Circularity Assessment in a BIM Environment

EngD Thesis

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Preface

This report represents the final deliverable of my EngD project, which I have dedicated the past two years to working on. It covers the design methodology, literature background, and explanation of the design solutions of the project. Although the design artefact - the BIM-based circularity assessment tool is not included in this report, the main findings and design architecture are discussed thoroughly in this report.

While only my name appears on the front page, I want to acknowledge the contributions of many others without whom this project would not have been possible. First and foremost, I would like to express my gratitude to my university supervisors, Dr. Ir. M.C. (Marc) Van den Berg, Dr. J.T. (Hans) Voordijk, and Prof. Dr. Ir. A.M. (Arjen) Adriaanse. Your guidance, expertise, and valuable insights throughout my research journey have been truly invaluable. Your positive affirmations and constant encouragement have been a source of motivation for me.

Secondly, I extend my appreciation to my external supervisors: Rob and Frank from the University of Twente (Campus Facility and Management) and Willem from DigiGo. I cannot thank you enough for your willingness to help and support me throughout the research project. Your prompt responses and assistance have been invaluable, and I have enjoyed our conversations about both the project and our personal life. Moreover, a long list of experts generously shared their insights and ideas for this project and provided me with valuable information and data which are prerequisites for me. While it may not be feasible to individually acknowledge each and every one of you, I deeply appreciate your kind help.

Thirdly, I want to express my gratitude to all my colleagues and friends from the Department of Construction Management and Engineering, especially those in room Z202-204. Working with you has been a big pleasure over the past two years, and I have gained so much joy and enthusiasm from our conversations and social events.

Lastly, I want to give my deepest appreciation to my boyfriend, Jason, and our family. Your support and encouragement have been a constant source of motivation for me. I am grateful for your unwavering love, support, and understanding, which have been vital to my success. I cannot express my appreciation in an adequate way, but I love you all and thank you very much.

I hope you enjoy reading this report.

Li Jiang

April 25th, 2023
Executive summary

The construction industry is in the transition from a linear to a circular economy (CE) where economic growth is decoupled from materials extraction. The increasing interest in CE requires construction companies to identify transition strategies, which entails an understanding of their circular performance along with the associated risks and opportunities. Furthermore, the construction industry has witnessed a surge in information-centric approaches, which has encouraged the development of Building Information Modelling (BIM), providing the possibilities for incorporating various analyses. Hereby, with the growing societal relevance of a CE, BIM technologies can be incorporated into CE-driven research, to facilitate the development of circularity assessment methods for monitoring and quantifying the progress toward a CE in a BIM environment.

Problem context and project goals: However, although several BIM-based methods are available for measuring the circularity performance of construction assets, most of them have not specified the requirements regarding the LOD (Level of development) of BIM models, or limit themselves to conducting a circularity assessment in a specific project phase. In essence, these methods are not flexible enough to accommodate the different levels of information availability across different phases of construction. This often results in a one-size-fits-all calculation method that may rely on subjective assumptions from project stakeholders, especially in early project phases where information is limited. To identify opportunities and facilitate circular designs, project stakeholders require timely and relevant information in different project phases of a building process. Hereby, the objective of this EngD project is to: Develop a prototypical BIM-based tool to assess the actual circularity performance of construction projects in different project phases.

Methods: In this study, the BIM-based circularity assessment tool was iteratively developed following the steps of design science research methodology. Following this methodology, this study follows three iterative design cycles with several interrelated steps, namely, Problem Identification, Treatment Design, Treatment Validation and Treatment Implementation. Two case projects, a renovation and a new-build project, located in the Netherlands, were selected for the study. Stakeholders from different design disciplines and client representatives have collaborated over the course of the project through meetings, interviews and presentations.

Specifically, initialized by the problem identified before, the development of the tool was guided by requirements summarised from a literature review and also driven by “design requirements” translated from stakeholders’ needs. Specifically, these “design requirements” progressed from high-level needs to a more detailed examination of requirements in Treatment Design. Simultaneously, the tool’s development also generates knowledge regarding information management and circularity assessment, which serves as ancillary knowledge in this study. Validating the assessment tool was achieved through the step of Treatment Validation based on a case demonstration and user-based interviews in each iteration of the design cycle. Last but not least, in line with the stakeholders’ requirements, the step of Treatment Implementation centred around activity theory, aims to develop new workflows as by-products, which can support the integration of the tool into the case projects.

Main Results: This study commenced by examining current approaches utilized by stakeholders and corresponding challenges inherent in the case projects, with the primary objective of offering insights into the domains of information management and open standards. To enhance information management practices, the recommendations set forth in this study entail the integration of European Technical Information Model (ETIM) standards and the development of mapping tables to facilitate unambiguous communication among different standards. This study also developed three calculation models considering different levels of information availability, leveraging a circular project model. These models were tailor-made for different project phases namely initial phases (approximately with LOD (Level of Development) ≤ 200), design phases (200 < LOD ≤ 350), and construction phases (LOD > 350/400). Drawing on the potential of BIM, they were then digitized as a prototypical BIM-based circularity assessment tool. Considering the project goal in support of a circularity assessment...
throughout different project phases where different BIM-authoring software may be used, the tool was designed as a standalone application using IFC (Industry Foundation Classes) as an information carrier. Moreover, the BIM-based tool’s development adhered to the structure of the IPO model (Input-Processing-Output) as depicted below.

1) The input component concerns information identification and structurization, where the requisite information was categorized into product-specific information (stored in BIM models) and generic information (extracted from an external database). The utilization of diverse open standards and guidelines, such as NL-SfB, NAA.KT and ETIM, is needed for effective information management in support of circularity assessments.

2) The processing component is based on three tailor-made calculation models, which are automatically selected based on the amount of available information in a BIM model/IFC file(s) provided by users.

3) The output component presents circularity insights via a Graphic user interface (GUI), including 3D colour-coding and 2D analysis charts. The corresponding circularity insights vary according to the selected calculation model, with more insights presented as more information becomes available over the course of a construction project.

Contributions and Future Work:

