A BIM-based Building Circularity Assessment tool for the early design stage

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Abstract
Since Circular Economy (CE) has proved its contribution to improving environmental impacts in the architecture, engineering and construction (AEC) industry, assessment approaches of building circularity are required for designers to control the circularity of their projects in the early design phase. However, problems exist in current assessment tools applying CE for buildings. There should be different calculation methods for different design steps during the whole process and the output of the tools needs to be simplified to meet the needs of users since the users of these tools may come from different majors and have little professional knowledge in CE. To solve these problems, this research develops a BIM-based Building Circularity Assessment (BCA) framework that uses an accurate calculation method and facilitates easy understanding. This framework can bring benefits to the design of the circular building by providing decision-making support.

Keywords: Building circularity, Building Information modeling (BIM), Assessment tool, early design stage

1 Introduction

The world is experiencing a growing threat of waste, emissions, and other environmental changes. It requires an agile transformation in sectors like construction and transportation (IPCC, 2014). 31.7% of waste and 36% of CO2 in the world originated from architecture, engineering, and construction (AEC) activities (Wang, 2015). The AEC industry has huge potentials in reducing waste and emissions. Circular Economy (CE) has become a possible solution to solve these problems in the AEC industry.

Building Circularity Assessment (BCA) is a developing tool that facilitates designers to have clear assessments in building circularity. It can provide designers with decision-making suggestions by applying Building information modeling (BIM), which has advantages in information integration and management (Volk, Stengel and Schultmann, 2014). Users can adjust their schemes according to the results of the assessments. However, most current BCA tools ignore the special working process of building design in the early stage that there are differences between each design step. It is necessary to focus on different design steps and providing assessment results that are easy to understand for designers to optimize their schemes.

2 Literature review

2.1 The development of CE in the AEC industry

2.1.1 Concept of CE in the AEC industry

Circular Economy (CE) is a new concept that contrasts with the “take-make-dispose” linear economy and refers to an industrial economy based on closed loops. One of the most used definitions for CE that originates from the Ellen MacArthur Foundation is “an economic and industrial model that is restorative by intent and design” (Ellen MacArthur Foundation, 2013). And for the definition for CE in the AEC industry, CB23 states it as “Circular construction means the development, use, and reuse of buildings, areas, and infrastructure without unnecessarily depleting natural resources, polluting the environment and affecting ecosystems.” (Platform CB’23, 2019)

2.1.2 BCA tools

Kovacic, Honic and Sreckovic pointed out that the concept of CE does not introduce into the AEC industry well (Kovacic, Honic and Sreckovic, 2020). Most stakeholders lack the knowledge of how the concept can be applied practically. And it is important to apply CE in a construction project from the beginning period, which can provide most opportunities for designers to choose suitable materials and manage the whole project well. Some studies and companies have explored the assessment models to measure building circularity. Material circularity indicator (MCI), Platform CB’23, Building Circularity Index (BCIX), Madaster Platform and OneClickLCA are introduced here.

MCI is a circularity calculation approach that is developed for all industries. In MCI, there are two cycles in the circular process: the technical cycle - the recycled properties of materials and the biological cycle - the environmental influence of the building. The current practice of circularity focuses on the technical cycle (Ellen MacArthur Foundation, 2015). The model focuses on both the material flow and utility of the whole product lifecycle for the technical cycle.

Platform CB’23 (2019) claims the inclusion of the biological cycle, which develops a comprehensive framework.

The BCIX model is developed by Alba Concepts (2018). It contributes to applying MCI in the AEC industry, such as the development of circularity indicators in the AEC industry.

The Madaster Foundation developed Circular Indicators (CI) (Madaster, 2018). It also borrowed the concepts from MCI and made some adjustments. In the model, three scores for the three-phase of buildings are calculated separately: the production phase, the usage phase, and the demolishment phase. It uses the same indicators as the model from MCI, but it excludes the efficiency of the recycling process and the function units achieved during the usage phase.

