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A B S T R A C T

Facing circular transition challenges, building circularity should be evaluated in the early design phase to reduce the risks of circular and environmental performance problems found in later project phases. However, due to the current design workflow, such practice is hindered because there is not enough information to evaluate building circularity in detail in the early design phases. An improved workflow to emphasize circularity more in the early design phase is thus needed. This research explores the current workflow and designs an improved workflow by developing an automated decision support system to assess early design phase building circularity with limited available information, aiming to improve the working efficiency and efficacy. This automated system helps in data-driven decision-making by integrating different data sources and presenting the calculated results interactively with business intelligence interfaces. The interfaces involve different types of evaluations based on the data availability in both schematic design and detail design sub-phases. It also visualizes the data quality and future scenarios. This system has been designed based on interviews and literature studies, and verified and validated with practitioners. This study serves as a starting point to rethink the workflow to improve circularity with currently available technology.

1. Introduction

The construction industry belongs to one of the sectors with the highest waste generation and environmental impact [20]. It accounts for 33% of greenhouse gas emissions, 40% of raw material consumption, and 40% of waste generation [4]. Therefore, the construction industry should step up and minimise its environmental impact by putting a halt to linear economy principles and shifting to a circular economy (CE) philosophy. This transition aims to eliminate waste, reduce harmful environmental emissions, and create a closed-loop system for resources. However, how to achieve such transition goals are not yet concrete for construction projects. On the other hand, the emerging trend of Building Information Management (BIM) and Data-Driven Decision-Making could play an important role in this transition by facilitating circular building design with database development and integration, automatic performance evaluation and scenario design.

For this to happen, data is essential. Nowadays, construction companies are not only constructing new buildings or bridges, but they are also generating tons of data during design, construction, and operation [18]. All this data could be collected with BIM and used to better substantiate complex decision-making processes regarding sustainability and circularity, by consulting the most viable design option using performance comparisons. However, 96% of all the data currently captured in the built environment is not effectively used by firms due to a lack of interoperability, information exchange procedures, supporting technology and associated implementation costs [25]. Access to high-quality and timely available information would allow project managers to make smarter and better-informed decisions, facing circular transition challenges.

To evaluate the performance of building design circularity, a standard evaluation method is needed. However, in the built environment, the implementation of CE is relatively new, and circularity assessment methods are still in development. There is no standardised approach to measure circularity yet [21]. In the past, different assessment methods have been developed, focusing on circularity in general or on a single aspect of circularity. The Ellen MacArthur Foundation and Granta Design [12] developed a 'Circular Indicators Project' which consists of several tools that allow companies to append a circularity value to their

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products. One of the tools is the Material Circularity Indicator (MCI) which provides an indication of the 'degree of circularity' focusing on minimising the linear flow and maximising the restorative flow. However, MCI is only limited to the microscale, addresses only partially the environmental view of circular design principles, and often gives contrasting results with the Life Cycle Assessments (LCA). This is because the circularity indicators only provide a partial view on the environmental performance of a system. Circularity metrics may be masking a burden shift towards increased energy consumption or polluting emissions [10,22].

In the Dutch context, Platform CB'23, which is an organisation that develops working agreements, frameworks, guidelines, and material passports, aims to achieve the circularity goals. The circular design guideline of Platform CB'23 is considered a good method that provides individual circularity indicators for three core principles: protection of the existing stock of materials, environmental protection and value retention. Nevertheless, it is difficult to use the individual indicators as a steering instrument to assess circular building design and the disassembly potential is only supported qualitatively with this method. Expanding on Platform CB'23 and the Ellen MacArthur Foundation, Verberne [27] has developed the Building Circularity Indicator (BCI) to assess circularity performance on material, product, system, and building levels. The BCI measurement method includes the disassembly potential quantitatively and integrates the individual circularity indicators in a one-point score for a final assessment. Later, Van Vliet [28] addressed the limitations and redeveloped the BCI model, mainly focussing on the disassembly potential. The latest version of such a method is developed by Alba Concepts and BCI Gebouw [3]. This version also considers the environmental impact of products while using the latest version of the BCI, which ties well with the uniform and effective core measurement method of Platform CB'23. The same circularity principles are used as starting point. However, the BCI is ahead of the core measurement method of Platform CB'23 because it has integrated the circularity indicators into a single building assessment score.

Even though researchers are focussing more on the integration of BIM and LCA, the research on integrating BIM and circular design strategies with circularity indicators for LCA is still under development. It is recognised by Xue et al. [29] that the integration of CE into a BIM-based LCA for design is hardly implemented in the literature. They point out that there is a need for simpler strategies where the interaction between CE, LCA, and design is assessed. The theoretical implementation of circularity is quite well established but the construction industry needs practical tools that assess circularity performances of design options and that stimulate the added value of circularity along the full lifecycle [4].

Specifically for the early design phase, there is a demand for quantitative building circularity assessment methods and tools that support circular designs in the early design phase as this would reduce risks for reworking in the later phases due to circular and environmental performances' issues [26]. However, the challenge lies in the information available for circular assessments in the current design workflow. In the early design phase, information is uncertain and incomplete in the BIM approach. The maturity of a design develops throughout the design process. The usefulness and reliability of circular assessment methods to steer circular building design depend on the information availability per design phase. Therefore, it should be considered to fit the circular assessment tools with the available information per design phase.

Regarding specific tools developed for BIM, LCA and circularity evaluation, Building as Material Banks [8] and Madaster [16] have developed circular building assessment tools to assess material resource flow during the lifetime of buildings and the building's circularity performance. Thereby, BIM-based information is captured in standardised exchange files and processed and analysed in external software. However, this requires inefficient and time-consuming manual procedures to perform circularity assessments [30]. Designing a building is an iterative process where for every step these procedures need to be redone. Therefore, to be effective as a steering instrument throughout the design workflow, there is a need for more automated circularity assessment tools that directly evaluate the circularity [4]. Akanbi et al. [1] and Di Biccari et al. [11] have developed BIM-based assessment tools to evaluate the circularity performances of the building as a whole. However, both these tools only focus on the whole building level, while in the early design phase it is needed to have insight into circularity performance at the building component level and for multiple design options. Another limitation of current circularity evaluation tools is their static presentation of the results which makes it difficult for decision-makers to investigate why certain building elements negatively influence the circularity score of the design. To take circular assessment tools to the next level, interactive and dynamic dashboards could enhance user involvement and provide them with more elaborate analyses for circular building design in the early design phase [19].

Following the literature review and interviews with professionals in the Dutch construction industry, it becomes clear that there is a demand for suitable design tools that support circular building design quantitatively. It is preferred to determine the circularity early on in the design process. It would benefit the industry when decision support tools are used as a steering tool for developing design options, instead of an evaluation tool to determine the final score at the end of the design. Thereby, a design option represents an alternative 'version' of the design at the same level of development (LOD) [17]. For such purposes, an improved workflow is necessary to match the level of information with the circular assessment method throughout the early design phases. The iterative and continuously developing nature of the design process requires timely decisions when evaluating design options. Therefore, a high level of automation and minimal manual procedures are beneficial to support design choices quickly.

To positively contribute to the transition from a linear to a circular economy for the construction industry, this research aims to develop a decision support system for circular building design in the early design phase with a high level of automation and interaction. An improved workflow is proposed to deal with the limited information available in the early design phases, while still performing a sound circularity assessment to steer the design process. The target is to create an automated and interactive circular design dashboard, as part of the process, to provide the design team and sustainability specialists insight into the circularity performances of different building components in various design options. This means that they are directly in control of the decisions made in the design process, and they can substantiate the design choices objectively and transparently. In this way, the design team can steer towards circular design early in the process. To instantly evaluate and assess the circularity performance of design options, the system will be developed with software that has great interoperability with BIM and high automation potential.

2. Context

2.1. Circular building design phases

The early design phase is highly important when striving for circular building design. It is recommended to steer on design choices as early as possible in the process to achieve a higher degree of circularity. Fig. 1 shows that in the early design phase, the impact of circularity measurements is high, while the costs for circular design changes are relatively low. This comes from a well-known concept, the MacLeamy curve, which states that pulling the design effort to earlier design processes

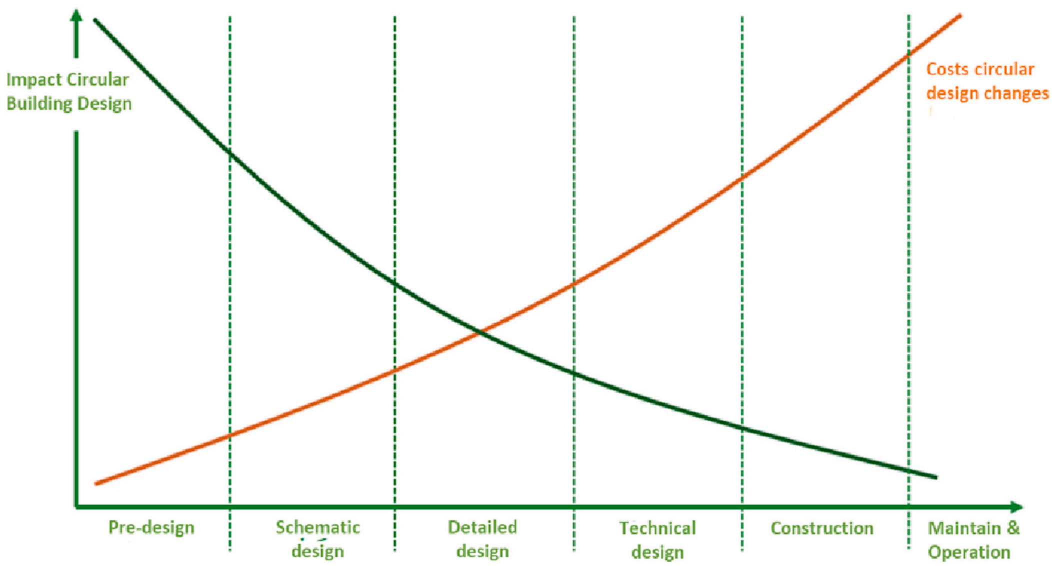

Fig. 1. The MacLeamy Curve applied to Circular Building Design.

increases the flexibility of design changes while lowering the costs to implement changes [9].

For this research, it is not feasible to assess circularity quantitatively in the pre-design phase because the model is represented only in a conceptual manner. In this phase, circular building design could be included qualitatively by formulating circular ambitions and design strategies. Therefore, the focus of the decision support system in this research is on the next two phases: the schematic and detailed design. In the schematic design phase, building elements are modelled with approximate sizes and materials, with a low LOD. However, circularity analysis can be performed based on quantity and material usage estimates. A higher LOD will be achieved during the detailed design phase, which makes it possible and desirable to perform a more accurate analysis based on specific material data and the disassembly potential of the chosen elements.

2.2. Building circularity assessment methods

To support and evaluate circular building designs, it is necessary to measure the overall circularity quantitatively. Currently, there is no consensus yet on strategies for circular building design and circular assessment methods. According to Corona et al. [10], there is no literature evaluating circularity strategies has successfully addressed the impact of early designs on the environment, economy and society simultaneously. However, the main principles of circularity are generally accepted by all the different schools of thought, which makes it possible to find a thread through the various circularity assessment methods. In addition, it is recommended in the literature to continue to build on current circularity assessment frameworks instead of developing completely new CE metrics. Therefore, in this research, the BCI measurement method of Alba Concepts is adopted. The BCI measurement method is developed to steer circular building design by assessing the circularity of products, elements, and the building itself. The BCI is not a new circularity assessment method but unites existing methods such as the LCA, Material Circularity Indicator and the core measurement method of Platform CB'23. The BCI method ties in well with the uniform and effective core measurement method for circular design from Platform CB'23. The same circularity principles are used as starting point and there is a similarity in the measurement of key performance indicators. Additionally, the BCI assesses the disassembly potential

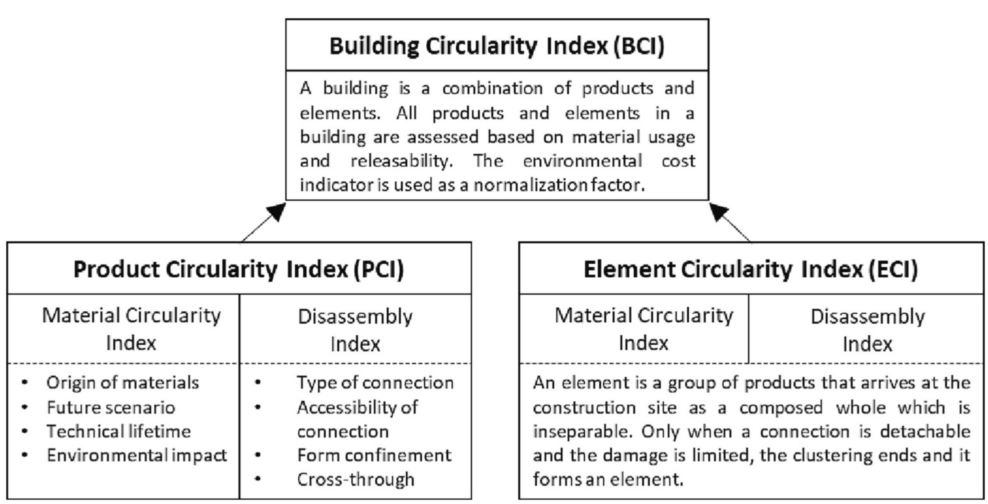

Fig. 2. Building Circularity Index of Alba Concepts.

quantitatively and integrates the individual circularity indicators into a final building assessment score. The full BCI measurement method and calculations are provided in a whitepaper of Alba Concepts and BCI Gebouw [3].