This study enriches knowledge about information management and standards utilization pertaining to circularity-related information. Specifically, the study explores the utilization of diverse open standards for structuring such information. Additionally, the study makes a scientific contribution by providing insights into circularity assessment under different levels of information availability. It thus provides project stakeholders with timely and relevant information to make circularity-related decisions in different phases of a building process. Another contribution of this study is a practical tool for digitizing the assessment process utilizing BIM’s capabilities of holding customized information. The tool also exhibits a high degree of intuition with a GUI to enhance user experience. Furthermore, it is noteworthy that the tool has the potential to work complementary with the existing method under the context of the case projects. In future research, it is recommended to focus on the validation of the calculation models. Furthermore, efforts should be directed towards developing operational tools by developing a supportive database (which contains circularity-related information), and analyzing and testing the developed solutions in other construction projects. Additionally, the creation of an integrated decision-making tool that accounts for both circularity potential and broader aspects (e.g., cost and schedule) is crucial in promoting an effective decision-making process that balances trade-offs between various considerations.
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<tr>
<td>CE</td>
<td>Circular Economy</td>
</tr>
<tr>
<td>EoL</td>
<td>End of life</td>
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<tr>
<td>BIM</td>
<td>Building Information Modelling</td>
</tr>
<tr>
<td>EngD</td>
<td>Engineering Doctorate in Engineering program</td>
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<td>UT</td>
<td>University of Twente</td>
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<tr>
<td>CFM</td>
<td>Campus Facility &amp; Management</td>
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<td>LOD</td>
<td>Level of development</td>
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<td>MCI</td>
<td>Material Circularity Indicator</td>
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<tr>
<td>LCA</td>
<td>Life Cycle Analysis</td>
</tr>
<tr>
<td>MPG</td>
<td>MilieuPrestatie Gebouwen; Building Environmental Performance</td>
</tr>
<tr>
<td>EPG</td>
<td>Energieprestatiecoëfficiënt; Energy Performance Standard</td>
</tr>
<tr>
<td>DSR</td>
<td>Design science research</td>
</tr>
<tr>
<td>CPM</td>
<td>Circular Project Model</td>
</tr>
<tr>
<td>NMD</td>
<td>Nationale Milieudatabase; National Environment Database</td>
</tr>
<tr>
<td>BoQ</td>
<td>Bill of quantities</td>
</tr>
<tr>
<td>ILS</td>
<td>Informatieleveringsspecificatie; Information Delivery Specification</td>
</tr>
<tr>
<td>GUI</td>
<td>Graphic user interface</td>
</tr>
<tr>
<td>SE</td>
<td>System Engineering</td>
</tr>
<tr>
<td>DfX</td>
<td>Design for X, e.g., Design for Disassembly/Detachability</td>
</tr>
<tr>
<td>DfD</td>
<td>Design for Disassembly/Detachability</td>
</tr>
<tr>
<td>MKI</td>
<td>Milieukostenindicator; Environmental Costs Indicator</td>
</tr>
<tr>
<td>GPR</td>
<td>GPR Gebouw; GPR Building</td>
</tr>
<tr>
<td>IFC</td>
<td>Industry Foundation Classes</td>
</tr>
<tr>
<td>ETIM</td>
<td>European Technical Information Model</td>
</tr>
<tr>
<td>DNR-STB</td>
<td>StandaardtaakbeschrijvingNew Rules Standard Task Descriptions</td>
</tr>
<tr>
<td>IPO</td>
<td>The model of Input-Processing-Output</td>
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<td>CMT</td>
<td>Classification Management Tool</td>
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1. Introduction
As a resource- and waste-intensive sector, the construction industry consumes an estimated 50% of natural resource consumption and it contributes about 40% of total waste (Rijkswaterstaat, 2015). Moreover, there are no signs of a decrease in materials extraction and waste generation (Coenen et al., 2021). Material depletion is inevitable if the current rate of materials extraction and waste production continues (Akinade et al., 2020). These concerns are attributed to an unsustainable “linear” model, where materials are taken, consumed and eventually become worthless after the End of life (EoL) (EMF, 2015). The concept of Circular Economy (CE) has emerged with the aim of decoupling economic growth from materials extraction (EMF, 2019). A CE is defined as “an economic system that is based on business models which replace the “end-of-life” concept with reducing, alternatively reusing, recycling and recovering materials […], with the aim to accomplish sustainable development […], to the benefit of current and future generations.”, according to Kirchherr et al. (2017), who have analyzed 114 CE definitions and conceptualizations. Recognizing the contributions that the CE can potentially achieve, the Netherlands sets targets for the whole country: 50% less primary raw material consumption in 2030 and a fully circular economy by 2050. In concrete terms, this means that virgin resources should be minimized, and buildings are encouraged to be designed in a way to promote reuse possibilities with maximum retained value (Jiang et al., 2022; Rijkswaterstaat, 2015).

Van den Berg et al. (2020) proposed complex challenges and difficulties emerge during the transition towards circular construction, which urgently requires theoretically grounded and empirically validated insights and tools. One of the growing interests and methodological debates concerns how to quantify, attribute the benefits and identify opportunities in circular strategies (Walker et al., 2018). This is because CE initiatives can only be sustained when an evaluation framework is appropriate for monitoring progress towards a CE (Saidani et al., 2019). An upswing in information-centric approaches has encouraged the development of Building Information Modelling (BIM) in the construction industry (Akanbi et al., 2018). BIM is regarded as a promising approach which enables the management and exchange of semantically rich 3D models among various project disciplines (Di Biccari et al., 2019; McAloone & Bey, 2009). By utilizing BIM, a building works as a database or information management system, providing the possibilities for incorporating various analyses (Di Biccari et al., 2019; McAloone & Bey, 2009).

1.1 The EngD project
In this context, this project aims to generate knowledge of circularity assessment and BIM techniques in the construction sector. It is executed as part of the Engineering Doctorate in Engineering program (EngD). An EngD is a two years post-Master’s program focusing on the direct needs of industry, with the aim of providing creative and innovative designs for complex issues with a multidisciplinary team. Part of the program is a tailor-made project in close consultation with an industry partner(s). Specifically, this EngD project is commissioned and guided by the “industry partners” - the University of Twente (the department of Campus & Facility Management) and DigiGo (digitaal samenwerken in de Gebouwde Omgeving, digital collaboration in the Built environment in English). An overview of the main project characteristics is presented in Table 1.

<table>
<thead>
<tr>
<th>Project title</th>
<th>digi-meten en weten van circulariteit (in English: ‘digi-measurement and knowledge of circularity)</th>
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<tbody>
<tr>
<td>Project type</td>
<td>Engineering Doctorate (EngD)</td>
</tr>
<tr>
<td>Project Client</td>
<td>Campus and Facility Management (CFM) &amp; DigiGo (Co-funding)</td>
</tr>
<tr>
<td>Project period</td>
<td>April 2021 - 2023</td>
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The CFM has a unique role as the asset manager of the campus and has a special interest in developing the end product and relevant knowledge in the world of construction, for a healthy, green, and...
sustainable campus. Aiming to make the entire industry smarter and faster, DigiGo works closely with the government, clients and executing parties to accelerate the digitalization of the built environment. With bottom-up movement, it utilizes new and existing digitization initiatives in the form of acceleration projects (versnellingsprojecten in Dutch).

1.2 Problem statement

1.2.1 Circularity assessment of construction projects

An appropriate circularity method is essential for guiding project stakeholders to move from linear to circular. Several different circularity assessment methods at the building-, component-, and product-level have been developed. Among them, material efficiency is commonly regarded as an essential dimension. It emphasizes a system in which virgin resources and unrecoverable waste are minimized or eliminated (Coenen et al., 2021). However, most of the existing circularity methods rely on lifecycle information about buildings, products or materials, depending on judgements and often leading to overly optimistic estimations. Taking one of the most popular methods as an example, the Material Circularity Indicator (MCI) (EMF, 2019), high uncertainties are embedded in the process of determining the EoL material treatments and expected building lifespan. In the construction industry, the MCI has also been customized in a BIM environment like the Madaster Circularity Indicator, which inherits the MCI’s uncertainties given that users tend to overestimate the positive effects of future scenarios. Similarly, as acknowledged by Platform CB23 (2020), high uncertainties may be embedded in their method given the fact that users tend to overestimate the positive effects of future scenarios.

In essence, the aforementioned methods fail to measure the degree of circularity performance in construction projects due to their reliance on some input information (e.g., EoL scenarios), which are typically absent during a project period. Consequently, the use of such methods for measuring the circularity performance of construction projects necessitates subjective estimations, which may compromise the accuracy of the circularity insights gained by designers and other stakeholders. However, nowadays, circularity gradually plays an increasingly important role in tenders and decision-making during design/construction projects, where stakeholders need timely, relevant and accurate information to make agreements and reduce uncertainty (Tushman & Nadler, 1978). To address these challenges, there is a need for a practical method with actual circularity insights to facilitate resource efficiency in practice, rather than providing inflated assessment results attributed to an over-optimistic estimation.