And the OneClickLCA (2021), a comprehensive assessment tool for building optimization both in the aspect of environment and economy, contains circularity calculation. The users choose the type of components in their database in the design and then the tool calculates automatically. The results are shown by a group of charts.

2.2 Gaps in current BCA tools

Among all the studies and companies introduced above, MCI is a widely used fundamental calculation method that is developed for all the materials in different industries. Other methods borrowed the metrics from it and revised them to suit their own target industries.

Although the details of other methods mentioned above are different, they are all used under the assumption that the designers are ready to choose the type of each component. However, building design is a complex process that at least contains four steps: programming, schematic design, design development and construction drawings. The designers keep revising and refining the design step by step and make more detailed decisions gradually. During the first step, the designers change the style and shape of the whole building, which means that it is hard to confirm the quantities and types of components at this step. And for the second step, only parts of the components are chosen. Moreover, the studies show that the earlier the design changes are, the more environmental impact is influenced (Price, Wrigley and Matthews, 2018). This means that we need the BCA tool for all steps of design, especially for the beginning of the design.

Another problem that exists here is complex output during the use of the tool. The designers lack professional knowledge of CE. And the environmental impact is only a factor that may influence the building design. The designers may not have too much time to test the circularity of all the changes during the design process. So, groups of complex tables and figures may reduce the efficiency of the tool. It is important to make the results easy to understand.

3 BIM-based Building Circularity Assessment Method

3.1 Metric establishment

The calculation method developed here is based on the MCI calculation method and provides the result by a figure ranging from 0 to 1. As shown in Figure1, for different design steps, different levels of detail are used for calculation. For example, for the first step of programming, LOD100 is used.

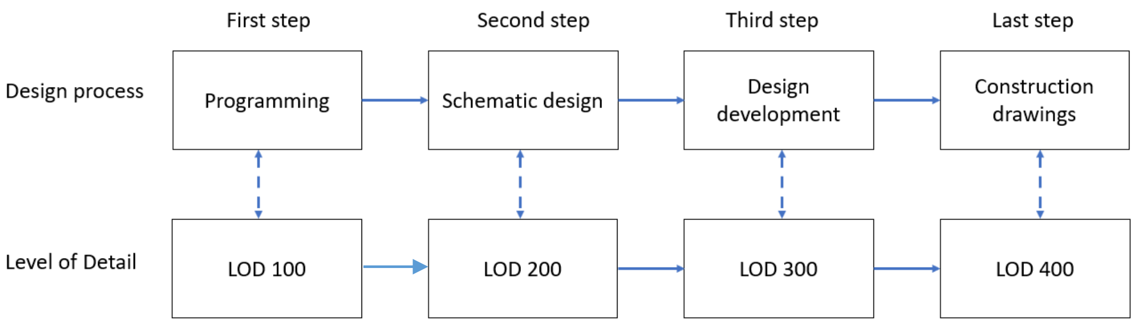


Figure 1. Relationship between design process and level of detail

And there are six layers composing the whole building which are shown in Figure 2, containing stuff, space plan, services, skin, structure and site (Brand, 1994). The number of layers taken into consideration during the calculation is decided by the level of detail. For example, for the first step of programming, only the structure layer is chosen.

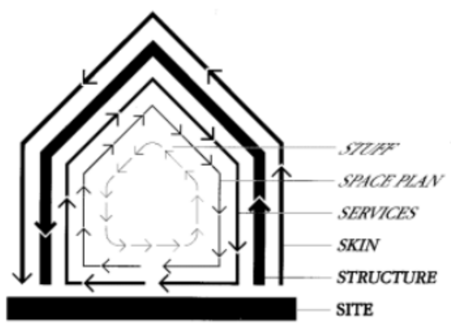
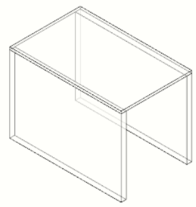
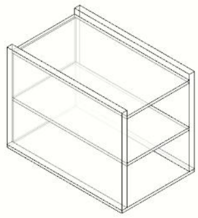
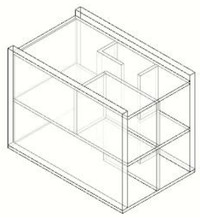


Figure 2. Six layers of change (Brand, 1994)

The first, second, and third steps of the design process are considered here for circularity calculation, as shown in Table 1.

