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Information flow-centric approach for reverse logistics supply chains

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ABSTRACT

Reverse logistics supply chain (RLSC) helps resources recovery at the End-of-life (EoL) of buildings. However, there is a huge potential for improving the existing RLSC through systematic information management. Very little research has been carried out on the interactions between RLSC operations and information needs for an efficient and effective resources recovery process. This study proposes a conceptual model of a building information model that could effectively address the information needs during demolition, testing, grading and reprocessing of salvaged materials. The study uses semi-structured interviews and action research to identify information needs and Building Information Modelling (BIM) functionalities to develop the conceptual model using an Application Programming Interface (API) plug-in. The model when fully developed can extract the volumes of salvage, sorting, testing, reprocessing and integrate that information for optimised resources recovery. The extracted information in a single platform can help demolition planners and recyclers to design downstream operations, particularly testing and grading of salvaged products enabling an information flow-centric reverse logistics supply chain.

1. Introduction

The construction industry generates a large amount of waste often destined to landfills generally known as 'construction and demolition waste' (CDW). The industry pays less attention to resources recovery to divert this waste from landfills. There are two types of CDW generated in the industry. During construction, repair and renovation activities which are commonly referred to as construction waste (CW); and at the end-of-life (EoL) of a structure known as demolition waste (DW). According to Jiang, Feng and Ouyang [1], out of the total waste generated by the construction industry, DW is significantly higher than CW. Most of the buildings are demolished at the end-of-life, and little is recovered as salvage for reuse. Reverse Logistics Supply Chain (RLSC) provides infrastructure to manage the entire resource recovery process. This is to re-capture value from salvage materials which is an environmentally sustainable alternative to landfilling [2–4].

The RLSC process that deals with demolition waste has not benefited from a well-organised information flow. The infrastructure is often fragmented [5]. Rahini and Ghezavati [6] emphasised that fragmentation and uncertainties are caused mainly because of information deficiencies. To overcome the challenges of information deficiencies, researchers have suggested that RLSC operations should be managed using a well-organised and well-subscribed information repository [7,8]. The information repository will enable decision-makers to consider EoL of building scenarios at the design stage of a project and incorporate information such as number of possible reuses of a component; volumes of debris generated at demolition; deconstruction potential; etc. in their design decisions. According to Akanbi et al. [9], this will shift the procurement of a built asset from a design-centric approach to an information-centric approach facilitated by information technology (IT). To incorporate such information during the design stage, Building Information Modelling (BIM) is an appropriate platform [10]. Nevertheless, according to Akanbi et al. [9], BIM-enabled approaches are yet to be used in RLSC operations except in the estimation of demolition volumes [11], assessment of recyclability and reusability of salvage materials [9]. After an extensive literature review in this topic, we are yet to find a single comprehensive study addressing the information needs of the entire RLSC including testing and grading to enable quality assurance and marketing of salvaged products.

To fill the above knowledge gap, this research is aimed at developing a conceptual model based on a BIM platform by identifying the information needs of the RLSC, specifically focusing on DW, to facilitate BIM-enabled RLSC operations. To achieve this aim, the study first identified the information needs during the entire RLSC process that

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comprises of deconstruction, sorting, testing, grading, recycling and reuse of salvaged materials. The study explores the BIM functionalities that could support an efficient and effective RLSC. The study provides a conceptual model, integrating the RLSC operations through a BIM platform using an Application Programming Interface (API) plug-in. Once fully developed, this model will provide an information flow-centric approach. This will enable the estimates of quantities of demolition waste, sorting, testing and reprocessing volumes generated during the RLSC and help integrate the entire supply chain. Additionally, it will help designers, builders, and sub-contractors to make informed decisions by considering EoL of a building at very early stages of its life-cycle.

This paper is organised as follows: first, a literature review introducing RLSC operations and how it can be enhanced by an effective information flow is presented. This is followed by a justification of the methods used to collect and analyse data. Then the results of the study are discussed with a demonstration of the conceptual model of a BIM plug-in to enhance information flow in RLSC operations. Finally, the implications of the study for designers, demolition contractors, salvaging companies, recycling companies and landfill operators are highlighted with limitations and further research recommendations.

2. Literature review

2.1. RLSC operations: demolition waste management perspective

RLSC operations are designed to help recover and reprocess salvaged materials generated at EoL of buildings, otherwise destined to landfills and generate value-added resources for secondary markets. Fig. 1, illustrates the RLSC operations which elaborate inputs, process and output. The starting point of RLSC is the EoL of a building and salvaged materials and components will become inputs to the subsequent resources recovery process [2,6]. Therefore, the succeeding stage is a production process which includes the collection of salvage, testing, sorting and reprocessing. Outputs are considered as both secondary products and residuals [5]. The following sub-sections highlight RLSC stages and opportunities for incorporating sustainable practices [12].

2.1.1. Dismantling

RLSC starts with the dismantling of a building at its EoL. Dismantling is mainly carried out in two ways: mechanical demolition or deconstruction (also known as selective deconstruction). Mechanical demolition ensures time and costs savings, particularly making the land available for new construction within a short period [13]. However, mechanical demolition creates huge stockpiles of debris from which materials cannot be easily recovered and as a consequence, mainly directed to landfills. Deconstruction is effective and a much more environmentally sustainable method compared to demolition, where a building is systematically ripped off for high quality salvage. In particular, deconstruction supports the circular economy and facilitates sustainability [9,13]. However, deconstruction is not practical from an economical viewpoint [14,15]. A hybrid that combines demolition and deconstruction enable the trade-off between time, cost and quality of resources recovered [16,17]. Nevertheless, demolition has been extensively used in practice, and a significant gap could be found in the literature in promoting deconstruction or selective deconstruction to help maximise resources recovery.

2.1.2. Collection, sorting and testing

After dismantling, the materials are collected for sorting. The method of sorting is significantly influenced by the type of demolition where sorting is to take place [19]. Deconstruction maximises resources recovery allowing effective sorting and segregation to take place.

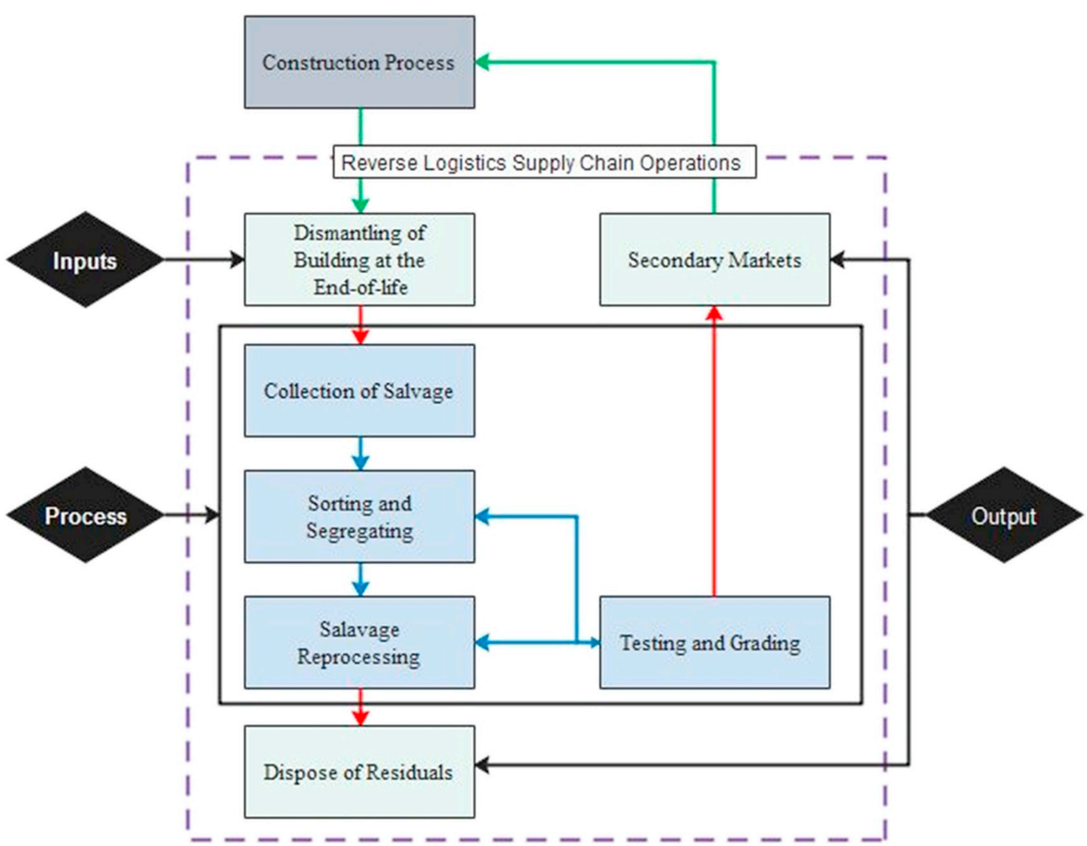

Fig. 1. Operational system of the reverse logistics supply chain.
(Source: [2,3,5,12])

Table 1
Reprocessing methods.
(Source: [2–4,7,15,23–25])

Recovery method	Description
Direct reuse	Components and parts are subjected to new use after extraction and cleaning (direct recovery) - e.g. structural steel, wood, bricks, doors and windows.
Repairing	Regain the working conditions of broken items (includes few stages of assembling) – e.g. pipelines, metal, ductwork
Refurbishing	Modules or parts are dismantled (partially) and inspected for discrepancies. Then the required parts are replaced and even subjected to technological advancements (quality upgrade) – e.g. pipelines, metal, ductwork
Re-manufacturing	Modules and parts are subjected to complete disassembly, and malfunctioning parts are replaced while upgrading the quality - e.g. pipelines, metal, ductwork
Recycling	Extracted Materials are subjected to reprocessing to produce the same material with the same or higher/lower quality (up-cycling/down-cycling) – e.g. metal, crushed concrete and damaged bricks to aggregate

Sorting and segregation process is in two types based on the location (on-site and off-site sorting). In particular, on-site sorting is considered to be an effective method compared to off-site sorting which also avoids mixing and contamination [11,20]. Sorting is undertaken manually or with the help of machines. According to Noguchi, Park and Kitagaki [21], sorting to produce recycled concrete, sorting devices is selected based on the type of aggregate needed. Quality of the salvaged aggregate also depends on the method of sorting. During the dismantling and sorting process, if contaminated materials found, those are subjected to testing [22]. It helps segregate non-contaminated salvaged materials suitable for reprocessing.