1.2.2 Digitalization for circular buildings

As a potential game-changer for most project stakeholders (Sebastian, 2011), BIM shows huge potential in terms of process automation and data management (Honic et al., 2019). According to international standards, a BIM model is defined as “a shared digital representation of physical and functional characteristics of any built object…” (ISO, 2010). From a perspective of information processing, at its core, BIM describes the exchange, interpretation, and usage of data/information surrounding a 3D object-oriented model, supporting multiple requirements for various stakeholders at all stages of a project (Gerrish et al., 2017). A BIM model contains information about geometry, spatial relationships, quantities, properties of building elements as well as material inventories (Honic et al., 2019), which are required for designing and monitoring circularity-related activities. Researchers have emphasized the advantages of BIM utilization in measuring circularity. For example, Hollberg et al. (2020) pointed out that digital tools based on BIM have the capacity of decreasing the additional effort for assessment, consequently accelerating the process.

In contemporary design practices, BIM-based techniques have been widely utilized for sustainability or LCA (Life Cycle Analysis) studies in the construction industry, given BIM can potentially offer sufficient information about building geometry and functionalities in support of sustainability assessment (Feng et al., 2022). Because of this, researchers have developed various plug-in/software to enable BIM-based LCA. This is normally achieved by linking the quantity take-off and standard material libraries from BIM-associated software and LCA database respectively to facilitate the measurement of
environmental measures of construction assets (Feng et al., 2022). With the growing popularity of CE, BIM techniques can be extended to CE-driven research, to evaluate circular design options in a BIM environment (Pomponi & Moncaster, 2017). Given the benefits of CE, as highlighted by many scholars (e.g., Akanbi et al. (2018)), there is a need to prove the concept of BIM integration into design processes to promote CE initiatives. In recent years, scientific studies about using BIM for circularity assessment have gradually increased in the literature and new tools have been developed for this purpose.

The modelling of objects and the level of development (LOD) is regarded as a critical point during the application of LCA or circularity assessment (Soust-Verdaguer et al., 2017). LOD describes the degree to which elements’ geometry and attached information are presented in a BIM model. More information about LOD is provided in sub-section 4.3.1. However, most scholars have not specified the LOD of BIM models used in their studies (Soust-Verdaguer et al., 2017), or limit themselves to conducting a circularity assessment in a specific project phase. In other words, many existing methods are not flexible enough to accommodate the variable availability of information across different phases of construction. This often results in a one-size-fits-all calculation method that may rely on subjective assumptions from project stakeholders, especially in early project phases where information is limited. To provide feedback for project stakeholders (e.g., designers and contractors) and inform decision-makers, the actual circularity results/assessment should be provided throughout different project phases.

The significance of open standards in the construction industry, particularly in the realm of Building Information Modelling (BIM), cannot be overstated. Given the lengthy lifespan of buildings, BIM open standards are critical for ensuring long-term data storage and management of assets (Patacas et al., 2015). By structuring information processing needs, open standards facilitate the collection and verification of information at the early stages, which can then be managed throughout the entire building life cycle. This is of utmost importance given the abundance of protocols and information exchange standards being utilized in the built environment, which has led to an intensification in the urgency for open standards (Dave et al., 2018). Additionally, the prevalence of various BIM-authoring applications within the construction industry further underscores the necessity of open standards for enabling effective information exchange and system interoperability. In the Netherlands, some organizations (e.g. BIM Loket/DigiGo and BDR (Bouw Digitaliserings Raad, Building Digitization Council in English) work actively to generate standards for smooth BIM integration into construction projects. A list of open standards and minimal requirements for data recording and transferring have been developed. However, these guidelines only consider the general data of a project, without making specifications for customized circularity-related information. Despite the consensus among scholars that BIM offers possibilities for effective usage of data and information to make decisions about circularity, more insight is still needed into how this relevant information for making circularity feasible and transparent can be recorded in public standards.

1.2.3 Summary

The construction industry is undergoing a transition towards a CE where economic growth is decoupled from materials extraction. To facilitate this transition, appropriate methods are required to gain insight into the degree of circularity performance of a building in construction projects. In this context, BIM has emerged in support of information collection and management, to smoothen the process of circularity assessment. Several assessment methods have been developed or are under development for investigating how to measure the circularity performance of a structure (in a BIM environment). However, these methods fail to provide actual insights for guiding a circular design since they rely on subjective judgements and estimations. This is because their required input information is commonly not available during project periods. Moreover, information availability varies across different project phases and LODs, yet most existing BIM-based tools fail to account for these differences. As a result, estimations are often necessary, particularly during the early stages of construction projects where required information may be limited or unavailable. Additionally, there is a need for further investigating how to record and manage circularity-related information with the utilization of open standards.
1.3 Project goal and project deliverable

In response to the challenges outlined in subchapter 1.2, this project aims to provide new insights into how to measure project-based circularity performance under different levels of information availability, with tailor-made calculation models. Leveraging the potential of BIM, these calculation models are digitized in the form of a prototypical BIM-based circularity assessment tool, serving as the primary end-product of this study. Different from most existing (BIM-based) tools where estimations have to be made over the whole lifecycle of a structure, this project-based approach focuses specifically on the material flows in and out of construction sites (see details in sub-section 2.1.1). Moreover, the proposed tool seeks to provide actual circularity insights by accounting for differences in information availability across different project phases, thereby enabling effective guidance of circular design.

Consequently, the main goal of this project is to:

“Develop a prototypical BIM-based tool to assess actual circularity performance of construction projects in different project phases”

The development of the BIM-based circularity assessment tool entails the generation of knowledge pertaining to circularity assessment and information management, as illustrated in Figure 1.

Specifically, this study delves into the knowledge surrounding circularity assessment under different levels of information availability through the development of circularity calculation models. Furthermore, this study also seeks to expand upon the knowledge regarding information management and open standards. Specifically, this study will investigate the information requirements/needs necessary for supporting circularity assessments and explore how relevant information can be captured, exchanged and standardized to facilitate a streamlined assessment process, leveraging BIM open standards and information structure. Furthermore, in accordance with one of the stakeholders' requirements (see Table 23 in sub-section 5.3.1), this study also contributes to exploring how the BIM-based circularity assessment tool can synergize with the preexisting tool in the case projects (see sub-section 3.2.2 and sub-section 7.1) to enable more effective decision-making processes. As a result, new workflows have been developed as by-products of this study, to facilitate the integration of the new tool into the ongoing project processes of the case projects (see sub-section 3.2.2 for the detailed introduction), as depicted in Figure 1.
1.4 Report structure

This report is structured as follows (Figure 2). Chapter 2 introduces the project scope, specifying the project position and boundaries within the domain of circularity and building. The rest of the report follows the structure of the methodology presented in Chapter 3, which contains the background of design science and design cycles. In Chapter 4, the theoretical background regarding the topics addressed in this study is presented, including circularity, BIM and open standards. Moreover, this chapter reviews the current approaches of circularity assessment and techniques of BIM integration, to identify the gaps in the literature. Chapter 5 offers the design solution and ancillary knowledge in response to the gaps including insights into information management, calculation models and a prototypical BIM-based circularity assessment tool. The BIM-based tool is applied to a case project, which offers ground for the (iterative) user-based evaluations in Chapter 6 and subsequent design improvements. Chapter 7 analyzes the current workflow of circularity/sustainability assessment in case projects, and concerns the issues and accordingly adjustments when integrating the BIM-based tool from activity theory perspective. Finally, in Chapter 8, the conclusion is first presented to list some main findings and developments of this study. Subsequently, recommendations and guidelines in support of the utilization of open standards and the BIM-based circularity assessment tool are summarized. Finally, recommendations for future research directions are offered to conclude this chapter.
2. Project Scope

This EngD project focuses on circularity in the building sector. This indicates two domains: building and circularity performance. The position and scope within these domains are discussed below.