Table 1. The variables and weight

Level of detail	Design model	Model Level	Model elements
LOD 100		Structure	Beam Column Load-bearing wall Roof
LOD 200		Structure Skin	Beams Column Load-bearing wall Roof Floor Curtain wall
LOD 300		Structure Skin Space plan	Beam Column Load-bearing wall Roof Floor Curtain wall External wall

3.1.1 The calculation methodology for LOD 100

In the first step, only the overall building information is represented, such as the area, height, volume, location and orientation. For assessment in this step, the designers simply decided the structure types and main material types of their design. Table 2 shows summarized examples of common house structure types (Allen and Iano, 2019). There is no specific element in this stage. So, here the whole building is seen as a big component. Only the structure level is considered. By the shape of volume, structural type, and the body material, the quantities of the structural materials are roughly calculated, and no other detailed components need to be chosen. The aim of the assessment in this step is to show the influence of the overall building block shape, total volume and main materials on the building circularity.

Table 2. Examples of common house structure type

No	Structural type	Material type
1	Wall bearing	Wood(roof) Brick (Wall)
2	Wall bearing	Wood(roof) Stone (Wall)
3	Beam-column	Wood (Beam, column and roof)
4	Beam-column	Steel (Beam, column) Concrete (roof)
5	Beam-column	Concrete (Beam, column and roof)

For example, for a 6mx6m one-story beam-column structure concrete house, the designers simply decide the volume, block shape and main construction style of the building. The calculation is conducted following a general situation under these conditions: the structure level contains the components of four columns, which are 400mmx400mmx3300mm, four beams which are 200mmx400mmx6000mm and a roof which is 150mmx6000mmx6000mm. Then the whole volume of the structure is calculated as $9.432m^3$. Following the MCI metrics, the score of the circularity is calculated. MCI is defined by Liner Flow Indicators (LFI) and utility factors (F). LFI is generated by the number of recycled materials (Fr, Fu), reused materials (Cr, Cu) and recycled efficiency (Ec, Ef) in construction and demolishment. F (X) is a utility factor influenced by the utility of a component, including lifespan (L, Lav) and intensity (U, Uav) (Linder, Sarasini and Loon, 2017).

3.1.2 The calculation methodology for LOD 200 and 300

Then, designers create the LOD 200 model that contains the approximate quantity, size, location. In the third step, the design begins to accurately resemble what will be installed, including the accurate quantity, size and location. For the second and third steps, the metrics work as following: managing materials as basic elements first and calculating the circularity of each material by MCI, then dividing the building into several hierarchies and calculates following the hierarchies from detail to overall. Finally, a series of scores is obtained as the circularity assessments of each hierarchy and the whole building. It adopts the hierarchy of building by Durmisevic and Brouwer that contains "Material – component –system - building" (Durmisevic and Brouwer, 2002). The equations (1) (2) (3) show the calculation approach.

$$CCI = \sum_{i=1}^{n} \frac{MCI \times \frac{Vs}{\sum_{i=1}^{n} \mathrm{Vi}} + MCI \times \frac{Ws}{\sum_{i=1}^{n} \mathrm{Wi}}}{2} \tag{1}$$

Vs is the volume of material and Ws is the weight of material.
MCI is the circularity score of each material.
CCI is the circularity score of each component.

$$SCI = \sum_{i=1}^{n} \frac{CCI \times \frac{Vi}{V\sum_{i=1}^{n} \mathrm{Vi}} + CCI \times \frac{Wi}{\sum_{i=1}^{n} \mathrm{Wi}}}{2} \tag{2}$$

Vi is the volume of a component and Wi is the weight of component i.
SCI is the circularity score of each system.

$$BCI = \frac{\sum_{i=1}^{1} SCI \times Di}{\sum_{i=1}^{n} \mathrm{Di}} \tag{3}$$

Di is the system dependency of a system
BCI is the circularity score of the whole building.

