Development of a conceptual digital deconstruction platform with integrated Reversible BIM to aid decision making and facilitate a circular economy

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Abstract

Construction and demolition waste accounts for about 33% of all waste within the EU. Circa 50% of this amount is currently recycled in most EU countries, however, the majority of waste is destined for backfilling and other low value applications. Poor knowledge of material and product composition, building reversibility, disassembly capacity of buildings and poor digitization of the construction sector are factors hindering better exploitation of multi-layered capacity of buildings and their circular opportunities. A highly digitalized deconstruction process (using digital tools to support inventory, strategies for material recovery and planning of deconstruction process) can contribute to a circular built environment, bringing key enabling technologies on digital deconstruction platform to be exploited, such as: Building Information Modelling (BIM), scan-to-BIM methods, materials' databases, blockchain, and most importantly method for reversibility assessment of existing building and its components (Durmisevic, 2009) integrated in BIM (so-called Reversible BIM). This paper presents the ongoing developments for the integration of a reversibility assessment method within a larger scope deconstruction platform.

Keywords: Reversible BIM, Digital Reversibility assessment, Reuse Potential, Circular economy, Deconstruction, Construction and Demolition Waste, Digital Deconstructions Platform

1 Introduction

Construction and Demolition Waste (CDW) is the largest waste stream in the EU and has been identified as a priority waste stream by the European Union. The EU Waste Framework Directive aimed to have 70% of CDW recycled by 2020, however the current rate in most EU countries is only about 50%. In addition, the construction industry currently applies typically low value recovery processes: the majority of CDW is destined for backfilling and other low value applications (downcycling), while the amount of CDW subject to reuse and high-quality recycling (upcycling) remains below 3% (European Commission, 2018).

Furthermore, consumption of raw materials in construction has tripled in last few decades according to the UN report, while research in the Netherlands indicates that use of raw material in construction is responsible for 67% of CO2 in comparison to 33% of CO2 emissions related to construction site activities and transport. (UNEP IRP, 2017) A key factor in stopping further rise of Construction and Demolition Waste and negative impacts of raw material consumption is prevention by reuse and upcycling. EU Waste Management Protocol has adopted CDW management in line with the waste hierarchy (with a priority for prevention and reuse as higher-ranking options than recycling and recovery) (European Commission, 2018).

Deconstruction of buildings can effectively improve the overall performance of CDW and reverse "the end of life" of building materials to "restart of new life" of building materials, by enabling high value recovery. However numerous challenges hinder the high value recovery of building materials. Deconstruction and reuse operations of existing buildings are relatively costly and require more time than usual demolition practices, partly caused by the lack of appropriate technical knowledge and information on the feasibility and actual implementation procedure of the deconstruction process (Durmisevic, 2019). There is also a lack of information about material composition of existing buildings, potential value of products in existing buildings and their actual reuse opportunities. Finally, there is a mismatch between supply and demand in terms of quantity and quality of recovered materials.

IT development and digitalisation of built environment can, in great deal, contribute to overcoming above mentioned challenges.

Deconstruction processes and development of reuse strategies for building materials that are extracted from the existing buildings involve multiple stakeholders and expertise. In order to support transition towards circular economy in construction it is crucial that real-estate owners and managers are equipped with tools and protocols that will enable them to make solid cost-benefits analyses of deconstruction and reuse strategies prior to the deconstruction process. It is also crucial for deconstruction companies to develop standardised protocol to assesses the complexity of recovery procedures for high value recovery of materials, while architects and designers need timely information about materials and elements that have high reuse potential and could be integrated into a new design solution. Above mentioned inventories involve integrated multidisciplinary decision making processes that involve (i) inventory of materials in a buildings (i.e. including hazardous materials), (ii) inventory of building technical composition by assessment of building's reversibility and reuse potential of its materials associated with carbon embodied value, (iii) analyses of market conditions and market demand at certain point in time, (iv) assessment of embodied energy in existing materials, (v) analyses of deconstruction strategy, deconstruction steps and associated costs, (vi) inventory of refurbishment costs of recovered materials, (vii) connectivity with sales platforms.