Fig. 2 presents the hierarchy of the BCI method of Alba Concepts. The BCI is built up of the Material Circularity Index, Disassembly Index, Product Circularity Index, and Element Circularity Index. Thereby, a building is composed of products and elements, where elements are a group of inseparable products or sub-products that arrive at the construction site as a composed whole. The BCI gives meaning to the concept of circularity through three main aspects:

- Material usage,
- Disassembly potential,
- Environmental impact.

The BCI measurement method can act as a measurement and control instrument which makes it suitable to steer on circular building designs in the early phases. The scope of the BCI assessment includes the following elements in the Layers of Brand [6]: structure, skin, services, and space plan.

In this study, the BCI measurement method is adapted in such a way that the assessment fits with the level of information per design phase. In consultation with the end users, the BCI measurement method is adopted in two different formats. An indicative BCI assessment is performed for the schematic design, while the detailed design is assessed by a provisional BCI calculation. The indicative and provisional BCI assessments are defined as follows:

- Indicative BCI assessment: An indicative BCI assessment is conducted in the schematic design phase and will be used as a base estimation for the circular building performance. The goal is to identify circular hotspots, which are building elements that have a positive or negative influence on the total circularity of the building, and to propose circular design options, strategies, and measures. In this phase, the BIM model consists of general dimensions and materials without non-graphical information like disassembly parameters. Therefore, it is most suitable to use the BIM model for the estimation of the quantities to assess the MCI. It is not feasible to make a proper estimation of the disassembly potential per product. In consultation with the end users and the literature, a range of possible valuations have been drawn up for such disassembly potentials, see Table 1. In this way, the material usage of the design can be assessed with the MCI, and together with the range of disassembly potentials. And an expected BCI score can be estimated to gain insight into the building circularity performance.

- Provisional BCI assessment: A provisional BCI assessment is conducted during the detailed design phase and can be used to substantiate circular building design decisions. The goal is to evaluate whether circularity objectives will be met and to optimise and compare circularity measures. At this point, the model includes specific element sizes and non-graphical information in the form of material characteristics. In addition, it is possible to estimate the disassembly indicators for products and include this in the BIM model. This means that the full BCI measurement method could be applied to determine the degree of circularity.

Table 1
Potential disassembly scenarios [2].

Potential disassembly scenario	Score
Minimum	0.10
Low	0.40
Average	0.60
High	0.80
Maximum	1.00

2.3. Decision support systems

Designing a building is a complex process that deals with multiple decisions where choices need to be made between different design aspects. For sustainability and circularity, the design objectives are sometimes conflicting due to their dependencies and mostly, the decision-maker's preference determines the solution for a large part [15]. Therefore, decision support systems can facilitate the problem-solving process by offering qualitative and quantitative information to assess, compare or rank alternative design options to determine the most suitable option that meets the objectives best. Decision support systems increase the efficiency, productivity, and effectiveness of the decision-making process, while also promoting communication and quick problem-solving [15]. According to previous state-of-the-art BIM and CE integration approaches, the following three main streams can be concluded for BIM-based decision support systems [29,30]:

- External circularity assessments with standardised exchange files: This stream captures BIM-based information in standardised exchange files, such as Industry Foundation Classes (IFC). The exchange files function as input for external software or platforms to assess the building circularity.
- Circularity assessments within the BIM environment: The next stream is to internalise the building circularity information in the BIM environment. Custom circularity parameters could be created to capture various element attributes such as the origin of materials, end-of-life scenario, and lifespan. Once the necessary circularity attributes are captured in the model, the calculation for the assessment can be performed with custom plug-ins.
- An automated link between BIM and external building material databases: The third way of BIM-CE integration is to establish an automated process between the BIM environment and external material databases, also called semantic enrichment. This method generally consists of a data platform with two layers: a data layer and an application layer. The data layer accommodates the information from the BIM environment and material databases, and it supports the data analytic operations. The application layer is where the results are analysed and visualised to support decision-making processes.

For this research, the third stream is the most suitable for a BIM-CE integration to develop a decision support system for circular building designs in the early design phase. A decisive factor for this stream was the high automation and interaction needs and the potential of data platforms to scale up for more complex projects, and the possibility to develop an interactive and dynamic dashboard in an external application convenient for the end users. Automation of the process is essential to reduce the manual procedures and speed up the circular assessment process, which makes the decision support system more usable as a steering tool for circular building design in the early design phases. The interactive and dynamic dashboard has the advantage to engage the end user and creating a better understanding of complex data.

3. Methods

3.1. Development cycle

In this research, the development of a decision support system for circular building design follows a cycle for product development. The development process of the decision support system is presented in Fig. 3 and consists of four major phases: analysis, synthesis, simulation, and evaluation phases, which is in line with the Delft approach for product development ([23], pp. 87–94). The analysis phase aims to

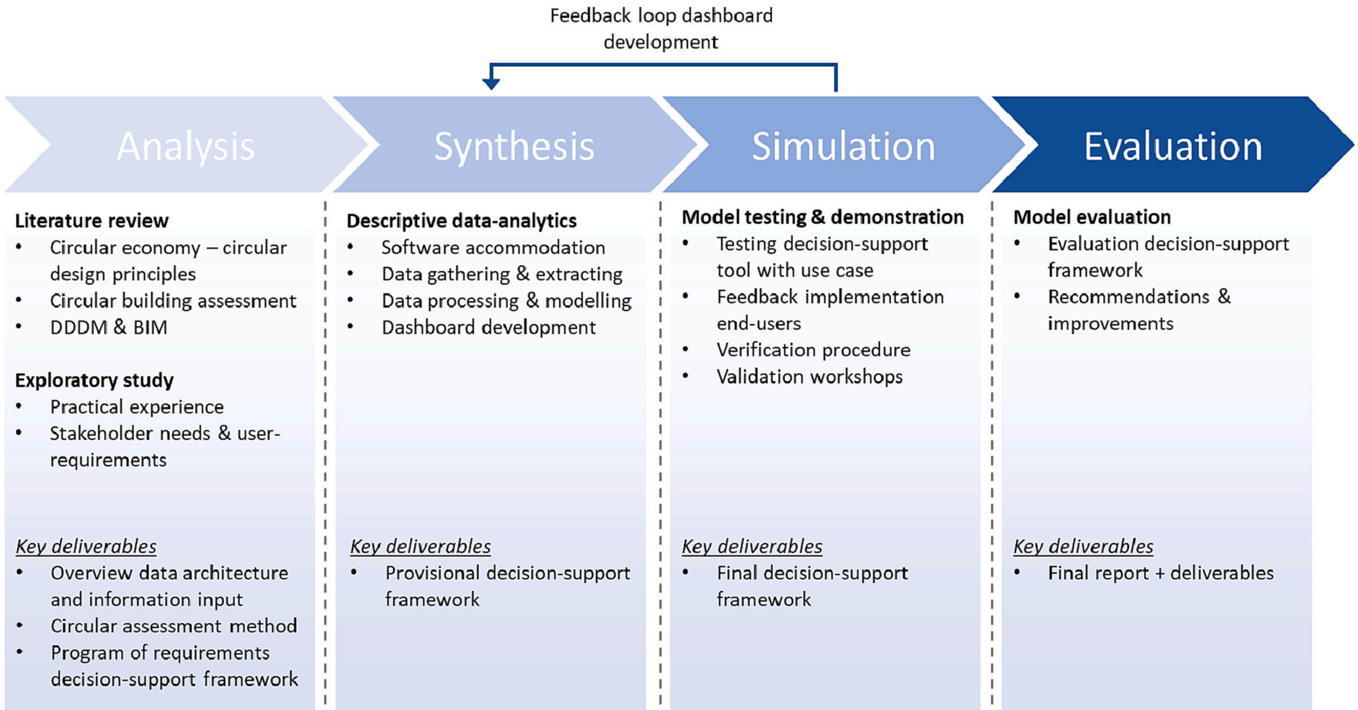

Fig. 3. Development cycle.

identify the needs of stakeholders and to observe suitable and desirable solutions. As a first step, a literature review and exploratory study with semi-structured interviews are conducted in the analysis phase. At the end of this phase, it is determined which circularity assessment method is applied and a program of requirements is set up to capture the technical specifications of the system and the end-user's needs and wishes for the assessment tool. In the synthesis phase, the identified problem and requirements are translated into a practical solution choice for the development of the decision support system. A detailed description of the decision support system architecture is presented in chapter 4.1. In the simulation phase, a simulated prototype takes place to demonstrate the dashboard and to see if the actual behaviour of the system met the desired behaviour. This is performed before the actual testing with practitioners to reduce the design risks during the process. The system is verified and validated with practitioners in the construction industry, using a pilot project. In this phase, it is determined if the decision support system meets the functional and technical requirements set up in the analysis phase. Lastly, the research and tool are evaluated, the results are interpreted, and future recommendations and improvements are given in the evaluation phase.

3.2. Data collection

3.2.1. Analysis phase

The qualitative data gathering in the analysis phase consists of an exploratory study of circular building design, Data-driven Decision-Making (DDDM), and the input for the program of requirements. This is based on interviews with key stakeholders with knowledge of circular building design, supporting software, and BIM. Besides that, interviews are held with end users to determine their needs and wishes for the decision support system. The interviews are conducted in a semi-structured way with some predetermined questions to lead the direction of the interview and sketch the context but leaving space for the exploratory nature of the interviews. Semi-structured interviews are widely used in qualitative research to generate ideas and explore participants' experiences to develop an evaluation tool [14]. The semi-structured interviews allow following up questions from different

Table 2
Sample of interview questions.

Category	Interview questions
Sustainability & Circularity	How is it dealt with circularity in the design process of the company?
	How are the material properties regarding circularity collected/registered within BAM?
	What is the relationship between the design team and the sustainability specialists?
Building Information Management	To what extent are circularity assessments automated and linked with BIM?
	Where can optimization be achieved in the current workflow/bottlenecks of the automation of BIM-CE integration?
	How do BIM specialists deal with the LOD in BIM models in the early design phase?
Decision support system	How is the current data/system architecture set up within the company?
	At which moment in the design process do decisions need to be supported by the use of a dashboard?
	Are there any issues/bottlenecks with the implementation of current decision support systems or design tools?

Table 3
List of interviewees and profession.

Stakeholders: decision-support framework	
Participant 1	Head of Department: Digital Construction Program
Participant 2	Project leader BIM
Participant 3	Specialist Digital Construction
Participant 4	Project leader Sustainable Buildings
Participant 5	Consultant Circularity
End-user: circular design dashboard	
Participant 6	Manager Sustainability and Environment
Participant 7	Manager Sustainability IP
Participant 8	Design leader – Civil
Participant 9	Design team / architects

angles [7]. A sample of the pre-determined interview questions is provided in Table 2.

The participants for the interviews are selected using a purposive sampling method. The purposive sampling method is a non-random technique that deliberately chooses the participants based on profession and qualities. This method is mostly used for exploratory studies and qualitative research where specific groups will be targeted to deliver information that leads to a more comprehensive understanding of the problem and to better identify the input requirements [13]. Table 3 presents the list of participants for the exploratory study. As a result of the interviews, a program of requirements is set up where the end-user's needs and the intended functionality of the system are translated into technical and functional requirements. The technical requirements are designed to make the system run smoothly while integrating various data sources and performing data analytics. The functional requirements are more towards different roles' requirements for such a system to guide their decision-making process transparently. The program of requirements that the decision support framework must fulfil is presented in Appendix A: Program of Requirements.

3.2.2. Synthesis phase

The next step is to collect the necessary data for the decision support system to perform a circularity assessment. The input data can be divided into two categories: project data and material data. Project data is design-specific data which is captured in the BIM model. Material data is in the form of material passports and contains characteristics of specific materials and products. For this research, project data is captured in Autodesk Revit and material data in Microsoft Excel.

- Project data

The first type of data is project data that is captured in BIM. Effective cooperation in BIM can be accomplished with unambiguous agreements specified in an Information Delivery Specification (IDS). For the decision support system, the following aspects must be included in the IDS: NL-SfB classification, NAA.K.T material classification, and disassembly parameters.

The NL-SfB classification is a semantic standard that captures definitions for building element classifications. The functional building elements table classifies the elements based on a four-digit code, where the first two numbers stand for the main elements and the last two numbers for the functions or applications. In the decision support system, the NL-SfB classification must be correctly assigned in the models as assembly code. This is a built-in parameter in Revit which can be linked to an NL-SfB classification code file and can be assigned to all elements.

Besides the classification based on building elements, there is a material classification. The element in the BIM model must be classified with a uniform material convention. It is important to have a uniform and unique material name so all applications recognise the same material. Therefore, the NAA.K.T. material classification is assigned as a keynote parameter to all the products to ensure a uniform classification. The NAA.K.T. classification is an unambiguous material designation introduced in the latest BIM-based Information Delivery Specification in the Dutch construction industry [5]. The goal of the NAA.K.T. classification is to create an unambiguous name convention that is generic to apply in the sector but specific enough to be of added value.

The last type of information that is needed in the BIM model is the project-specific circularity parameters which can be included in the BIM model as shared parameters. This group consists of the four disassembly parameters which are needed to assess the disassembly potential and the functional lifetime of elements to determine the utility factor. The disassembly potential is the extent to which an object can be dismantled at all building levels, without degradation of the product or damage to surrounding objects. The full method for measuring the disassembly index is explained in the report Circular Buildings [2]. The disassembly parameters and the corresponding codes and scores are presented in Table 4.