From MCI to BCI, a crucial point is the normalizing factor chosen for each level and the way the normalizing factor works. The normalizing factors are chosen for each hierarchy, such as weight, volume, price, or detachability. Also, although a more detailed analysis can provide us with more accurate results, a rougher analysis is more conducive to automatic calculations and time-saving (Verberne, 2016; Vliet, 2019). So, this study chooses attributes of weight and volume as normalizing factors for the component and system hierarchy. And these two factors are considered equally important, so they are the same in terms of weight. For the building level, the method by Verberne, which uses system dependency as the factor, is adopted. Each system is given a system dependency here: space plan (0.9), services (0.8), skin (0.7), structure (0.2), and site (0.1) (Verberne, 2016).

3.2 Data collection

3.2.1 Data needed

Two types of data are required for the assessment: one is recycled properties of materials and components, which is needed to be collected through the material database, and the other is project-oriented data: such as the volume and weight of the materials and components used in construction, which can be collected from the model. According to MCI, calculation of material circularity needs data: proportion of recycled and reused material input and output (Fr, Fu, Cr, Cu), material recycled efficiency(Er, Ef), lifetime and utility of materials (L, Lav, U, Uav). Project-oriented data of weight and volume of materials and components (Vi, Vs, Wi, Ws) is the input for CCI and SCI calculation separately (MacArthur, 2013). For building hierarchy, normalizing factors are already defined, so they do not need extra data.

3.2.2 Data code

This study focuses on Dutch general specifications. NL/SfB is a classification of which the codes are in a number string of three groups (NL/SfB, 2005). The classification scheme of NL/SfB can be used as a fundamental coding system in this study. The structure of NL/SfB comprises three groups of digits, in the format of "XX.XX.XXX", identified the location, functions and materials of the component, respectively. According to it, coding is established for each design step.

For the first step, the same coding of three groups of digits is used. For the second and third steps, it adds a fourth group of digits that represents weight-based order. For example, in NL/SfB, the code "22.12.XX" refers to components of "outer wall which is structural and made of concrete": "22", "12" and "XX" refers to "outer", "structural" and "concrete" separately. However, there may be more than one wall with a different weight in a project. To distinguish them, the fourth group of digits plays a role: "22.12.02.03" refers to components of "outer wall which is structural, made of concrete and third weight in this project" (NL/SfB, 2005).

3.2.3 Collection approach

Since in LOD100, no detailed components are decided, the average data of a certain area is used, which is the method written in the report by Ellen MacArthur (Ellen MacArthur, 2015), such as the average data of the concrete in the Netherlands. Due to the lack of basic material data and data confidentiality, data of recycled properties are difficult to collect. All the existing material databases and material passports provide parts of all these data. For example, NMD contains LCA data for a wide variety of building components and materials and NIBE integrates the recycling collection rate of some components (NMD, NIBE). Also, some data can be obtained from the manufactures of the components or some related books. For example, the utility of a component is suggested to be assessed by companies from warranty return rates and component testing. If the data is missing in all databases and related manufactures and books, the average data of a certain area can be used again.

4 BIM-based Building Circularity Assessment tool

4.1 General framework

This tool has been specifically developed for data extracts generated by Autodesk Revit, the main design application used in the early design stages. There are three main steps of the operation of the tool: input, analysis and output. The whole process is shown in figure 3.