In order to support such complex decision-making process, the Digital Deconstruction (DDC) Interreg NWE project[1] involving 14 EU partners is working on development of the DDC platform. This platform will integrate above mentioned inventory and analyses by use of four independent modules that will together enable user friendly and integrated decision-making process during deconstruction project.

This paper will elaborate the methodology behind the DDC platform and highlight the role of Reversible BIM (as one of the four modules on the platform) which provides digital reversibility and reuse potential assessment of buildings and its elements.

2 Background

2.1 Circular economy in construction

In a linear "take – make – waste" economy of today, ever increasing consumption of natural resources results into increase of CDW, CO2 emissions and degradation of living conditions on the planet. Shift from linear use of raw materials to a circular "Take – Make – Remake" economy has been

[1] https://www.nweurope.eu/projects/project-search/digital-deconstruction/

recognized as a key to a resilient future by the UN and EU, aiming to reach zero CO2 emissions by 2050 and drastically reduce raw material consumption and CDW (UNEP IRP,2017), (UN, 2015).

A circular economy is characterized as an economy which is regenerative by design, with the aim to retain as much value of products, and materials as possible through a system that allows for the long life, optimal reuse, refurbishment, remanufacturing and recycling of products and materials (Kraaijenhagen, 2016, Ellen MacArthur Foundation, 2016).

With 344 million tons of mineral waste and 972 million tons of total waste coming from construction and demolition activities in 2018 (Eurostat, 2020), the construction sector is responsible for over 35% of the EU's total waste generation. The EU Circular Economy Action Plan as well as the "European Green Deal" (European Commission, 2019) defined construction and buildings as a key product value chain and pointed out the necessity to revise material recovery targets set in EU legislation for construction and demolition waste and its material-specific fractions.

The CDW consist mainly of mineral fractions (i.e. concrete, bricks), but also wood, metals, gypsum and plastics. Except for the reuse of metal which has a positive market value, the other materials, are most frequently landfilled. The construction sector has high potential for resource preservation. For several decades, researchers are actively addressing the elimination of CDW and increase of reuse capacity of existing materials, studying the possibility to design for disassembly and considering building as a material banks for future buildings. The notion of reversibility which is defined as "*a process of transforming buildings or dismantling its systems, products and elements without causing damage*" *(Durmisevic, 2019)* becomes the key concept for circular economy in the AEC sector.

Above transitional challenge will require introduction of change in a broad sense and full implementation of technological, social and system innovations. This paper will elaborate on technological innovation that can boost implementation of circular building in the near future.

2.2 Reversible BIM for deconstruction and reuse

A key to circular construction is change of conventional perception of buildings as static structures (designed for one end of life option, demolition), to buildings as dynamic, reversible and upgradable structures with multiple reuse options in mind (Durmisevic, 2006). Recent EU Buildings as Materials Banks (BAMB)[2] project has elaborated on the necessity of this paradigm shift and produced comprehensive framework for circular build environment including guidelines, tools, business and policy models. Its reversible building design protocols and tools build on the model of (Durmisevic 2006, 2019) have been integrated into European Commission's Circular Principles for Building Design (European Commission 2020). EU BAMB project produced definition on reversible building arguing that the design of reversible building should *guarantee multiple reuse options of the building, its systems, products, components and materials and provide incentives to retain or increase building value through reuse, repair, reconfiguration or remanufacturing (Durmisevic, 2019)*. In order to be able to manage ever growing number of data sets needed for circular material stewardship within the built environment Durmisevic argued that the only way further is through full digitalisation of Reversible Building Design tools (validated through EU BAMB project) and upgrading of BIM to Reversible BIM (Durmisevic, 2020).

