soft-striping, ii) machine use and iii) waste generation. Accordingly, the impact conversion at each phase is explained at the following section in detail.

Impact for soft-stripping

Element	Material	Aim	volume (m3)	Total softstripping impact					
				cost (£)	labour (Man*h)	Eco point	concrete	mineral	......
Wall	clay	Rc	0.0	0.0	0.0	0.0	0.00	0.00	
Column	concrete	Rc	0.0	0.0	0.0	0.0	0.00	0.00	
Beam	concrete	Rc	0.0	0.0	0.0	0.0	0.00	0.00	
Slab	concrete	Rc	0.0	0.0	0.0	0.0	0.00	0.00	
Roof	concrete	Rc	0.0	0.0	0.0	0.0	0.00	0.00	
Door/window	wood	Ru	0.0	0.0	0.0	0.0	0.00	0.00	
Staircase	concrete	Rc	0.0	0.0	0.0	0.0	0.00	0.00	
Covering	mineral	Rc	0.0	0.0	0.0	0.0	0.00	0.00	
Set properly		Total	0.0	0.0	0.0	0.0	0.0	0.0	

Please set the number of labour for soft-stripping.

labour number (Man)	10
duration of strip (h)	0

Impact for machine use

cost (£)	labour (Man*h)	Eco point
4197.3	8.6	1.0

Please set the number of onsite inspecter you would set.

Onsite inspecters (Man)	2

Impact for waste generation

cost (£)	labour (Man*h)	Eco point	concrete	mineral	......
5974.9	0.0	-99.3	15.8	0.0	

Duration of demolition(h)	1.6

Total impact

cost (£)	labour (Man*h)	Eco point	concrete	mineral	......
10172.2	8.6	-98.3	15.8	0.0	

Duration in total (h)	1.556666667

Figure 199 Impact calculation table with three phase

A4.3.1 Soft-stripping

The whole impact calculation process here is summarised as Figure 200. After the users' material designation and the treatment method decision for each element type, the component for each element is calculated according to the above Table 95 (flow①). At the same time, each soft-stripping impact for the element is automatically evaluated for three impact factors; i) cost, ii) labour and iii) fuel. This is based on the values which are surveyed by BCIS (2014). According to the impact value for the related onsite work in the reference, the soft-stripping impact for each elements are summarised as shown in Table 96. (flow②). Following this, the waste treatment impact is finally calculated and added to the soft-stepping impact to get the total impact value (flow③). Here, the waste treatment impact is converted with Table 97. Since it can only return the cost and labour requirement, the environmental impact is evaluated from the volume of waste and the fuel consumption (flow④). According to the 'Eco point' conversion table (BRE, 2007), the unit environmental impact can be summarised in Table 98. With this table, the total environmental impact can be unified to the 'Eco point' so that different planning can be compared each other.

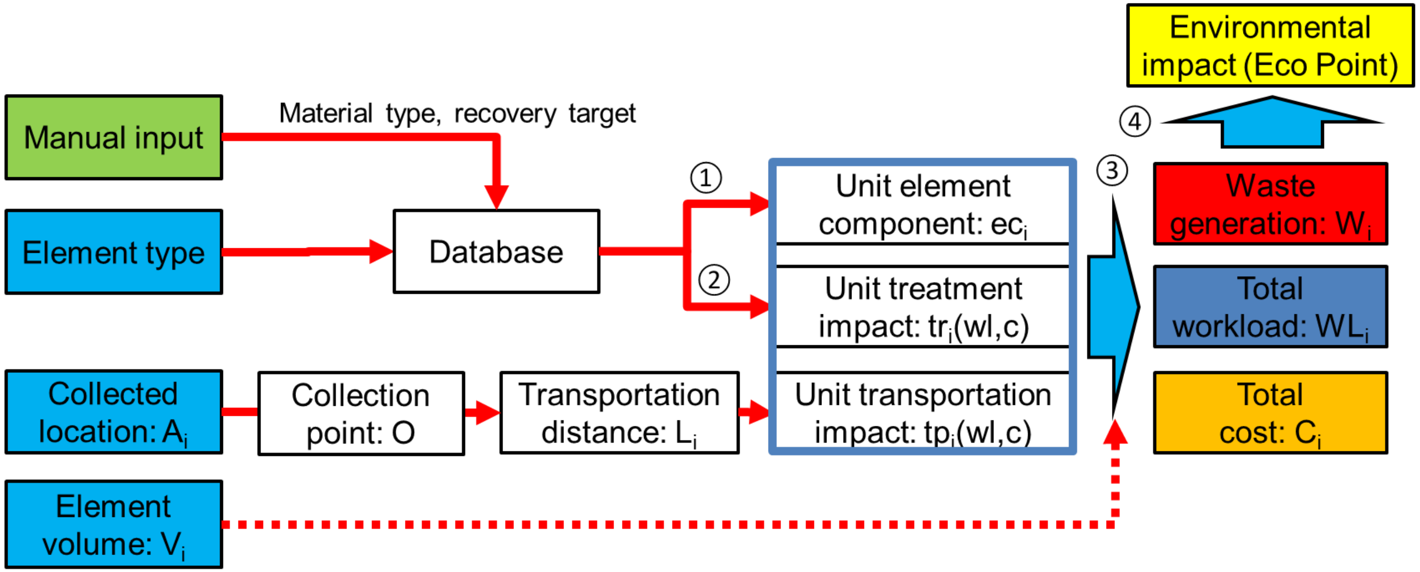


Figure 200 Impact conversion flow with soft-stripped elements data

Table 96 Soft-stripping impact for each element type and aimed recovery method (flow②)

		cost(£/t)							labour(MH/m3)							fuel(L/m3)						
		Concrete	mineral	clay	ferrous	non-ferrous	wood	other	Concrete	mineral	clay	ferrous	non-ferrous	wood	other	Concrete	mineral	clay	ferrous	non-ferrous	wood	other
Wall	Ru		45.83	106.14						4.01	9.27						0.00	0.00				
	Rc	183.70	23.21	38.69			10.18	8.16	12.76	2.03	3.38			0.89	0.57	9.74	0.00	0.00			0.00	0.00
Column	Ru																					
	Rc	62.74			129.92		5.21		4.36			7.57		0.46		3.33			2.33		0.00	
Beam	Ru																					
	Rc	163.18			147.81		10.99		11.33			8.37		0.96		8.65			2.61		0.00	
Slab	Ru																					
	Rc	121.85					12.49	12.05	8.51					1.11	0.85	6.50					0.00	0.00
Roof	Ru																					
	Rc	279.74					12.49	6.30	19.39					1.11	0.53	14.81					0.00	0.00
Door	Ru					26.74	20.58						2.09	1.22						0.00	0.00	
Window	Rc					22.85	8.39						2.00	0.55						0.00	0.00	
Staircase	Ru																					
Landing	Rc	160.62				63.21	30.85		12.41				5.53	2.02		9.48				0.00	0.00	
Covering	Ru																					
	Rc		45.42							1.70							0.00					

where Ru: Aiming to reuse the soft-stripped material and Rc: Aiming to recycle the soft-stripped material

(source: BCIS, 2014)

Table 97 Material treatment impact conversion table (flow③)

	unit	concrete	mineral	clay	ferrous	non-ferrous	wood	paper	glass	plastic	plaster	other
Ru cost*	(£/m3)	-36.20	-48.35	-57.15	-360.00	-12143.54	-137.50	0.00	-18968.85	0.00	0.00	-47.23
Rc cost*	(£/m3)	-14.02	-9.10	-10.50	-27.50	-618.75	-58.79	0.00	-10.00	0.00	0.00	-34.40
Ru impact**	(BJ/kg)	-0.24	-0.20	-15.00	-264.75	-82.93	-47.79	-48.49	-78.28	-255.85	-7.29	-80.08
Rc impact**	(BJ/kg)	0.36	0.26	-14.55	-193.50	-71.14	-39.14	-20.74	-46.88	-101.05	-3.93	-49.03
Waste volume***	(m3/m3)	1.09	1.06	1.07	1.00	1.46	0.80	0.74	0.99	0.83	0.98	1.00

(source: *Johnson, 2008, **Hammond and Jones, 2008 and ***Mercante et al., 2012)

Table 98 Material treatment impact conversion table (flow④)

	Unit	Fossil depletion	Gas emission			Minerals extraction	Waste disposal
			CO2	NOx	CO		
Climate change	kg CO2eq(100 years)	0	1	0	0	0	0
Acid deposition	kg SO2eq	0	0	0.7	0	0	0
Human toxicity (to air)	kg tox	0	0	0	0.012	0	0
Low-level ozone creation	kg ethen eq	0	0	0	0	0	0
Eutrophication	kg PO4eq	0	0	0.13	0	0	0
Fossil fuel depletion	tonne	1	0	0	0	0	0
Minerals extraction	tonne	0	0	0	0	1	0
Waste disposal	tonne	0	0	0	0	0	1
	Conversion to Eco Point	2.689486553	0.002852718	0.12442275	0.000859978	0.6	0.833333333

(source: BRE, 2007)

A4.3.2 Waste generation

The whole impact calculation process here is summarised as Figure 201. After the simulation, the waste generation data is extracted as the data set of 'original element', 'debris volume', 'collected location', 'collected time' and 'collection number'. According to the collection number, the waste component is calculated by the original element types for each unit. According to the requirement of waste purity for the recycled concrete aggregate in BS 8500-2 (BSI, 2002), the threshold value for each requirement as the recyclable material is set at 95%. In addition, the threshold for the sorting plant acceptance is temporary set to 20% according to the number of type which tend to be found in the MRF (WRAP, 2015). According to those threshold values, the wastes are classified to be sent to recycling plants, sorting plants and landfill sites (flow①). Then, the waste treatment impact is calculated as same as the calculation of soft-stripping (flow②). Following this, the collected location and time data can be plotted on the onsite map to visualize the waste distribution as the project progress.

