BIM-based circular building assessment and design for demountability

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Abstract. The on-going transformation of the linear economy model (LE) to a sustainable circular economy (CE) creates new challenges for information management, evaluation methods, and information exchange. This impacts also the traditional definitions of roles and processes in the AEC sector. OpenBIM and a proper definition of the design process and the key decision points based on EN ISO 19650 and using the IDM framework (EN ISO 29481) can help to master these challenges. This is complemented by the need for reliable product data that could be satisfied by implementing EN ISO 23386 and 23387 together with the more specific EN ISO 16757 tailored for the needs of the HVAC sector. While the general methodology has recently been defined in these international standards, the concrete application for sustainable design and many implementation details remain still open. This paper presents a BIM-based scoring approach for Circular building assessment (CBA). It defines the information needs at different design stages: from the requirements in an early design stage to the solutions chosen in the detailed design stage. The same methodology can be applied to structural elements of the building envelope as well as to technical equipment and HVAC systems, providing a common framework for the integrated design of sustainable buildings. Besides the methodology, this paper describes a first implementation for the case of the Living Lab (LL) building, a prototype dwelling in Ghent (Belgium) built in the scope of the Circular Bio-Based Construction Industry (CBCI) project funded by the EU Interreg 2 Seas program. The aim of this paper is to demonstrate how BIM can be used to partly automate decision-making and evaluation for the specific needs of CBA and design for demountability. The proposed solution based on Alba Concept is creating an efficient link between an external database and the BIM model. This is performed by extracting the necessary object information and integrating it for further evaluation during the lifecycle of the building including the design, construction, operation, end-of-life and re-use phases.

Keywords. Building Information Modelling (BIM), circular building, demountability assessment, circular building assessment, decision making process, BIM model adaptation, Dynamo.
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1. Introduction

Building Information Modelling (BIM) support in the construction industry is an important component due to increased interdisciplinary activities and the amount of construction data.

To unlock the full potential of a collaborative BIM-based design and construction process as well as support for circularity, the data management and exchange needs to be based on open, standardized data-structures and exchange formats. While the framework is already described for a big part in European standards, the application to different disciplines within the construction sector and the implementation are still work in progress.

However, owing to an impetus and governmental support, the CE has gained momentum and considering the latest EU commission publications [1] it can be envisaged that the circular building approach will become an integral part of the design process. These concepts involve data management across the entire building lifecycle and the need to integrate circular methodology into the BIM environment and define appropriate data structures. Future proof approaches like OpenBIM based on the above-referenced standards can help to master these challenges.

The aims of this conference paper are:

1. to provide an overview of the existing BIM tools that are available to support sustainable circular economy (CE) focused on demountability assessment;

2. to provide more insight in the current evolution of European (CEN) and international (ISO) standardisation in order to provide workflows and data management for construction projects that can be implemented and used today and will allow a smooth transition once the standardisation framework will be fully implemented.

3. to present a framework that was developed in the scope of the Living Lab (LL) prototype in the CBCI project, while considering the future possibility of its applicability to, not only the building envelop but in a latter phase also the HVAC and electrical systems.

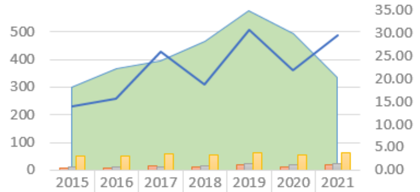
This paper focusses on the development of the framework and lessons learned from the workflows and information needs of the design phase of the case study.

Numerical results of the demountability assessment and a comparison of different assessment methods are outside the scope of this paper.

2. Methodology and current state of the art

The use of BIM as a supporting tool for research and application is on a rise in the last decade. Several points of research interest are environmental impact, circular design and optimization of BIM processes. This study focuses on the integration of BIM with LCA and DfD research efforts as seen in Figure 1.

LCA is a comprehensive environmental impact assessment framework as defined in the ISO 14040:2006 standard which takes into account the whole life cycle of a product or building. Design for Deconstruction (DfD) is an emerging concept that focuses on demountability of building components.



	2015	2016	2017	2018	2019	2020	2021
BIM	298	368	395	465	577	492	337
BIM DfD	7	8	15	10	19	12	18
BIM LCA	10	13	10	17	23	20	23
General DfD reseach	50	51	58	53	62	55	61
Percentage of BIM DfD to general DfD research	14.00	15.69	25.86	18.87	30.65	21.82	29.51

Fig. 1 - Number of publications and its distribution on the topic "BIM", "LCA" and "DfD" in engineering technology, building and architectural construction sector (Scopus, Mendeley, Web of Knowledge).