2.1 Buildings

2.1.1 Nano-level for buildings

The circular strategies and corresponding circularity assessment methods are primarily divided among the macro, meso and micro levels (e.g., Corona et al. (2019); Harris et al. (2021); Saidani et al. (2019); Kirchherr et al. (2017); Lei et al. (2021). The fourth level of circularity so-called nano-level is identified by authors, like Saidani et al. (2019) and WBCSD (2018), who subdivide components, materials and buildings into nano-level, and micro-level stands for companies and consumers (Roos Lindgreen et al. (2021)), as depicted in Figure 3 in the context of construction industries. The greater specificity eliminates the common confusion caused by a too-broad micro-level (Roos Lindgreen et al., 2021). A well-established method has the potential to distinguish the impact of building performance (affected by specific materials and components) from the circularity of construction companies. However, as elaborated by Saidani et al. (2019), the characteristic of the nano-level is intrinsically embedded in the micro/meso/macro level, which implies that the circularity degree of upper levels can be benefited by improving the performance of buildings, components and materials (Roos Lindgreen et al., 2021). Under this premise, this project aims to examine and address the issues of assessing a building in the construction environment.

![Figure 3. The levels of circularity assessment in construction industries (the project focuses on the Nano-level)](image)

A building in a CE is not a whole system, but a collection of layers with different lifespans (Circle Economy, 2019). The most popular principle may be Brand’s building layers, supposing a building can be decomposed into different layers including site, structure, skin, services, space plan, and stuff (Brand, 1995). Another popular way of building subdivision into levels of scale is proposed by Platform CB’23 (2020), considering a building evolves from raw materials, materials to construction products, elements, and structure, which can further become building complex and area, as shown in Table 2. In this project, the expected BIM-based circularity assessment tool is applicable to the whole building/structure in the construction sector within different decomposition principles. It contains different levels of scale (e.g., material and product level), which will be further discussed in sub-section 4.1.

<table>
<thead>
<tr>
<th>Levels of scale</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area</td>
<td>An area</td>
</tr>
<tr>
<td>Building complex</td>
<td>A building complex consisting of interconnected structures</td>
</tr>
<tr>
<td>Structure</td>
<td>A building</td>
</tr>
<tr>
<td>Elements</td>
<td>Internal walls</td>
</tr>
<tr>
<td>Construction Products</td>
<td>Metal stud wall</td>
</tr>
</tbody>
</table>

Table 2. Buildings’ levels of scale (based on the definition of Platform CB’23 (2020))
2.1.2 Project lifespan
Although the ultimate goal of CE is to simulate continuous and long-lasting resource utilization by considering the whole or even multiple lifecycles in the future (as encouraged by Platform CB'23 (2020)), project stakeholders within a construction project have limited impact when a project finishes. Hence, this project aims to provide insights/guidelines to promote circular possibilities during the project’s lifespan so-called project-based. In other words, the proposed BIM-based circularity assessment tool concerns the importance of information availability within project phases, avoiding the inflated assessment results attributed to an over-optimistic estimation of future scenarios during the whole building lifespan, as illustrated in Figure 4.

![Figure 4. The BIM-based circularity assessment tool only covers the lifecycle of a construction project](image)

2.2 Circularity performance
Saidani et al. (2017) propose that the concept of CE is compatible and consistent with sustainable development through its three associated pillars (economic, social and environmental; see also Figure 5). This is because a CE can generate not only economic benefits (e.g., contributing savings and value creation from the reduction of raw material depletion) but also environmental benefits (e.g., reducing environmental impact) and indirectly social benefits (e.g., health and comfort and culture value). Pomponi and Moncaster (2017) further introduce a ‘six pillar’ framework, in which three other dimensions including governmental (authorities and policy support), behavioural (e.g., people’s attitude towards recovered materials) and technological (e.g., circularity-related information and new tools for resources sharing) are incorporated. However, European Environment Agency (2014) proposed that the CE concept mainly emphasizes the aspects of material and physical resources (under the environmental domain), and provides a constructive pathway towards sustainable development. Taken together, CE can be regarded as a recovery system that contributes to 1) energy usage; 2) water efficiency; 3) emission reduction; 4) material depletion (WBCSD, 2018), by regenerating, narrowing, slowing and closing the resources loop (Çetin et al., 2021). This study adopts the latter definition and perceives circularity as a means for conserving material and physical resources, which falls under the umbrella of the environmental domain as put forth by other scholars (e.g., Saidani et al. (2017) and Pomponi and Moncaster (2017)).

Regarding physical resources, air and water pollution is attributed to the consumption of fossil energy to a large extent, while materials usage stands separately, although energy usage and pollution could not be avoided during the extraction and production of materials (Coenen, 2019). Furthermore, the former three aspects (energy, water and emission) can be assessed with the help of some existing methods like MPG (MilieuPrestatie Gebouwen, or Buildings Environmental Performance) and EPG (Energieprestatiecoëfficiënt, or Energy Performance Standard). Specifically, as typical Dutch instruments, MPG and EPG are statutory requirements in the building sector for new residential buildings and offices. Several indicators are involved in MPG, like, the use of water, emission of particulate matter, and climate change (fossil use). However, material depletion is beyond the scope of the current ways of environmental assessment. Therefore, the project (or the circularity assessment
method) is narrowed to material and the three directions (energy, water, and emission) within the environmental domain are not taken into consideration, as presented in Figure 5.

![Figure 5. The aspects of circularity assessment (the project focuses on material depletion)](image)

2.3 Summary
In sum, the project narrowed its focus in the context of the built environment and circularity performance. In line with the scope of this project, the following boundaries are set:

- The project will limit itself to buildings/structures at the nano level, which concerns different levels of scale (e.g., materials and products).
- The project is intended to provide insights into the circularity performance of an individual construction project, rather than providing an inflated circularity value by estimating possible future scenarios during the whole buildings’ lifespans.
- The project is narrowed to material aspects and the three directions (energy, water, and emission) within the environmental domain are not taken into consideration.
3. Project Methodology

In order to realize the aforementioned goal, a systematic and rational design methodology is needed. As introduced in sub-section 1.3, except for contributing scientific knowledge to construction projects, this study mainly focuses on designing practical artefacts (a prototypical BIM-based circularity assessment tool). Hence, a research approach based on design science was selected. Design science is a form of research that supports the development of practical application design solutions and scientific knowledge under the predefined problem context (Van Aken et al., 2016). Numerous studies have been conducted to advance the theoretical underpinnings and practical implementation of design science research methodology (e.g., see (Hevner et al., 2008), Peffers et al. (2007) and Wieringa (2014). Hevner et al. (2008) started to identify and understand the existence of environment and knowledge base, which interact and influence a DSR. Afterwards, Wieringa (2014) developed a similar DSR framework following Hevner (2008)’s study. For example, Wieringa (2014) supposes that except for the DSR itself, the problem context can be extended with social context and knowledge context (Figure 6), which align with the environment and knowledge base in Hevner (2008)’s study. Certain improvements are also involved in the framework of Wieringa (2014), such as the distinguishing of design and investigation in a DSR (Figure 6). Furthermore, Wieringa (2014) also introduces a detailed process for performing DSR with several interrelated steps in a design cycle (Figure 7). Therefore, this project follows the design cycle theory provided by Wieringa (2014).