Dynamo, an open-source visual programming language for Revit, is chosen here to facilitate the assessment. It is a convenient programming language that allows users to develop workflows through formalizing algorithms. The tool created by Dynamo can integrate data from Revit model and external libraries, process the data following certain approaches and show the results virtualization. As mentioned before, the application of Dynamo follows the three phases of "input-analysis-output".

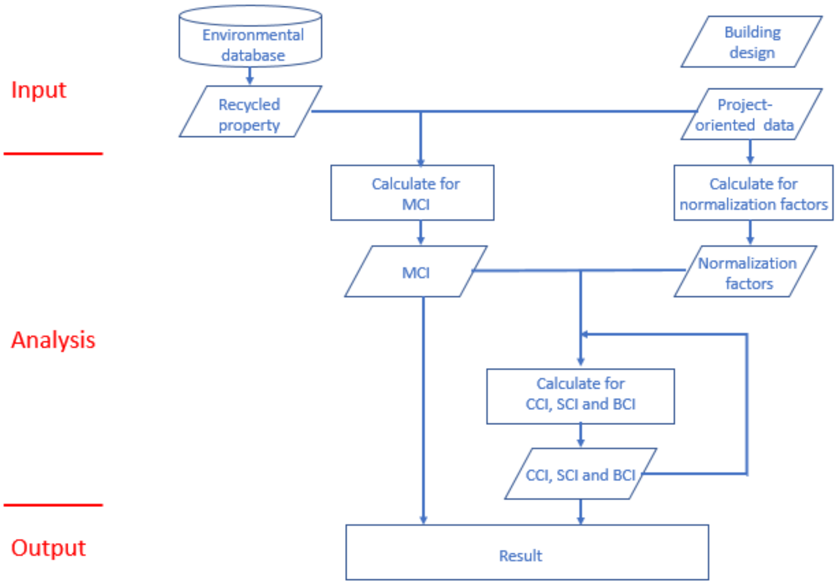


Figure 3 System architecture

4.2 Dynamo implementation

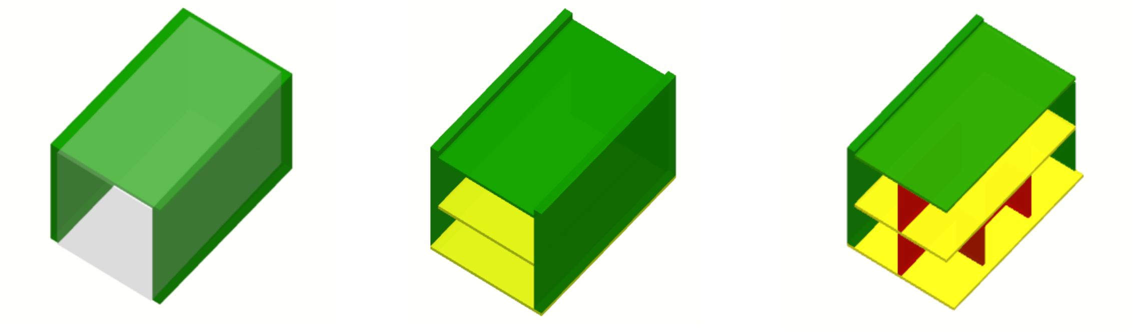
First, it connects the recycled property data from the environmental database which is in Excel format and the project-oriented data from the Revit model. The link between them should be the classification code mentioned in section 3. When the BIM model is exported by Dynamo, the classification code nested in it can be extracted. Then a list of classification codes is created. Finally, the data of properties that match the same classification code can be searched and appended to an empty list. The default nodes and the custom nodes arranged by Jianli (Jianli, 2020) are used here. For the project-oriented data, the 'All Elements in Active View' node is used to select elements in the Revit and capture design changes first. Then, 'Element GetCategory'node, 'List.FilterByBoolMask' node and 'Parameter.ParameterByName' node are input for filtering out the unnecessary elements and getting the values of determined parameters. For the environmental data in Excel, the 'Read Excel' node is employed to extract the useful data in Excel. Finally, the 'Sheet: ProductCircularityData' code block is used to link the two different kinds of data. Second, based on the metrics mentioned before, the calculation is conducted using the integrated data. Last, the output is provided in a graphical user interface (GUI) of the pop-up window, which consists of three components: Catalogue, Step, and Result. The Catalogue provides an overview of all components available in the tool, including their classification code and brief descriptions. The Step function lets the users choose the step they would like to do by pressing the button, such as for LOD 100. The Result provides two ways of presenting. One is scores of the calculation with some calculation process information. For example, when calculating for system circularity, the results of material circularity and component circularity are indicated as well. Also, when users change the design, the former calculation results of the same object are also shown for comparison. The other feedback is in 3D models that present the scores of a different design decision in different colors. Since the scores range from 0-1, the components which get the score above 0.8 would be shown in green well. The components that obtain scores above 0.6 and below 0.6 are shown in yellow and red separately.