Table 4
Disassembly parameters - BCI measurement method [3].

Disassembly factor	Description	Code	Score
Type of Connection	Accessory external connection or connection system	TC1	1
	Direct connection with additional fixing devices	TC2	0,8
	Direct integral connection with inserts (pin)	TC3	0,6
	Filled soft chemical connection	TC4	0,2
	Filled hard chemical connection	TC5	0,1
Accessibility of Connection	Accessible	AC1	1
	Accessible with additional operations which causes no damage	AC2	0,8
	Accessible with additional operations which is reparable damage	AC3	0,6
	Accessible with additional operations which causes damage (20%)	AC4	0,4
	Not accessible - total damage of elements	AC5	0,1
Form Confinement	Open – no obstacle for (interim) removal of products or elements	FC1	1
	Overlap – a partial obstacle to the (interim) removal of products or elements	FC2	0,4
	Closed – complete obstacle to the (interim) removal of products or elements	FC3	0,1
Cross-Through	Modular zoning of objects	CT1	1
	Intersections between one or more objects	CT2	0,4
	Full integration of objects	CT3	0,1

- Material data

The second type of data is material data, especially the sustainability and circularity characteristics of materials. The data can be captured in a material database. This is a database which represents a digital registration of the products used in a building model. This document consists of qualitative and quantitative information on building materials, such as the description of the product, the environmental impact, the origin of the material, future scenarios, and the lifespan of materials. For this research, a template for a material database is constructed and presented in Appendix B: Template material data, based on the information required to perform a circularity assessment in the early design phase. The input for the material database originates from publicly available material databases for the Dutch construction industry, the 'Nationale Milieu Database' (NMD) and 'Nederlands Instituut voor Bouwbiologie en Ecologie'(NIBE).

The BCI measurement method does not only consider individual products but also elements. An element is a composite product of sub-products which arrives at the construction site as a whole and where the disassembly of the composition is decisive. The circularity of an element is assessed with the Element Circularity Index (ECI). To integrate elements in the circularity assessment system, columns for product types and element codes are included in the material database. The sustainability specialist can assign per material if it is a product, element, or sub-product. In the case of an element with a sub-product, a unique element code must be assigned to the element and corresponding sub-products which indicates that these belong together. In such a manner, it is possible to include inseparable elements in the circularity assessment.

3.2.3. Simulation and evaluation phases

A case study is used to demonstrate, verify, and validate the decision support system developed. A Revit Autodesk tutorial of a single-storey commercial retail building is chosen as a pilot project. The Revit project only applies architectural modelling, so the mechanical, electrical, and piping systems are not modelled. It fits well with the scope of this research to only include the building structure, skin, and space plan of buildings. The original Revit model is adjusted to suit the setup for the decision support system described in the previous section, i.e. the model is adapted according to the context to assess circularity with the indicative and provisional BCI in the schematic and detailed design. Thereby, two design options are worked out in the detailed design phase to perform a comparative analysis of the two design options. The design options differ in the type of roof. One option has a roof of steel sandwhich panels with a low degree of demountability, while the other option has a timber frame roof that is easily demountable. Moreover, all models are equipped with the right parameters necessary for the circularity assessment. Detailed characteristics of the two design options are presented in Appendix C.

The verification is performed to check if the system meets all the technical specifications and if the system runs as intended without any errors. The verification process includes all activities associated with the construction of the decision support system. Therefore, all three layers of the system have been subjected to an internal test in an artificial environment. All the operations in the data, analytical, and application layers are verified step-by-step with the use of the case study. The step-by-step verification of the system determines whether the system satisfies the technical requirements which are drawn up in the program of requirements. To assess the technical requirements, a reflection is objectively made by the authors. The technical requirements are evaluated based on three possible outcomes: does not satisfy the requirement (1), partially satisfies the requirement (2), and fully satisfies the requirement (3). This way, the verification process helps assuring the correctness of the framework and data flow, and that it operates as intended without producing any errors or crashes.

The focus of the validation is more on the application layer of the system, i.e. the circular design dashboard in Power BI, as that is the tool the end users apply to steer on circularity in the design phase. The goal is to determine the added value of the circular design dashboard and fulfilment of the end user needs, whether it stimulates and supports circular building design in the early design phase, and if it satisfies the user experience. The validation is performed through two interactive workshop sessions with potential end users. The participation of end-users and their background is presented in Table 5. The workshops are performed physically and are divided into two parts. The reason for this is that a physical workshop stimulates the engagement of participants and makes it easier to analyse the non-verbal actions of participants facing challenges when working with the tool. In the workshop, the first part focuses on delivering information to the participants with a presentation about the research in general, the decision-support framework, and the workflow and assessment for circular building design. This part includes a short tutorial on the dashboard in Power BI with instructions and an explanation of the functionalities. In the second part, the participants engage in a hands-on experience with the dashboard by working on a case study themselves. The validation of the circular design dashboard is assessed in the form of peer reviews and a subjective assessment of the functional requirements of the system. The peer review is given in feedback rounds which reflect on the general impression of the dashboard, advantages and disadvantages, and the user experience from the practitioners. The subjective assessment is performed with a questionnaire. In this questionnaire, the fulfilment of end-user needs is determined based on scores on the functional and system requirements. The functional requirements are ranked by the participants as follows: fail (1), moderate (2), pass (3), good (4), and excellent (5). The final score per requirement is the average score of all the participants. The result of the validation process, the average score of the participants in the survey, is presented in Appendix A: Program of Requirements.

Table 5
List of participants and background.

Session 1: Sustainability specialists	Workshop 2: Design team
Department head: Sustainability	Architect 1
Manager: Sustainability and Environmental	Architect 2
Tender Manager	Project manager
Sustainability specialists 1	Design leader
Sustainability specialists 2	

For the evaluation phase, all the data collected will be used to evaluate the impact of the tool on the whole process and propose an improved workflow accordingly.

3.3. Data analytics

3.3.1. Data extraction

The data extraction focuses on the project data in Revit. The Revit model can be seen as a project database where all the design information is stored. A built-in option to export the data from Revit is material take-off schedules. However, the quantity take-off shows a high level of detail about the assembly of a component, while this is not suitable for the circularity assessment. Besides that, in Revit schedules, the overview is lost when there are a lot of different parameters available in big projects. This makes it difficult to choose the correct set of parameters for the schedule. To solve these problems with Revit schedules, Dynamo is used as a plug-in to extract the data from the model. Dynamo gives the flexibility to create and format a quantity take-off at the right level of detail which is most suitable to perform a circularity assessment later. Also, once the script is written, the BIM specialist only has to run the script with the Dynamo player to automatically perform and export a quantity take-off. Thereby, no intervention in the Dynamo script is necessary which ensures the consistency of the data export because everything is set up in a predefined way. The Dynamo script to extract and export the project data is presented in Appendix D: Data Analytic Codes. The Dynamo script for the material take-off consists of three steps. First, the Revit data is imported from the model. Thereby, it filters only the elements required for the circularity assessment, so only the elements that represent a 3D geometry and contain material quantities. In the second part, the necessary parameters are stored per element and the data structure is organised. Last, the structured data is exported to Excel in a common database environment. For research purposes, only a computer is used as a local database for the extracted Excel files. However, for commercial goals, it is suggested to set up a database management system which can better handle and secure data.

3.3.2. Data processing

The next step of the data analytical layer is to transform the data, which includes filtering, cleaning, formatting and merging the data. These operations are performed in Jupyter Notebook, an open-source web-based development environment supporting Python. Two scripts are written, one to convert the material database to a Keynote text file for the NAA.K.T. classification in Revit, and one to process the project and material data. The steps in the Jupyter Notebooks are explained and attached in Appendix D: Data Analytic Codes.

The first script ensures the consistency of the material classification and creates a keynote for Revit. This script aims to create a consistent name convention for elements in Revit and the materials in the material database. The end product of this script is a text file that lists all the materials in the correct structure and format. This text file is linked to

Revit as a keynote, which gives the BIM specialist the possibility to assign material names to all elements from a drop-down menu and with the correct NAA.K.T. classification code.

The second script performs the data processing. Therefore, a Python library, Pandas, is used to work with multiple datasets. The goal of the script is to clean the datasets, merge the data, and perform the calculations for a BCI assessment. In the end, the processed data is stored as a new file in the database, which is directly ready to import for visualisation and reporting purposes. The following four steps are performed to process the data:

- Import datasets: importing the data is a relatively straightforward function in Pandas because the Revit and material data are stored in Excel. The script automatically recognised different Revit data files in the database folder, so there is no need to manually assign the different files. Next to the Revit and material data, a table is created with scores for the disassembly indicators.
- Clean datasets: this is the process of removing incorrect data or dealing with missing data and is necessary to increase the data quality. In the material data, several elements have missing data. This is expected because this data needs to be constructed based on the aggregation of underlying data of sub-products of an element. The weight, environmental cost indicator, and CO2 emission are determined with the summation of the sub-products, while the technical lifetime is determined based on the minimum lifetime of the sub-products. More important are the model elements that do not have a NAA.K.T. classification and it is impossible to link them with the corresponding material data. It is chosen not to remove or handle this data in Python because the data must be added to the Revit model itself. The model elements with missing values will be kept in the database. However, in the circular design dashboard, the missing data does not contribute to the circularity assessment and the end-user will be alerted to the missing elements and values on the data quality page.
- Merge Datasets: the third step is to merge the Revit and material datasets into one. There are multiple merging types in Pandas. In this case, a left join is applied. This means that all the records of the Revit data are presented, while the material data is attached to it, irrespective of whether the keys in the Revit data can be found in the material data. The unique NAA.K.T. classification codes of both datasets are used as an identifier to join the datasets.
- Calculate BCI: the calculations are performed according to the BCI measurement method of Alba Concepts [3]. There are two things worth mentioning. For the material circularity index per element, the origin of materials and future scenarios of the elements are determined based on the values of the sub-product, in the same way as dealing with the missing values before. Thereby, the environmental cost indicator is used as a weight factor. The second thing is the dataset for the indicative BCI assessment in the schematic design phase. In this dataset, a range of possible product circularity indexes is determined, which are used to establish an expected BCI score.

4. Results

4.1. The proposed decision support system

For the integration of BIM and circularity assessments, a data platform has been set up with an automated connection between BIM and an external material database. The decision support system is an interoperable system that analyses the design to inform decision-making. The concept of the data platform and the used applications are presented in figure. Currently, the data layer and analytical layer both run on a local server. The application layer is in Power BI, which can be used as a Windows desktop application, or as an online 'Software as a Service' with Power BI Service. For the sake of simplicity of this research, the desktop application of Power BI and a local server for BIM is used. However, for business purposes, this can be upgraded to a full cloud-based server hosted on for example Autodesk Construction Cloud and Microsoft Azure.

This system consists of three layers (Fig. 4): the data, analytical, and application layer. The data layer collects the necessary data, the analytical layer accommodates the connection between different data sources, processes the data, and performs the calculations, and the circular design dashboard is developed in the application layer. An automated connection is created between BIM and an external material database. The circularity assessments are performed within the database, and the results are visualised in an interactive and dynamic dashboard to support the decision-making of the end users.

The data collected in the data layer is explained in the previous section. It is important to invest up-front in the quality of the data and to capture the data consistently according to procedures gathered in an IDS to increase the reliability and automation of the assessment. The next part of the system is the analytical layer. This layer involves data analytical operations to extract, clean, merge, and process the data, and perform the circular assessment calculations. For data extraction, Dynamo is used as a plug-in for Revit to export the bill of quantity. Dynamo gives the flexibility to create a uniform quantity take-off at the right level of detail which is most suitable to perform a circularity assessment later.

Next, Python is used to process the project and material data. In this

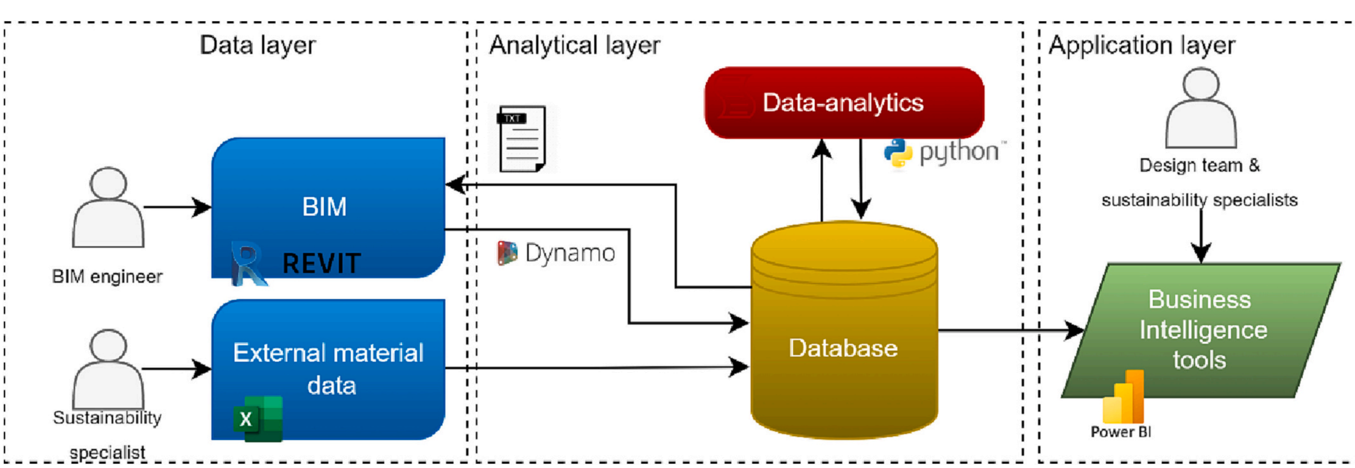

Fig. 4. Decision support system with applications.

process, missing data is coded, stored and registered for model health monitoring. The datasets are merged, and the BCI assessment calculations are performed. In the end, the processed data is stored as a new file in the database, which is directly ready for visualisation and reporting purposes in the next step.