Figure 6. The design science framework (Wieringa, 2014)

A customized resulting picture of DSR is presented in Figure 7. Specifically, the social context is where stakeholders locate. These stakeholders are those who have a close relationship or are concerned about the whole project (Wieringa, 2014), including the University of Twente, digiGO, and other stakeholders involved in the case studies. The existing theories are served as knowledge input by producing new designs or answering knowledge questions, belonging to the knowledge context (Wieringa, 2014). Two main approaches including literature review and case studies are used to explore the knowledge context. Furthermore, DSR employs an iterative process to achieve an ideal design outcome. Approaching the project from the DSR perspective, this design science project is taken with a fixed, but iterative, a succession of steps, following the design cycle including problem investigation, treatment design, treatment validation, and treatment implementation, shown in Figure 7.

Figure 7. The design cycle (Wieringa, 2014)
3.1 Exploration of social context

The exploration of social context starts with the identification of stakeholders and is followed by corresponding needs. As proposed by Wieringa (2014), stakeholders are “who may affect the project or may be affected by it”, and include possible users and operators, and most importantly, include the sponsors of the project. Mitchell et al. (1997) developed a method of stakeholder identification by analyzing “what” and “who” affect the project. Mitchell et al. (1997) suppose the stakeholders can be assessed considering three dynamic qualities: power - the power of stakeholders for proposing their requirements, legitimate - if stakeholders’ requirements are appropriate in the socially constructed system (Suchman, 1995), and urgency – if stakeholders’ requirements are urgent. The EngD candidate started to identify three main groups of stakeholders, including project sponsors (UT and digiGO) and the potential users of case projects, as summarized in Table 3. These stakeholders are categorised according to Mitchell’s (1997) model, which aims to understand the relative importance of their needs/requirements.

Being the users of the BIM-based circularity assessment tool, these stakeholders include project managers, and design and construction engineers, who are recognized as “dominant stakeholders”. This is because they hold the ability to propose requirements to the EngD candidate and evaluate if the developed design solution fulfils their expectations. In addition, the EngD candidate relies on the resources (e.g., BIM models) provided by those stakeholders, who can possess the power to control the design process. Furthermore, the user group are “legitimate”, because their claims and requirements are appropriate in the socially constructed system (Suchman, 1995). This is because the incentive to start the project is to encourage the construction industries to move toward circularity, which is desirable for social values. However, these stakeholders are not urgent for immediate attention, since they have an existing method so-called GPR (see sub-section 7.1) to support a sustainability assessment. Therefore, this stakeholder can be recognized as the dominant stakeholder with high importance and expected to receive much attention (Mitchell et al., 1997). Two sponsors of the EngD project – the University of Twente and digiGO are two important stakeholders, which provide financial support for conducting this design science project. Similar to the user groups, the stakeholders have direct power in proposing requirements for the project, and simultaneously, their requirements have a positive impact on social values. Furthermore, the EngD project has a time constraint, and the trainee is expected to finish the project within two years, which mean their requirements are relatively urgent. Therefore, these stakeholders can be recognized as definitive stakeholders.
In summary, the stakeholders outlined in Table 3 are deemed critical, and their requirements should be given the utmost consideration. A series of (group/individual meetings) were conducted to examine existing circular solutions (in the case projects) and understand the needs of those stakeholders. The exploration of social context is also complemented by project documents, observations and site visits. The detailed examination of social context and stakeholders’ requirements will be introduced in subsection 5.3.1.

Table 3. Stakeholders identification

<table>
<thead>
<tr>
<th>Stakeholders</th>
<th>Roles</th>
<th>Stakeholders’ Needs</th>
<th>Stakeholder groups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stakeholders involved in the projects (case studies), including like design, realization, and maintenance team</td>
<td>Users, Operators</td>
<td>Gain a clear insight into the circularity level of the project throughout different phases, by effective BIM utilization</td>
<td>Dominant stakeholder</td>
</tr>
<tr>
<td>University of Twente (UT) (Department of Construction Management &amp; Engineering; Campus &amp; Facility Management Department)</td>
<td>Implementation and supervision of the project; Co-funding; Clients of the projects (providing case projects)</td>
<td>Has a special interest in developing the end product and relevant knowledge in the world of circular construction, circularity assessment and information management.</td>
<td>Definitive stakeholder</td>
</tr>
<tr>
<td>digiGO</td>
<td>Co-funding</td>
<td>Has an interest in guidelines and recommendations for the development of BIM open standards and information management, with an ultimate goal of contributing the digitalization in the construction sector.</td>
<td>Definitive stakeholder</td>
</tr>
</tbody>
</table>
Specifically, digiGO has recognized that the coherence between different parties is still often lacking, although an increasing number of construction and installation companies work with data and digital systems. In order to allow the entire construction industry to work smarter and faster, digiGO works hard to promote open standards for digitization, which is a means to be able to respond more quickly to the social demand for energy-neutral and circular-built homes (digiGO, 2021). This design science project can provide a series of partial results that contribute to digiGO’s goal, as follows (Figure 9):

- **Goal 1:** To develop or improve norms and standards (ancillary knowledge 1)
- **Goal 2:** To explore additional knowledge in relation to circularity and design (ancillary knowledge 2)
- **Goal 3:** To develop a “digital system for the built environment” (end-product)

This project contributes a digital system for the built environment by providing a practical example of digital circularity measurement, which combines an application, embedded algorithms, and a dashboard in a BIM environment (Goal 3). This results in a series of ancillary knowledge that contribute to other individual digiGO goals. Firstly, the project sets up information agreements to establish how and which digital information should be stored to enable multiple uses (e.g., for circularity assessment), with the help of (BIM) norms and standards (Goal 1). Secondly, this study delves into the knowledge surrounding circularity assessment under different levels of information availability, in response to Goal 2.

![Figure 9. DigiGo's goals and project contributions](image)

### 3.2 Exploration of knowledge context

#### 3.2.1 Literature Review

An integrative literature review was conducted, on the one hand, to generate knowledge input in the design science project, and on the other hand, to compromise the existing work on the topic of interest (Figure 7). Specifically, a literature review was conducted to show a broad overview of the topic (Onwuegbuzie & Frels, 2016). Based on the objective, a literature review was conducted mainly in two fields: circularity assessment and BIM integration, which served as input for building the BIM-based circularity assessment tool. In addition, connections were made with relevant developments in the field of information management and open standards, which work together, in return, to provide a comprehensive theoretical background for this study. Chapter 4 presents the main results and findings from the literature review.

#### 3.2.2 Case projects

Two case projects – the Langezijds project (Figure 10) and the Cube project (Figure 11), are selected with the purpose to provide an open learning environment. Case studies are particularly advantageous when studying complex phenomena within their real-world contexts (van den Berg et al., 2021; Yin, 2009). The rationale for the selection of the cases is based on their uniqueness, specifically with regard to their emphasis on circularity practices, as well as BIM utilization.
These two cases are both located in the University of Twente, following the same overall strategy – a healthy, green, and sustainable building” and are designed and built around the same time. Originally built in 1968, the big building (in the Langezijds project) with a gross floor area of almost 19000 m² and was used for the chemical engineering department (for 35 years). But it has been partly abandoned since 2003 and will finally be redeveloped as a home base of the faculty for Geo-Information Science and Earth Observation (ITC) in 2023. The previous building elements are preserved to the largest extent. Furthermore, although for a renovation project, the MPG (see sub-section 2.2 for the introduction of MPG) is not mandatory for an environmental permit, the ITC building sets an ambitious goal – MPG should be limited below 0.6 € /m², which is even lower than the maximum limited value of 1.0 stipulated by the Dutch government. Although another project (in the Cube project) is a new-built one; however, in order to become as “circular” as possible, attention is given at the early stage, and various circular actions are planned to carry out. A sustainability measurement tool (GPR building) was also applied in both projects to ensure satisfactory sustainable and circular performance. More insights about the GPR are provided in sub-section 7.1.