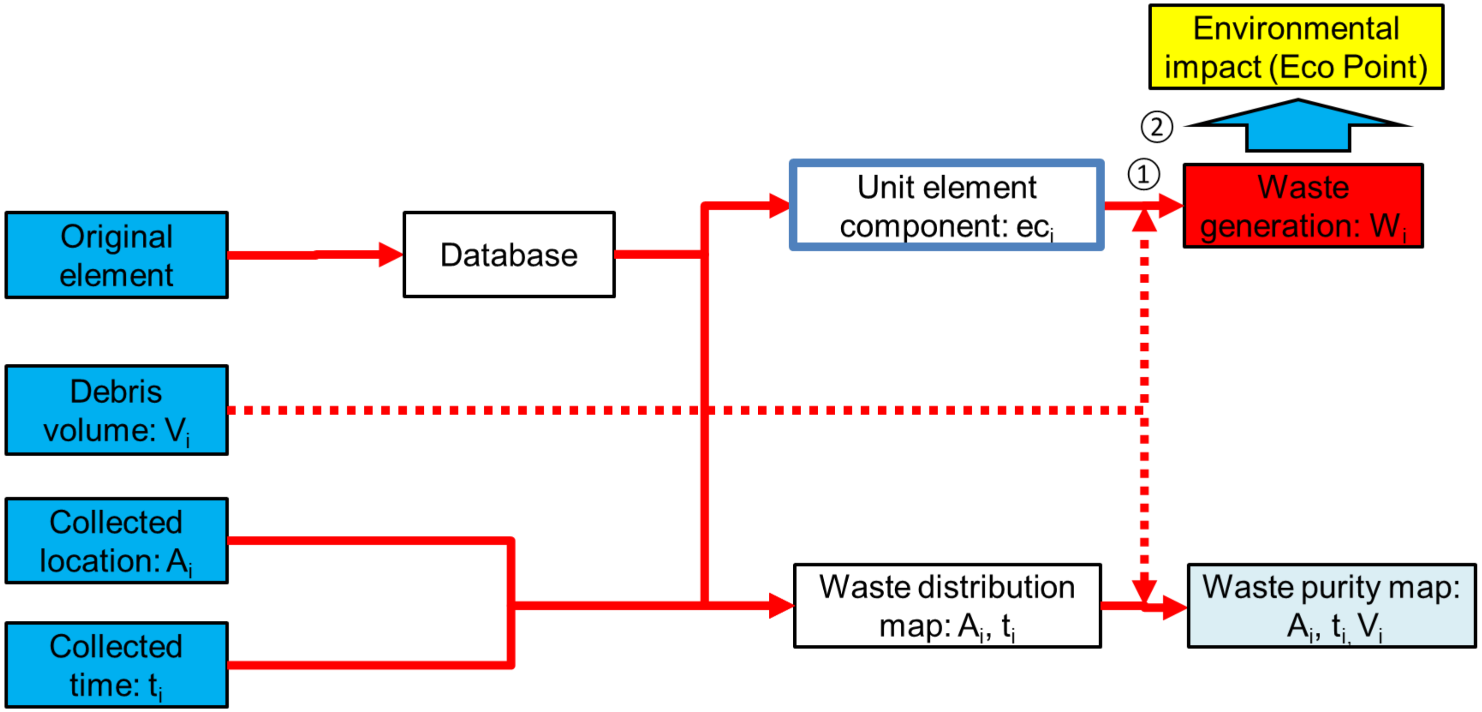


Figure 201 Impact conversion flow with waste generation data

A4.3.3 Machine use

The whole impact calculation process here is summarised as Figure 202. After the simulation, the applied machines are listed and the operation time is output. Based on the general machine property list introduced at the previous section, the unit impact (e.g. cost, fuel use and gas emission) can be given (flow①). Therefore, the total impact can be calculated by the product of this unit value and the operation time. For the labour cost, the values in 'Payment in Construction: A Practical Guide' (BCIS, 2014) which are summarised in Table 99 are applied (flow②).

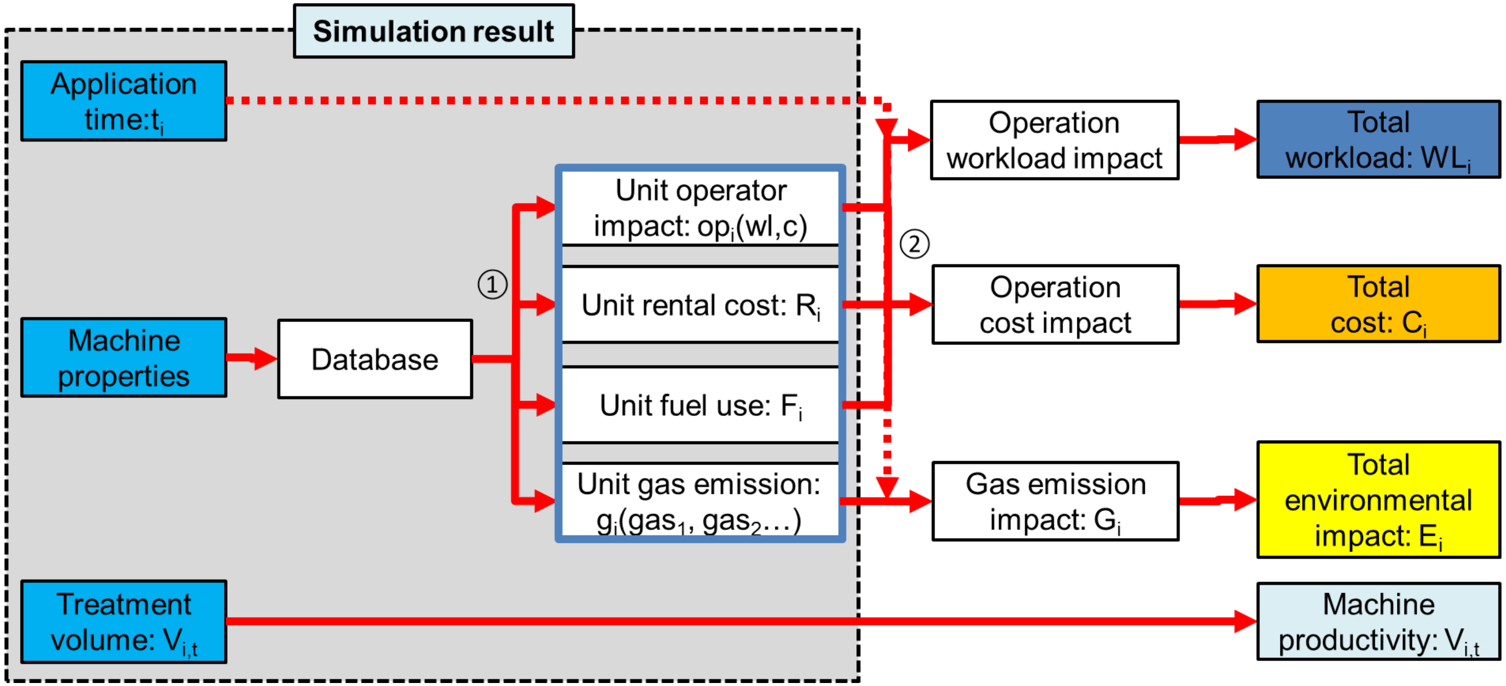


Figure 202 Impact conversion flow with waste generation data

Table 99 Labour cost (flow②)

Labour cost	
type	cost (£/h)
General operative	11.44
Demolition	
Concretor	
Formwork	
Brick/blockwork	
Rubble walling	
Recon. Stonework	
Roof slating/tiling	
Plastering	
Apprentice Plumber(3y)	12.23
Drainlayer (skill rate3)	12.26
Drainlayer (skill rate4)	12.94
Craft operative	15.28
Shuttering carpenter	
Brick/block layer	
Rubble wall layer	
Stone block layer	
Roof slater/tiler	
Wood machinist	
Workshop joiner	
Plasterer	
Advanced plumber	19.88
Senior Craftsman (+ Supervisory Responsibility)	17.63

(source: BCIS, 2014)

Appendix5. Algorithm setting

In this appendix, the corresponding algorithm settings to the algorithm designs introduced in Chapter3.4. are described with illustrations. To remind the suggested algorithms, same table is introduced here (Table 100). These movement algorithms are compared in Chapter4 in which a gap between the optimal and the random demolition planning is regarded as the expectation of impact reduction with the model application. The value is used in Chapter5 to estimate the total impact reduction in the UK, which is the decisive factor of model application for the society.