2.1.3. Reprocessing

The sorted salvage materials are transported for reprocessing. Table 1 provides reprocessing options for different types of salvage.

Among the reprocessing methods, reusing and recycling are the most frequently used [15]. Reusing is effective compared to recycling in terms of time, cost and energy efficiency [9]. While deconstruction facilitates reusability, recycling is the most popular for concrete, steel and timber [16]. In particular, structural concrete elements are recycled to produce recycled aggregate, and they are the most recycled materials in the construction industry [14,26]. Similarly, recycling of glass, gypsum and composite materials have gained momentum and considered to be more cost-effective than landfilling [27]. However, downcycling is not favoured by researchers which lowers the quality of the output while consuming considerable energy in the process [27–29]. The reused and recycled products are further tested and subjected to grading based on accepted standards before dispatching to the secondary market [27]. These products are tested based on the properties they display after reprocessing using some commonly available testing methods listed in Table 2.

2.2. Barriers in promoting salvaged products in the secondary market

The salvaged building materials are subjected to different operations, pressurised workflows and ends up with issues in appearance; quality and performance [26,30]. Consequently, the products have a poor image by its nature. According to Chileshe et al. [8] and Saraiva, Borges and Filho [36], this is mainly due to lack of infrastructure facilities for resources recovery, lack of awareness and inadequate government support to promote reuse and recycling. These barriers cause reverse logistics operations to be fragmented and unorganised. For instance, effective recycling is achieved only with a well-planned deconstruction operation. Sorting as the next stage (refer Fig. 1) is also affected by the type of dismantling method employed. If deconstruction is not properly carried out, a pile of contaminated mixed waste would be the outcome. Fig. 2 illustrates how these barriers in reverse logistics operations affect the reprocessed products.

As explained in Fig. 2, one of the main reasons for these barriers is the lack of appropriate information flow within the RLSC [6,7,37]. Even if the information is available, manual handling of this information as often practised in the industry, does not improve RLSC operations [11]. According to Akanbi et al. [9], BIM and BIM-related technologies have been recognised as a way forward to effectively manage relevant information flows on the RLSC process [38]. The concept of using BIM as a tool to manage information is very positive for RLSC as well as for the entire project life cycle from design to EoL and beyond [36]. The following section discusses the current BIM applications related to EoL of buildings.

2.3. BIM related applications for EoL of buildings

In any field, information management can be often obtained through the concept of 'BIM' [39] or BIM-related to the internet of things (IoT) [40]. Therefore, BIM can be extended to enable technologically advanced to automate the integrated fields to attain sustainability. One such application is EoL of building where BIM is adopted as a tool which systematically manages the information related to EoL operations [41]. BIM has been widely used for design validations given avoiding generation of Construction and Demolition (C&D) waste in the first place is the aim of designer [42]. It should be noted that waste avoidance is the highest in the waste hierarchy and should always be the most preferred option for waste management. Therefore, the work of Won, Cheng and Lee [42] is very significant from a sustainability perspective. Ge et al. [43] adopted BIM in deconstruction operations; a BIM-enabled model is developed to visualise the connections between the building elements. BIM supports the development of a customised simulation of the deconstruction process before actual deconstruction. Henceforth, contaminated substances within the building structure can easily be recognised at the very early stage and could be removed appropriately. The process facilitates the categorisation of salvage for reprocessing. Chang and Ma [11], Dave et al. [40] and Lu et al. [44] proposed a waste estimation system for construction, renovation, and demolition projects based on BIM. Both Chang and Ma [11] and Lu et al. [44] use an API to connect the existing BIM model to calculate volume of waste materials. The system used by Chang and Ma [11] predicts the volume of materials extracted at demolition and renovation activities and predicts 'waste generation level' and the number of pick-up trucks for their disposal. However, Lu et al. [44] adopted the 'waste generation level' basically to construct 'waste generation rate'. According to the authors, waste generation level is more suitable in BIM-enabled models for calculating the performance measurement in the waste generation system. Further, the concept of Design for Deconstruction (DfD) is merged with BIM in the work of Akinade et al. [17], where they developed a BIM-based De-constructability Assessment Score (BIM-DAS) to address deconstruction performance at the design stage. Park et al. [45] developed a BIM-based demolition waste database and disposal routes based on characteristics of materials and products. These applications facilitated waste minimisation, avoidance, effective and efficient demolition and deconstruction. According to Akanbi et al. [9], BIM enables the estimation of the recyclability and reusability of different salvaged components. However, other stages of the RLSC including salvage collection, sorting, reprocessing, testing and the operation of secondary markets were yet to be supported by BIM or other information management systems to make the entire RLSC effective and efficient.

Table 2
Properties and possible tests for major recycled materials in construction.
(Source: [26,27,30–35])

Properties	Test
1. Recycled aggregate concrete	
Particle size, colour, shape and texture	Visual inspection
Water absorption capacity	Water uptake from soaking testing
Porosity	Vacuum saturation
Workability	Slump test
Compressive strength	Test for compressive strength
Tensile and splitting strength	Test for tensile strength
Flexural strength	Test for flexural strength
Modulus of elasticity	Cylinder strength for recycled-aggregate concrete cube strength for recycled-aggregate concrete
Damping capacity	Damping capacity is tested regarding logarithmic decrement which measures the decrease in amplitude of free vibration at the end of 28-day
Drying shrinkage	The test is done using 100 × 100 × 400 mm prisms, which are moist-cured for 28 days and allowed to dry in an unsaturated laboratory environment
Creep strain	100 × 100 × 400 mm prisms are used under constant sustained load to determine the creep of concrete at the age of 28 days
2. Recycled timber	
Density	Non-destructive wood density testing (using volume and mass)
Bending strength and apparent modulus of elasticity (MOE)	Wood bend test by applying a continuous load
Tensile strength parallel to grain	Flexural test methods
Compressive strength	Compressive strength testing both parallel to the grain and perpendicular to gain by applying a continuous load
Beam shear strength	Small clear wood and of full-size structural timber under flexural and torsion loadings
Bearing strength perpendicular to grain	
Bearing strength parallel to grain	
Modulus of rigidity in torsion	Torsion testing
3. Recycled steel	
Minimum tensile strength	Tensile test
Nominal stress under proof load	Proof load test
Minimum elongation	Tensile test for full-size fasteners
Head soundness	Head soundness test
Hardness	Hardness test
Maximum surface hardness	Carburization test
Behaviour under fire conditions	Transient-state test
Stress and strain values	Steady-state test method

Reprocessing is one of the main stages in the RLSC operation [18]. It depends on effective deconstruction, sorting and testing for contaminated materials and carried out under a systematic approach to produce materials (and products) to an acceptable standard. Most of the BIM applications discussed above had been in the deconstruction stage, where the BIM functionalities can be directly linked to deconstruction requirements. However, the application of BIM to the rest of the RLSC stages is not well developed. For instance, Chang and Ma [11] highlighted that there is potential to extend their demolition estimating model based on BIM by adding a default recycling rate to capture other stages of the reverse supply chain. However, those developments are yet to be implemented. Information needs of other stages including testing, sorting and grading of salvage could be facilitated by BIM as they are the most important stages from an environmental sustainability perspective. In addition, a partial solution to a supply chain issue will not help much as all stages of the RLSC are interconnected. A

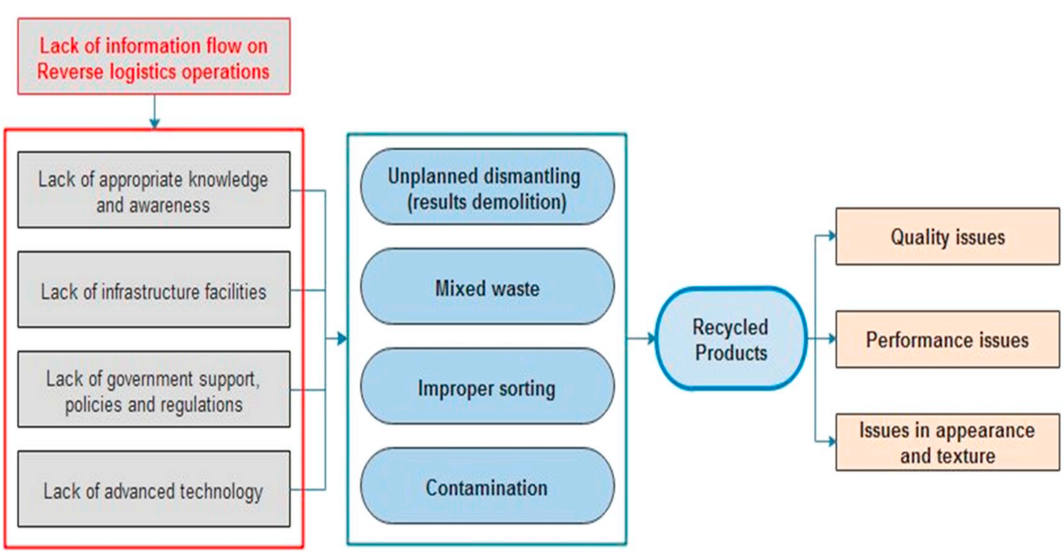

Fig. 2. Negative effects on the demand for recycled products.