During past decades numerous researchworks as well as standardisations (cfr. ISO 20887:2020) have been produced in order to define terms as design for disassembly (DfD), Circular building (CB) as well as to provide tools for AEC practitioners that will support development of CB. In their paper, Cruz Rios & al presented key requirements for DfD: 1) Documentation about materials and related deconstruction process, 2) Easy-to-dismantle connections and joints, 3) Separation of non-recyclable, non-reusable and non-disposal components, 4) Use of standardized components and dimensions, 5) Design aligned with AEC practices, productivity and safety. Furthermore, research works started to define methodologies for DfD for example based on LCA and measuring the carbon footprint of design choices (Densley & al. 2012) and studying the connection typologies between the building components to assess disassembly potential and reuse capacity of building products (Durmisevic, 2006). More recently, approaches based on BIM such as (Akanbi, 2019; Akinade, 2015) have proposed tools in order to evaluate end of life waste performance analysis.

[2] https://www.bamb2020.eu/

Within DDC project, exploration of Reversible BIM (RBIM) module is a follow up of the EU BAMB project and further digitalisation of reversible building tool measuring reversibility & reuse potential of building parts. RBIM is the first tool that enables assessment of building connections and dependences between building elements within BIM. Its reversibility indicators are twofold and are used as design aspects for design of new buildings and as assessment indicators (see Figure 3). During DDC project RBIM will be testing assessment of reversibility indicators and reuse potential calculations on existing buildings (see section 5).

3 Methodology for DDC platform development (quick description + diagram)

In the DDC project, a precise methodological framework has been designed in order to develop a platform aiming at assessing scenario of deconstruction. In order to align the technological tool with the end users' needs, the team has first identified the categories of stakeholders who corresponds to the priority targeted public for the application being:

1. The actors from design phase (i.e., architects, design and consultancy firms and demolition expert),
2. The actors from construction phase (i.e. (construction contractors, demolition actors, and material producers),
3. The public and private client.

The end users' needs have been collected based on an online questionnaire survey. The results of this study have been used to define requirements for the digital deconstruction platform. Then, data flows between the different modules have been analyzed: 3D scan, reversible BIM, material DB and blockchain, and interaction points needed to answered individual user needs. This analysis has been done during manual testing of individual modules in a first pilot project in Heerlen, The Netherlands. Afterwards, use cases have been developed for the platform as a whole. It is expected to deploy firstly the modules and secondly, the platform in a total of 10 real life pilot projects. This experiment of the IT tools in a real context will allow collecting end user feedback and progressively refine the modules and the platform. Such a user-centric approach will enable improving the DDC platform's adoption by the professionals.

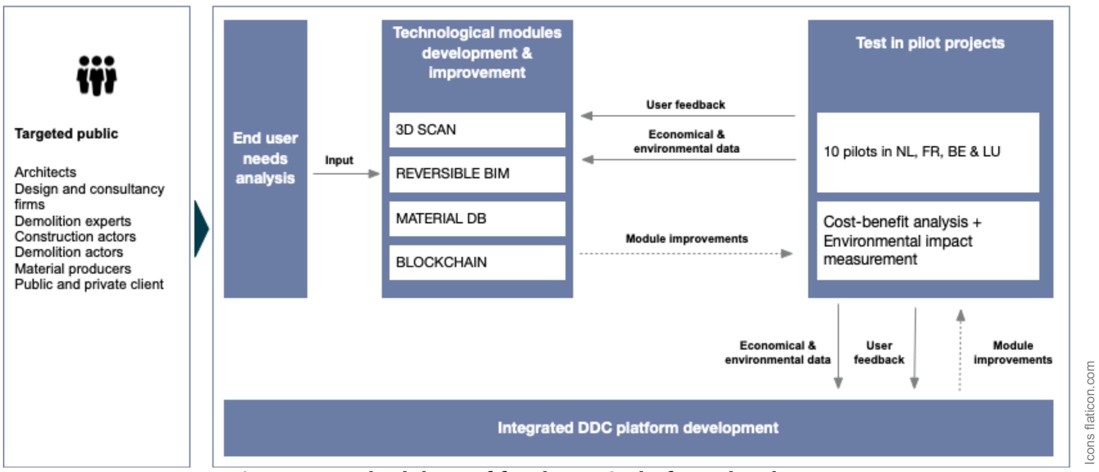

Figure 1. Methodology of for the DDC platform development

Moreover, the pilot projects will include a cost-benefit analysis and environmental impact measurement that will enable the validation of the deconstruction project from both economic and environmental point of view. An overview of the methodological framework of the DDC platform has been presented in Figure 1.