Research has focused initially on quantitative resource performance indicators for Life Cycle Assessment (LCA) and dynamic LCA [2], but an increased focus towards a DfD direction can also be seen, which emphasizes the attention of LCA for the required adaptability, usability and maintenance for building materials throughout the entire lifecycle.

Prior to 2014, only one-third of LCA tools were BIM integrated, but none considered the aspects of deconstruction. For this reason, this study was conducted on existing information from 2015 onwards. However, a fluctuating line illustrates the recent three trends of BIM-focused studies to the total amount of DfD research and keep its level near 23-30% for the last 3 years.

The first two are oriented to the demountability calculation by considering the detached component (covers the information requirements of "Level of detail" (LOD 350)) as well as an element level (LOD 200) defined by the American Institute of Architects (AIA)) [3]. And, respectively, the third is based on time and cost analysis of assembly works based on 4D and 5D modelling [4].

Several BIM integrated DfD concepts have been developed and published. BCI Gebouw is a standalone platform that gives an overview of the possibility of disconnecting a building based on a measurement method developed by Platform CB'23 based on the list of indicators considering waste and material flow (Circular Construction 2023) [5]. The BAMB project works on the BIM-integrated Reversible Building Design Tools, including aspects of reuse potential reversibility and disassembly, with significant attention to the interrelationships between components [6].

To our best knowledge there are no existing studies that mention the DfD BIM concept for HVAC systems. In the early studies, Shuo Chen [7] focuses on materials in his environmental impact analysis and treats HVAC systems as recyclables with transportation taken into account. Also identified are early studies [8] incorporating some performance criteria into Fuzzy multi-criteria evaluation. Recent studies include HVAC systems as a full component of LCA analysis methods, but do not take into account demountability factors [9].

2.1 Technical barriers preventing the DfD integration into BIM

A significant barrier in the DfD development linked to the AEC sector is the lack of a well-defined and standardized methodology, thereby also affecting the evolution of other interlinked related studies such as LCA and material passport certification [10].

However, to analyze interrelationships among different factors one can deduce, that a collaborative study of DfD BIM provides a better understanding of the general methodology's needs due to the identification and analysis function of component attributes. There are several key concerns in data extraction automation: differing techniques and rules for 3D model design, use of different classification and nomenclature systems between partners, collaborative work with various linked files, and software compatibility issues. Therefore, particular attention should also be paid to the data-structure and the exchange format, e.g. the IFC (Industry Foundation Classes) format [11] to ensure correct data exchange and model coordination.

Furthermore, the absence of a database of connectors and their associated characteristics increases the amount of required manual entry during the design phase. Consequently, at some point, it becomes inappropriate to modify the 3D model. Such databases with a standardized data structure, provided for example by the manufacturer of components, would allow improving visualization and usability for the demountability process, in addition, to incorporating DfD into parametric designs maintaining the object attributes, behaviours and constraints.

Also contributing to complexity is the fact that the Revit API [12] inheritance hierarchy structure for various objects is different and the method syntax needs to be clarified in the case of custom input, for example: "loadable families", adaptive components, etc.

2.2 European and international standardization and its current implementation

To be able to exchange information digitally and take full advantage of a collaborative project development, standardization is key.

The technical committees ISO/TC 59 SC 13 and CEN/TC 442 have developed standards for data structures that are published as EN ISO 12006-3, EN ISO 23386 and EN ISO 23387. More specifically to the HVAC sector a series of standards is under development. It is based on work that was published as a German guideline, the VDI 3805. The EN ISO 16757 series aims at a complete framework for reliable product data exchange for HVAC. While part 1 and 2 are already published, current work is dedicated to align this standard with the other standards for data templates and to define a scripting language that is integrated into the exchange format IFC and enables the definition of dynamic system properties of HVAC components like the pressure drop of a duct component depending on the volume flow.

Further work is required for implementation, specifically the governance, maintenance and hosting of the required databases. The definition of product properties will be done in close collaboration with other CEN/TC's. CEN/TC 442 is working on the methodology, while other TC's have the necessary competence to apply that methodology to their domain and define the actual content.

So currently it is common practice in construction projects to use proprietary BIM software and data-structures, that are ad-hoc defined for a project, aligned with company standards or in the best case following local guidelines.