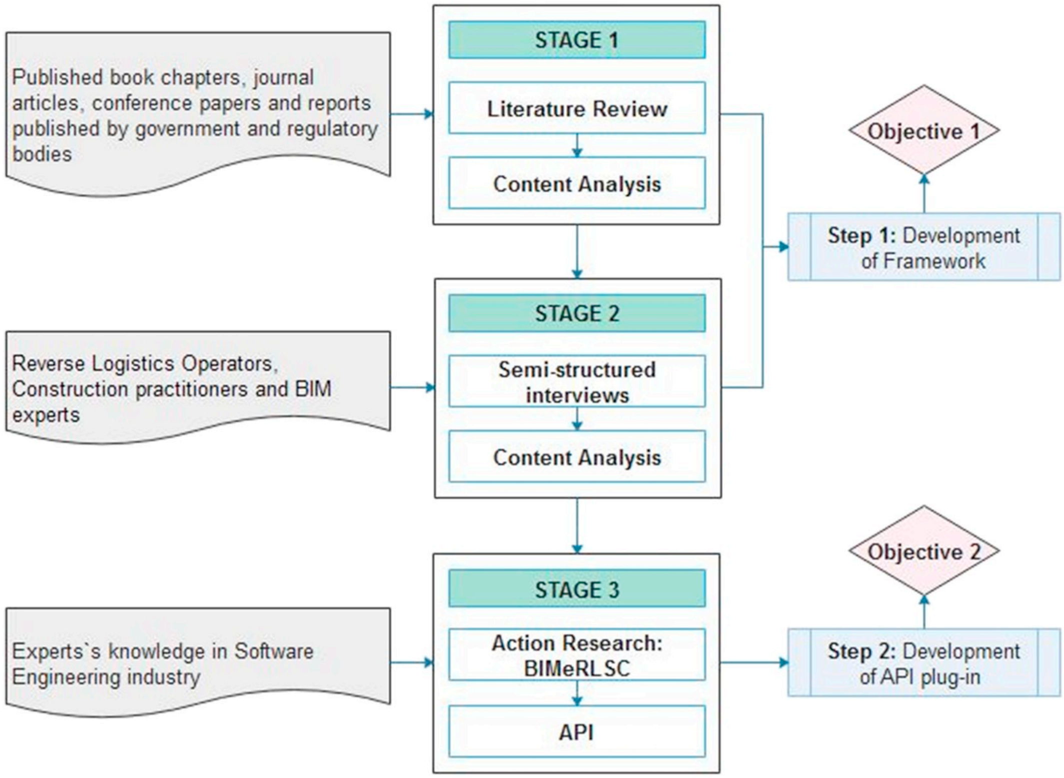

Fig. 3. Research design.

holistic solution is needed for the management of information across the entire resource recovery process.

3. Research methods

To accomplish the aim and objectives of this research, a three-stage research design was employed as illustrated in Fig. 3. During stage 1, a comprehensive literature review provided an insight into the RLSC concept and operations related to sorting, recycling, testing and grading of salvage, BIM related functionalities needed to support this process. In particular, investigations into past BIM-enabled applications can be considered as "lessons learned" which is crucial in developing future applications. The literature review was supported by published book chapters, journal articles, conference papers and reports published by government and regulatory bodies. The collected literature was analysed using content analysis

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Stage 2 of the research design comprised semi-structured interviews as a data collection tool to identify information needs for RLSC operations and BIM functionalities that could support the information flow and enhance current operations. Eight interviews were conducted, with construction industry stakeholders, two of each representing various stages of the project life cycle and two BIM experts based in South Australia. Respondents each representing the demolition sub-sector, salvaging sub-sector, construction and design consultancy, including BIM expertise, were selected using a purposive sampling method to generate a robust set of opinions related to information needs in RLSC in line with BIM functionalities. The profile of the selected interviewees is given in Table 3. Interviews were conducted face-to-face, using a semi-structured guideline at an agreed time. Each lasted 30–45 min. Each interview was tape recorded with the consent of the interviewee, transcribed, coded and analysed using content analysis method with the assistance of *Nvivo* 12 software.

Table 3
Profile of interviewees.

Interviewee code	Organisation	Role	Years of experience
D1	Demolition	Project Manager	25
D2	Demolition	Managing Director	16
S1	Salvaging company	General Manager	12
S2	Salvaging company	General Manager	23
B1	Builder	Cost Engineer	8
B2	Builder	Contracts Manager	12
BIM1	Design consultancy	BIM expert	7
BIM2	Academia	BIM expert	15

The third stage of the study employed Participatory Action Research (PAR). Researchers acted as facilitators to extract relevant information from software development experts in different fields and blended it with the researcher's explicit knowledge to achieve the conceptual model outcome. It was facilitated in a Revit platform, which is one of the commonly used software that supports BIM functionalities. Non-geometric information related to RLSC operations was supported through the API plug-in. Here the API is used as an encapsulation mechanism of information which supports BIM extensions such as BIM-enabled approaches [39]. Parn and Edwards [46] and Farghaly et al. [47] used the same method to develop the API plug-in software to support facilities management and asset management functions, respectively. This was based on the researchers' and industry experts' collaborative knowledge; a method that facilitates fact-finding and learning for all participants involved [46]. The PAR took place in Adelaide, South Australia from 23th November 2017 to 15th February

Table 4
Profile of experts involved in the PAR.

Expert's designation	Years of experience
CEO	15
Technical Manager	10
UI/UX developer	6
Software developer	5

2018. This included four phases of interactions where researchers facilitated and immersed in the entire process. Experts were from a software development company, and their profile is given in Table 4.

4. Results

4.1. Information needs in RLSC operations

The information needs represent RLSC operations including dismantling, sorting, segregation and reprocessing of salvage. At the dismantling stage, current industry practice does not seem to focus on planning. However, according to Interviewee D1 the availability of drawings at the EoL of the building is still sceptical. Thus, the majority of interviewees agreed that referring to construction drawings is not practical. Arguably, Interviewee D2 stressed that demolition contractors are often experienced enough to handle old buildings. Nevertheless, past experiences are not kept explicitly within an organisation in a formal way. Consequently, formal knowledge management practices within demolition contractors would be very useful.

Interviewees identified four stages in a demolition. The sequence of the dismantling and time allocated for each task are vital to providing important information for segregation and sorting of salvage. The first stage of dismantling is to disconnect services. According to Interviewee D1 "*Once the building is inspected, as the very first step, services are normally disconnected*". The second stage is the identification of hazardous materials such as asbestos. All interviewees discussed issues encountered while removing asbestos. For example, Interviewee D2: "*Most of the old buildings can contain a certain amount of asbestos, and their safe removal, storage and transportation and disposal using necessary safety equipment are essential*". Undertaking precautions and compliance are the essential steps to mitigating the risks when handling hazardous substances during dismantling. Next stage is soft stripping, to remove higher value salvageable items including doors, windows, tap fittings, air-conditioning units, floors and desirable items such as timber. Interviewee B1 observed: "*Especially in multi-storied buildings, this require the Engineer's inspection due to the loads associated with the use of heavy machinery on upper-levels*". Accordingly, when scheduling works, the type of floor plate and structure must be considered for this reason. Often, this requires propping or shoring for removal of walls, linings, finishes, fixtures and fittings. Soft-strip follows the principles of deconstruction as the basis. Finally, mechanical demolition takes place. It is prone to some hazards and requires sound safety procedures to avoid accidents and injuries to workers. Information related to dismantling is crucial in identifying hazardous materials and helps in ensuring and maintaining the quality of salvage.

The outcome of dismantling is largely a pile of mixed waste which requires both on-site and off-site sorting for effective separation which is very expensive. The separation of waste is mostly limited during the *soft-strip*. Interviewee S1 observed that "*contractors do not consider separating materials during demolition*". Arguably, Interviewee S2 highlighted that "*while separating other materials and elements, reinforced concrete and steel are placed in a separate bin. These materials are then transported to a third-party site where there may be a degree of separation, and most of them end up back in the supply chain*". When the salvage is commingled, manual handling at the site will prevent further dismantling activities due to workplace health and safety concerns.

The stage is reprocessing the salvage despite dumping at landfill sites interviewee S2 suggested that "*it is far too expensive to take all materials to landfill so they must be recycled, and that dumping rates are much higher if the materials are not separated into the same order in which they will be able to be reused or recycled*". Therefore, the efficiency of separation and sorting should be improved regardless of the location, with the consideration of declining unnecessary transportation of the salvage. Although there is a growing consensus on the need for resource recovery, lack of demand for these materials, hinder its widespread implementation due to the quality and performance levels of recovered products. Interviewee S1 stressed that "*materials could only be accepted and salvaged if they are in 'good condition and fit for resale'*". For this reason, the factors influencing both reusing and recycling of different types of materials are one of the best sources of information. Apart from that properties of the recovered products through appropriate tests and the condition of the product to be used in future construction facilitates the grading of a product.

Lack of knowledge about resource recovery facilities and markets for these products directs the salvaged into landfills. Interviewee S2 highlighted the former issue: "we *have no easy access to recycling and recovery facilities due to being located far away, therefore facing many issues in investing in these facilities*". Interviewee D1 argued that lack of communication between demolition and salvaging companies regarding marketing the products and expected quality results fragmentation in RLSC operations. The fragmentation issues can be overcome through waste tracking. According to Interviewee BIM 2, waste tracking enables demolisher and recycler to be in one platform along with transportation and reprocessing. This enables stakeholder's awareness of the quality, type, and desirability and destinations of salvaged materials and possibilities of getting re-used within a new building. Hence, information plays a critical role in the communication of product quality and performance while acting as an integrator of the production infrastructure.