4.3 Case study

A demonstration of the tool's potential is provided by assessing a schematic design of a two-story building design. The main structure of the building consists of two load-bearing walls, floor and roof. It is tested on all three steps of the LOD 100, the LOD 200 and the LOD 300 which means that structure CCI, skin CCI and space plan CCI are shown in figure and color. The example is shown in Figure 5.

In the LOD 100, the designer decides the overall shape, construction type and structural material of the building: a two-story building with an area of 5700mm* 8900mm, which is load-bearing and constructed by wood. Then the CCI of load-bearing walls and roofs are tested. As shown in the picture, they are all green which means that they get a score over 0.8 and meet circularity requirements very well. It suggests to the designers that in the context of CE, the design has been performed well enough and the designers do not have to make further changes for the circularity improvement.

In the LOD 200 and LOD 300, more complex components are assessed. The circularity of the floors is not very good, of which scores are between 0.6 and 0.8. And the circularity of the interior wall is worse, which is blow 0.6. The designers are suggested to change the type of interior wall in this design to improve the circularity performance. The designers may choose to change the floor components by considering other performances, such as the construction period.



LOD100 LOD200 LOD300

Figure 4. An example of color shown for components

There is also a table that shows the basic circularity information of the building design, including (1) the calculation result of the circularity calculation of building, systems, components and materials (2) the weight, volume and recycled data of each system, component and material that has been chosen in the design and (3) the calculation result of the previous scheme within the last three revisions. Although the figures in the table are not intuitive as colors in the picture, they can be used as a supplement to the image to give the designers a more detailed and accurate reference. Also, they can be used to compare different schemes. An example of the result table is shown in Figure 5. S1, S2 and S3 refer to scheme one, scheme two and scheme three. S1 uses sustainable wood to construct the structure system, while three different kinds of prefabricated concrete are chosen for load-bearing walls, roof and floors in S2. In S3, the load-bearing walls are made of bricks and the roof and floors are made of wood. Glass is used for curtain walls in all three schemes.

Result

LOD 200		Circularity score		
		S1	S2	S3
Material	Wood	0.98		0.35
	Concrete		0.42	
			0.67	
			0.88	
	Brick			0.21
	Glass	0.72	0.42	0.42
Component	Load-bearing wall	0.98	0.42	0.21
	Roof	0.98	0.67	0.35
	Floor	0.98	0.88	0.35
	Curtain wall	0.72	0.42	0.42
System	Structure	0.98	0.59	0.28
	Skin	0.72	0.42	0.42
Building		0.78	0.46	0.39

Figure 5. An example of the result table

5 Conclusion

This research proposes the framework of a BIM-based building circularity assessment tool. The tool could be used for all the three early steps of the building design and show the results efficiently. The tool's implementation can provide helpful support for the designers to optimize their design in circularity.