4 A conceptual digital deconstruction platform

Based on previous research the initial conceptual architecture of a digital platform aiding the deconstruction of buildings is proposed, as shown in Figure 2. At its core, the Digital Deconstruction (DDC) platform acts as a fusion of existing technologies and as a data integrator to aid the decision-making process on deconstructing existing buildings.

The platform conceptual architecture is modular, comprising various independent modules (M1-4) into a full-fledged interoperable system, based on already established use-cases described below:

1. Scan-to-BIM – a conventional building scanning technique (M1) which assumes a capture of hybrid point clouds (using laser scanning) and photo recordings (using photogrammetry). The post-processed scans are used as input for the creation of an as-built BIM. This information is later required for applying the reversible BIM methodology;
2. Reversible BIM - various condensed geometric assets to be used for Digital Reversibility Assessment (DRA) of the building (to be deconstructed). This would allow an initial indication of reuse values and recycling options. Thus, this should ideally be provided in a high-level semantics BIM format (e.g. IFC). The representation of digital assets considers the deconstruction methods of built assets for high quality reuse and their eventual value – to be defined by deconstruction processes;
3. Asset catalogue creation – data regarding building components' materials is surveyed either on site or based on the 3D scans and added to the list of digital assets describing all the components to be deconstructed and re-used.
4. Design/Deconstruction value cost assessment – the digital assets are further enriched with material related data and a value assessment is provided based on costs, embedded carbon, toxicity of embedded substances to provide input for a decision-making process. Based on their assessment, the products with a higher reuse potential are published for sale on external digital marketplaces for construction materials.
5. Blockchain-based ownership tracking - using the blockchain technology (M4), the digital assets are linked and tracked as they change ownership, giving increased transparency and responsibility between traders regarding the quality and accuracy of posted information.

The use-cases above can be regarded as an initial conceptual workflow embedding the logic of the creation of the digital objects representing deconstructed physical assets on the ground.