The last step is the development of the circular design dashboard in the application layer. Power BI is used as the application platform to develop the circular design dashboard. The dashboard is the place where all the data comes together and provides important circularity metrics through visualisations to support decision-making. The processed data is imported in Power BI, relationships between tables are created, data transformations are performed with the Power Query Editor, and measures are constructed for dynamic assessment of the BCI. This study applies the involved company's specific approach to the quantity take-off, but different software packages can be adopted by different means based on the upfront analysis.

An important aspect to mention is the bi-directional connection between the BIM environment and the central database. The consistency and uniqueness in the name convention of products is essential in a data platform. The NAA.K.T. classification ensures a uniform and unambiguous material classification. However, consistency and uniqueness are not yet guaranteed. Therefore, a script is written that converts the products in the material database to a material list, readable as a keynote file in BIM. Thereby, each material has its unique NAA.K.T. material classification with the use of a suffix for duplicate names. The keynote file can be imported into the BIM environment which results in a dropdown list to assign a material keynote to design objects. In this way, a unique, uniform, and consistent material classification is created for different applications in the decision support system.

4.2. Circular building design dashboard

The circular design dashboard is the end product of the decision support system. It is where all the data comes together and will be used by the end user as an evaluation tool to steer on circular building design. The dashboard is divided into seven pages:

- Overview,
- Definitions,
- Schematic design evaluation,
- Detailed design evaluation,
- Comparative analysis,
- Building passport,
- Model health monitor.

Two examples are presented in Fig. 5 and Fig. 6 to show the evaluation of schematic and detailed designs respectively. And all the pages of the dashboard can be found in Appendix E: Circular building design dashboard.

The circular design dashboard can be used by the design team to evaluate the circularity performance of alternative design options. The interactive and dynamic nature of the dashboard supports decision-making and can motivate design decisions to clients transparently. The circular design dashboard provides the sustainability specialists with a deeper level of understanding of the degree of circularity, which helps them to identify circular hotspots and to determine effective circular building measures. Furthermore, the data quality of the decision support system is visualised, which contributes to the transparency and reliability of the decision-making process.

For example, the design team and sustainability specialists can analyse the circularity of the building at different levels by filtering on building elements. This can assist in identifying circular hotspots and performing more targeted measures on system or product levels. In addition, the end-user can gain insight into the underlying attributes of the circularity score such as the origin of materials, future scenario and lifetime utility. This gives a more complete view by evaluating specific

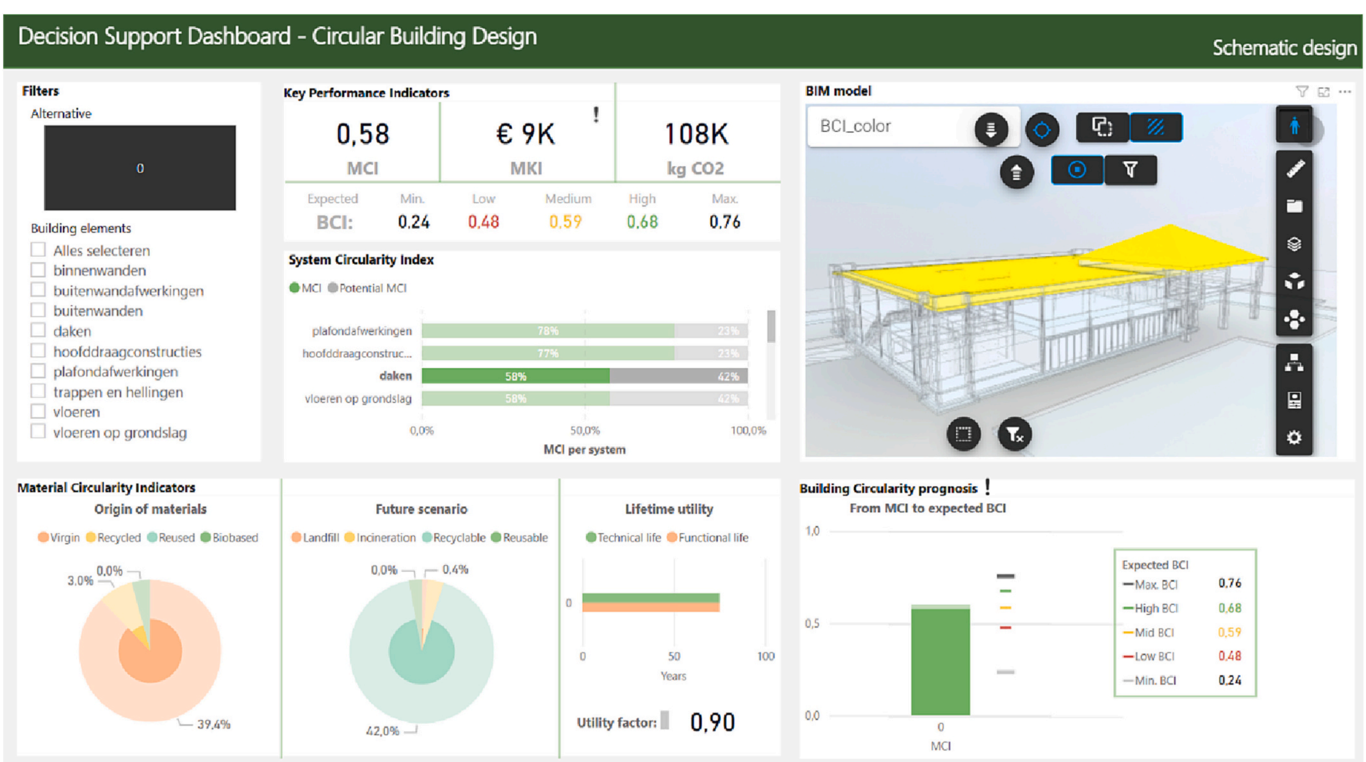

Fig. 5. Circular design dashboard - schematic design page.

Fig. 6. Circular design dashboard - Detailed design page.

circularity measurement indices that each addresses a different area of circularity. Furthermore, the building circularity prognosis provides the design team already an expected BCI score in an early stage of the design when not all information is available, as is explained in chapter 2.2. Building Circularity Assessment Methods.

4.3. Verification and validation

In the analysis phase, interviews are held to identify the end user needs and to map out the desired functions. The intended functionalities are translated into functional and system requirements. Besides functional requirements, there are technical requirements such as performance, safety, and security requirements. In this study, the focus is limited to technical requirements that keep the system up and running, so performance-related requirements. In Appendix A: Program of Requirements, the functional, system, and technical requirements are presented. In the simulation phase, the technical requirements are used to objectively verify the system and the system requirements are used to subjectively validate the end product.

The main focus of the verification process is to assure the correctness of the system and data flow, and that it operates as intended without producing any errors or crashes. The verification process includes all activities associated with the construction of the decision support framework and tests if the decision support system fulfils the technical requirements. The result of the verification, thus the objective scores of the technical requirements, is presented in Appendix A: Program of Requirements. The main takeaways of the verification process are:

- The systems operate almost automatically, while only a few manual procedures must be performed to select the frequency to update the data.
- The frequency of the updates and how to set up the updating procedures can be captured in a BIM protocol.
- The data from different information systems can be integrated seamlessly, while no errors occur during the data processing phases.

Therefore, the decision support system is ready for implementation in the existing data platforms of organisations.

The functional and system requirements are used to validate the decision-support system with the end user. The validation of the functional and system requirements is performed subjectively based on the workshop experience, the feedback rounds, and the questionnaire. However, we do acknowledge the potential bias during the process. The result of the peer reviews for the validation indicates that the decision support system can assist practitioners to steer on circular building design in the early design phase in the following way:

1. Motivate design choices between alternative design options in a transparent way:
   The dashboard allows the end user to substantiate design choices with objective circularity performance indicators. Besides that, the evaluation of the data quality contributes to the transparency and reliability of decision-making.
2. Support the design team with feedback on circular building design in the early design phase:
   The decision support system gives the end user a method, with indicative and provisional BCI, to assess the circularity in the schematic and detailed design phase. Furthermore, the circularity of a building can be assessed as a whole, or for individual building components.
3. Provide sustainability specialists with insight into the degree of circularity of the design:
   The dashboard allows sustainability specialists to investigate the circularity of design options. Especially, the insight into the individual circularity indicators is a great addition because it decomposes the final score and therefore more effective circularity measures can be proposed targeting specific aspects.
4. The user interface of the tool is suitable for the intended audience:
   The user interface of the dashboard is adjusted to the technical skills of the end user. This makes the dashboard user-friendly and simple to use. Furthermore, the interactive and dynamic features of

the dashboard contribute to a better user experience because more detailed analyses can be performed.

5. Discussion

In this chapter the interpretation of the results is discussed, the new insights that are gained based on the evaluation process are presented which leads to the proposal of an improved workflow for circular building design, and the limitations of the research are addressed.

The first aspect of this decision support system is the circularity assessment method. Literature shows that the performance indicators for circularity performance are still under development, while different methodologies are investigating how to systematically and practically assess circular building design [24]. Therefore, the drawbacks or limitations of the assessment methods need to be considered carefully when implementing the decision support system. One of the drawbacks is that even though the BCI measurement method mainly focuses on three aspects: material usage, environmental impact, and disassembly potential, circularity encompasses more aspects than just these three. For example, Platform CB'23 is working on a method to implement value retention with indicators to measure techno-functional and economical value in the form of functional and technical performance of products in multiple design stages. Also, adaptive capacity could play a role in circular building design. Currently, the BCI measurement method includes only the disassembly potential of products in their assessment which focuses more on technical adaptability. Thereby, it does not consider the size of the elements, the complexity of the joints, and the number of connections, which are relevant aspects in terms of adaptive capacity. However, it is beyond the scope of this research to address the flaws of the circularity assessment method itself. For this research, the assessment method of Platform CB'23 and Alba Concepts is considered the most suitable and well-applicable for the Dutch construction industry.

It should be mentioned that during this research new insights came to light regarding the availability of data in the early design phases and the input needed for a BCI measurement method. Although the method focuses on circularity at an early phase of the design process, it does have some irregularities regarding the required and available data per phase. In the schematic design, it is uncommon that the design model includes non-graphical information such as building sequence or disassembly parameters. This makes a sound estimation of the individual parameters to determine the disassembly index of products difficult. In the authors' opinion, the circularity assessment method should be harmonised with the level of information corresponding to a certain design phase. To implement this new insight in the decision support system, the application of the BCI measurement method is slightly adapted to fit the BIM model maturity in the schematic and detailed design phases. This results in the proposed system of performing an indicative and provisional BCI. The reader should be aware that the solution with the indicative and provisional BCI is a proposed solution to tackle the problem of data availability in early design processes, but that the method is not yet theoretically or practically verified.

At the end of the study, the participants of the workshops indicated that they see great potential in the tool, but their main concern for the decision-support system lies in the integration in the current, more linear, design workflow. Currently, it is uncommon to create different design options in BIM and directly evaluate a certain degree of circularity to steer the process. Most of the time, the circularity assessment is performed once the design decisions are made because of the time-consuming process. Therefore, for the successful implementation of this decision-support system, changes in the current design workflow are necessary. This study serves as starting point to rethink the transition into a design workflow for circular building design with the current technological potential. In Fig. 7, an improved workflow for circular building design is proposed. For the transition to a design workflow for circular buildings, two main changes are:

- First, more effort needs to be invested in the development of the models and maintaining a material database early in the process to perform circularity assessments.
- Second, a more iterative workflow is necessary with more collaboration between the design team, BIM, and sustainability specialists to assess the impact of circularity measures throughout the design.