4.2. BIM related functionalities relevant to reverse logistics operations

Building Information Modelling (BIM) facilitates the integration of RLSC. BIM can contain information about 3D geometric, including its location, dimensions and appearance under the "parametric modelling" functionality [44,48]. Interviewees discussed BIM's ability to facilitate geometric data thus helps avoid some of the shortcomings in conveying the quality of the salvage materials to potential users. Regarding deconstruction, Interviewee BIM 1 observed: "*Additional geometric data can be added to the existing model, such as physical connections between structural elements which will be useful in deciding upon the best and optimum ways of deconstruction*". A similar opinion was voiced by Interviewee B2 about non-geometric data: "*Other properties and information, such as brand, colour, specification, weight, capacities and much more can be attached as non-physical traits to an item*".

Majority of interviewees stated the importance of adding supplementary information to an existing BIM model to make it functionally suitable to help RLSC operations. For example, Interviewee BIM 2, pointed out that "*any other information which is non-geometric can be incorporated into an existing BIM model, for instance when addressing the recycling activities and testing and grading the quality of products*". According to Bilal et al. [49] and Oti et al. [39], these types of information 'are typically out of the box' which means the use of non-geometric data (supplementary data) in addition to 3D geometric data in existing models would have to be supported by 'intelligent modelling' functionality. The frameworks will possibly be able to generate generic information and pre-populate within models to a certain degree. Alternatively, generic line items can be used with the developer inserting relevant information manually. For instance, according to Interviewee BIM2, "*this non-physical data can be useful as it is capable of providing the information about the reuse of an item as well as characteristics on its reuse and specifications which it was manufactured to. To ensure*

Table 5
Summary of findings: the information needs in reverse logistics operations.

Reverse logistics operations related information needs		Useful BIM functionalities
Dismantling	• Investigation of a building at the EoL (a type of building; size; types of construction; structural capacities; structural stability; state of materials; suitability and desirability of materials; requirements for alterations to materials before re-enter into the supply chain) • A detailed assessment of construction drawings (structural, architectural, mechanical, plumbing and electrical) • Data repository of past project experiences • Work breakdown structure for demolition activities • Investigation into hazardous substances (e.g. asbestos and other contaminated materials) • Building elements that are first to be stripped-off • The extent, the elements and materials to be stripped-off before mechanical demolition	**Parametric modelling**: • Inbuilt capability to store specific information related to building elements • Capture design intent in building models using parameters
Sorting	• Identification and removal of contaminated materials • Information about on-site sorting and type of materials sorted on-site • Information on mixed waste streams (inclusions) which requires further sorting off-site • Possible recovery methods of the stripped-off elements • Type of waste streams which cannot be further sorted • Information on transportation and reprocessing facilities.	**Intelligent modelling**: • Facilitates attaching supplementary data to building objects • Link objects to external sources such as reverse logistics operational information • Use of material database, such as demolition factor, (conditional factor), material properties (mechanical, physical and chemical), relevant test details and criteria
Reprocessing	• Possible recovery methods for sorted salvage • Possible secondary products • Properties of secondary materials and products • Suitable tests and criteria, standards etc. to test the quality of secondary products • Residual materials which cannot be further recycled	• Facilitates using Application Programming Interface (API)

that this is achieved with a level of conformity and accuracy, the use of Industry Foundation Classes (IFC) can be utilised". IFC provides for a platform where objects are assembled in BIM to define the building representations and for transferring data and semantics among applications [49]. The use of IFC allows for a neutral data format throughout the entire industry as a means of exchanging data in the form of a 'standard building model schema' [48].

Interviewees also discussed the use of BIM for other aspects in the RLSC including demolition planning. According to Galic et al. [50], the use of a BIM model for planning demolition operations achieves greater accuracy in the scheduling of these works with the help of a Work Breakdown Structure (WBS). Interviewees agreed that optimisation of an RLSC network consisting of collection points, salvage yards, reprocessing centres, secondary markets through a Geographic Information System (GIS)-BIM interfaces are still at its infancy. For instance, Interviewee B2 mentioned that unlike the construction phase, tracking important information related to EoL of a building have not been effectively implemented in practice. The consensus among interviewees is the lack of BIM capability stakeholders of the salvaging sub-sector hinders its adoption. Although it is evident that BIM could assist in all stages of RLSC including deconstruction, testing, sorting and reprocessing, the salvaging industry is far from appreciating its usefulness. In summary, Table 5 illustrates the findings as reported above related to information needs in reverse logistics operations along with BIM functionalities that could support such needs.

5. Modelling information flow

Based on the information needs identified from the interviews and BIM functionalities discussed above, a framework to demonstrate the working of the proposed conceptual model for the BIM-enabled platform is illustrated in Fig. 4. This framework is further considered as the foundation for the demonstration of an API plug-in as described in Section 6. RLSC operations at EoL of the building and their sequence until the end of secondary markets or appropriate disposal have been adopted in the development of the framework based on Fig. 1. Accordingly, once the building is dismantled at the EoL and salvage is collected, the first task is to get the contaminated materials separated on-site and then tested and disposed of to the next stage of the process. This is where the testing could be done for quality and compliance prior to reprocessing [22]. Generally, salvage gets sorted on-site and again off-site, mostly at a reprocessing yard. Once the salvage is reprocessed, the outputs are then tested for their physical and mechanical properties and appropriately graded before dispatching to secondary markets. The residuals of reprocessing which cannot be further reprocessed for the required quality are disposed of at landfills.

Unlike in other recent BIM-enabled models such as Cheng and Ma [11], Akanbi et al. [9], and Lu et al. [44], this model caters to the entire RLSC while considering the demolition volume, testing and sorting volumes, and the subsequent disposal volume. For the conceptual model, the framework considers the RLSC for commonly reprocessed materials in the industry such as concrete, steel and timber [9,11]. Firstly, at the stage of dismantling, the volume of salvage generated is measured through "volume by materials" which includes the volume of the given different elements of materials such as concrete, steel, bricks timber, etc. The succeeding activities are mainly based on the type of materials that got salvaged. Then the "volume by materials" is multiplied by the "demolition factor" or "condition factor", to obtain the actual demolished volume, which is used for further calculations. Demolition factor is supported by an external database having been developed through experience and experiments. The calculation process beyond this point is supported by the Parametric Modelling [49] and interoperability of BIM [39], where the demolition information can be extracted from building objects. According to Bilal et al. [49], using this functionality, total quantities can be calculated under one material type. Consequently, the demolition volume under each material can be easily calculated to support other assessments in the RLSC operation. To proceed with the other stages, an API plug-in software needs to be developed. In general, API helps to coordinate with the downstream operational information beyond the BIM specific geometric information to improve the operational effectiveness [39]. This process is supported by the BIM's Intelligent Modelling functionality that enables attaching supplementary operational data for processes such as testing, sorting, reprocessing app.

The calculated demolition volume is considered for testing of hazardous and toxic substances. The volume of hazardous substances is considered as an external data feed through the add-on software. In contrast, the density of asbestos should be provided in an external

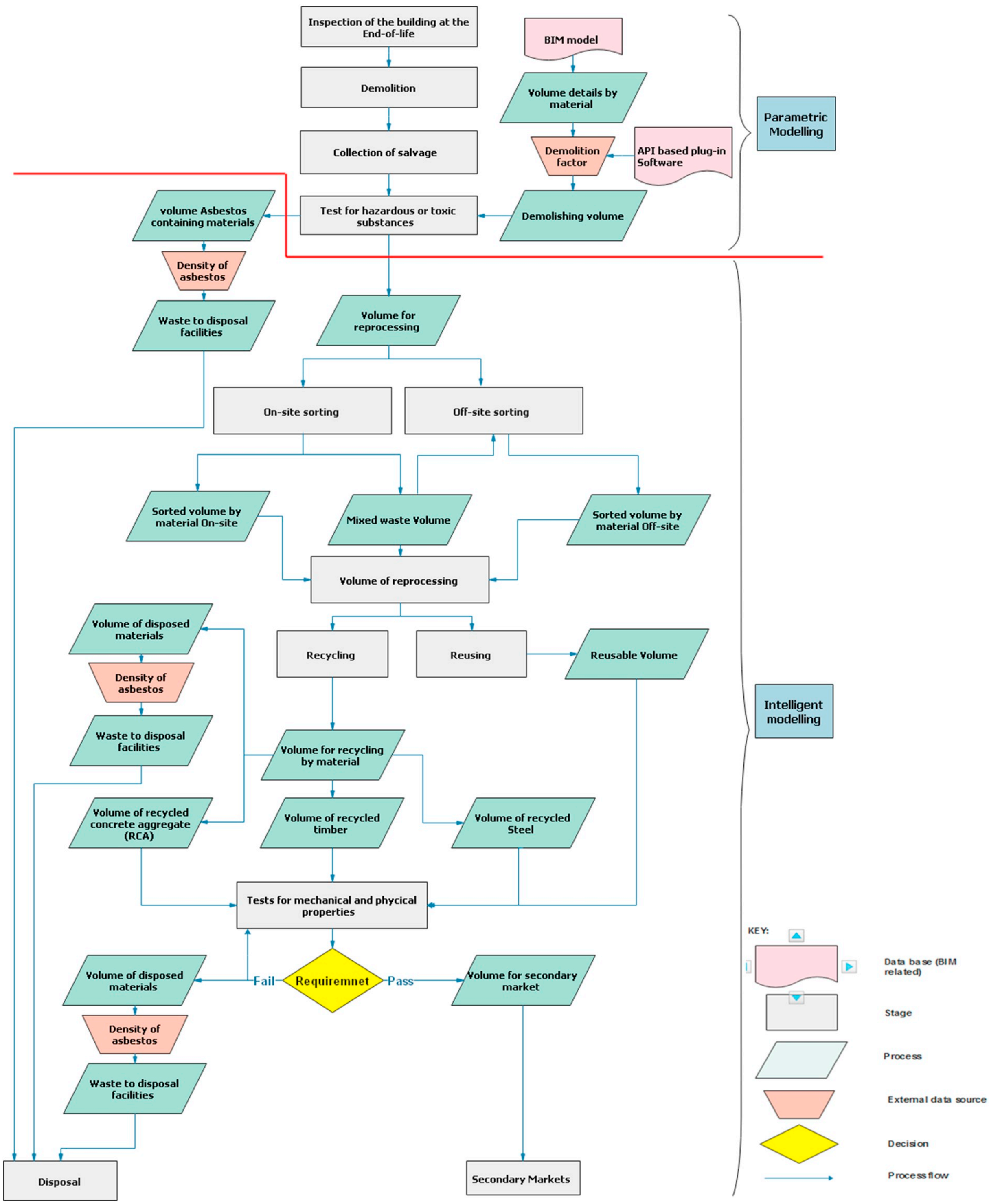

Fig. 4. Information flow chart for BIM-enabled RLSC model.