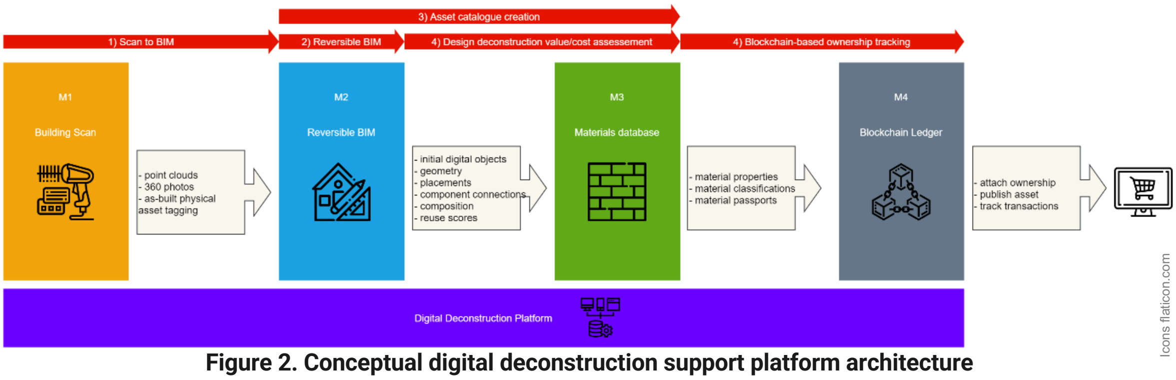

Figure 2. Conceptual digital deconstruction support platform architecture

From a technical point of view, the system modules should be considered as being independent and replaceable components. However, the hybrid types of data along the described workflow requires a high level of information interoperability (semantics of the data models), and a high level of integration between system components. Existing practices and standards around the subject of BIM, reusability and classification of construction materials need to be considered. The IFC schema (IFC 2x3 (buildingSMART International, 2007), IFC 4 (buildingSMART International, 2017)) can offer a good starting point in representing building components, their connections and associated material types. Therefore, the use cases of 1) scan-to-BIM and 2) reversible BIM should consider alignment with certain concepts from the schema to ensure some degree of interoperability with other use cases.

5 Use case: Reversible BIM

The general approach for supporting the deconstruction process and the methodology used have been described in the previous sections. This section will elaborate one of the DDC modules namely, Reversible BIM module which represents digital twin of a building with its 3D geometry, technical composition including type of connections, assembly levels and material properties.

5.1 Technology and workflow

Reversible BIM module enables assessment of technical composition of building and recovery options of building components by assessment of technical and physical dependences between building parts based on model (Durmisevic, 2006). Reversibility module calculation takes into account hierarchical dependence within assembly of building parts, pattern and number of relations between building elements, assembly sequences, base element of the assembly, level of prefabrication, geometry of product edge, type of connections, Life Cycle Coordination and remaining technical life (see Figure 3). Conventional BIM does not support above specified indicators of reversibility and reuse potential because key reversibility related data, as number of relations and type of connections cannot be extracted from conventional BIM Model. Relations between objects are not easy to identify/distinguish and information is lacking regarding the type of connections. In order to upgrade conventional BIM towards Reversible BIM key data representing indicators of reversibility and reuse (as number of relations between elements, type of connections, assembly dependencies, number of assembly sequences) have been integrated into Revit by adding plugins. This has created a smooth transition from linear BIM towards circular /Reversible BIM (BAMB Boom Strategies for Circular Building, Durmisevic, 2019).

Reversible BIM is the process of designing, constructing and operating a building (i) with the reversibility principles specified in model (Durmisevic, 2006) and (ii) with reuse of computer-generated object orientated information in mind. It is identified as a value maintaining and re-creating process through the multiple lifecycles of a building and its parts (Durmisevic, 2019).

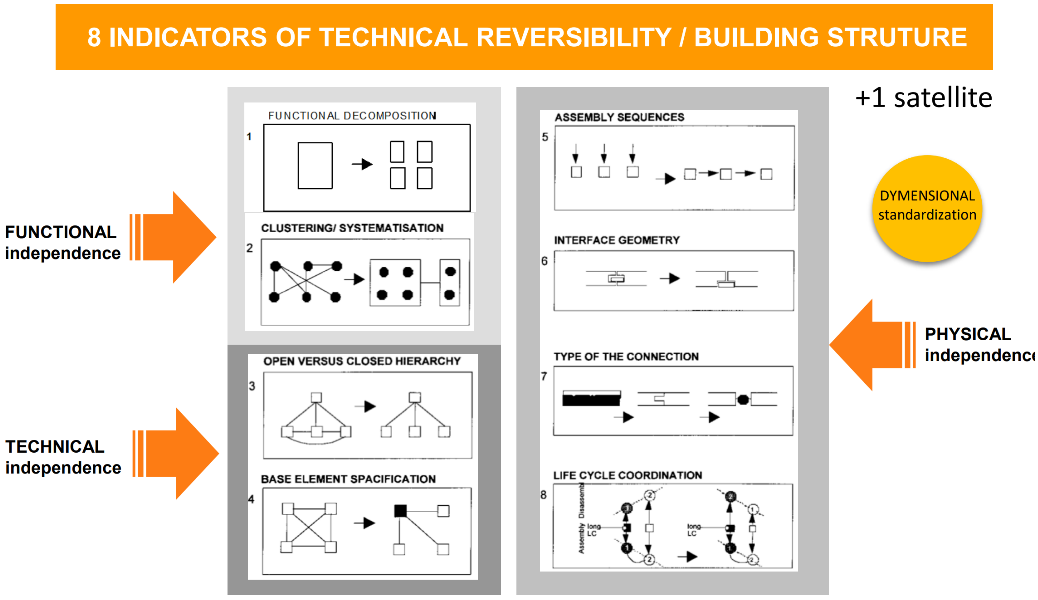

Figure 3. Indicators of technical reversibility of building being a part of Reuse Potential and transformation capacity calculation (Durmisevic, 2006)