In the end, it will be more time-consuming and costly in the early design phases to develop the BIM model and include circularity components while starting to adopt these tools. On the other hand, if we

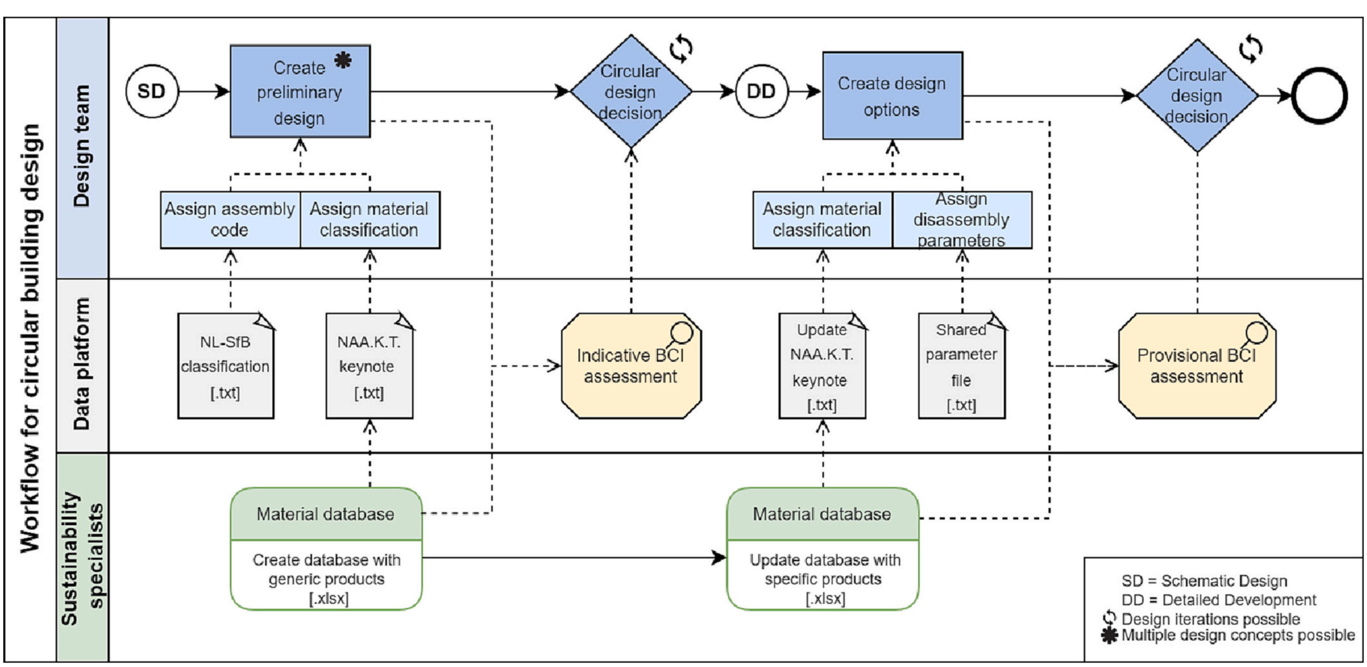

Fig. 7. Proposed design workflow.

want to achieve circularity ambitions, we must invest in the early development of models and the benefits will be achieved later on. The new design workflow makes it possible to perform circularity assessments throughout the design process instead of only after the detailed design when decisions are already made. This means for this research that for the decision-support system to be effective, the design workflow must change first. It would be interesting to see if in the future work processes shift to a circular design workflow, and how the decision-support system would work out in real projects.

One of the limitations of this research is that the developed decision support system uses specific commercial applications. The system uses Autodesk Revit as the main program for the design. This poses limitations if projects are designed with other software. A proposed solution could be to capture and extract BIM-based information as standardised exchange files, such as Industry Foundation Classes (IFC). IFC is an open file format used to facilitate interoperability across different BIM programs. Also, in the application layer Power BI is used for visualising and reporting, which is paid business intelligence software that not every company has. Furthermore, Power BI is integrated with the Microsoft Office 365 environment, so it poses limitations for organisations that do not work with Microsoft. Nevertheless, the concept of the framework can still be implemented within other programs.

Besides that, another limitation faced during the synthesis phase was linking the Revit data with material data from the external material databases, like NMD, NIBE, and Alba Concepts database. It was not feasible to create a direct back-end connection with the material database, so all material data must be transposed manually to a local Excel database. Ideally, a direct link with the external material databases would be constructed, so the material data is always up-to-date, and the sustainability specialist does not have to transpose this manually.

6. Conclusion

This research explores the current workflow and designs an improved workflow by developing an automated decision support system to assess early design phase building circularity that matches the limited available information, aiming to improve the working efficiency and efficacy. The developed decision support system fills in the gap of current circular assessment tools by functioning as a tool to steer on circularity early in the design instead of an assessment at the end of the design phase. The decision support system distinguishes itself by applying a suitable and quantitative circularity assessment with an emphasis on the model maturity and level of information in two early design phases. The adopted BCI measurement method with the indicative and provisional BCI assessment considers the level of information per design phase. The indicative BCI assessment is conducted based on the material usage and an expected range of the disassembly potential, while the provisional BCI is conducted according to the full BCI measurement method with available disassembly parameters. Data analytics is used to deal with the available data and to predict and assess the circularity of the design options.

Technically, the decision support system integrates the necessary information systems and automates the data analytical procedures to reduce manual procedures for circularity assessments. The data layer collects the necessary data, the analytical layer accommodates the connection between different data sources, processes the data, and performs the calculations, and the circular design dashboard is developed in the application layer.

The validation process shows that the decision-support system and circular design dashboard would be a great solution for the end user to steer on circular design with large implementation potential for future projects. The circular design dashboard can be adopted as a steering instrument throughout the design phase instead of just an evaluation tool when decisions already have been made. The dashboard supports the design team by assessing the circularity of design options, it supports and substantiates design decisions, and sustainability specialists can gain insight into the degree of circularity of the design. Moreover, to be effective as a decision support system, the system must operate correctly and as intended. This is verified by the verification process which shows that most of the technical requirements are fulfilled. The automation of the process is guaranteed, while only a few manual procedures have to be performed to update the data frequently.

For successful implementation of the decision support system in the current design practices of companies, it is recommended to include the data input procedures for circularity aspects in the BIM protocol for projects that attach great importance to sustainability and circularity. Furthermore, it is suggested to integrate the data architecture of the decision-support system into the data analytical platform and existing software of the company. The quantity take-off of the project data and the material database must be exported to a central data warehouse within the organisation. The quantity take-off and material database could be used for other analyses as well, so the central data warehouse safeguards a single source of truth. In the data warehouse, data analytical operations can be performed to process the data. With the integration of the decision-support system in the current data analytical platform, the process for automatically assessing circularity can be standardised and centralised for all projects. Lastly, the circular design dashboard should be available for the design team and sustainability specialists as a circular assessment tool.

All in all, the decision support system and circular design dashboard are useful and effective instruments for the design team to enhance circular building design. However, to ensure the implementation of such a system, an improved design workflow is needed to facilitate circular building designs. Currently, the circularity assessment is performed once the design decisions are made because of the time-consuming process of data collection, processing and analysis. Therefore, for the successful implementation of this decision-support system, changes in the current design workflow are necessary. Based on the evaluation of the process, an improved workflow has been proposed to incorporate the automation tool in the circular building design process to facilitate the circular transition in the construction industry.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The code has been provided in the Appendix

Acknowledgement

Special thanks go to BAM Nederland for the opportunity to perform this research. Also, we would like to thank and acknowledge the participants of the workshop and interviews for the time and effort they have devoted to evaluating the decision support system.

Appendix A. Program of requirements

Regarding the technical requirements, a reflection is objectively made by the authors. The assessment of the requirements results in three possible outcomes: does not satisfy the requirement (1), partially satisfies the requirement (2), and fully satisfies the requirement (3). The result of the verification process is presented in Table A1.

Table A1
Verification of the technical requirements.

Subject	Technical requirements	Score
System operation	1. The system runs as intended on existing Revit models	**3**
	2. The system produces no errors during the data analytical procedures	**3**
	3. The system removes manual procedures for circularity assessment	**2**
Integration of data sources	4. The system can extract the project data to a database	**3**
	5. The system can link the material data to the corresponding project data	**3**
	6. The system can process the data and perform circularity calculations	**3**
	7. The circular design dashboard can import the data from the database and update the visualisations frequently	**3**
	8. The circular design dashboard can visualise the 3D Revit model	**3**
Data analytic performance	9. The system can regenerate the circularity assessment dynamically	**3**
	10. The system can verify the data quality of the system	**3**
	11. The end user can change and play with the weight factor of the BCI measurement method	**1**
	12. The end user can filter the data in the circular design dashboard according to their needs	**3**
Design workflow	13. The system separates the data input and responsibilities from different disciplines	**3**
	14. End user has access to the data from intermediate steps to control the input data	**2**

The validation of the functional and system requirements is performed subjectively. The requirements are ranked by the participants as follows: fail (1), moderate (2), pass (3), good (4), and excellent (5). The final score per requirement is the average score of all the participants. The result of the validation process is presented in Table A2.

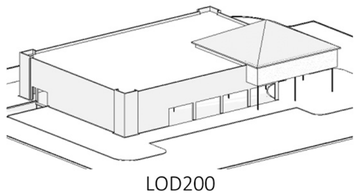
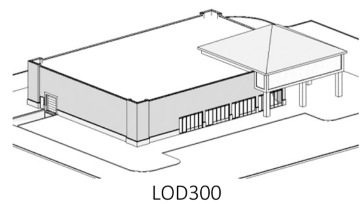
Table A2
Results validation.

Functional requirements	System requirements	Score
1. Motivate design choices between alternative design options in a transparent way	1.1. The tool substantiates design decisions and stimulates the discussion process	4.2
	1.2. The tool evaluates multiple design options with circular design trade-offs	4.5
	1.3. The tool involves stakeholders through dynamic and interactive reports in a transparent way	4.1
2. Support the design team with feedback on circular building design in the early design phase	2.1. The tool facilitates steering on circular design early in the design process	4.1
	2.2. The tool assesses the building circularity score in a quantitative way	4.5
	2.3. The tool evaluates the circularity for the building as a whole, as well as for specific building components	4.5
	2.4. The tool gives insight into the reliability of the data	4.0
3.Provide sustainability specialists insight into the degree of circularity of the design	3.1. The tool analyses the individual circularity aspects of the design: the material flow, disassembly potential, environmental impact, and lifespan of materials	4.4
	3.2. The tool identifies circular hotspots, both positive and negative	4.3
	3.3. The end user can specify certain data for comprehensive and detailed analysis	4.3
4. The interface of the tool is suitable for the intended audience	4.1. The tool is user-friendly with an intuitive interface	4.1
	4.2. The tool is applicable for non-experts without technical skills or knowledge of the software	4.4

Appendix B. Template material data

Asssembly Code	Phase	Category NMD	Producttype	Element code	Product	NAA.K.T	Unit	Weight [kg/unit]	MKI [€/unit]	CO2 [kg/unit]	Virgin material [%]	Reused material [%]	Recycled material [%]	Biobased material [%]	Landfill material [%]	Incineration material [%]	Recycleable material [%]	Reusable material [%]	Technical lifetime
21.22	Developed	3	Product		Betonsteenmetselwerk; incl. stucwerk	steenachtig_baksteen_generiek	m2												
21.22	Developed	3	Product		Baksteenmetselwerk; incl. stucwerk	steenachtig_baksteen_generiek	m2												
31.20	Developed	3	Element	1	Prefabricated curtain wall element	glas_helder_element	m2												
32.20	Developed	3	Subproduct	1	HR (dubbel) glas; coating, 4/12/4 mm	glas_helder_generiek	m2												
28.11	Developed	2	Product		HEA 120; verzinkt	metaal_staal_profiel	m												

Appendix C. Revit model characteristics for design options

Characteristics	Schematic design	Detailed design
Alternatives Level of Detail	Alternative 0  LOD200	Alternative 1 & 2  LOD300
Design output	Basic alternative modelled as generic elements with approximation of quantities, shape and orientation	Specific design options with specific elements and accurate sizes, shapes and oriantation
Model building elements	• Foundation • Floor • Roof • External & internal walls • Load-bearing structure • Stairs and ramps	• Foundation • Floor • Roof • External & internal walls • Load-bearing structure • Stairs and ramps • Doors & windows • Wall, floor, ceiling, and roof finishing
Non-graphical information & parameters	• Assembly code • NAA.K.T. classification • Functional lifetime	• Assembly code • NAA.K.T. classification • Type of Connection • Accessibility of Connection • Cross-Through • Form confinement • Functional lifetime
Material properties	Generic material properties for global building elements	Product specific properties for accurate building elements