To make the transition to a fully implemented, standardized framework for product data according to EN ISO 23386 and 23387 it is essential to gain more insight into the required information at different stages in the lifecycle of a built asset.

The case study presented in the following chapter contributed to this aim, as information requirements have been analysed and translated into the implementation of a tailor-made software tool based on the REVIT API.

While the implementation of standardised product data is still under development, the methodology for project setup and workflows is already fully defined in the EN ISO 19650 series. These standards describe a proper definition of the design process and the key decision points. Following this standard enables the creation of BIM-based collaborative projects.

3. The CBCI case study

The research is based on a case study which was conducted as a part of the CBCI project which investigates the efficient and sustainable use of building materials and technologies in the construction industry, thereby reducing environmental impact, e.g. CO2 emissions. This study aims to achieve project task automation and calculations support (mainly assessment tools for environmental impact and circularity measures) based on model data created in the BIM tool used by the project partners (REVIT).

Several circular construction tools were used to assist the CBCI objectives and were tested in the real-life case study during the design and construction phase of the LL Ghent. The design is a 2-storey residential building (including an attic) with a 98.8 m2 total gross area, designed according to the 19th-20th century terraced houses typology (Fig.2). The total front facades (west, east) measures 56 m2 and the side facades (north, south) add up to 129 m2. The window area in all facades is 22.7 m2. The roof area is 46m2 with a 19.1 m2 roof-top window area.

Fig. 2 - 3D and exploded view of the CBCI LL Ghent.

Based on preliminary studies of the building envelop [13], it was decided to develop a tool that can reduce the time needed for an expert design and evaluation based on the Alba Concept method [14]. The tools' methodology represents four technical factors for the assessment, which are connection type, accessibility of connections, crossing type, form enclosure, which are detailed in the Tab.1.

Tab. 1 - The rating types of the technical factors [14].

Type	Score
Connection type	
Dry connectors (dry, velcro, spring)	1.00
With additional connectors (bolt/nut, ferry, corners, screw)	0.80
Direct integral connect(pin, nails)	0.60
Soft chemical connect (organomercuric, foam)	0.20
With the hard chemical connections (glue, weld, recycling mat, cement, chem. anchors)	0.10
Accessibility of connections	
Freely accessible	1.00
Accessible with additional actions, don't cause damages	0.80
Accessible with recoverable damage weight	0.40
Inaccessible - irreparable damage to objects	0.10
Crossings type	
Modular zoning of objects	1.00
Intersections between one/more objects	0.40
Full Objects integration	0.10
Form enclosure	
Open, no inclusions	1.00
Overlap on one side	0.80
Closed on one side	0.20
Closed from several sides	0.10

These technical factors are rated between 1.00 and 0.10. A difference is made between the connection demountability Index (Dlc) and the composition demountability Index (Dls) of each item, which is respectively influenced by the connection between the elements (Fig.3). The demountability index is a combination of both indexes, taking into account the volumetric parameter as a normalization factor [13]. To define a level of detail during the modelling and calculation phase, BB/SfB, a Belgian version of the international classification system CI/SfB - was applied [15].

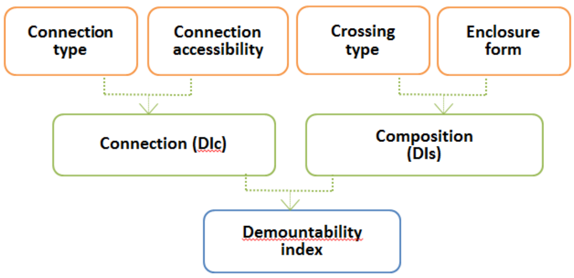


Fig. 3 - Demountability index assessment.

4. Workflows and tool implementation

The developed tool in this research is based on a Dynamo [16] script through which the assessed elements can be selected and have a connection type assigned with subsequent simulations and calculation. Dynamo is a Revit-based visual programming interface that enables users to build code with algorithmically linked nodes (data and operations), thereby setting up and automating the workflow of building information data. The automated script was written within both the standard and custom nodes using Python and Revit API programming languages by supporting the following general workflow (Fig.4).