Reversible BIM has two integral features:

1. ***Digital Parametric representation of Building*** with information about geometry, position, function, relations and connections between building elements. Digital representation of Building uses Reversible BIM template which is structured in a way that enables assessment of reversibility (i.e., disassembly and reuse potential) of building products, being the second feature of Reversible BIM. Reversible BIM translates 3D point-cloud files form 3D

scanning into a standardised geometry and properties which enables digital reversibility analyses of the building and its materials. Such reversibility assessment enables generation of reuse and disassembly strategies for high value recovery of components and materials.

2. ***Digital Reversibility Assessment (DRA)*** provides assessment of reversibility/Reuse potential using model of (Durmisevic, 2019, 2020), developed to assess how easy building products and materials can be recovered without damaging surrounding parts. It also links the assessment to multiple reuse options and category of reversibility of the building/product. The model measures effort and time needed to recover an element form the building as well as the level of damage that occurs during disassembly process (to the element itself and surrounding elements). This Reversibility assessment is being carried out on three levels of building's technical composition (i.e., building, system and component level) (Durmisevic 2019, 2020).

Based on Digital Reversibility Calculation a score indicates Reuse Potential of each element in a building. Reuse Potential (RP) score (ranges between 0,1 worst and 0,9 best) sorts all building elements into three categories: (i) irreversible buildings (are building elements/materials with low Reuse Potential, materials are in degrading loop towards recycling and down cycling), (ii) partly reversible buildings (partial Reuse Potential, materials can be remanufactured or reused after major repair and (iii) reversible buildings (buildings whose materials can be directly reused or after minor repair or reconfiguration). Reversibility of buildings measured by Reuse Potential indicates reuse options that products and materials have after being recovered. As it measures the effort and time, the model also considers number of disassembly steps and operations needed to recover an element. Ultimately models results form a solid base for environmental and economic assessment of disassembly and recovery operations (See Figure 4). This calculation system is based on Model Durmisevic published in 2006 updated in 2009 and tested and verified during EU H2020 BAMB-Buildings as Material Banks Project (Durmisevic, 2006), (Durmisevic, 2019).