Table 100 Estimation result of waste generation with the Solis et al model

target algorithm			target output
optimization target	**target machine operation**	**target setting**	
machine control	individual	path finding	machine operability
		element demolition	
		relocation	total demolition impact
		arm folding	
	tandem	machine traveling	machine operability
		waste collection	total demolition impact
demolition order setting	tandem (excavator+bulldozer)	locational setting	machine operability
		material setting	total demolition impact

A5.1. Machine control algorithm

A5.1.1. Individual machine control

A5.1.1.1. Pathfinding

Transportation distance is fundamental for reducing the machine use regardless of machine roles in demolition (e.g. demolition, treatment, collection). A great deal of research has been conducted to solve the shortest path problem such as Dijkstra's Algorithm or A-star Algorithm. The basic idea of those algorithms is how to check the path distance is effective. They set nodes and connecting path with weight, and compared a minimum cost of paths in terms of total weight. As seen in Figure 203, an edge of obstacles was set on the corner of buildings and intersections with a straight line from machine to target were added to corners as nodes. The shorter path among right and left can be chosen as the closest path. While much research produced a significant number of nodes with unit grids for shortest path problem, this algorithm could reduce the number of nodes into relatively small scale. Edge groups were formed by the Convex Hull algorithm which algorithm rapped building elements with a smallest convex polygon so that the machine would never crash into building objects which might cause a fatal accident in reality. Even if building elements formed a concave polygon as Figure 204, machines could follow the closest path connecting a point of contact and a final corner node in a straight line.

Two scenarios were set to compare machine productivities according to the strategy of edge setting as shown in Figure 205. While the original scenario fixed the edge shape through the whole demolition process, the edge was continuously updated in the second scenario in order to minimise the path distance. It aimed to estimate the influence of site clearance on machine mobility onsite. If the updating scenario showed better results, the immediate waste collection would indicate its huge great advantage which will be also discussed in the second section, ‘Tandem’. However, the safety for onsite workers also needs to be considered when the moving path will be changed over time.

<set scenario> i) Edge fixed

ii) Edge updated (with Convex Hull)

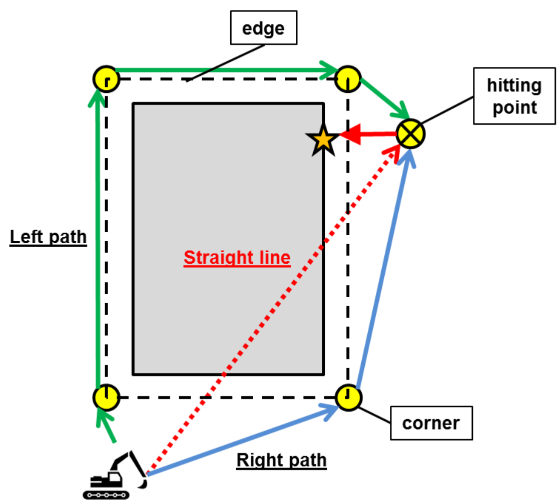


Figure 203 Path finding algorithm

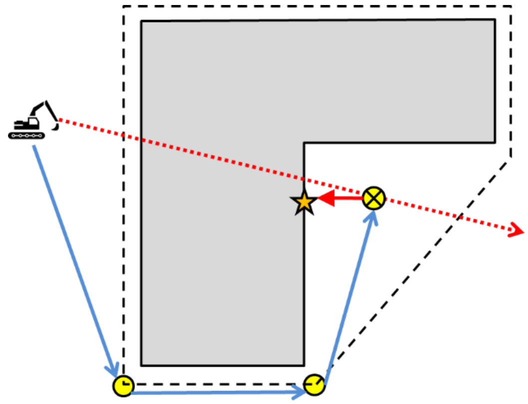


Figure 204 Path finding with a concave polygon as a target building

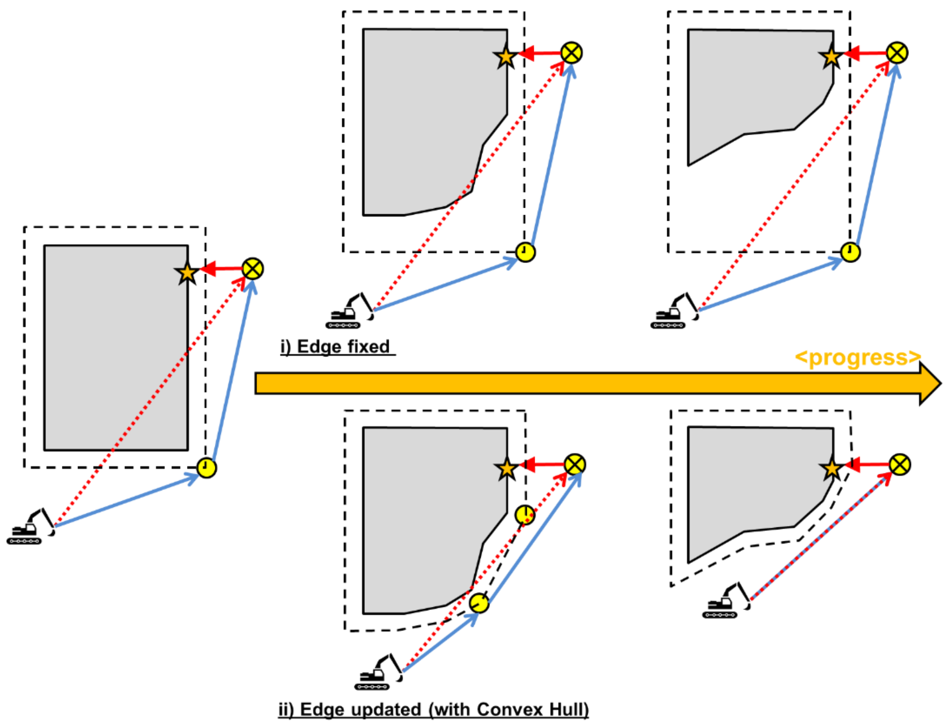


Figure 205 Scenario setting of path finding: i) Edge fixed and ii) Edge updated (with Convex Hull)

A5.1.1.2. Demolition order setting for element unit

Hitting order is discussed here among single target elements which consist of element units. This order of unit demolition can recreate the fragmentation of debris from elements in the model. According to the size of element demolition, machines (e.g. excavator) need to hit several times to complete demolition. Aiming for closest target is set as the practice-recreating algorithm which can be frequently seen in onsite visual data. On the one hand, the order of element demolition is sorted by target location to minimise the distance between targets. Minimising the duration of machine application is expected from both algorithms to shorten the arm movement and the machine travel distance as described in Figure 206.

<set scenario> i) Decision with distance

ii) Sorted with location

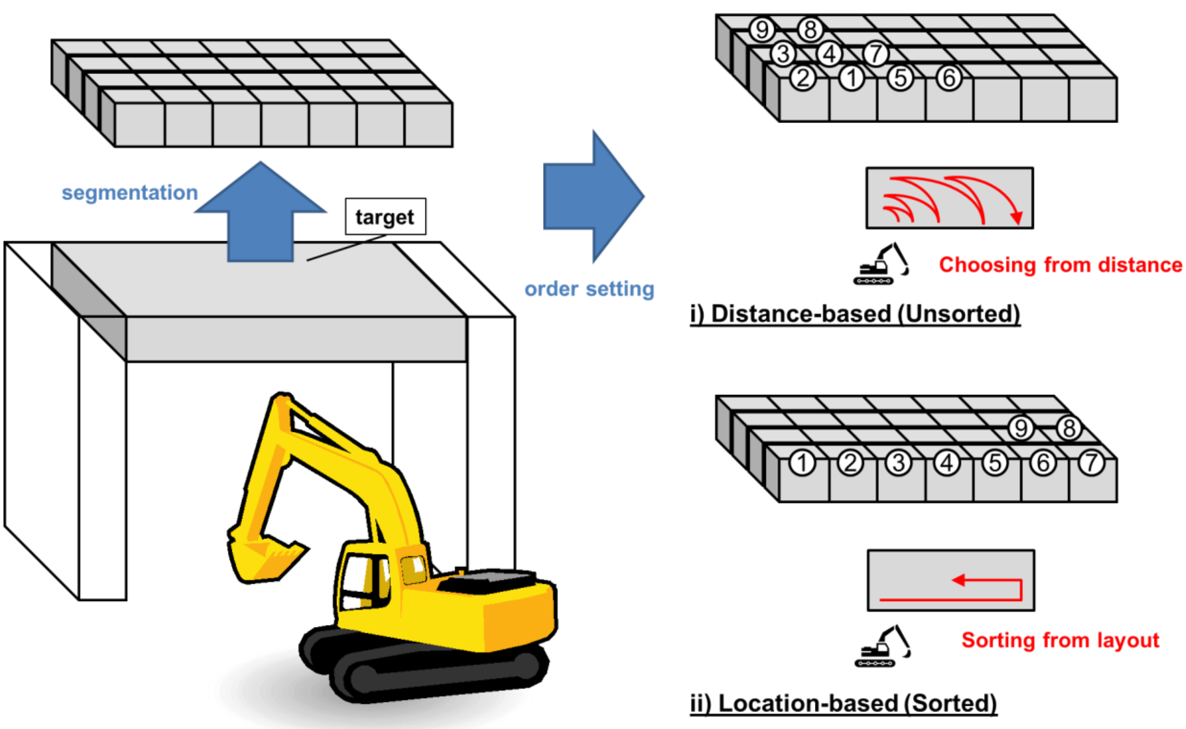


Figure 206 Scenario setting of single element demolition order: i) Decision with distance and ii) Sorted with location