The limitation of this research is that it only calculates the technical circularity score, which is one of the indicators for environmental assessment. The calculation of LCA and LCC follow similar approaches of the data collection, data link, calculation and result shown. So although the data collected and the calculation metrics are different, they can work through the same workflow and get all the results at the same time. Combined this tool with other LCA methods or LCC methods, more assessment approaches can be developed, and more comprehensive and convenient decision-making suggestions can be provided. And the combination of all these assessments can show how circularity influences the environment and economic performance.

Another limitation is that yet the tool lacks automatic optimization functions. The further development of the tool may solve this problem and automatically provide users with suggestions of design.

6 References

Alba Concepts, (2018). *Building Circularity Index.* [online]Available at: https://albaconcepts.nl/buildingcircularity-index/s [Accessed 01 May. 2021]

Allen, E. and Iano, J. (2019). *Fundamentals of building construction: materials and methods.*

Brand, S. (1994). *How buildings learn: What happens after they're built.*

Durmisevic, E. and Brouwer, J. (2002). Design aspects of decomposable building structure. [online] https://www.researchgate.net/profile/ElmaDurmisevic/publication/268298060_DESIGN_ASPECTS_OF_DECOMPOSABLE_BUILDING_STRUCTURES/links/54becfa30cf2f6bf4e0486e5/DESIGN-ASPECTS-OF-DECOMPOSABLE-BUILDING-STRUCTURES.pdf [Accessed 01 May. 2021]

Ellen MacArthur Foundation. (2013). *Towards the circular economy, economic and business rationale for an accelerated transition.* Ellen MacArthur Foundation: Cowes, UK.

Ellen MacArthur Foundation. (2015). *Circularity Indicators: An approach to measuring circularity.* [online]Available at: http://www.ellenmacarthurfoundation.org/circularity-indicators/. [Accessed 01 May. 2021]

IPCC. (2014). *Climate Change.* Chapter 9.

Kovacic, I., Honic, M., and Sreckovic, M. (2020). Digital platform for circular economy in AEC industry. *Engineering Project Organization Journal,* (2020), 1-16, 9

Linder, M., Sarasini, S., and van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology,* 21(3), 545–558.

Madaster. (2018). *Madaster Circularity Indicator explained.* [online]Available at: https://docs.madaster.com/. [Accessed 01 May. 2021]

NIBE database. [online]Available at: https://www.nibe.info/nl/milieuclassificaties. [Accessed 01 May. 2021]

NL/SfB. (2005). [online]Available at: https://www.stabu.nl/mijnstabu/files/NL-SfB_BNA_Boek_2005-ISBN-10%2090-807626-3-6.pdf. [Accessed 01 May. 2021]

NMD database. [online]Available at: https://milieudatabase.nl/opbouw/database/. [Accessed 01 May. 2021]

OneClickLCA. [online]Available at: https://www.oneclicklca.com/. [Accessed 01 May. 2021]

Platform CB'23. (2019). [online]Available at: Core method for measuring circularity in construction. https://platformcb23.nl/leidraden. [Accessed 01 May. 2021]

Price, R., Wrigley, C., and Matthews, J. (2018). Action researcher to design innovation catalyst: Building design capability from within. *Action Research.*

Van Vliet, M. (2018). *Disassembling the steps towards Building Circularity.* Master. Eindhoven University of Technology.

Verberne, J. (2016). *Building Circularity Indicators – An approach for measuring circularity of a building.* Master. Eindhoven University of Technology.

Volk, R., Stengel, J. and Schultmann, F. (2014). Building information modeling (BIM) for existing buildings – Literature review and future needs. *Automation in Construction*, *38*, 109–127.

Wang, Y. (2015). *Whole life cycle carbon emissions research of industrialized precast construction.* PhD. Southeast University.

Zhai, J. (2020). *BIM-based building circularity assessment from the early design stages.* Master. Eindhoven University of Technology.