database. The volume is considered as a disposable volume which needs very specific procedures to be followed in its disposal. For transportation and waste tracking, asbestos density is used as an external data source to calculate the mass. The remaining volume is considered as suitable for reprocessing. Under the "volume for reprocessing", on-site and off-site sorting volumes need to be calculated separately. Once "on-site sorting volume" is entered then the rest is considered as "mixed waste volume", which occurs mainly due to mechanical demolition, and are directly transferred to off-site sorting. In the end, both on-site and off-site sorting volumes are used as "volume of reprocessing". It is a mix of both "reusable volume" and "recyclable volume". The reusable volume can also be known as a result of on-site sorting since some salvaged products can be used in secondary markets after appropriate testing. Once "reusable volume" is entered the rest is considered as "recyclable volume".

While "reusable volume" can be directly added to the testing stage, the "recyclable volume" is divided into four categories, considering the commonly recycled materials as an example: "volume for recycled concrete aggregate"; "volume of recycled timber"; "volume of recycled steel" and "volume of disposable materials". These three main recycled

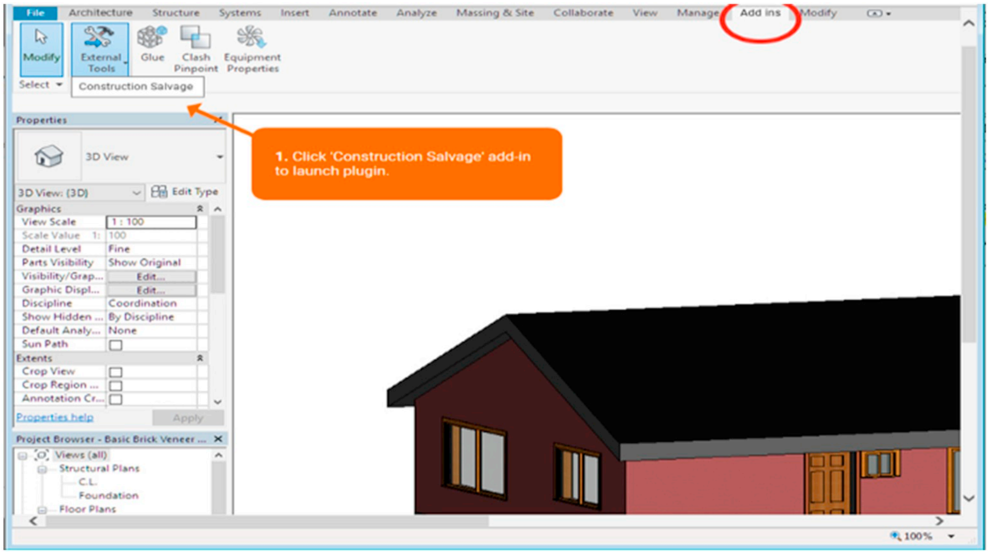

Fig. 5. The starting point of the API plug-in software.

products are then subjected to tests for physical and mechanical properties (refer Table 2). According to the inserted test results into the add-on software, the products which satisfy the required qualities and characteristics are selected for the secondary market. Others are sent back to a further testing process for continuous quality assessment. At the end, the "volume for secondary markets can be calculated". Then the volume of the residuals which cannot meet the quality requirement is considered under the "volumes of disposables".

6. Conceptual model of a BIM-enabled RLSC platform

This section demonstrates the conceptual model of the BIM-enabled RLSC using the information flow discussed in Section 5. The conceptual model is demonstrated using a flow diagram as shown in Fig. 6 (including the key applicable to subsequent figures - Figs. 10, 12, 5). According to Fig. 6, the starting point of the process is uploading the Revit file. Then the file is linked with the 'add-in' software. Fig. 5 shows the screenshot of the starting point of the developed API plug-in software. The user can enter the API plug-in software by clicking the "Add-ins" tab. Clicking the external tools, the user can load the relevant plug-in into Revit. In this project, the plug-in is named as, "Construction Salvage Software" (CSS). Thereby the plug-in communicates with Revit, which is facilitated through the API. Once logged into the CSS plug-in software, the user will see a dashboard containing a list of projects they have created (as well as any that have been shared).

Each project will have a name, date created, and status. The project management screen will facilitate functionalities such as: manage material (worksheet); share project; download original Revit file; upload pictures; print report. The project management screen will show the total volume of mass divided by material (this study has only considered the salvage of the most commonly recycled materials - concrete, steel and timber). The functionalities in the dashboard are given in Fig. 7 (see Fig. 6 for the key).

Hereinafter, the development process requires some calculations to establish salvageability of the materials at EoL of a building. Table 6 presents the variables which are used for the development of the conceptual model.

Fig. 8 illustrates one of the dashboard functionalities. The functionalities show the demolished volume ("expected quantity") of concrete, steel and timber after considering the conditional factor. According to Fig. 9, the conditional factor for each material type should be provided to the CSS plug-in software, as an external data source. The volume of materials can be derived from the Revit BIM model. Therefore, the initial quantities can be extracted through the given BIM model based on Revit software. The BIM model and the plug-in software has been linked through API. According to Lu et al. [44], the volume can be extracted by connecting to the database. Following Algorithm 1 is used at the API to extract the material volumes and weights in this research. Here the 'elements' include, concrete, timber and steel as depicted in Fig. 8.

Algorithm: 1.

1. Get all "Elements" (AutoDesk.Revit.DB.Element) in the model
2. For each Element …
   a. Get the list of "Materials" (AutoDesk.Revit.DB.Material) in the element
   b. For each Material …
      i. Identify the class (or category) of the material (Material.MaterialClass)
      ii. If that Class is in the list of materials we are interested in
         1. Use the Material's ID (Material.Id) to interrogate the Element for its volume (Element.GetMaterialVolume())
         2. Add this result to the collection of volumes we are compiling

The user can select the required material to be ssessed for its salvageability, reprocessing capacity and testing and grading requirements. The algorithm explains how the API plug-in automatically extracts the volume, weight, area, etc. [41,44]. According to Lu et al. [44] depending on the type of materials the unit of measurement can be changed. However, in this research, concrete and wood are measured using cubic meters (*m3*), and steel using tonnes (*t*). The extracted quantities under those units of measurements are then represented on the user interface in the plug-in software.

Once the volume of the materials is extracted (V_{ei}), the structural condition of the building elements can be assessed using the condition factor. The condition factor ($ø_c$) calculates the existing condition of the building element after considering the deterioration into account [51,52]. Table 7 represents the structural condition table for the materials extracted at the EoLB.

Based on Eq. (1) the expected quantity is calculated (after considering the structural condition) (V_{Ei}).

$$V_{Ei} = V_{ei} \times \varnothing_c \tag{1}$$

The total expected volume of a selected material (V_E) is given by Eq. (2):

$$V_E = \sum_{i=1}^{n} V_{Ei} \tag{2}$$

Thereby the initial quantities given in Fig. 8 can be derived. This allows the user to start the "analysis", which is proceeded in three

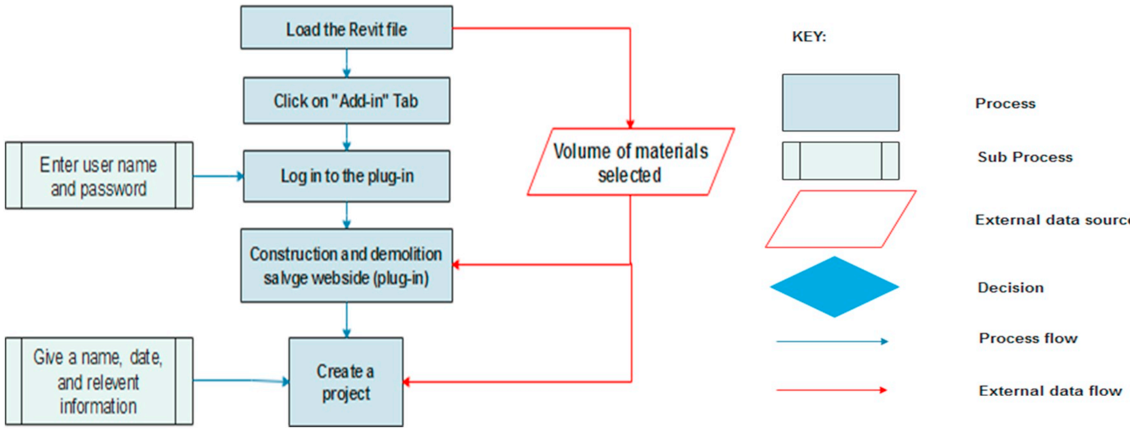

Fig. 6. Uploading details of material volumes into API plug-in.

stages as follows:

Stage 1: calculation of materials free from hazardous substances;
Stage 2: calculation of remaining quantities after sorting; and
Stage 3: testing for quality of secondary products.