A5.1.1.3. Relocation of hitting point

In terms of safety, demolition behaviour (e.g. hitting and drilling) is to be achieved by machines in a stable position. In this research, this position is set as a 'hitting point' which was already described in the above path finding section. As shown there, machines can only hit targets after they reach the hitting point which is believed to be more productive and safer. However, it might be less effective when the next target is located within the machines' working range. Therefore, machines would not be relocated if the next targets are within working range in the second scenario. Nevertheless, the? hitting target above other elements may scatter debris unexpectedly. Aiming to comprehend the safety and the impact on the purity of collected waste, a machine needs to relocate its own position whenever a hitting point is set in the other direction in scenario 3 as described in Figure 207.

<set scenario> i) Continuous relocation

ii) (Continuous relocation) except working range and visible targets

iii) except working range

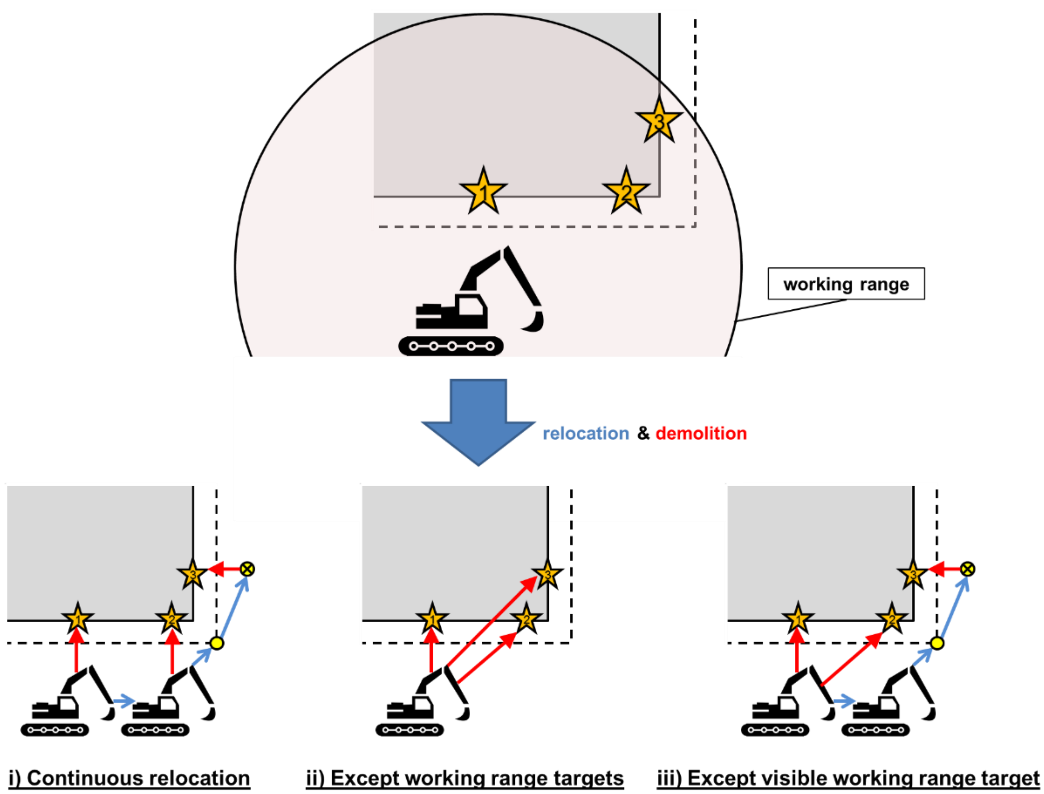


Figure 207 Scenario setting of path finding:
i) Continuous relocation, ii) Except working range targets & iii) Except visible working range target

A5.1.1.4. Arm folding for hitting

Excavator attachments are regularly composed of three parts; boom, arm and bucket in order of the distance from the body part. In the suggested model, the hitting movement is designed as the following process. At first, machine attachments are set on the preparation position. To prevent unexpected collision with building elements during rotation, they are raised high before hitting. Then, target joint angles would be decided as seen in Figure 208. The coordinate information for machine and target would return the distance and the angle to target (γ). Application of the cosine theorem to the triangle formed by arm, boom and distance decide the angle of corners. According to the target angle, attachments would be moved to the target in order from the body part (boom, arm and bucket). This is mainly because of the scale of movement at the same angle which can be described as L·θ. In order to prevent debris spreading widely, the machine tries to adjust the hitting place with the bucket part. Once it hits the target, again the attachments are raised to the preparation position for next demolition. In the scenario, two preparation positions are suggested as shown in Figure 209. For the first scenario, as mentioned before, it aims at the height which is decided by the highest location of building elements. On the other hand, the height is determined by the next target which must make the demolition process quicker but the machine may hit other elements when it rotates to aim at the next target. The trade-off between productivity and instability of demolition would be compared with the amount of unexpected demolition and waste purity from both results. If it needs to move to the other hit point, the arm has to be unfolded before relocating for safety reasons.