Moreover, organizations are increasingly working in a new collaborative environment for achieving higher levels of quality. One of the case studies – the Cube project, clearly figures out the importance of working together – to reinforce each other to get the right thing to achieve a supported, feasible, and integral design. Specifically, the need for collaboration is emphasized in some specific themes like
flexibility, durability, and smart building, which are all under the scope of circularity. In terms of information exchange, BIM360 is applied to share project documents and Revit models during the design phase between designers (architects, engineers, and installation designers). Similarly, the other project (Langezijds) also recognizes that the collaboration between involved participants in construction projects is pivotal to efficient asset delivery and operation, and hence; a collaborative platform (BIM 360) has also been used for Revit model sharing. The application of BIM360 is the first try in the CFM, as introduced by the project manager (of Langezijds project). BIM applications are also reflected in other aspects. For example, standardization is also a requirement of these two projects, where BIM protocol is applied to lay down the minimum agreements that project partners must strive to meet the information needs of the client. Furthermore, the contractor who plans to fulfil the BIM protocol during the implementation of the project is asked to record the details in the form of a BIM implementation plan. Overall, these two projects are represented as good examples not only on circularity potentials but also about BIM utilization in terms of collaboration and standardization; hence, in line with the project’s interests. The general information of these two case studies is presented in Table 4.

The case studies are informed by project documentation, site visit (e.g., see Figure 12), and interviews. In both cases, the accessibility of the BIM collaborative environment (BIM 360) is also recognized as one of the important knowledge sources (e.g., to gather models and project documents). In addition, an essential adopted method for a comprehensive knowledge exploration stems from interviews with key project stakeholders. This study used the method of semi-structured interviews, which enables reciprocity between researchers and participants (Galletta, 2013; Kallio et al., 2016), allowing researchers to modify follow-up questions based on participants’ answers (Hardon et al., 2004; Kallio et al., 2016; Polit & Beck, 2009; Rubin & Rubin, 2005), and leaving room for participants’ personal verbal expressions. In other words, a semi-structured interview method is useful to enable interviewees to provide information on their own terms (Van den Berg et al., 2020). However, a structured list of questions is still required with a certain level of previous studies (Galletta, 2013; Kallio et al., 2016).

Figure 12. An example picture of a site visit in the Langezijds project (van den Berg & Jiang, 2021)
Table 4. The general information of case studies

<table>
<thead>
<tr>
<th></th>
<th>1. ITC building</th>
<th>2. Cube project</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project phase (when the EngD project starts)</strong></td>
<td>Ready for construction work</td>
<td>Ready for technical design</td>
</tr>
<tr>
<td><strong>The current phase (when the EngD finishes)</strong></td>
<td>During construction work</td>
<td>Ready for construction work</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>University of Twente</td>
<td></td>
</tr>
<tr>
<td><strong>Background</strong></td>
<td>Old building renovation</td>
<td>Circular new-built building</td>
</tr>
<tr>
<td><strong>Applied sustainability/circularity methods</strong></td>
<td>The GPR assessment (Involves MPG and EPG calculation)</td>
<td></td>
</tr>
<tr>
<td><strong>BIM-associated software and guidelines</strong></td>
<td>BIM360; Revit models; BIM protocols/ILS/BIM implementation plan etc.</td>
<td></td>
</tr>
<tr>
<td><strong>Involved stakeholders</strong></td>
<td>Client: University of Twente</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Construction Teams: Dura Vermeer Hengelo/Trebbe, Croonwolter&amp;dros</td>
<td>Construction teams: not yet decided</td>
</tr>
<tr>
<td><strong>Expected lifespan</strong></td>
<td>50 years</td>
<td>50 years</td>
</tr>
<tr>
<td><strong>Gross floor area</strong></td>
<td>13162 m2</td>
<td>4500 m2</td>
</tr>
</tbody>
</table>

3.3 Design cycles

As indicated in sub-sub-section 1.3, this project considers different aspects such as information management, calculation models, and a BIM-based circularity assessment tool (composing several components like results visualization in a Graphic user interface (GUI)). Considering the complexity of the project with several interdependent aspects, a systematic approach was applied with the help of the System Engineering (SE) process and tools. SE puts effort into system design, aiming to achieve an integrated understanding of the system by stakeholders’ needs and required functionality, and then proceeding with design development and system validation, to achieve a desirable design result (Balslev, 2017). The concept of SE can be reflected by the V model, following the decomposition and integration sequence (Figure 13).

The researcher collected project data, including, construction drawings (Revit models), circularity-related reports (e.g. requirements, and MPG calculation reports) and reports concerning BIM applications (e.g. BIM protocol and ILS), which are closely related to the study’s interests. Moreover, stakeholders from different design disciplines and client representatives have collaborated over the course of the design science project. These stakeholders include project managers, sustainability consultants, BIM experts, and design and construction engineers. Several meetings took place in an informal setting meant for reviewing current circular solutions. Follow-up individual semi-structured interviews were organized to deeper understand and evaluate stakeholders’ needs and requirements. These requirements of a “circularity assessment tool” in a BIM environment were concretized as “design requirements” for guiding the architectural design and component design (Figure 13). The architectural design aims to create a conceptual model that represents the structure and behaviour of a system (e.g., the system of supporting a circularity assessment in a BIM environment). The sub-section 5.3.2 outlines the system architecture model designed in this study, which composes of several interlinked components; for example, an external database, a BIM model, and a BIM-based circularity assessment tool. The architectural design provides a comprehensive view of the system and facilitates the development of each component involved in the system.
The integration process commences with the preparation and development of individual components, which are subsequently integrated into a complete system utilizing BIM techniques, resulting in the BIM-based circularity assessment tool. Adhering to the V model, this study also places an emphasis on the operability capability of the BIM-based circularity assessment tool, supported by an implementation plan.

3.3.1 Treatment design

The treatment design is a relatively intensive problem-solving process to design one or more artefacts that could solve the problem (Wieringa, 2014). As outlined in sub-section 1.3, this project aims to design and develop a BIM-based circularity assessment tool, which serves as the final deliverable. In conjunction with this end product, ancillary knowledge regarding information management and circularity assessment will also be generated, as illustrated in Figure 1. The methods employed to generate these outcomes are listed as follows:

Ancillary knowledge 1: In the pursuit of recording circularity-related information through the use of open standards, a literature review was conducted to identify the standards currently available in the construction industry (see details in sub-section 4.4). Furthermore, an examination was launched to gain insights into the standards employed by different project stakeholders to facilitate information management in the case projects. To gain a deeper understanding of how different parties record such information and the standards they employ, BIM models were gathered from designers and contractors involved in the case projects. The examination was further enhanced through interviews with key model producers/controllers such as BIM experts and construction engineers. The results of this study not only shed light on the current approaches utilized by stakeholders in information management but also identify the challenges faced by them, such as ambiguous communication. In response to these challenges, the study proposes potential solutions and makes recommendations to enhance information management practices, thus enabling a circularity assessment.