For the CBCI framework, the script works not only as a data delivery tool, but also as a calculation engine, and can be divided into six sections, each with various functions:

- GUI (graphical user interface) activation;
- object selection;

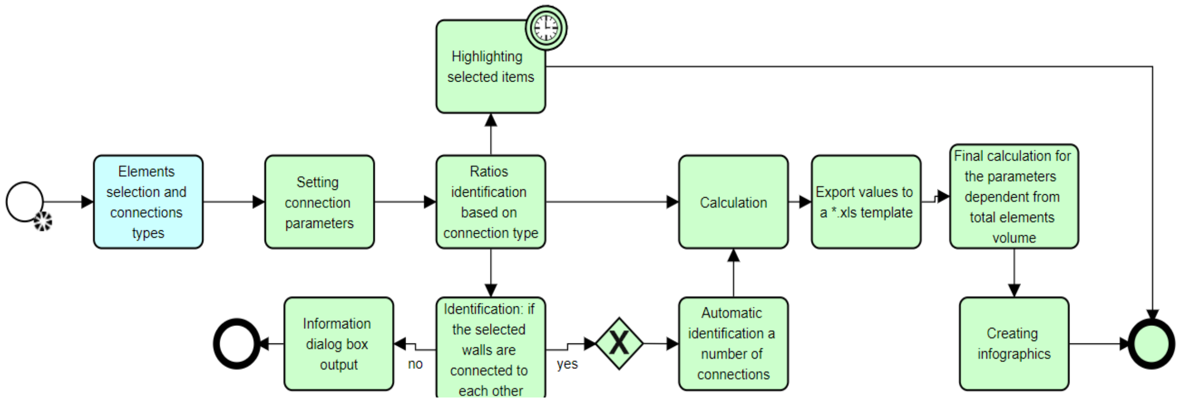


Fig. 4 - CBCI demountability index calculation tool workflow.

- connection type assignment;
- database reading;
- mathematical calculation and data export to Excel.

During the initial phase, the Dynamo script activates the GUI (graphical user interface) by which users select elements for assessment (Fig.5, 1) and their connection types and connection accessibility based on expert evaluation (Fig.5, 2).

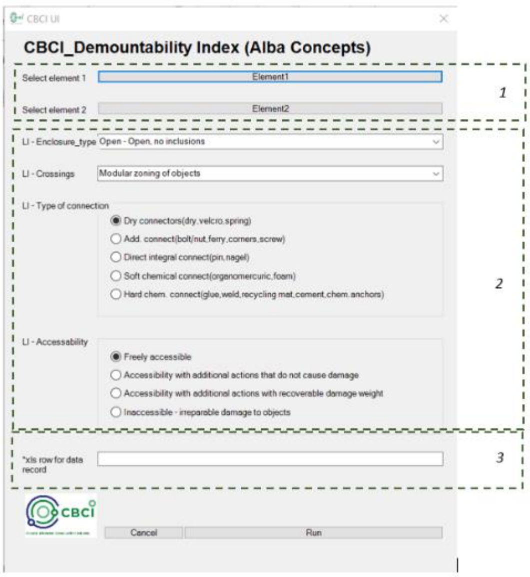


Fig. 5 - GUI (graphical user interface) for the CBCI demountability tool.

After the required experts' input, the script starts the element connection checking process, extracts the necessary geometric attributes from the model, and directly assesses formulas. In a final step, the collected intermediate results are averaged and normalized to rate the considered structure in one single score.

Accordingly, all input and output building data can be classified into various categories. General attributes provide an element identification by their ID, family type and BB/SfB code. Geometric attributes provide the element dimensions and its materials' densities. Coordination attributes provide an automated determination of the number of attached elements. Selective attributes provide the data stored internally within the assessment scenario to identify the type and coefficients of connections.

A Demountability Index normalized (DI_n) parameter was taken out of the main analysis in the Dynamo script as it is based on the total volume of all elements. It is technically possible to implement in the extra-functional nodes group with the additional data import from the same excel template, but as a consequence, it increased the speed of data processing. As a final result, the user obtain a CBCI excel template containing all imported data and assessment results, diagrams subdivided into 'Structure', 'Skin', 'Services', 'Space plan' layers [13]; and element filtering tool (Fig.6).

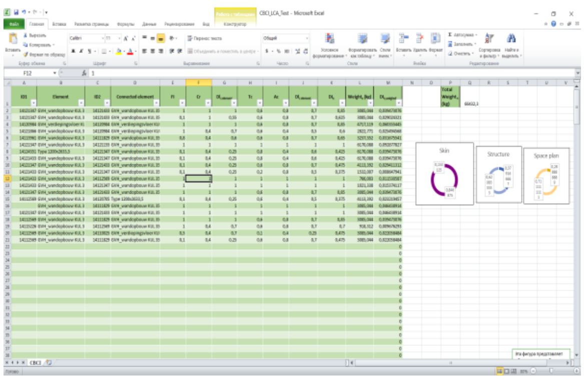


Fig. 6 - A sample of a visual display of the results window.