<set scenario> i) Setting to highest, ii) Setting to next

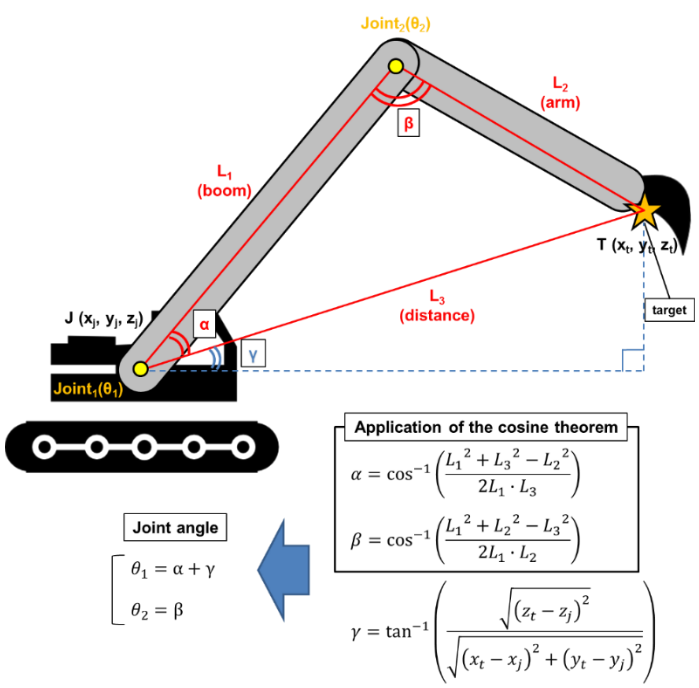


Figure 208 Calculation of target joint angle

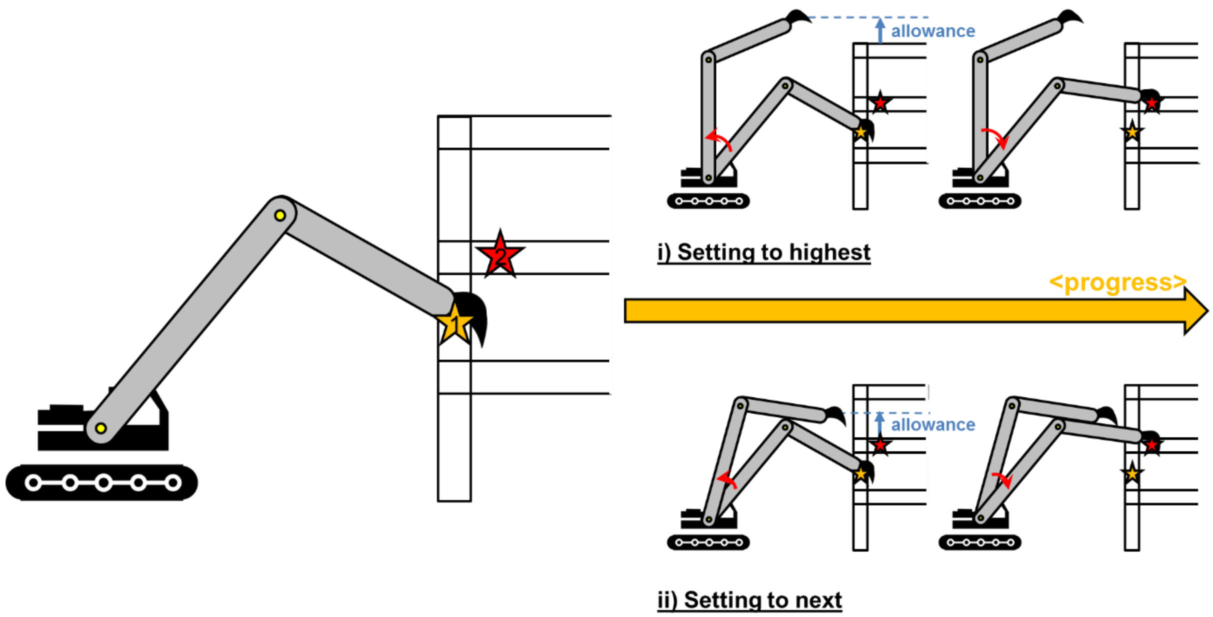


Figure 209 Scenario setting of arm preparation: setting to i) highest and ii) target

A5.1.2. Tandem machine control

A5.1.2.1. Machine traveling

There are two basic strategies to avoid a collision accident during relocation of machines which can be defined as static and dynamic. For static, machines can wait for the others' relocation with a discipline that only one machine can relocate onsite at once. In this rule, machines can find a path by adding other machines to the edge objects so that they can divert other machines from the path finding process as shown in Figure 210. Since this algorithm may hinder the other machines relocation, dynamic aversion may improve the productivity. In dynamic strategy, the machine can move regardless of other machines' movement. It only stops machines when one of them proceeds into the safety space. Once this happens, both machines stop and the one can stay and wait for the other to avert as described in Figure 210. Priority of machines should be set at project design to decide which machine should be prioritised more in the demolition process. It implies the priority of collection machines would be set as less important and can only work after demolition.

<set scenario> i) Single travelling

ii) Multiple travelling

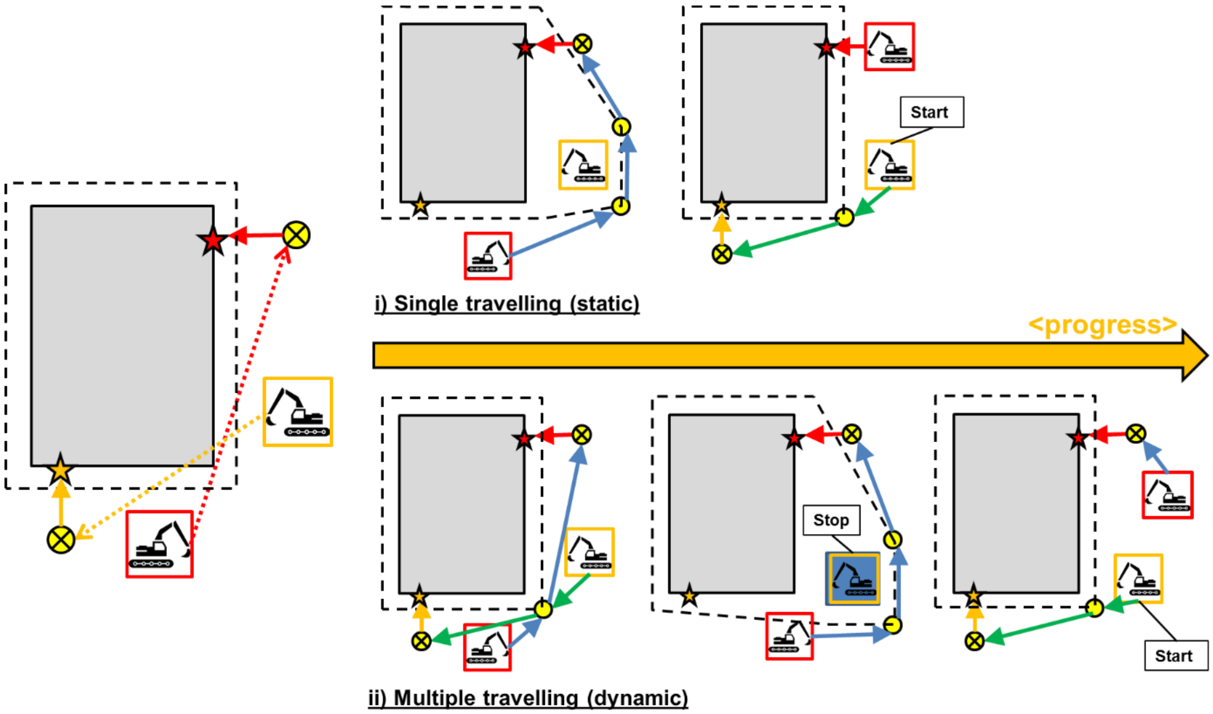


Figure 210 Scenario setting of machine travelling: i) single and ii) multiple travelling

A5.1.2.2. Waste collection

Machine process is separated into three main phases; i) demolition, ii) treatment and iii) collection. In order to simplify demolition, the treatment process is set as the future task to make the model more accurate at the moment. According to the order of process, the collection strategies are designed by how collection machines achieve collection after machine demolition. While the previous section discussed the multiple travelling of machines having the same roles (i.e. demolition function), this section aims to survey the optimal operation of machines with a parent-child relationships (i.e. demolition and transportation function) due to the order of works. To compare the efficiency of waste collection in terms of both waste purity and machine workability, algorithms are set for the two main agents, collection machines and demolition machines. When it is designed based on the collection machines workability, the distance or the location of target debris from collection machines are set for the first algorithm. As described in Figure 211, the collection machines can minimise the transportation distance for waste collection. However, this approach does not consider the interaction with demolition machines or the order of demolition. As a result, the recovered waste wouldn't be same as what users can expect from the planned order of demolition. On the contrary, algorithms can be designed based on the distance between the demolition machine and the debris to consider the machine interference. The target of collection can be set to the furthest debris from the demolition machines in order to maximise the productivity of each machine, as the second suggestion. By setting the closest debris from demolition machines as the collection target in the third algorithm, the collected waste can be sorted more by element type. Collection machines are ordered to aim at the closest debris from demolition machines in the third although it may slow down the machine operations to maintain the safety distance among them. Trade-off between workability and waste collection impact related to the waste purity would be the main focus in the scenario comparison here.

<set scenario> i) Collection of closest debris from **collection** machines

ii) Collection of farthest debris from **demolition** machines

iii) Collection of closest debris from **demolition** machines

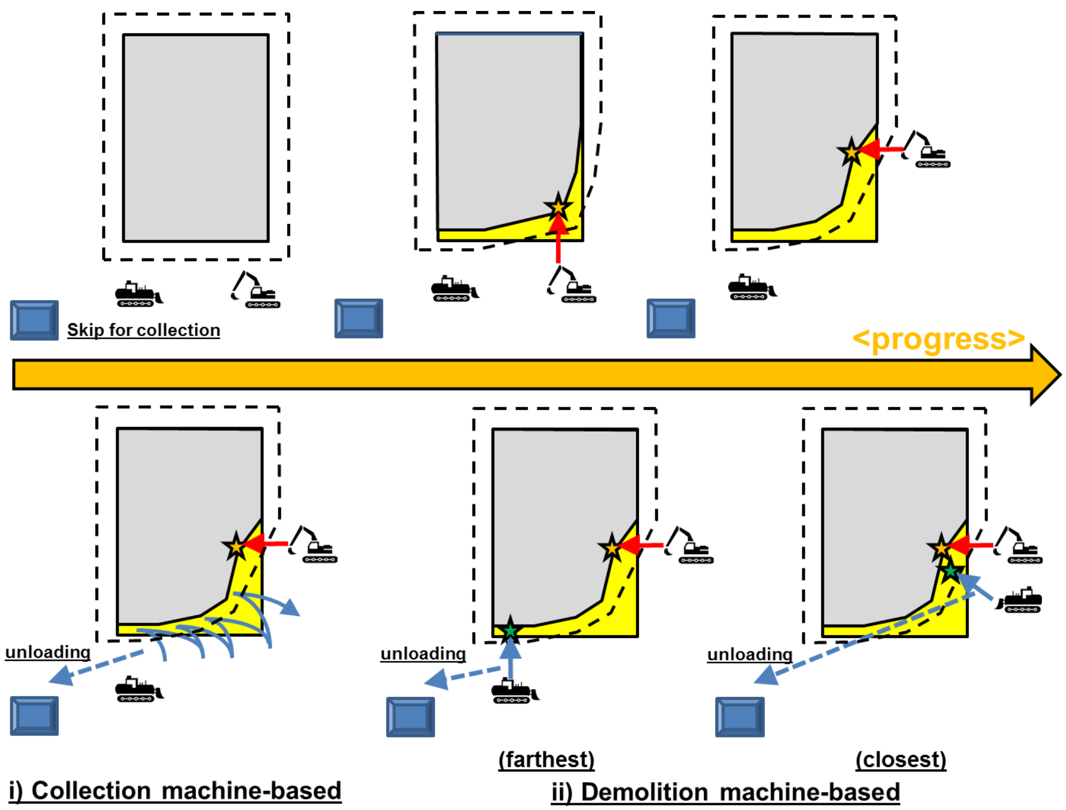


Figure 211 Scenario setting of waste collection: i) Collection machine-based, ii) Demolition machine-based (Farthest) and iii) Collection machine-based (closest)