Ancillary knowledge 2: The various existing ways of measuring assets' circularity and current gaps are both studied. Three criteria (or desirable quality) were selected for evaluating circularity metrics, namely, reliability, operability and intuitiveness. Keeping the criteria and current gaps in mind, a circular project model (CPM) developed by Van den Berg et al. (2019) was chosen as the foundation to develop the “tailor-made calculation models” in this project. It can be visualized the flow of materials in and out of a construction project and align with the project’s scope (about material efficiency in construction projects) and has the potential to be designed into a circularity assessment method. Furthermore, after analyzing the level of information availability in different project phases through interviews with a BIM
expert, three primary stages were identified, and calculation models were tailor developed (based on the CPM) for each stage considering the amount of available information.

**End-product:** Before starting to design the digital tool, system requirements were first defined as guidelines and constrictions. A requirement is a property of the treatment desired by stakeholders, and it is a goal for a to-be-designed treatment (Wieringa, 2014). In other words, system requirements are used as guidelines to consider the question “what does the system need to fulfil” in order to satisfy stakeholders. The requirements of the proposed tool are generated from two sources: learning from literature/existing methods and stakeholders (involved in the case projects). Specifically, this study followed a design science research cycle that progressed from high-level needs to a more detailed examination of stakeholder requirements. This progression was achieved through the treatment validation in each iteration of the design cycle. Simultaneously, different BIM integration ways and possible workflow for supporting circularity assessment were studied. Afterwards, system architecture was developed to depict the structure of the tool, according to the Input-Processing-Output (IPO) model. The aforementioned ancillary knowledge was used in support of the development of the BIM-based circularity tool. Guided by stakeholders’ requirements, the technique of BIM integration was chosen, and accordingly, the calculation models (ancillary knowledge 2) were digitized into a BIM environment. The usability is ensured by designing a GUI. Concurrently, PyCharm and Python programming languages were used in support of the process of digitalization and visualization processes, in the form of a BIM-based circularity assessment tool on a system level (Figure 13). Table 5 provides an overview of used Python packages and their area of application in this research. The running code is packaged as a standalone application, which can be shared and downloaded by different users.

**Table 5. Main Python packages used in this project**

<table>
<thead>
<tr>
<th>Main Packages</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pandas &amp; Numpy</td>
<td>Some (general) circularity-related information is stored in an Excel file, working as an external database for supporting a circularity assessment. Pandas and Numpy are used for data extraction, manipulation and analysis from the excel file by using its built-in data structure and operations.</td>
</tr>
<tr>
<td>Matplotlib</td>
<td>Matplotlib is a comprehensive library for embedding static, animated and interactive plots into applications. It is used in this study for producing 2D charts and graphs to visualize assessment results.</td>
</tr>
<tr>
<td>IfcOpenShell</td>
<td>This study proposes an IFC-oriented solution for enabling interoperability among different BIM-associated software. IfcOpenShell is used for reading information stored in IFC file(s).</td>
</tr>
<tr>
<td>PythonOCC</td>
<td>One major feature of the GUI is 3D colour coding (using different colours to distinguish circularity performance in a 3D model). This 3D visualization is realized by PythonOCC.</td>
</tr>
<tr>
<td>Qt Designer &amp; PyQt5</td>
<td>Qt and PyQt5 are used to create the GUI application.</td>
</tr>
</tbody>
</table>

### 3.3.2 Treatment validation

In the step of treatment evaluation, system tests are followed centralized by users’ experience to verify if design requirements are met (or not). This user-based evaluation generates new design requirements in each design cycle (see Figure 7), adding details to the design of the components, assemblies and system (Figure 13).

In order to achieve a thorough comprehension of stakeholders’ viewpoints and requirements with regard to the tool, the evaluations were formulated to enable users to engage with the tool themselves. These types of evaluations are referred to as user-based evaluations, and they have the potential to enable valuable insights into how the tool is perceived and utilized by its intended users. Hereby, the EngD candidate can have a more comprehensive understanding of the tool’s strengths and weaknesses through
active users’ feedback. A standardized method recommended by ISO (1998) was chosen to provide guidelines on how to conduct user-based evaluations to evaluate the usability of the BIM-based circularity assessment tool. After explaining the purpose of the prototypical evaluation, the stakeholders were asked to interact with the tool on their own using the described tasks, which allow participants to explore the embedded functions of the tool (see Appendix A). IFC files are prepared in advance to assess a case project (with main elements like floors and walls.). Furthermore, instead of working “silently”, the participants were asked to voice their thoughts by “talking or thinking aloud” (Maguire, 2001), during which the researcher can gain an instant view of how participants feel about the tool. The task-based process was video and audio-recorded to gather information about user performance and comments as they operate the tool. In addition to prioritizing usability aspects, the EngD candidate has also sought to investigate the information requirements of stakeholders pertaining to circularity-related decision-making. In order to accomplish this objective, a post-interview was conducted, which involved structured questions to ascertain users’ levels of satisfaction and other pertinent circularity-related information needs. The insights gleaned from this evaluation process were subsequently utilized to generate new design requirements aimed at fostering iterative design. Detailed materials related to the user evaluations are presented in Appendix A. Moreover, during the user-based evaluation sessions, the BIM-based circularity assessment tool was evaluated regarding the major aspects of usability. Here, usability is defined as to what extent the stakeholders know (more) about the circularity value of their projects concerning effectiveness, efficiency and satisfaction with the BIM-based tool. During this process, the effectiveness of the interaction was measured by the degree of task completion. Efficiency was determined by the time usage of each described task. The users’ satisfaction and other requirements were reflected through the think-aloud process and the post-interview. The detailed evaluation results are presented in sub-section 6.3.

Furthermore, in the stage of Treatment Validation, certain self-evaluation methods (for the EngD candidate herself) are concurrently integrated, encompassing the requirement evaluation and case demonstration. In particular, the candidate employed pre-established requirements as an assessment instrument to verify the fulfilment of each of these requirements by the BIM-based circularity assessment tool (see details in sub-section 6.1). Moreover, the tool was demonstrated by (part of) a case project, to exhibit the tool’s ability to provide actual circularity insights in different project phases, as defined by the objective in this study (see sub-section 6.2).

In addition to the aforementioned evaluation methods, there exist alternative channels to obtain valuable feedback aimed at improving the BIM-based circularity assessment tool prior to its finalization. One such channel involves engaging with supervisory teams, comprising university superiors and external supervisors, through regular meetings. Furthermore, a workshop was organized during the final phase of the evaluation process, where the EngD candidate demonstrated the tool in real-time to all members of the supervisory team and this generated a series of thought-provoking discussions and valuable insights. Another opportunity for real-time demonstrations of the tool was at a research day held at the University of Eindhoven, centered on digitalization within the built environment. Lastly, the EngD candidate presented her findings (see Jiang, Van den Berg, et al. (2022)) at a conference in Glasgow, providing a forum for discussion and promoting the iterative development of the tool.

3.3.3 Treatment implementation

Treatment implementation represents how to implement design solutions or end products in the original problem context. Therefore, within the context of this project, implementation means the actual utilization of the BIM-based circularity assessment tool in the construction industry to support the assessment of different construction projects. However, due to its conceptual and theoretical nature, the prototypical tool is unable to support the circularity assessment of other projects, although the study proposes recommendations for supporting the implementation of the tool in practice (more details are provided in sub-section 8.4.2). Therefore, the step of treatment implementation is reflected through its potential to implement in the case project. In line with one of the stakeholders’ requirements in the third-round design cycle (see Table 23 in sub-section 5.3.1), the focus of this step is to consider how the tool
can work together with the existing tool (in the case project) to facilitate a better decision-making process.