Once the 'expected quantity' is calculated by considering the conditional factor; the volume of hazardous; asbestos or any other contaminated substance; (V_{hi}) should be entered to the system through external sources; which then enables the calculation of the remaining materials free from hazardous substances (V_{fhi}).

Fig. 9 demonstrates the materials free from hazardous substances and obtaining quantities after sorting. As shown in Fig. 9, the volume of hazardous substances should be removed under the volume of disposable materials. Eq. (3) provides the volume of demolished materials free from hazardous substances.

$$V_{fhi} = V_{Ei} - V_{hi} \tag{3}$$

The volume of hazardous substances (V_{hi}) can be derived using a norm based on mass and density as given in Eq. (3a).

$$V_{hi} = \frac{M_{hi}}{D_{hi}} \tag{3a}$$

The total volume of demolished materials free from hazardous substances (V_{fh}) for a given material is obtained using Eq. (4).

$$V_{fh} = \sum\nolimits_{i=1}^{n} V_{fhi} \tag{4}$$

As discussed in Section 4, Fig. 10 and Eq. (1), calculations are based on different types of materials and their sub-categories. For instance, five different steel types have been accommodated in the system. It can address various sub-categories of materials based on the type and complexity of the selected building category. Based on the type of material/category the conditional factor varies.

Stage 2 establishes the remaining quantities after sorting (see Fig. 11). At the "volume after sorting" interface, the unsorted volume of the specific material feedstock is entered. The unsorted volume of salvaged materials (V_{usi}) includes the mixed waste volume which cannot be further reprocessed and need to be considered under the disposable volume. This calculates the volume after sorting as given in Eq. (5).

$$V_{asi} = V_{fhi} - V_{usi} \tag{5}$$

The total volume of demolished materials free from hazardous substances (V_{as}) for a given is obtained using Eq. (6).

$$V_{as} = \sum\nolimits_{i=1}^{n} V_{asi} \tag{6}$$

Stage 3 describes the testing for quality of secondary products. The sorted volume can be categorised as reusable volume and recyclable volume, under the three different material categories. Once the reused volume is separated and added under the volume for secondary products (see Fig. 12), the remaining volume can be presented as the volumes of recyclable concrete, timber, and steel.

As illustrated in Fig. 13, the conditional factor can be used to calculate the recycled volume of each material. The volume should be tested with regards to quality and compliance against relevant standards. The test details for each material need to be provided as an external data source including conditional factors for each type of test. Once the recycled products are tested as complying with quality standards, then the volume can be added to secondary products of each material. For instance, recycled aggregate concrete can be tested for compressive strength; tensile strength, modulus of elasticity, etc. The API plug-in can provide the identification of products which satisfies

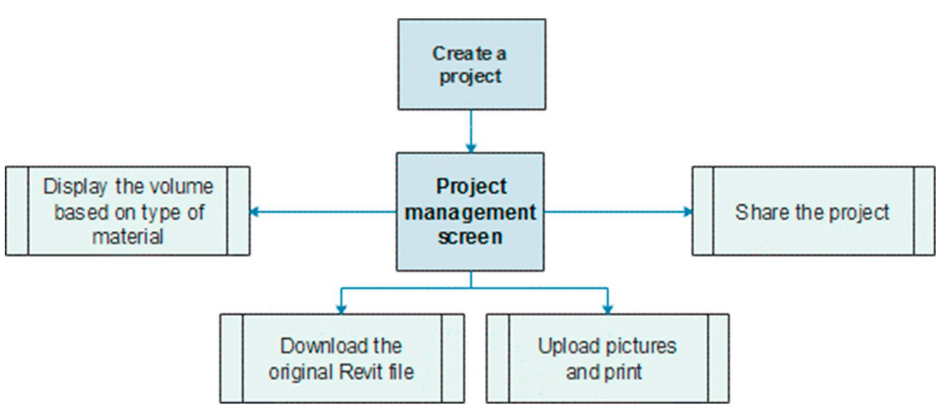

Fig. 7. Functionalities in the dashboard.

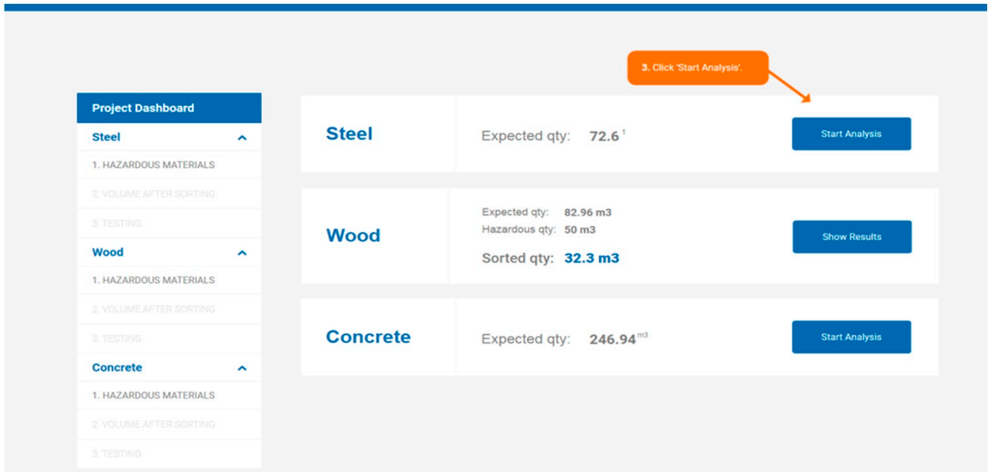

Fig. 8. Display volume based on the type of material.

the market requirements. If a product fails to meet quality standards, it needs to be reprocessed again until it satisfies relevant tests and standards. Materials that cannot satisfy further tests or cannot be further recycled is counted under the volume of disposables. According to Fig. 12, the results can be shared and stored as a state of the material worksheet. The model also has the potential to provide the density of materials as an external data source to meet the actual site situation. The model further facilitates communication between stakeholders related to RLSC such as demolition contractors and recycling companies. In addition, it provides practical norms of waste generation and identification of contaminated materials at a very early stage in the design process.

7. Discussion

The proposed conceptual model of the API plug-in software facilitating BIM-enabled RLSC is strategic due to its applicability during all stages of the project life cycle, especially at the very early design stage. This facility can be adopted at the design stage not only to estimate the volume of materials that could be generated at the time of demolition but also to test for hazardous substances and estimate sorting. During the supply chain operations, the model provides the functionality to handle recycled products by testing for their quality. The model automates the identification of volumes of material by integrating BIM functionalities and expert knowledge. The testing and grading functionality of the model is novel which was totally neglected in past studies. Testing and grading are very important as it conveys the quality of end products to potential customers, who currently consider salvaged products as inferior in quality compared to virgin products. This stigma attached to salvaged products has been identified as one of the major barriers preventing the uptake of reverse logistics in construction by past researchers [5,7,11].

Akanabi et al. [9] stressed the reusability and recyclability of the same material categories using recoverability curves. However, the results of this study would have been more helpful to the practice if it had targeted the quality of the recovered products. Since the test results

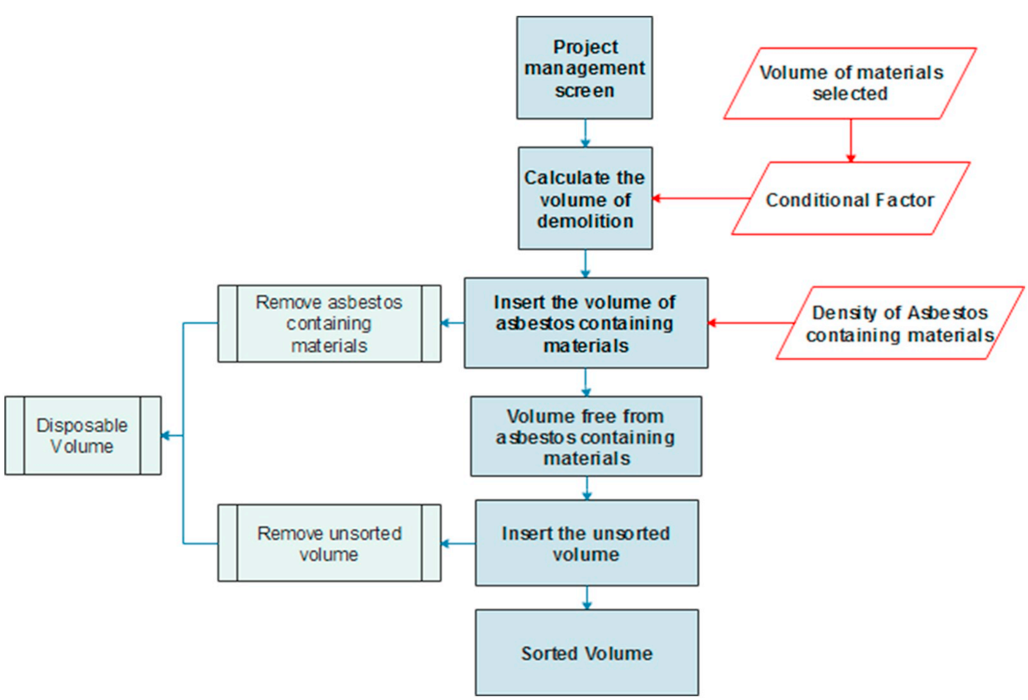

Fig. 9. Stage 1 and Stage 2 of API plug-in software.