A5.2. Demolition order setting algorithm

A5.2.1. Locational setting

Compared to the selection of target from distance, the sorted order from element location might result in more efficiency in terms of operating time and relocation necessity. In addition to this, the generated waste would be more suitable for recovery due to the location and element type resulting in sorted order. According to this, the distanced-based choosing algorithm and the location-based sorting algorithms are suggested as the single element demolition which is illustrated as Figure 212. As mentioned before, both algorithms are expected to shorten the arm movement and the machine travel distance. Including the recovery impact of generated waste, the superiority of algorithms would be compared by with the total demolition impact in the Chapter5.

<set scenario> i) Decision with distance

ii) Sorted with location

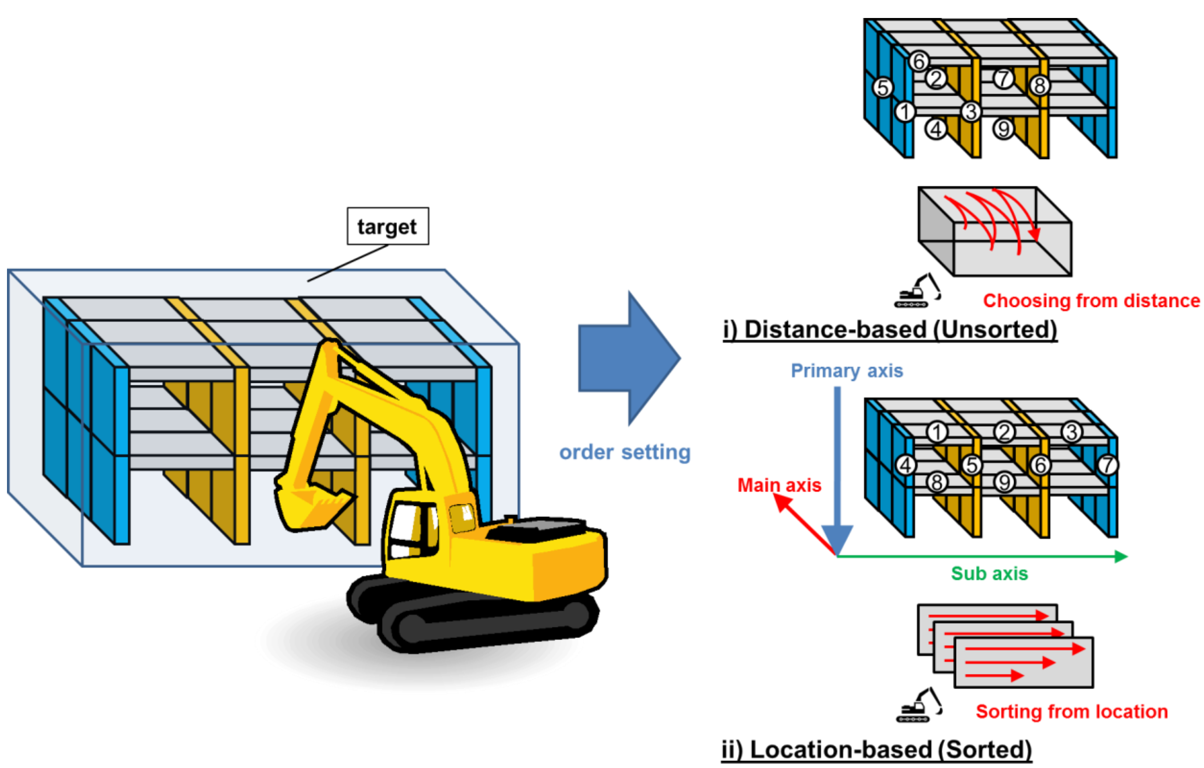


Figure 212 Scenario setting of demolition order: i) Decision with distance and ii) Sorted with location

A5.2.2. Material setting

This is the approach to maximise the efficiency of waste recovery by setting order based on the material type. Application of a material-based classification algorithm is expected to be a powerful tool to sort the target into material groups. The sorted minor materials are to be eliminated in advance from the site property to prevent comingling different types of materials in order to collect individually with high purity. It may, however, be a trade-off between the machine use and the waste sorting similar to the situation of labour investment to soft-stripping. The more sensitive the demolition, the more time and cost for machine application would be increased. On the other hand, the pure waste generation may prevent the sorting and treatment process and it can be sold as a resource to next constructors. This method is also beneficial to sort the contaminated waste from the rest. For example, the radiated internal concrete walls in nuclear power plants can be demolished afterwards the other elements which would be regarded as non-hazardous waste. It would result in the minimum treatment risk and burden in terms of cost, labour investment and sustainability from the whole demolition processes.

In order to achieve this goal, the material-based classification algorithm is applied to the element materials. This basically sets the order according to the material types from the one having the least volume onsite. However, it may cause a problem if the machine approach to target elements is not be considered at the same time. For instance, the plaster walls as the internal non-structural elements cannot be treated individually but involve the other structural elements. To prevent this inefficiency, the convex hull algorithm* is applied to identify the accessibility of each element type as shown in Figure 213. Like peeling fruit, target buildings are selectively demolished from external walls. To recreate this demolition order, the element locations are plotted on the grand plan (ignoring the vertical coordinate) with two assumptions; i) wastes would be naturally mixed with other wastes disposed in a vertical direction by gravity and ii) building designs tend to have similar floor design for each floor. Considering the access to targets, the elements are sorted by location into two types, external and internal (e.g. wall). As shown in the right side of Figure 213, the order of main demolition starts from the external elements (mainly walls) with the material-based classification algorithm. Then, the horizontal elements (mainly slabs) are demolished to improve the accessibility of internal elements. Due to the large average volume size in general construction, priority for each type is set as follows. If the material type is the same as the slabs, the element type can be included in the horizontal elements. Therefore, buildings with the same material type such as RC do not show any advantage but increase the operation type because of the unnecessary relocation for selective demolition. Therefore, this algorithm is applied to the masonry structure in the pilot study where slabs and walls are composed by RC and bricks respectively. The trade-off between the increase of machine operation time and the improvement of recovered waste purity will be discussed.

440 *If the target building shape is concave, the concave hull algorithm is more proper to classify the objects if they are located outside of floor elements. Due to the convex shape (rectangular) of target building, the convex hull algorithm is applied in the case study.

1. External elements	**window + door + column + beam + wall**
2. Floor elements (outside)	**slab**
3. Internal elements	**window + door + column + beam + wall**
4. Floor elements (inside)	**slab**

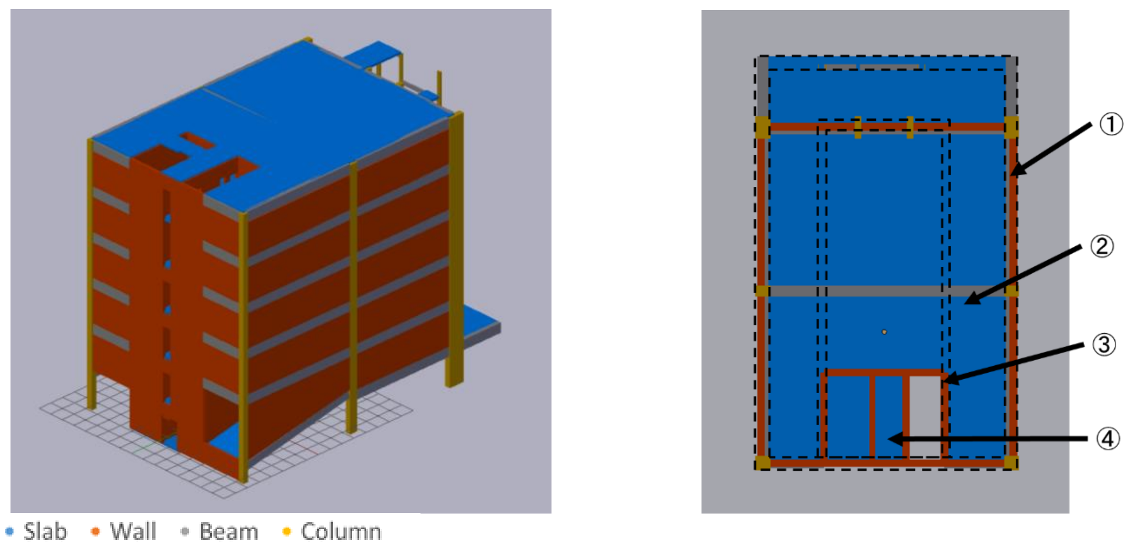


Figure 213 Target building in the pilot study and the demolition order with the material-based classification algorithm

Appendix6. Poisson distribution law and exponential distribution

The following calculations are extracted from "*Simulation Program with C*"(Ishikawa, 1994) to explain the exponential distribution of the time span for the event happening with Poisson distribution.