Appendix D. Data analytic codes

Dynamo script

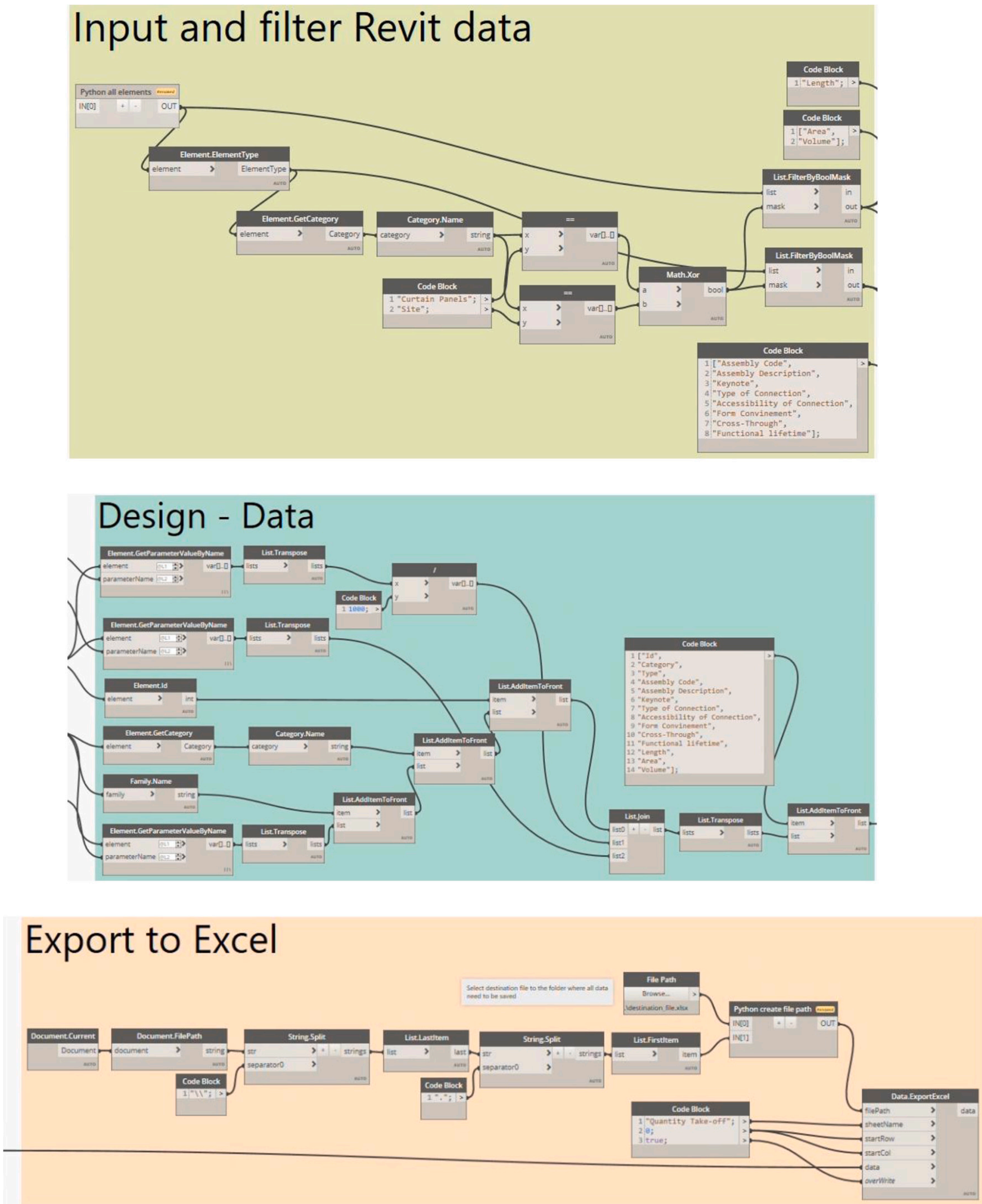


Fig. D1. Data extraction script - Dynamo.

Jupyter Notebooks

Creating Revit material textfile

The goal of this Python script is to transpose the material database to a Revit keynote file. In this way, all the materials can be assigned as a material classification parameter in Revit with a drop-down menu.

In [1]:
```
import pandas as pd
import numpy as np
```

Import data

Import material database and convert NAA.K.T classification to unique element NAA.K.T. classification by creating a suffix for all duplicate material classifications.

In [2]:
```
database = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv
```

In [3]:
```
options = ['Product', 'Element']
data = database[database['Producttype'].isin(options)]
```

In [4]:
```
uniq = np.unique(data['NAA.K.T'])

for i in uniq:
    count = 0
    base = i
    for row in data.itertuples():
        if data.at[row.Index, 'NAA.K.T'] == base:
            data.at[row.Index, 'NAA.K.T'] = base + '_' + str(count)
            count = count + 1
```

Create textfile for material list in Revit

Create a text file which can be linked as keynote in Revit. The setup is in layers in order to create the drop-down feature.|

Layer 1: lowest layer of the text file with all the individual material classifications

n [12]:
```
data.loc[data['Phase'] == 'Schematic', 'Placeholder'] = '0_' + data.loc[data['Phase
data.loc[data['Phase'] == 'Developed', 'Placeholder'] = '1_' + data.loc[data['Phase
```

In [6]:
```
file1 = data[['NAA.K.T', 'Product', 'Placeholder']]
```

Layer 2: the intermediate layer to categorise all the individual products based on the name and characteristcs/application

In [7]:
```
uniq_ph = np.unique(file1['Placeholder'])
data_txt = []

for i in uniq_ph:
    data_txt.insert(0, {'NAA.K.T':i, 'Product':'','Placeholder':"_".join(i.split("_

file2 = pd.DataFrame(data_txt)
```

Layer 3: the highest layer to categorise all the products based on the design phase

In [8]:
```
uniq_ph2 = np.unique(file2['Placeholder'])
data_txt2 = []

for i in uniq_ph2:
    if i[0] == '1':
        data_txt2.insert(0, {'NAA.K.T':i, 'Product':'','Placeholder':'Developed de:
    else:
        data_txt2.insert(0, {'NAA.K.T':i, 'Product':'','Placeholder':'Schematic de:

data_txt2.insert(0, {'NAA.K.T':'Developed design', 'Product':'','Placeholder':''})
data_txt2.insert(0, {'NAA.K.T':'Schematic design', 'Product':'','Placeholder':''})

file3 = pd.DataFrame(data_txt2)
```

In [9]:
```
txtfile = pd.concat([file3, file2, file1])
```

Export the data

In [10]:
```
txtfile.to_csv('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv/Document:
```

Example of the txtfile. This is the correct format for a Revit keynote file which creates a drop-down window with the material list.

In [11]:
```
txtfile
```

Out[11]:

	NAA.K.T	Product	Placeholder
0	Schematic design		
1	Developed design		
2	1_steenachtig		Developed design
3	1_metaal		Developed design
4	1_hout		Developed design
...	...	...	...
32	hout_zachthout_generiek_0	Europees zachthout; massief, gelamineerd; db [...	1_hout_zachthout
33	glas_helder_element_1	Prefabricated window element [inside]	1_glas_helder
36	beton_generiek_ihw_0	In situ betonvloer, 20% puingranualaat; incl. ...	1_beton_generiek
37	hout_hardhout_generiek_0	Dak elementen, houten ribben, steenwol, spaanp...	1_hout_hardhout
38	metaal_staal_element_3	Systeemwand met driedubbele rogipsplaat en ste...	1_metaal_staal

67 rows × 3 columns

Python data processing

The goal of this Python script is to proces the data in the database. Thereby, the different datasets will be merged and cleaned. Also, the Building circularity assessment calculations are performed.

In [1]:
```
import pandas as pd
import numpy as np
import os
import fnmatch
```

Import material and Revit data from database

Import material data, rename columns, and create subsets for the element and corresponding subproduct data

In [2]:
```
database = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv
database = database.rename(columns = {'MKI':'MKI_unit','CO2':'kgCO2_unit','Materia
```

In [3]:
```
options = ['Product', 'Element']
data = database[database['Producttype'].isin(options)]
subdata = database[database['Producttype'].isin(['Subproduct'])]
```

Create unique material classification codes for all products: NAA.K.T. classification

In [4]:
```
uniq = np.unique(data['NAA.K.T'])

for i in uniq:
    count = 0
    base = i
    for row in data.itertuples():
        if data.at[row.Index, 'NAA.K.T'] == base:
            data.at[row.Index, 'NAA.K.T'] = base + '_' + str(count)
            count = count + 1
```

Import the Revit data (Excel-files extracted with Dynamo). The script automatically searches for all Revit data files in the folders.

In [5]:
```
#Locate all Revit files in the folder where Revit data is exported
directory_path = 'C:\\Users\\marco.vander.zwaag\\OneDrive - Royal BAM Group nv\\Do
folder = os.listdir(directory_path)
filenames = fnmatch.filter(folder, '*.xlsx')
```

In [6]:
```
revitdata = {}
for i in range(len(filenames)):
    file = os.path.join(directory_path, filenames[i])
    df = pd.read_excel(file, sheet_name='Quantity Take-off')
    df['filename'] = filenames[i]
    revitdata[i] = df

revit = pd.concat(revitdata, ignore_index=True)
revit = revit.rename(columns = {'Keynote':'NAA.K.T','Length':'Length_m', 'Area':'A
```

Import additional tables Creating a table with the parameters and scores of the disassembly index according to the BCImeasurement method of Alba Concepts.

In [7]:
```
AC = {'Code':['AC1','AC2','AC3','AC4','AC5'], 'AC_score':[1.0,0.8,0.6,0.4,0.1]}
TC = {'Code':['TC1','TC2','TC3','TC4','TC5'], 'TC_score':[1.0,0.8,0.6,0.2,0.1]}
CT = {'Code':['CT1','CT2','CT3'], 'CT_score':[1.0,0.4,0.1]}
FC = {'Code':['FC1','FC2','FC3'], 'FC_score':[1.0,0.4,0.1]}
df_TC = pd.DataFrame(TC)
df_AC = pd.DataFrame(AC)
df_CT = pd.DataFrame(CT)
df_FC = pd.DataFrame(FC)
```

Import data to specify the alternatives and corresponding Revit models, and the disassembly range for the indicative BCI assessment.

In [8]:
```
LOD = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BAM Group nv/Doc
disassembly_range = pd.read_excel('C:/Users/marco.vander.zwaag/OneDrive - Royal BA
LOD['filename'] = LOD['Sourcefile'].str.rsplit('.', 1, expand=True).rename(lambda 
```

Clean data

Data cleaning by creating unique element data, and identifying and fixing the incomplete datasets. Creating a unique Id for all data by adding the alternative number to the Revit element Id.

In [9]:
```
revit['filename'] = revit['filename'].str.rstrip('.xlsx')
```

In [10]:
```
revit["Id"] = revit["Id"].astype(str) + '_' + revit['filename']
```

Identifying missing data in the two datasets: material data and revit data

In [11]:
```
data[data.isnull().any(axis=1)].head()
```

Out[11]:

	Asssembly Code	Phase	Category NMD	Producttype	Element code	Product	NAA.K.
0	00.01.1	Schematic	3	Product	NaN	Betonmortel C20/25 XC2, 0% puingranulaat, CEM ...	beton_generiek_ntb_
1	00.01.2	Schematic	3	Product	NaN	Betonmortel C30/37 XC2, 0% puingranulaat, CEM ...	beton_generiek_ntb_
2	00.01.3	Schematic	3	Product	NaN	Baksteen [Kilogram basisprofiel bij levensduur...	steenachtig_generiek_ntb_
3	00.01.4	Schematic	3	Product	NaN	Europees naaldhout; duurzame bosbouw [Kilogram...	hout_generiek_ntb_
4	00.01.5	Schematic	3	Product	NaN	Europees loofhout; duurzame bosbouw [Kilogram ...	hout_generiek_ntb_

Not all material has element codes because only this is only assigned to elements and subproducts, so this is not a problem. Furthermore, the material data has no value for elements because elements are a group of subproducts. Therefore, the missing element values can be determined based on aggregations of subproducts.

Filling in the missing values for elements regarding technical lifetime, total weight, MKI and CO2 per unit. The weight, MKI, and CO2 is based on underlying subproducts of the elements. For the technical lifetime, the BCI measurement method suggest to choose the minimum lifetime of the individual subproducts

In [12]:
```
#Fill in the technical lifetime, total weight, MKI, and CO2 per unit for all the e
elements = np.unique(subdata['Element code'])

for i in elements:
    data.loc[data['Element code'] == i, 'Weight_kg/unit'] = sum(subdata.loc[subdat
    data.loc[data['Element code'] == i, 'MKI_unit'] = sum(subdata.loc[subdata['Eler
    data.loc[data['Element code'] == i, 'kgCO2_unit'] = sum(subdata.loc[subdata['E
    data.loc[data['Element code'] == i, 'Tech_lifetime_yr'] = min(subdata.loc[subd
```

For the revit data, it is expected that there is missing data in the columns of Length, area, or volume because not all elements have both parameters. More important is the missing data that does not have an assembly code or NAA.K.T. classification. This data could not be fixed in Python, because it is project dependent and the BIM specialist has to upgrade the model. Moreover, the data will not be removed because it is important in the next stage (reporting in Power BI) to visualise the data quality.

In [13]:
```
revit.info()
```

```
<class 'pandas.core.frame.DataFrame'>
RangeIndex: 408 entries, 0 to 407
Data columns (total 15 columns):
 #   Column                      Non-Null Count  Dtype
---  ------                      --------------  -----
 0   Id                          408 non-null    object
 1   Category                    408 non-null    object
 2   Type                        408 non-null    object
 3   Assembly Code               400 non-null    float64
 4   Assembly Description        400 non-null    object
 5   NAA.K.T                     400 non-null    object
 6   Type of Connection          306 non-null    object
 7   Accessibility of Connection 306 non-null    object
 8   Form Convinement            306 non-null    object
 9   Cross-Through               306 non-null    object
 10  Functional lifetime         408 non-null    int64
 11  Length_m                    327 non-null    float64
 12  Area_m2                     318 non-null    float64
 13  Volume_m3                   389 non-null    float64
 14  filename                    408 non-null    object
dtypes: float64(4), int64(1), object(10)
memory usage: 47.9+ KB
```

In [14]:
```
revit[revit['NAA.K.T'].isnull()].head()
```

Out[14]:

	Id	Category	Type	Assembly Code	Assembly Description	NAA.K.T	Type of Connection
114	191870_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
115	191872_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
116	191880_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
117	191882_Basemodel_LOD300	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN
271	191870_Basemodel_LOD300_2	Doors	Curtain Wall Sgl Glass	NaN	NaN	NaN	NaN

Merging data

Replacing the disassembly factor codes in the Revit data with corresponding values from the disassembly dataframe

In [15]:
```
data_frames = [df_AC, df_TC, df_CT, df_FC]
```

```
columns = ['Accessibility of Connection', 'Type of Connection', 'Cross-Through', 'I

for i in range(4):
    revit = pd.merge(revit, data_frames[i], left_on= columns[i], right_on='Code', I

revit.drop(['Code_y','Code_x'], inplace=True, axis=1)
```

```
C:\Users\marco.vander.zwaag\AppData\Local\Temp\ipykernel_16576\654153352.py:5: Fut
ureWarning: Passing 'suffixes' which cause duplicate columns {'Code_x'} in the res
ult is deprecated and will raise a MergeError in a future version.
  revit = pd.merge(revit, data_frames[i], left_on= columns[i], right_on='Code', ho
w='left', suffixes=('_x', '_y'))
```

Merge the revit quantity take-off datasets and material data

In [16]:
```
#Merge circular data on revit data
merged = pd.merge(revit, data, left_on='NAA.K.T', right_on='NAA.K.T', how='left')
```

Merge the data with corresponding LOD

In [17]:
```
merged = pd.merge(merged, LOD, left_on='filename', right_on='filename', how='left'
```

Building circularity assessment (calculations)

Data processing of the merged database. The existing database is extended with calculated columns necessary for the circularity assessment.