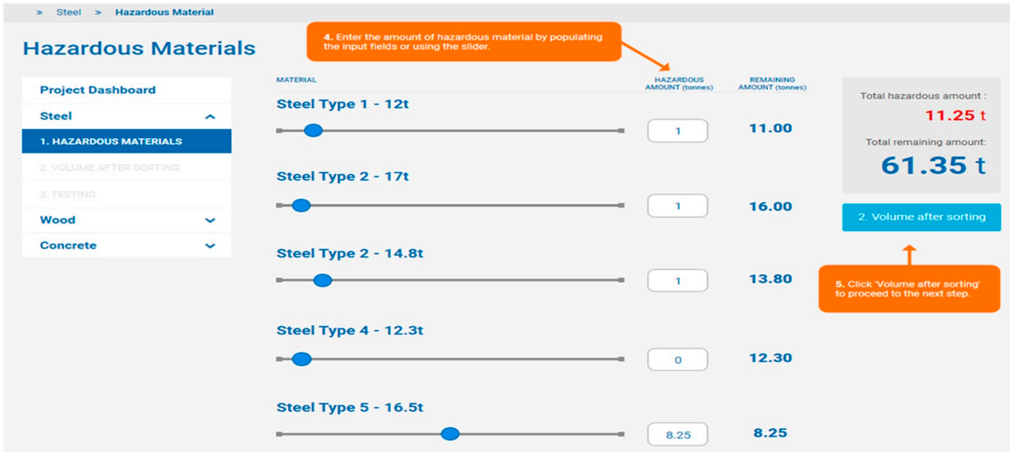

Fig. 10. Volume of material free from hazardous substances.

signify the nature and quality of the reprocessed product compared to virgin materials, it would help designers substitute virgin materials with reprocessed products. In addition, based on the test result, the appropriateness of the salvaged material for reprocessed can be analysed and then design parameters and compositions can be altered in the original BIM model. This approach is matched with, for example, designing structural concrete elements in practice.

Prior to recyclable volume, identification of the reusable volume is crucial (see Fig. 12). This will reveal the volume of materials that could preserve embodied energy compared to recycling volumes that need additional energy. Thereby the volume of reusable materials, for instance, steel (which has the highest reusability compared to other two materials considered in this study) could be incorporated in designs to further enhance reusability [9]. Then the designers can use Design for Deconstruction (DfD) techniques of steel enabling reusability. BIM has a major contribution, informing design, at very early stages so that the overall life-cycle cost is minimised. A BIM functionality called "bi-directional associativity" enables adequate changes to be carried out within the model without disturbing the overall arrangement [50]. For instance, when changing the design and connection patterns of a steel structure or changing the type of concrete to incorporate recycled aggregate, modifications in other elements and existing specifications could be done without much additional effort by the designer.

Apart from design merits, other end-user stakeholders, such as demolition contractors, salvaging companies, recycling companies and landfill operators can use this facility to estimate the volume of materials and products that could get diverted into one's domain in advance thus providing enough lead time for business decisions. In addition, demolition contractors could use this tool to optimize their operations, analyse safety hazards, while providing their workers with a platform for planning deconstruction/demolition jobs. The recycling companies would benefit by testing and grading of recycled products since it enables them to overcome market uncertainties and stigma due to low-quality secondary products. To enhance the quality of a product, recycling organisations must focus more on sorting to ensure the resultant output is free from hazardous substances. According to Noguchi et al. [21], during the production of recycled concrete aggregate, impurities such as contaminated substances can only be identified with proper sorting.

At the development stage of the model (API plug-in), three solutions could be adopted by end-users, namely: Offline Plugin; Shareable Workbook; and Public Website. The offline plug-in is entirely an offline solution, where the users do all the work within the API plug-in software and must have Revit installed to view and open their own and any other people's projects. The offline system can also provide a "portable workbook" solution that allows the users to easily share their workbook with others, using some commonly used document format such as excel spreadsheet. The other professionals involved in estimating the required quantities and quality of recovered products can get updated regarding the existing situation, even without access to Revit software.

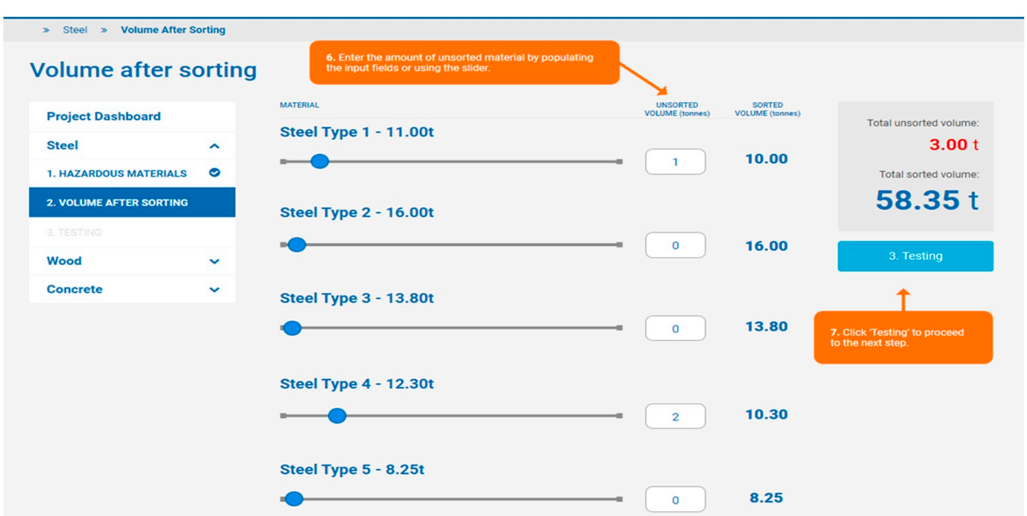

Fig. 11. Calculating volumes of remaining materials after sorting.

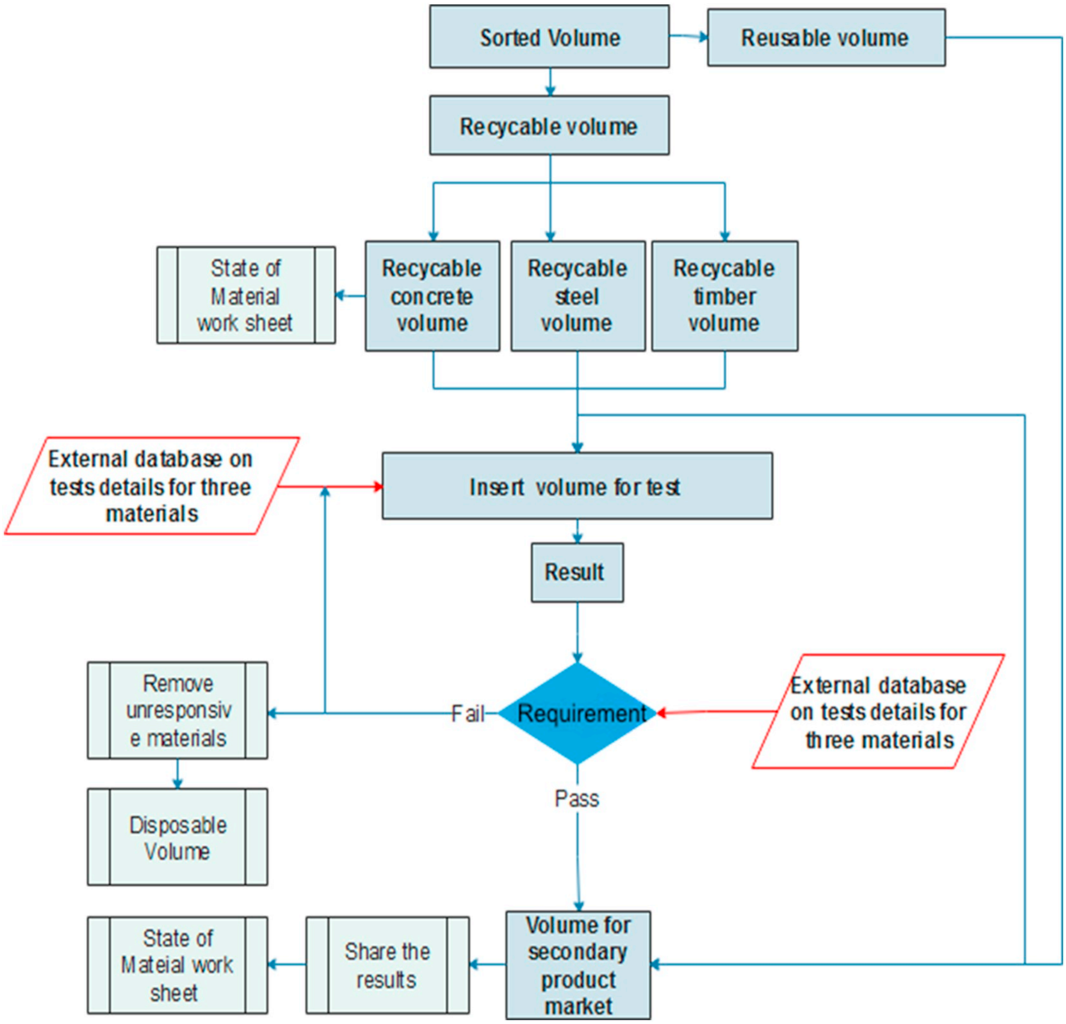

Fig. 12. Stage 3 of API plug-in software.

However, the public website provides a solution that uploads extracted data to an online platform. Once processed, data would be available via a public website without needing the original file. This enables data to be shared beyond an organisation, where the outsiders (stakeholders) interested in RLSC operations can have access to results from each data input. Table 8 presents the advantages and disadvantages of adopting these three solutions.

According to Table 8, the third solution, public website will be the most viable option where the end users can share the result at the end, despite the complexity in data and its processing. Under the online solution, data in workbook is easily shared (in a secure manner) and is always up to date; it provides a platform to distribute the plug-in and "sell" the project. Then the results can be categorised and presented under a "centralised database" to accommodate future operations.