Bernoulli trial and binominal distribution

A continuous trial is called Bernoulli trial if it has only two results for one action such as coin toss and the probability is constant. To think about the probability of coin showing head *k* times for n times toss, the single order can be happened with the probability $p^k q^{n-k}$, where p is probability for head shown and q is for tail. The pattern for all order for that result can be written in Formula.r1. Accordingly, actual probability of coin showing head *k* times for n times toss can be shown in Formula.r2. This distribution is called binominal distribution.

$$\binom{n}{k} = \frac{n(n-1)\cdots(n-k+1)}{k!} \tag{r1}$$

$$\begin{aligned} b(k) &= \binom{n}{k} p^k q^{n-k} \\ &= \frac{n(n-1)\cdots(n-k+1)}{k!} p^k (1-p)^{n-k} \end{aligned} \tag{r2}$$

Poisson distribution

To think about the Bernoulli trial which hardly happens, demolition generation represents it in this study, the Formula.r2 can be approximated as Formula.r3 using Taylor expansion as Formula.r4. This is called Poisson distribution, and after this its probability is showed as p(k).

$$\begin{aligned} b(k) &= \binom{n}{k} p^k q^{n-k} \\ &= \frac{n(n-1)\cdots(n-k+1)}{k!} p^k (1-p)^{n-k} \\ &= \frac{\lambda^k}{k!} e^{-\lambda} \qquad (\lambda = np) \end{aligned} \tag{r2}$$

$$
\begin{aligned}
b(0) &= (1-p)^n \\
&= (1-\frac{\lambda}{n})^n \qquad (\lambda = np) \\
\log b(0) &= n\log(1-\frac{\lambda}{n}) = -\lambda - \frac{\lambda^2}{2n} - \cdots \\
&\approx -\lambda \qquad (n >> \lambda) \\
\therefore b(0) &\approx e^{-\lambda}
\end{aligned} \tag{r3}
$$

$$
\begin{aligned}
\frac{b(k)}{b(k-1)} &= \frac{\lambda-(k-1)p}{k(1-p)} \\
&\approx \frac{\lambda}{k} \qquad (1 >> p) \\
\therefore b(k) &\approx \frac{\lambda^k}{k!}e^{-\lambda}
\end{aligned}
$$

The calculation for Poisson distribution can also write in Formula.r4 to describe the random event with time. Here, unit time is separated into n segment from total time, *t*. The unit time is assumed not enough small to include the event occurrence twice.

$$
\begin{aligned}
\Delta t &= \frac{t}{n} \\
\frac{\lambda t}{n} &= \lambda \cdot \Delta t \\
p(k) &= \binom{n}{k} \cdot \left(\frac{\lambda t}{n}\right)^k \cdot \left(1-\frac{\lambda t}{n}\right)^{n-k} \\
&= \frac{(\lambda t)^k}{k!}e^{-\lambda t} \qquad (1 >> \Delta t)
\end{aligned} \tag{r4}
$$

Exponential distribution

The time span, τ , for event happening according to Poisson is considered in this appendix. At first, the probability for nothing happen until time limit should be concerned. It can be described in Formula.r5 from Formula.r4. It indicates the time span for this event exceeds time limit and that can also be described in Formula.r6 with use of *f(* τ *)* as the probability for time span becomes τ . As a result, *f(* τ *)* can be written as Formula.r7, and this is called exponential distribution.

$$p(0) = e^{-\lambda t} \quad \text{(r5)}$$

$$\int_t^{\infty} f(\tau) d\tau = p(0) \quad \text{(r6)}$$

$$f(\tau) = \lambda e^{-\lambda\tau} \quad \text{(r7)}$$

Appendix7. Research of Abdullah in 2003 (Intelligent selection of demolition techniques)

A7.1. Relation with current research

In Abdullah's research, the impact estimation tool for the demolition project planning was developed to suggest the optimal demolition techniques. The current research also aims to suggest the impact estimation tool for project planning, and both of tools are assumed to be used as the decision support tool for the project planners. Accordingly, his research is referred in the literature review to clarify the gap with social demand, and also applied to the design of the model validation step which can be seen at Chapter6. Moreover, the results of questionnaire for the model quality are compared there. To clarify the compared model, the detail of his suggestion is explained at the following section.

A7.2. Aims of research

In his research, the aim was set 'to develop a decision support system to aid demolition engineers in selecting the most appropriate demolition techniques for a given structure.' Accordingly, as the research objective, to explore the potential of the application of Artificial Intelligence (AI) technique to the selection of demolition techniques was suggested.

A7.3. Research proposal

He pointed out the particular situation of demolition industry where the demolition planning was decided in an intuitive manner with considerable reliance on the individual specialists' experiences and knowledges. In order to resolve the inefficiency of the selection process according to this situation, he insisted the necessity of sound techniqueal framework for decision making. Through the literature survey of decision support systems (DSS), he suggested the prototype of Demolition technique Selection System (DTSS) which allowed demolition planners to select the most suitable demolition technique in the project. The detail of DTSS is explained in the next section. After the development, the demolition experts and the researchers in the university were selected to validate the model with formative evaluation methods (e.g. interview).

A7.4. Demolition technique Selection System (DTSS)

In his research, the system called Demolition technique Selection System (DTSS) was suggested to select an optimal demolition technique among the six (site overhead, decommissioning, soft stripping, waste disposal, general overhead, and profit). This system is separated into two stages as shown in Figure 214.

At the first stage, the priority of projects were ranked based on the users input. The problems had been defined based on the demolition expert's ideas and debates, and sorted at the hierarchic structure as Figure 215. Then, the ranking of the priority was decided from the users answer in the pairwise comparison for each factor with the sensitivity analysis.

At the second stage, the demolition cost for three different types of demolition techniques were calculated with the users input. Here, two possible ways are suggested; i) preliminary and ii) detailed cost estimation. The preliminary estimation use the building scale and unit impact according to the previous research. Due to the simplicity of method, there were about 20% of deviation in the result. On the other hand, the detailed estimation required the users to manually input the whole element quantity data. The total cost can be calculated based on the unit cost for each demolition technique. Then, the priority value which was calculated at the first stage was compared with the cost to estimate the ratio (priority value/cost). Consequently, the most cost effective technique was selected as the optimal choice under the current project circumstance including the users' preference.

In summary, this DTSS system allowed the users to quantify the priority of factors in the project according to their answer in the pairwise comparison. Then, the spreadsheet approach calculated the total cost for different six demolition techniques so that the cost effectiveness against the benefit (the priority value) can quantitatively suggest the most suitable decision for the current circumstance.