After conducting tests, several improvements were integrated into the CBCI tool with the aim to improve its usability, such as the dialog box (a message notification that specifies whether the elements are connected) and function for highlighting of selected objects in the 3D model.

5. Discussion

During the intermediate simulation, it occurred that connected elements were defined as not connected because of the minimum distance between elements (e.g., for design reasons). For this problem, the team developped a strategy in which indicators were created at the corners of the elements to determine an intersected element. They are illustrated by the blue lines in Fig. 7. Along the selected element's edges, at the top and base points, the six lines are automatically generated in various orientations by a user-defined length. As a next step, the developed tool determines whether these lines are intersecting with a surface geometry of the second selected element and generates a message. These indicators have their advantages and complexities and should be studied and improved further in the future. The disadvantage of this strategy is that these indicators are based on geometric nodes, which are quite capacious and complicated for the script workflow. But this concept can be applied for automation and identification of two other factors of the four defined; being accessibility connections and crossings type for the HVAC system for the purpose to identify adjacent elements.

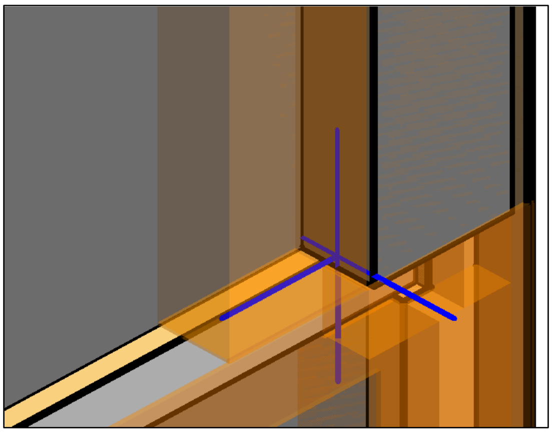


Fig. 7 - The CBCI wall indicators illustration (lines were enlarged for better visual clarity).

Besides this first strategy, two other strategies were tested throughout the work on the main concept. The first one is the adaptive family strategy which uses a set of key parameters for expert assignment. The second strategy is to examine the framework, also peculiar to the BCI Gebouw tool [17], which is supporting an assessment method developed by the CB'23[5], but its concept includes the "one element, one connection" hypothesis. This structure and hypothesis cannot be practical for structural building components and HVAC elements with multiple connections, for example: floors, ceilings, girder slab system, T-ducts, etc. In addition, another critical aspect to consider with this approach is that the absence of IFC format support reduces the model's data interaction within the platform, hence in the case of random/user-based connection identification; the attached elements cannot be transparent to other users.

The indicated gaps in research and tool application lead to the conclusion that a tool for HVAC models is needed. The conceptual analysis and CBCI LL test-case demonstrate the functionality and feasibility of this methodology for HVAC systems. Facilitating future research is the fact that the developed script can be adapted for data structural changes and other modifications such as an additional data requirements or functionality. The final evaluation and comparative studies will be published in the further thematic project reports, whereas the data related to this paper will be presented at the conference.

6. Conclusions and future work

From the review of existing studies it can be concluded that the DfD topic is interconnected with the general LCA research area, material reuse potential and environmental impact. However, only a few papers currently published are focusing on the technical feasibility to integrate DfD or LCA calculations into a BIM environment. A key research contribution is the BIM-integrated development approach based on the Dynamo Revit interface, which supports demountability analysis based on the Alba concept method. This visual programming script represents an algorithm with a graphical interface that automates obtaining geometric element data and expert value data with a subsequent assessment using a connection type database as well as a built-in mathematical computation. In the course of the CBCI LL test-case analysis, it was confirmed that this framework can also be applied to HVAC systems.

On the basis outlined in the previous chapters, several research perspectives and improvement potential in relation to the BIM area were identified, that arise from the practical experience of our team and project partners. In addition to the methodological work, potential in-depth automation is planned to cover the following items:

1. In-depth process analysis and effective data management between DfD experts and BIM/CAD modelers.
2. To continue the work on the existing tool, by further extension with a deconstruction plan, and as a result, create a direct Revit plug-in.
3. It is appropriate to investigate technical features to automate the identification and visual representation of connection type and subsequently reduce the manual work and expert decision, as well as the creation of a connectors' database integration to the BIM environment.
4. It is essential to perform a specific study and to evaluate the possibility of adapting the DfD assessment methodology to Algorithm-Aided Design (AAD) and existing BIM adaptive design tools.
5. A proof of concept implementation as a tool for detailed investigation of the workflows and the information requirements for DfD has been done. Additional step(s) from this proprietary solution towards a more general solution based on the described open, standards based framework, can be taken as soon as the required implementations become available.