It is determined what the value is of the corresponding unit of the products. For example, in the material database is the unit for hollow core slabs in m2, so the function calls the area as quantitiy as unit measurement

In [18]:
```
def unit_measure(df):
    if df['Unit'] == 'm':
        return df['Length_m']
    elif df['Unit'] == 'm3':
        return df['Volume_m3']
    elif df['Unit'] == 'm2':
        return df['Area_m2']
    elif df['Unit'] == 'unit':
        return 1

merged['unit_measure'] = merged.apply(unit_measure, axis = 1)
merged['Weight_kg'] = round(merged['unit_measure'] * merged['Weight_kg/unit'], 1)
merged['MKI_eu'] = round(merged['unit_measure'] * merged['MKI_unit'], 1)
merged['CO2_kg'] = round(merged['unit_measure'] * merged['kgCO2_unit'], 1)
```

Calculations of the parameters for BCI. The LFI for elements is determined with the MKI of subproducts as weightfactor.

In [19]:
```
#Calculate FX value per product
merged['FX'] = 0.9 / (merged['Tech_lifetime_yr'] / merged['Functional lifetime'])
```

In [20]:
```
#Calculate LFI value per product and per element
merged.loc[pd.isna(merged['Element code']), 'LFI_p'] = (merged['Virgin_material_%'

for i in elements:
    df = subdata[subdata['Element code'] == i]
    df = df.reset_index()
```

```
    MKI_numerator = 0
    MKI_denominator = 0
    for index, row in df.iterrows():
        MKI_numerator = MKI_numerator + row['MKI_unit']*row['Virgin_material_%'] +
        MKI_denominator = MKI_denominator + row['MKI_unit']
    merged.loc[merged['Element code'] == i, 'LFI_e'] = 1/MKI_denominator * MKI_num
```

```
In [21]: #Calculate MCI value per product and element
merged['MCI_p'] = np.maximum(0, (1.0 - merged['LFI_p'] * merged['FX']))
merged['MCI_e'] = np.maximum(0, (1.0 - merged['LFI_e'] * merged['FX']))
```

```
In [22]: #Calculate Disassembly Index per product and element
merged['LIs'] = 2 / (1/merged['AC_score'] + 1/merged['TC_score'])
merged['LIc'] = 2 / (1/merged['CT_score'] + 1/merged['FC_score'])
merged['DisassemblyIndex'] = 2 / (1/merged['LIc'] + 1/merged['LIs'])
```

```
In [23]: #Calculate PCI
merged['PCI'] = np.sqrt(merged['MCI_p'] * merged['DisassemblyIndex'])
```

```
In [24]: #Calculate ECI
merged['ECI'] = np.sqrt(merged['MCI_e'] * merged['DisassemblyIndex'])
```

Calculations of the origin of materials and future scenario in kg per product.

```
In [25]: #Transform the origin of materials and future scenario from % to kg per product
transform = ['Virgin_material_%','Reused_material_%','Recycled_material_%','Biobas
transform_kg = ['Virgin_material_kg','Reused_material_kg','Recycled_material_kg','
transform_unit = ['Virgin_material_unit','Reused_material_unit','Recycled_material

for i in elements:
    df = subdata[subdata['Element code'] == i]
    df = df.reset_index()
    for j in range(len(transform)):
        kg_material = 0
        weight_total = 0
        for index, row in df.iterrows():
            kg_material = kg_material + (row['Weight_kg/unit']*row[transform[j]])/
            merged.loc[merged['Element code'] == i, transform_unit[j]] = kg_materi
```

```
In [26]: for i in range(len(transform)):
    merged.loc[pd.isna(merged['Element code']) ,transform_kg[i]] = round(merged[tr
    merged.loc[merged['Element code'] > 0 ,transform_kg[i]] = round(merged[transfo
```

Drop unnecessary columns

```
In [27]: merged = merged.drop(['Virgin_material_unit','Reused_material_unit','Recycled_mate
```

Disassembly range

Calculations for the indicative BCI assessment which uses a range of disassembly scenarios to estimate the expected circularity in the schematic design phase.

```
In [28]: data_range = merged.loc[merged['LOD'] == 'LOD200', ['Id','MKI_eu', 'LOD', 'MCI_p']
```

```
In [29]: data_range = pd.merge(data_range, disassembly_range, left_on='LOD', right_on='LOD'
```

```
In [30]: data_range['PCI_min'] = np.sqrt(data_range['MCI_p'] * data_range['Min. DI'])
```

```
data_range['PCI_low'] = np.sqrt(data_range['MCI_p'] * data_range['Low DI'])
data_range['PCI_medium'] = np.sqrt(data_range['MCI_p'] * data_range['Medium DI'])
data_range['PCI_high'] = np.sqrt(data_range['MCI_p'] * data_range['High DI'])
data_range['PCI_max'] = np.sqrt(data_range['MCI_p'] * data_range['Max. DI'])
```

```
In [31]: data_range = data_range.drop(['LOD', 'Min. DI', 'Low DI', 'Medium DI', 'High DI',
```

Export of the data

Export the data in Excel in the database. The processed data is captured in the main data sheet and the data ranges for the indicative BCI in the data range sheet.

```
In [32]: output = 'C:\\Users\\marco.vander.zwaag\\OneDrive - Royal BAM Group nv\\Documents\'

         with pd.ExcelWriter(output) as writer:
             merged.to_excel(writer, sheet_name="main_data", index=False, header=True)
             data_range.to_excel(writer, sheet_name="data_range", index=False, header=True)
```

Appendix E. Circular design dashboard

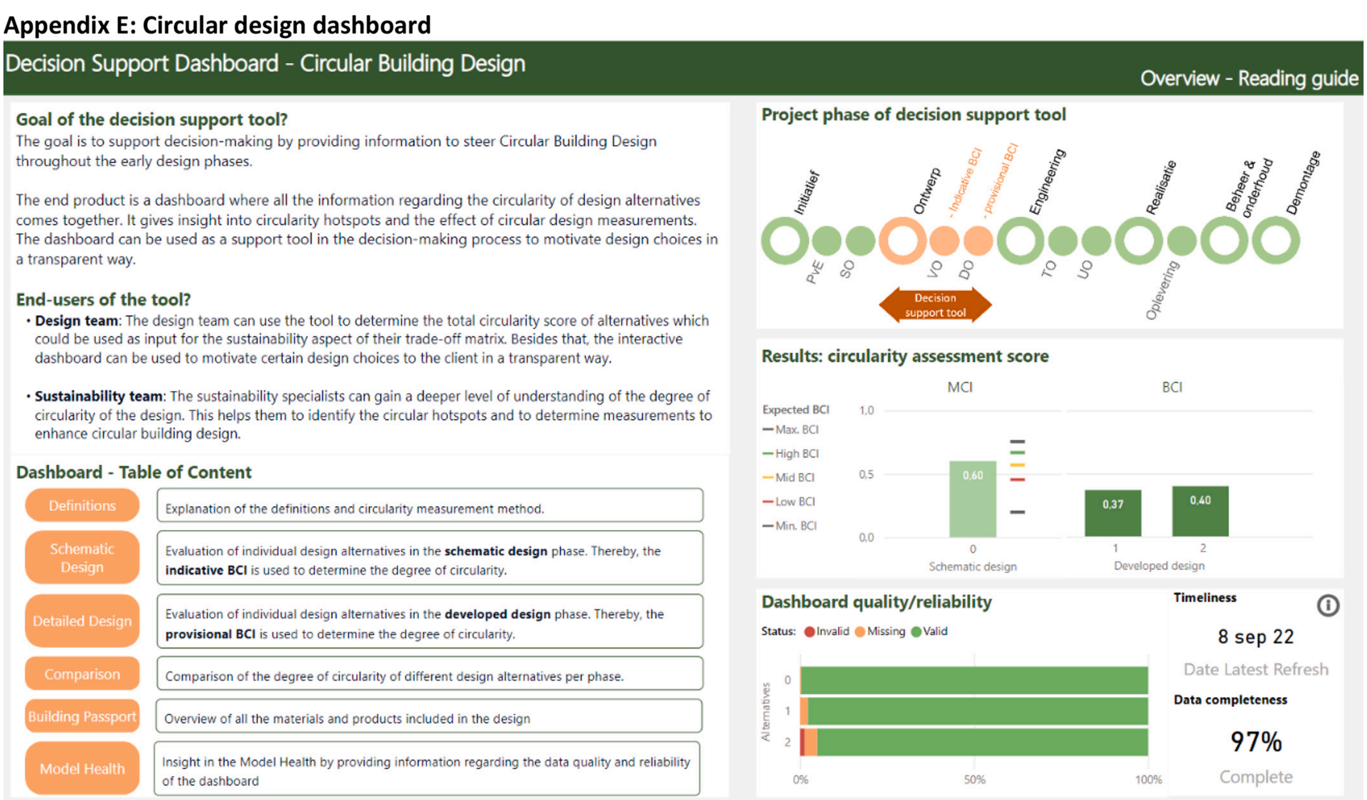


Fig. E1. Overview page.

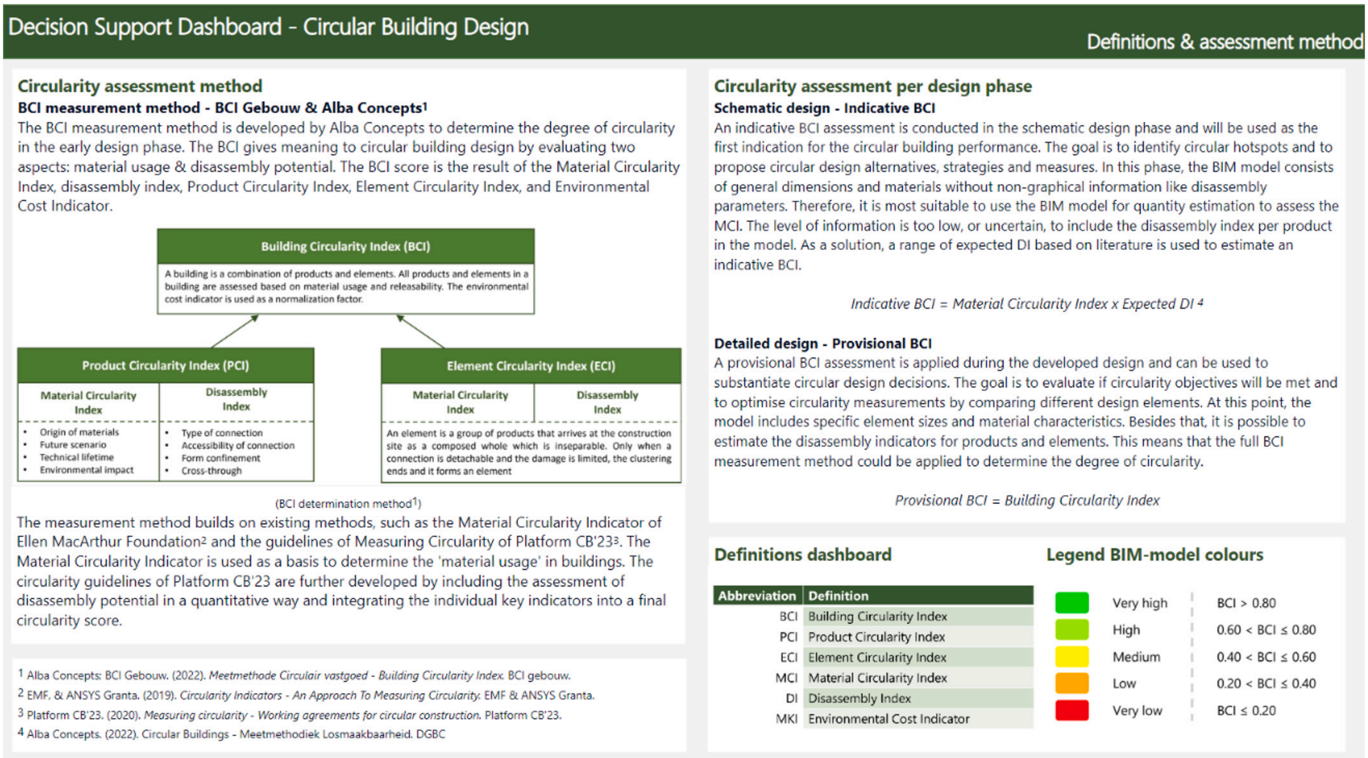


Fig. E2. Definitions page.