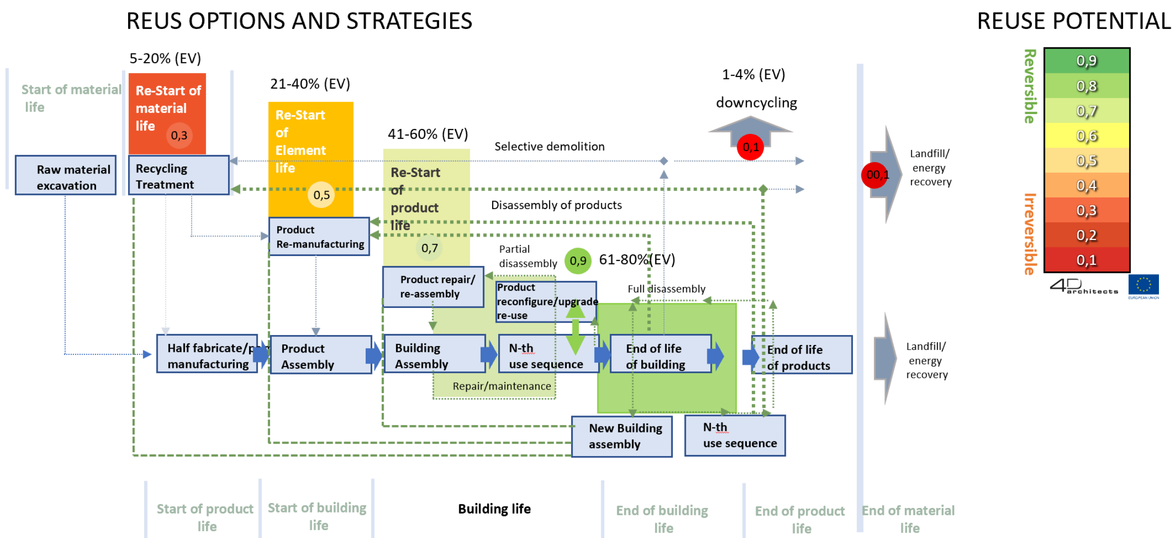

Figure 4. Relation between Reuse Potential score, reuse options of elements (Durmisevic, 2019)

With integrated Digital Reversibility Assessment, it provides reversibility rate of building structure, calculating reuse potential of each element in a building. Reversible BIM module is a BIM software module based on model (Durmisevic 2006 and 2015), that based on captured cloud of points (from 3D scanning) and with use of Revit plugin for digital reversibility assessment, enables the reconstruction of the digital models of existing buildings covering spatial dimensions, relationships, quantities and reversibility properties of building and its components.

Manual testing of Reversible BIM on a pilot (Municipality Building in Heerlen) illustrated 7 major steps and 16 sub-steps covering the process for data gathering (archives research and point cloud files), the creation of the reversible BIM, running RBIM plug-ins for Reuse potential calculation, 3D visualisation with colour coding (i.e., colours representing reuse potential score) and the access to BIM objects digital catalogue for architects who want to use components from deconstruction in a new construction project. Reversible BIM is viewed in 3D viewer (see Figure 5).

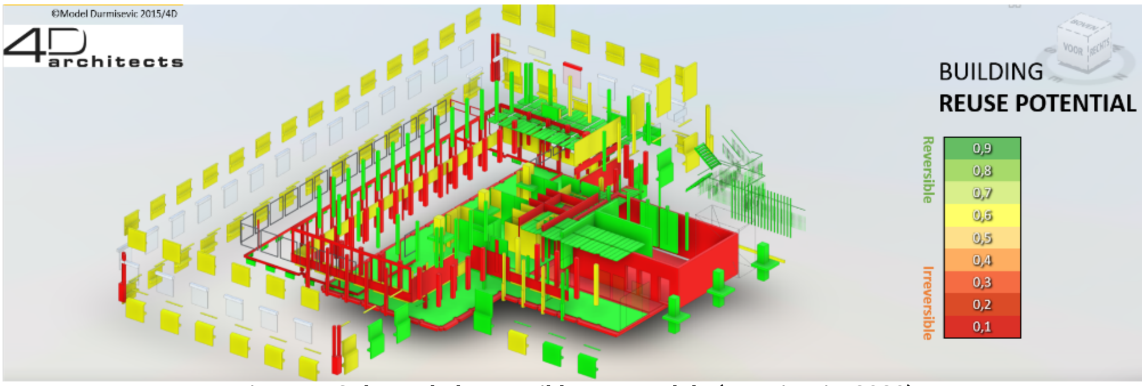

Figure 5. Color coded Reversible BIM module (Durmisevic, 2020)

Figure 5 illustrates the results of Reversibility Assessment and Reuse Potential of building elements indicating material streams and reuse options through colour coding. A colour scale from red to green enables to respectively visualise the components with a poor or high reuse potential.

5.2 First experiment and results

5.2.1 Pilot description

The RBIM module has been deployed to assist the deconstruction of a first pilot building in Heerlen, The Netherlands (see Figure 6). This building, which is the property of the Heerlen municipality has been constructed in 1982 and has a total area of 7698 m2. The construction method used was in situ concrete for lead-bearing elements, and prefabricated concrete facade panels. Partitioning wall system as well as ceiling tiles are prefab gypsum systems. The installation services are separated form load bearing structure and are freely accessible.