8. Conclusions

Development of an information flow-centric approach related to RLSC operations is very important for maximising the effectiveness of resources recovery and diverting demolition waste at the EoL of a building from landfill. BIM has been identified as an appropriate tool to manage this information. However, very few studies have dealt with the information needs of the entire RLSC to benefit from its linkages to a BIM interface [46]. In this study, the information needs have been assessed via expert opinion and the development of a process to link BIM functionalities and RLSC operations through API plug-in. This is demonstrated through a conceptual model. The conceptual model is developed using researchers' explicit knowledge along with the involvement of software engineers in a participatory action research setting. The proposed conceptual model provides guidelines to the end-users for adopting the API plug-in to illustrate and improve the collaboration between software application. The conceptual model potentially highlights the advancement of using API and its novel approaches which can be adapted to enhance RLSC operations and its performance.

For instance, the model compared to past research efforts presents the entire RLSC operation under one platform. This enables the inclusion of various crucial stages of the process, particularly the testing and grading to ensure quality. The testing is highlighted as a step which needs to be incorporated at the stage of dismantling of the structure, during sorting, and once the reprocessing of salvaged materials is completed. The conceptual model caters for the entire RLSC unlike past BIM enabled models that consider mainly the dismantling stage. Therefore the model is not limited to one particular organisation; demolition organisation or recycling organisation, integrating the entire RLSC operational process in one platform. The conceptual model, if developed, can provide advanced capabilities to end users such as designers, demolition contractors, salvaging companies, recycling companies and landfill operators to maximise resource recovery. Above stakeholders will be able to achieve competitive advantage by efficient planning and undertaking their segment of the supply chain in a cost-effective and environmentally sustainable manner. In particular, demolition contractor can foresee the destinations and result of the

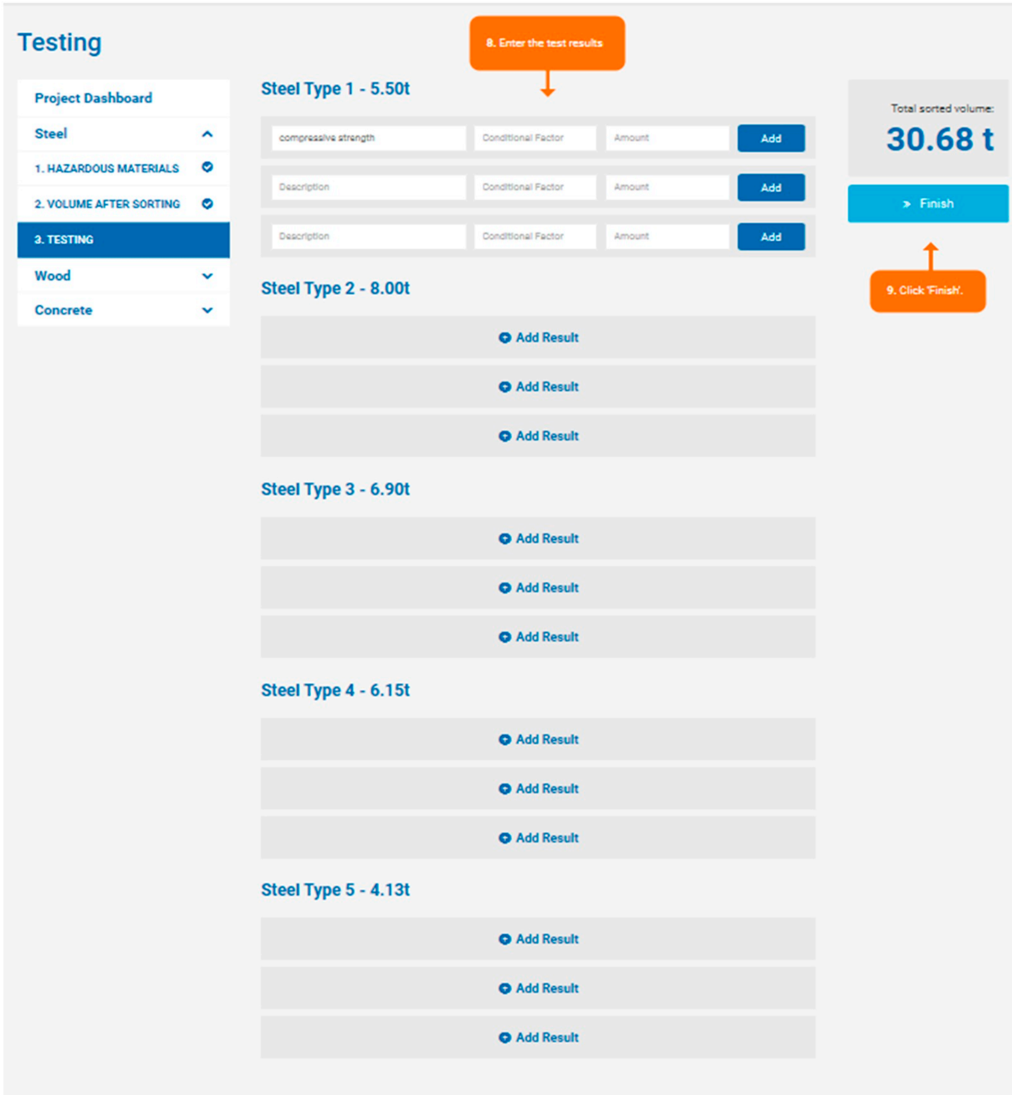

Fig. 13. Testing of quality of secondary products.

Table 6
Variables used in the development of the conceptual model.

Notation	Description
V_e	Volume extracted at EoL of a building (output of the BIM model)
$\varnothing_c$	Condition factor
i	Number of components under a material type
V_E	Expected quantity (volume after considering the structural condition)
V_h	Volume of hazardous substances
V_{fh}	Volume of demolished materials free from hazardous substances
M_h	Mass of hazardous substances
D_h	Density of hazardous substances
V_{us}	Volume of mixed waste which cannot be sorted/separated
V_{as}	Volume after sorting

Table 7
Structural condition of the element/member.

Structural condition of the element/member	Condition factor ($\varnothing_c$)
Good or satisfactory	1.00
Fair	0.95
Poor	0.85

extracted salvaged at the dismantling site. On the other hand, optimised on-site sorting mechanisms can target effective results in succeeding operational stages. The model further facilitates the recycling organisations where the amount of contaminated substances are known and can conduct further reprocessing by eliminating the contamination. At the end of reprocessing, products can be tested as per given tests and specifications. This ensures that the products comply with appropriate standards and quality criteria. In addition to implementing, designers maximise design efficiency.

Apart from technological advancement, the model empowers strategic improvements in the conventional information structure in both inter-organisation and intra-organisation communication. The model integrates each RLSC operation based documents and other information in a workflow process within an organisation (inter-organisation) and provides access to intra-organisational operational information sharing. The model caters to a high-level framework of key RLSC operations for information exchange and collaboration, to develop a single platform for otherwise fragmented RLSC operations.

Despite the main contributions of the study, there are some limitations which could be overcome through further research as shown in Table 9.

According to Table 9, the directions for further research can be empowered through relevant future applications. For instance, one of

Table 8
Advantages and disadvantages of different solutions.

	Offline plug-in	Shareable workbook	Public website
Advantages	• Entire workflow contained within plugin	• Easy to distribute data to people who do not have Revit • Probably the simplest solution to implement	• Easy to grant access to up-to-date workbooks • Centralised data enables future investigation and research • A platform for distributing and controlling plugin version
Disadvantages	• Only available to people with a Revit license (and plugin) • No platform for distributing plugin • No centralised data	• Unable to control project workbook versions once distributed • No platform for distributing plugin • No centralised data	• Two-step process with separated elements • Probably the most complex solution to implement

Table 9
Limitations and future research directions.

Limitations	Directions for further research
• The study has mainly focused on three materials: concrete, steel and timber	• The same flow diagram can be used to investigate other potential materials that could be recovered and their information needs in future research.
• The study needs to improve the testing and grading capacity of the selected recycled products within the proposed model.	• An enhanced model can be developed to enable the comparison among recycled products based on their, physical, mechanical and chemical characteristics. e.g. to analyse the relationship between compressive strength and the modulus of elasticity for recycled aggregate concrete.
• This study reports only a conceptual model for a BIM-enabled RLSC framework.	• Future research can be conducted to further improve, validate and upgrade the conceptual model using information related to reverse logistics supply chain operations, BIM functionalities and programming knowledge.
• The study has not focused on the embodied energy flow of the salvaged materials and the energy saving potential at the end of reprocessing.	• The study could be upgraded to facilitate the analysis of embodied energy in those materials as well as additional energy usage during the resource recovery operations. This could help optimize reprocessing decisions at different stages of the RLSC.

the limitations is that, this conceptual model has only considered widely used construction materials such as concrete, timber and steel. However, in future, researchers could adapt the model to represent the EoL of building operations of other materials. For instance bricks, mortar, rubble, glass, gypsum and other composite materials can be used under the same scenario. This reveals its deconstructability, amount of contaminated substances, appropriateness and ability for on-site sorting and reprocessing and quality of the end product. One of the limitatons is the application of this model for an existing building at its EoL, where no prior information, drawings and specifications can be obtained. To overcome this issue, the model can be linked with Augmented Reality (AR), Radio Frequency Identification (RFID), Geographic Information System (GIS). Combination of these information technology applications with the existing BIM model facilitates quality inspection, and retrieve actual environmental information at the site level. In particular, RFID technology supports the model for the analysis of embodied energy of the extracted materials, recovery process and transportation. The RFID labels provide sensors for monitoring not only physical parameters but also for monitoring temperature, pressure, toxic or harmful agents. Therefore, RFID information can be kept along with BIM to envisage and add functions of embodied energy to the existing model.

The proposed conceptual model can be developed to offer end-users with identification of appropriate testing method for physical, mechanical and chemical properties of a product or material. These characteristics can be linked with the initial information provided in the model such as the level of contamination; level of sorting and reprocessing method; to enable the effective decision making on the reprocessed product regarding its readiness for secondary markets.

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