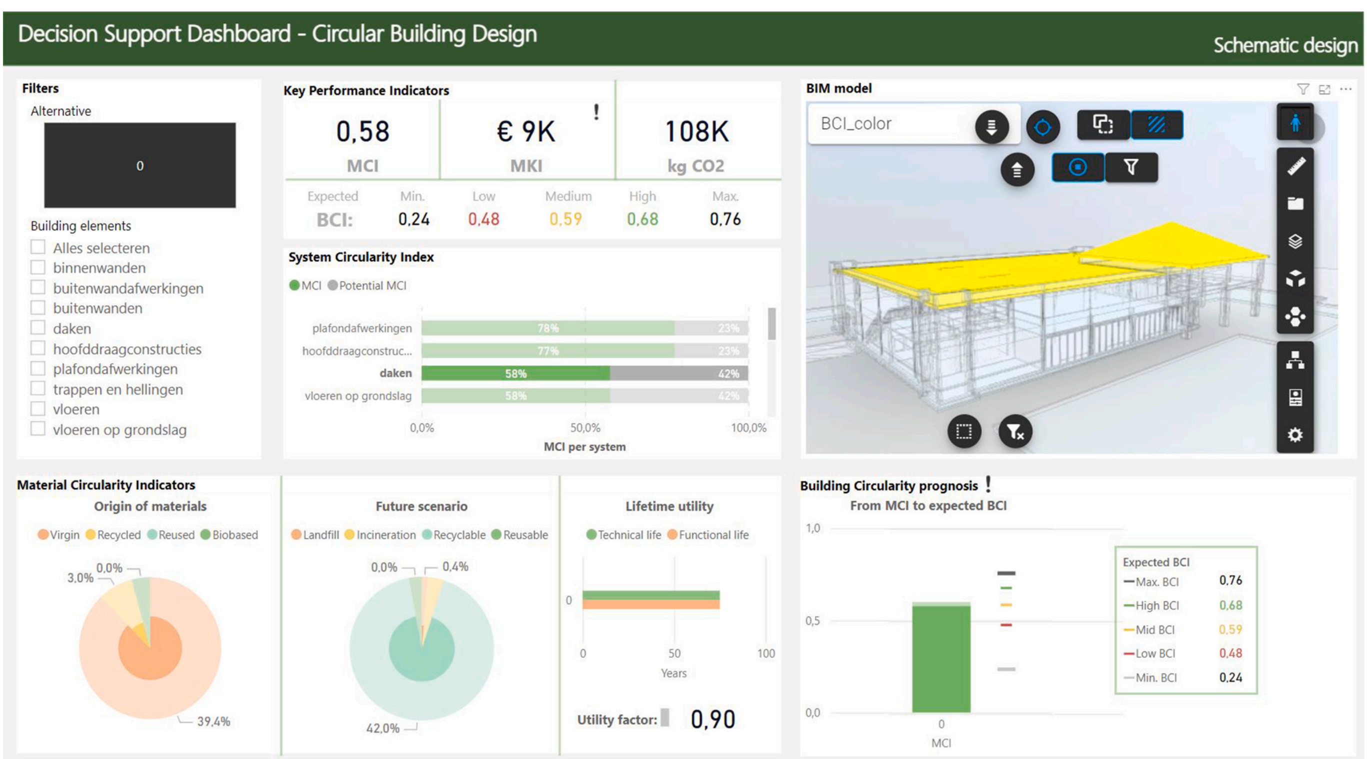


Fig. E3. Schematic design page.

Fig. E4. Detailed design page.

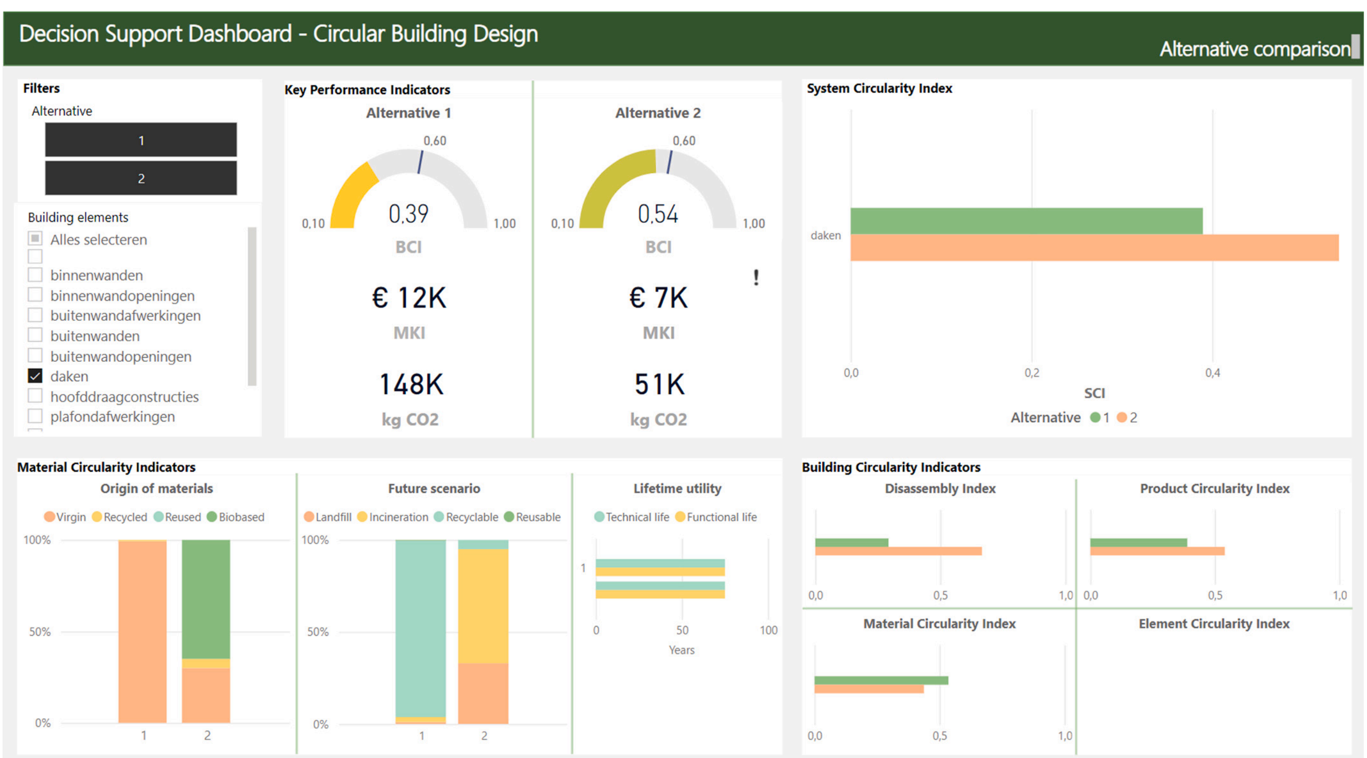


Fig. E5. Comparative analysis page.

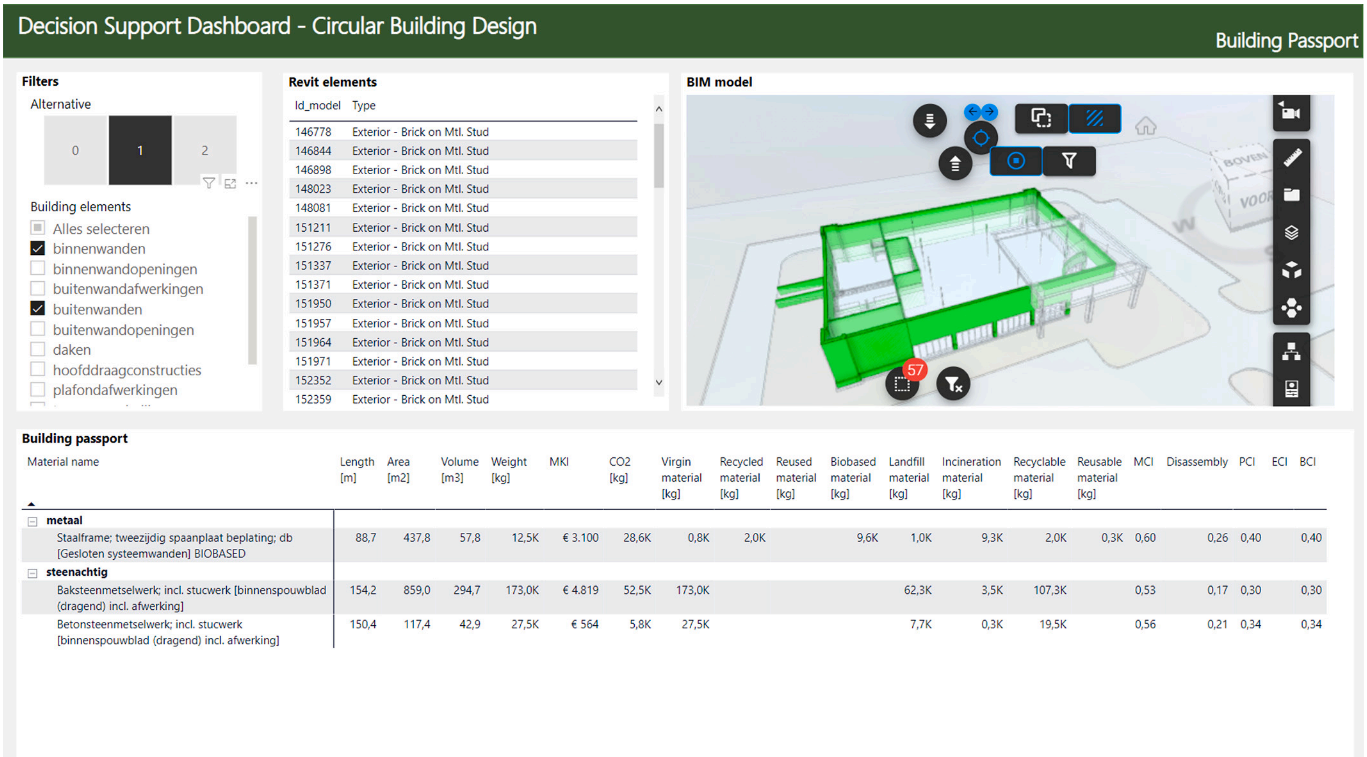


Fig. E6. Building Passport page.

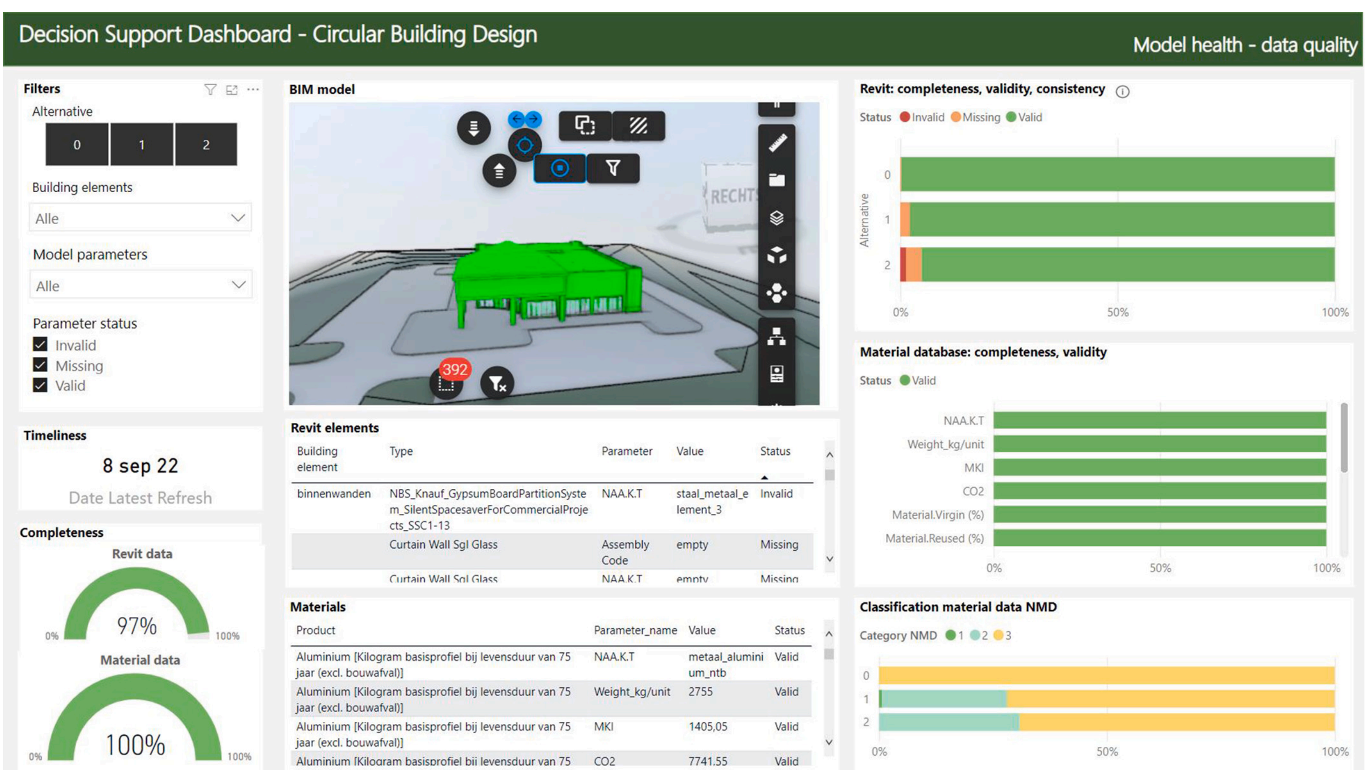


Fig. E7. Model health page.

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