The building has been renovated in 2016 and is in a reasonably good state. Circular deconstruction of the building will allow reuse of valuable building components and materials.

Figure 6. Heerlen building pilot, NL

Manual testing of Reversible BIM illustrated 7 major steps covering the process for data gathering (archives and point cloud files), the creation of reversible BIM, running RBIM plugins for Reuse potential calculation, 3D visualisation with colour coding (i.e., colours representing reuse potential score) and creation of BIM objects digital catalogue (of elements with high Reuse Potential) to enable architects to use them in a new construction project.

5.2.2 Results and discussions

Reversibility/reuse potential assessment as an integral part of Reversible BIM, offers an instrument which provides rather accurate information about value and future potential of materials within a building in a quick fashion. The model measures capacity of product structures to be disassembled and its materials reused. It ensures that the value of materials and components is aligned with the effort needed to recover them from the building. Model's report indicates structures' capacity to be deconstructed with high value recovery in mind.

In the case of Pilot project model calculated Reuse potential of all elements in a building and presented Reuse Potential score of building parts in 3d Reversible viewer (see Figure 5) as well as in

PDF report. Loadbearing structure of the Heerlen building has an average Reuse Potential score 0,1. This score reflects recycling and downcycling material stream (see Figure 4). Façade has an average Reuse Potential of 0,64 reflecting reuse options as reuse by remanufacturing. The same counts for the partitioning walls having Reuse Potential score of 0,65. While services ended up with Reuse potential score of 0,71 indicating reuse options as direct reuse by reparation.

The Reversible BIM informs:

1. building industry about potential economic gains from deconstruction and reuse;
2. deconstruction companies on the most effective deconstructions strategy for high-value harvest of the materials;
3. building owners about the reuse potential and reuse options of building materials after recovery.

Initial feedback from the end users panels (Vrijders, 2020) indicate that Reversible BIM can be beneficial for all users of the DDC platform:

1. Deconstruction companies would appreciate to have access to reuse potential information, deconstruction and reuse strategies for high-value recovery of the materials.
2. Building owners would appreciate to be informed about the reuse potential and reuse options of building materials after recovery.
3. Public authorities would be interested in accessing data about environmental and economic impacts of different reuse options and material stream associated with standardized reversibility categories of buildings.
4. Architects would be able to access to a catalogue of BIM objects of reversible products for designing new projects.

Next phase of development of Reversible BIM will involve development of API's between Reversible BIM and the DDC integrated platform as well as development of new functionalities for better integration of reuse potential calculation within BIM and rearrangement of BIM model to enable desired reporting through the DDC platform's Web interface.
Manual testing of all DDC modules on Building in Heerlen was used to develop use cases for the integrated Digital Deconstruction platform as a base for its further development.

6 Conclusion and future works

This paper elaborated on the framework of Digital Deconstruction (DDC) Platform that will support stakeholders in making decision about Deconstruction and Reuse strategies of existing buildings, being key to circular buildings.
The project's focus is on exploiting the potentials of advanced IT solutions, which enable more informed decisions related to deconstruction; facilitate high value recovery and reuse of materials and support matchmaking between supply and demand. The key enabling technology that is exploited in Digital Deconstruction (DDC) is the application of Building Information Modelling (BIM) in a form of its upgrade to Reversible BIM, which aids the digital representation of the physical and functional characteristics of a facility, also covering technical dependences, quantities and properties of building parts, connections and their reversibility. Application of BIM is currently mostly restricted to the design and maintenance of buildings, while its use has been largely ignored so far for end-of-use life activities.

By extending BIM with building's reversibility assessment, supporting reuse potential calculation of building elements, and selective demolition process DDC project goes beyond the existing practice of the industry. Next steps in DDC project development are (i) optimisation of DDC modules through real life pilot testing and (ii) integration of four DDC modules and testing of the integrated platform on the real-life pilot cases.

Acknowledgments

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