7. Acknowledgement

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The datasets generated during and/or analysed during the current study are not available yet because the project is not finalized and IP issues have to be checked with the project partners, but the authors will make every reasonable effort to publish them in near future.

8. References

[1] European Commission - Circular Economy - Principles for Building Design [Internet]. [cited 2021 Dec 2]. Available from: https://ec.europa.eu/docsroom/documents/39984.

[2] Akinade OO, Oyedele LO, Ajayi SO, Bilal M, Alaka HA, Owolabi HA, et al. Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. Waste Manag. 2017 Feb 1;60:3–13.

[3] Vandervaeren C, Galle W, Stephan A, De Temmerman N. More than the sum of its parts: Considering interdependencies in the life cycle material flow and environmental assessment of demountable buildings. Resour Conserv Recycl [Internet]. 2022 [cited 2021 Dec 13];177:106001. Available from: http://creativecommons.org/licenses/by/4.0.

[4] Guerra BC, Leite F, Faust KM. 4D-BIM to enhance construction waste reuse and recycle planning: Case studies on concrete and drywall waste streams. Waste Manag [Internet]. 2020 Oct 1 [cited 2021 Dec 13];116:79–90. Available from: https://pubmed.ncbi.nlm.nih.gov/32791461.

[5] Platform CB'23 (Circular Construction 2023). Core method for Circular economy assessment in the construction sector. [Internet]. [cited 2021 Dec 13]. Available from: https://platformcb23.nl/english.

[6] Durmisevic E, Jorissen A, Nijsen R, Broek K, et al. Circular economy in construction design strategies for reversible buildings. 2019 [cited 2022 Jan 10]. Available from: https://www.bamb2020.eu/wp-content/uploads/2019/05/Reversible-Building-Design-Strateges.pdf.

[7] Chen S, Zhang K, Setunge S. Comparison of three HVAC systems in an office building from a life cycle perspective. 2012 [cited 2022 Jan 1]. Available from: www.semanticscholar.org/paper/dc4e5bbf9c0889545c05ceb5a4e2cd5e457418d.

[8] Wang JJ, Jing YY, Zhang CF. Fuzzy multi-criteria evaluation model of HVAC schemes in optimal combination weighting method. Building Services Engineering Research & Technology. 2009;30(4):287–304.

[9] Ylmén P, Peñaloza D, Mjörnell K. Life Cycle Assessment of an Office Building Based on Site-Specific Data. Energies 2019, Vol 12, Page 2588 [Internet]. 2019 Jul 4 [cited 2021 Oct 27];12(13):2588. Available from: https://www.mdpi.com/1996-1073/12/13/2588/html.

[10] Charef R, Morel JC, Rakhshan K. Barriers to implementing the circular economy in the construction industry: A critical review. Sustain. 2021;13(23):1–18.

[11] Industry Foundation Classes (IFC) [Internet]. buildingSMART International. 2019 [cited 2022 Jan 10]. Available from: www.buildingsmart.org/standards/bsi-standards/industry foundation-classes.

[12] Revit API Docs [Internet]. Revitapidocs.com. [cited 2022 Jan 10]. Available from: https://www.revitapidocs.com/.

[13] Kayaçetin NC, Verdoodt S, Lefevre L, Versele A. Evaluation of Circular Construction Works During Design Phase: An Overview of Valuation Tools. Smart Innov Syst Technol. 2022;263:89–100.

[14] Van Vliet, M., Van Grinsven, J. and Teunizen, J. (2021). Circular Buildings – Meetmethodiek Losmaakbaarheid. V 2.0. Alba Concepts.

[15] De Troyer F, Neuckermans H, Havenne D, Simon F. BB/SfB Tabellen 1990 [Internet]. BB/SfB Tabellen 1990. Regie der Gebouwen; Brussel; 1990.

[16] Dynamo [Internet]. Autodesk.com. 2021 [cited 2022 Jan 9]. Available from: https://www.autodesk.com.

[17] BCI [Internet]. Bcigebouw.nl. [cited 2022 Jan 9]. Available from: https://bcigebouw.nl.