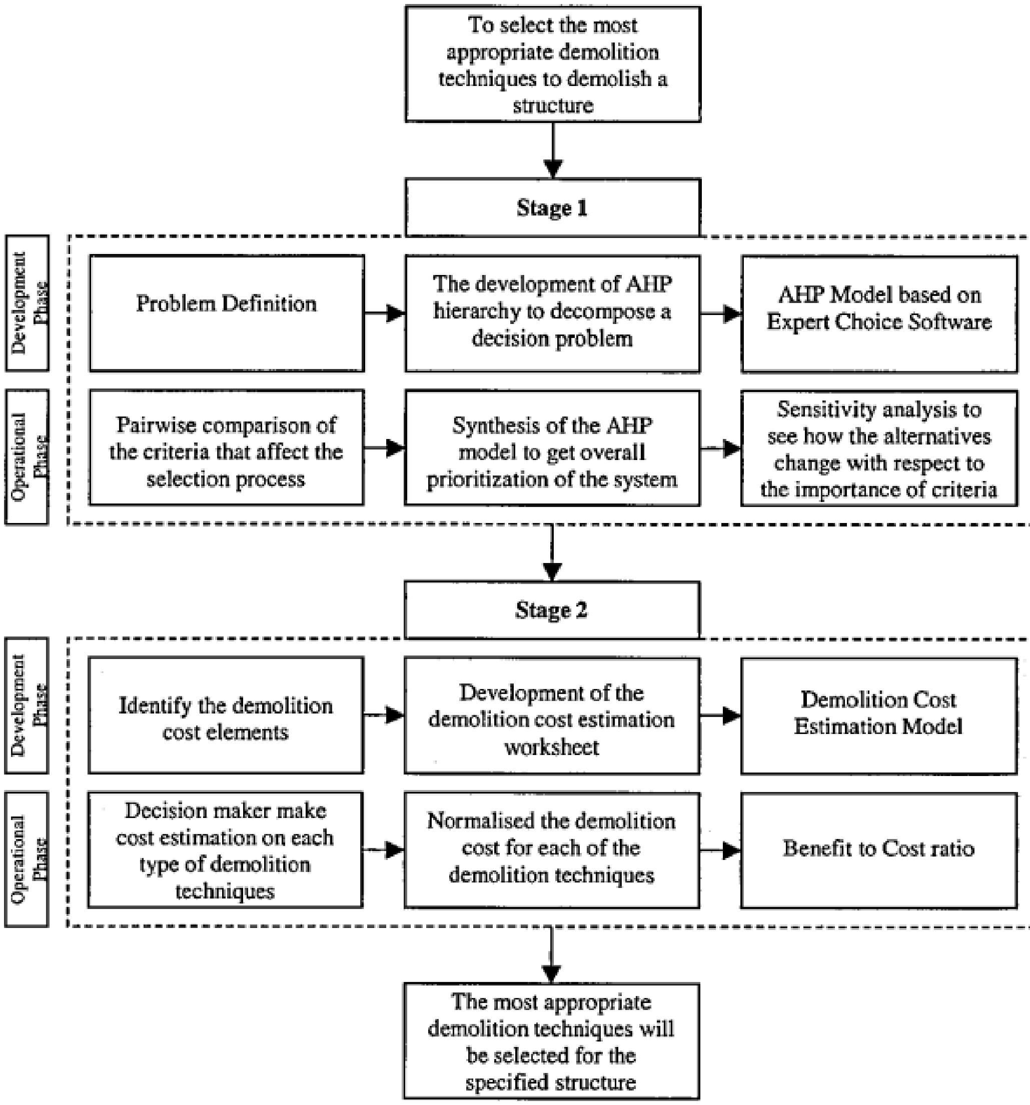


Figure 214 The functional architecture of the DTSS

(source: Abdullah, 2003)

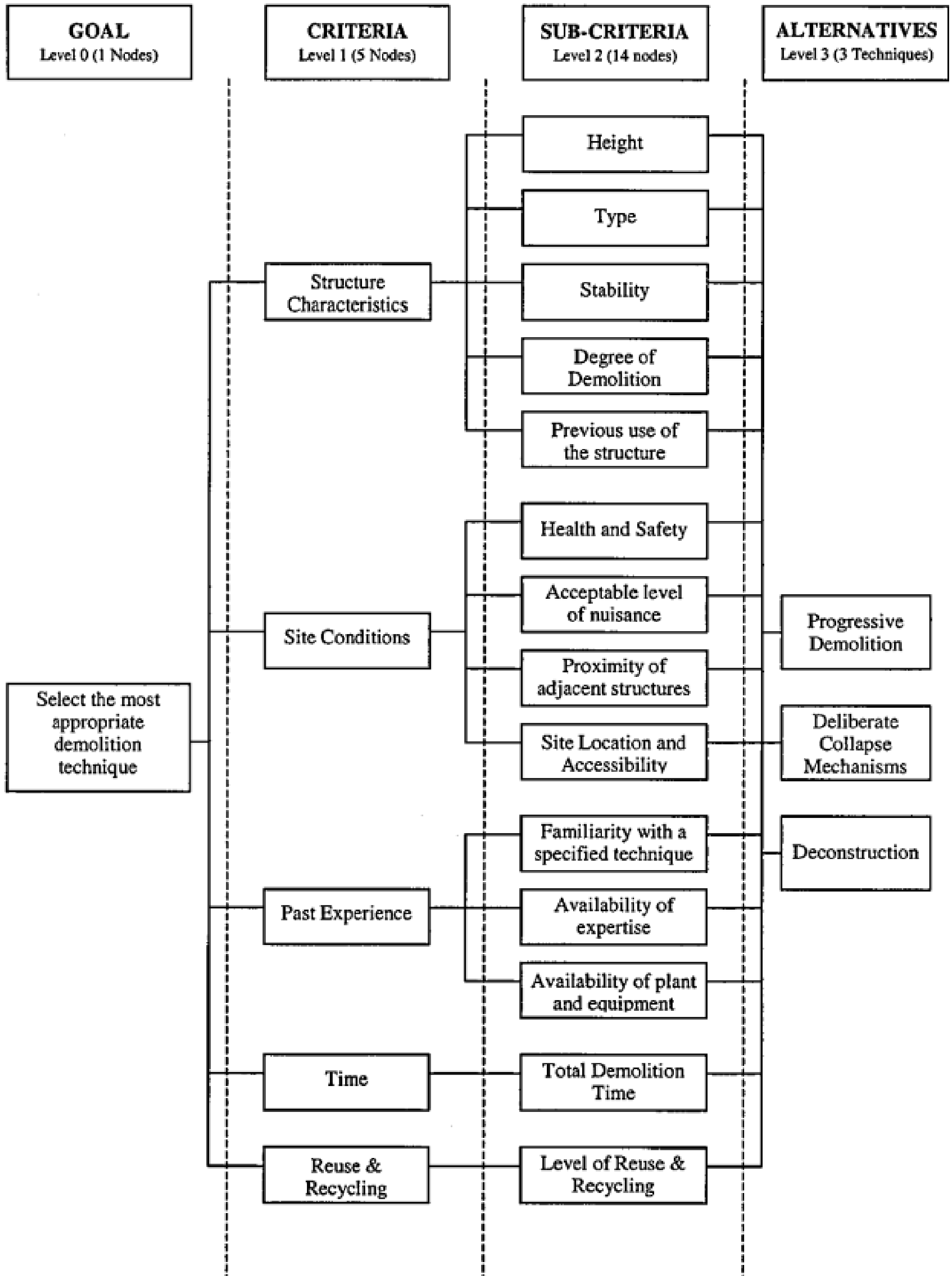


Figure 215 Hierarchic structure for the demolition techniques selection model

(source: Abdullah and Anumba, 2002, cited in Abdullah, 2003)

A7.5. Validation

After the development of the prototype model of DTSS, Abdullah held a model validation with questionnaires for two groups of target; i) demolition experts and ii) researchers in the university. The questionnaires were composed by two parts, the question part as Table 101 and the comment part. Based on the feedback, the appropriateness of the evaluation approach was evaluated.

Table 101 Questionnaires design

	DTSS Evaluation Questions	Rating									
		1 (Poor)		2 (Fair)		3 (Satisfactory)		4 (Good)		5 (Excellent)	
		DE.	Res.	DE.	Res.	DE.	Res.	DE.	Res.	DE.	Res.
The System Performance (overall rating, Figure 7.1)						**44%**	**31%**	**48%**	**52%**	**8%**	**17%**
1	How well does the system help in understanding how demolition techniques can be selected?					**20%**	30%	**80%**	60%		10%
2	How clearly are the selection criteria defined in the system?					**20%**		**80%**	80%		20%
3	How well are the demolition techniques explained in the system?					**60%**	40%	**20%**	40%	**20%**	20%
4	How useful will the system be in supporting communication between the demolition engineers and clients?					**20%**	10%	**80%**	60%		30%
5	How well does the Information Document help in making a decision?					**20%**	30%	**80%**	60%		10%
6	How appropriate is the Pairwise comparison aspect of the system?					**40%**	10%	**60%**	80%		10%
7	How well does the system reflect the decision-making ability in a real situation?					**100%**	60%		40%		
8	How useful do you find the sensitivity analysis within the system?					**20%**	20%	**20%**	30%	**60%**	50%
9	How accurately are the relative costs between demolitions options modelled in the system?					**80%**	60%	**20%**	40%		
10	How useful is the cost model in choosing a demolition technique?					**60%**	50%	**40%**	30%		20%
Applicability (overall rating, Figure 7.2)				**16%**	**2%**	**40%**	**34%**	**44%**	**44%**		**20%**
11	How effective/accurate is the system in the selection of demolition techniques?			**20%**		**60%**	30%	**20%**	60%		10%
12	How convinced are you that demolition industry professionals will accept (or use) the system?			**20%**	10%	**40%**	30%	**40%**	40%		20%
13	How effectively will the system increase the speed of the decision making process?			**20%**			40%	**80%**	30%		30%
14	To what extent does it represent an improvement (or help) in the decision making process?			**20%**		**40%**	40%	**40%**	30%		30%
15	To what extent is the system flexible in choosing the most appropriate demolition techniques?					**60%**	30%	**40%**	60%		10%
General (Overall rating, Figure 7.3)						**20%**	**38%**	**70%**	**59%**	**10%**	**3%**
16	How well organized (designed) is the system?						60%	**60%**	30%	**40%**	10%
17	How user friendly is the system?					**20%**	30%	**80%**	70%		
18	How well integrated are the different components of the system?					**20%**	40%	**80%**	60%		
19	What is your overall rating of the prototype system?					**40%**	20%	**60%**	80%		

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