Presently, the project has opted to undertake a GPR Building (GPR Gebouw in Dutch) calculation to obtain an understanding of the extent of sustainability of their designs. To support project stakeholders in comprehending their status in the implementation of the new tool and formulating implementation plans, a systematic and dynamic mechanism is necessary to thoroughly analyze contextual issues related to the integration of the BIM-based circularity assessment tool and the GPR. During the step of “treatment implementation”, activity theory was chosen as a theoretical framework to understand those contextual issues in the case projects. Interviews/meetings with stakeholders were conducted to understand what aspects (e.g., regarding rules) should be adjusted from a activity theory-based perspective, based on a well-known triangular graphic created by Engeström (1987). Utilizing the insights gained from these interviews/meetings, this stage outlined the current project workflow (of circularity/sustainability assessment) and propose a new workflow that incorporates the proposed tool. More details regarding activity theory and the triangular graphic are presented in sub-section 4.5.
4. Theoretical background

The construction industry consumes half of all extracted materials and generates one-third of total waste, making it a pivotal area for advancing toward a Circular Economy (CE) in Europe (European Commission, 2022). The realization of a CE necessitates the decoupling of economic growth from finite material consumption (EMF, 2019). This is distinguished from a “linear” model, in which materials are consumed and discarded after reaching their End of Life. The Dutch economy is in the process from linear to circular, still relying on the consumption of natural resources or low-graded recycling solutions. A future move forward to a CE asks for high-grade material recycling, and preferably higher volumes of product reuse (Potting et al., 2017).

The increasing interest of CE necessitates construction companies to identify transition strategies, which entails an understanding of their circular performance along with the associated risks and opportunities (de Oliveira et al., 2021; WBCSD, 2018). In other words, adopting appropriate circularity assessment methods enable companies to make informed decisions and implement more circular practices, which are essential for sustaining CE initiatives (Saidani et al., 2019). Therefore, circularity assessment is of utmost importance and urgency, particularly in the construction industry, given its sustainable resource consumption and waste generation, motivating both construction companies and government entities to transition to more circular approaches to address environmental challenges.

Although there is a lack of a universally accepted definition of CE among scholars and practitioners (e.g., see the definition of Kirchherr et al. (2017)), there is agreement that it promotes the extended use of components, materials, and products through techniques such as reuse, repair, recycling, remanufacturing, and refurbishing (Zacho et al., 2018). Similarly, López Ruiz et al. (2020) summarize that CE can be conceptualized as a system where materials products and component is maximum utilized and maintained in the production cycle. Accordingly, the circular structure (e.g., buildings) in the construction industry can be defined as a “Structure designed and constructed according to circular design principles and/or constructed using circular products, elements and materials”, based on Platform CB’23 (2020).

With these unambiguous definitions of CE concepts in the construction industry, Chapter 4, aims to investigate current advancements regarding circularity assessment and BIM techniques through a literature review. Sub-section 4.1 and 4.2 summarizes existing circularity indicators and methods, enabling a better understanding of how to measure the circularity performance of construction projects. The next part (sub-section 4.3) entails how BIM can be incorporated to facilitate a circularity assessment and concludes with the strengths and weaknesses of each integration technique. Then, the latest developments in terms of information management and BIM open standards commonly applied in the Dutch construction industry are reviewed and presented in sub-section 4.4. Finally, sub-section 4.5 introduces activity theory to consider the possibilities of incorporating the new tool into current case projects. This provides a framework for analyzing the complex relationships between individuals, tools, and their environment, thus facilitating a more nuanced and comprehensive understanding of the feasibility and potential impact of the proposed tool.

4.1 Circularity indicators

Verberne (2016) presented an overview of building circularity indicators which make circularity becomes measurable and four perspectives of indicators were distinguished, namely, technical, functional, perception and economic indicators. Technical indicators concern the technical characteristics of materials/products which facilitate circularity, and they are called intrinsic properties in the study of Geldermans (2016). For example, from a technical perspective, a material/product in a CE should be composed of sustainable original and consistent with biological cycle or technical cycles (e.g., reuse, recycle) (Geldermans, 2016). Functional indicators assess those aspects that affect “the attractiveness for usage”, including location, facilities and accessibility. Furthermore, the environmental impact including energy and water flow is incorporated into this aspect. Perception indicators cover the “attractiveness for the state of mind” and include the aspects like aesthetics, acoustic, comfort, light and
etc. (Verberne, 2016). The last one economic value serves as a drive to promote circular transition since those economic factors can influence organizations to apply circularity in their businesses from technical, functional and perception perspectives (Verberne, 2016).

In line with the project scope of material efficiency in the environmental domain, this study focuses explicitly on how to measure circularity performance from a technical perspective. The perspective of technical indicators (at the nano level, considering materials, products or buildings) consists of two basic principles.

1. **Circular material usage**: concerns the selection of the material, in line with the material flow in the butterfly model (see Figure 14). It aims to prevent material degradation through material regeneration in the biosphere and materials restoration in the technosphere, to protect and maintain the material value (Jelmer, 2019; Verberne, 2016).

2. **Circular design**: aims for designing products and components in a way that they can be disassembled for future usage, in favour of tight restoration cycles like reuse and remanufacture rather than recycling (Jelmer, 2019; Verberne, 2016).

![Figure 14. Circular Economy butterfly diagram (EMF, 2019)](image)

**4.1.1 Circular Material flows**

Materials/products can become restorative and regenerative through either a biological cycle or technical cycle in a CE. The biological cycle represents that biological materials can cascade through different applications and finally reintroduce their nutrients into the biosphere (EMF, 2012). For those non-nutrient-based products and materials, it is encouraged to enter the technical cycle, where technical materials/products can be recovered into the market to extend their lifecycle through different strategies/approaches like repair, reuse, refurbishment, recycling, etc.

**4.1.1.1 Circular strategies of circular material flow**

For achieving a low-intensity resource-dependent economy, various approaches in a technical cycle, commonly known as R strategies have developed. The Ladder van Lansink is one of the first-leading
approaches in the Netherlands, to model a hierarchy of preference of products’ EoL solutions. In this approach, reusing options are most appreciated, followed by recycling choices. If both of them could not be satisfied resulted from technological restrictions, energy recovery or the worst option of landfill have to be applied (Keivanpour & Kadi, 2016). EMF (2012) has developed the butterfly model which also defined a set of solutions in a technical cycle. Afterwards, in 2016, Potting et al. (2017) redefined the classification of the Ladder van Lansink into the “9R” waste hierarchy, with the objective of “smarter product use and manufacture”, “extending the lifespan of a product and its parts” and “useful application of materials” (Figure 15).

The overview of circular strategies introduced among scholars is presented in Table 6, which also shows their categories based on the level of scale.

**Table 6. The overview of circular strategies and their level of scale**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Circular Economy</strong></td>
<td>Prevention</td>
<td>Refuse</td>
<td>Structure-level</td>
</tr>
<tr>
<td></td>
<td>Reuse</td>
<td>Reuse /redistribute</td>
<td>Element-level</td>
</tr>
<tr>
<td></td>
<td>Maintenance</td>
<td>Repair</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Refurbish/Remanufacture</td>
<td>Refurbish</td>
<td>Product-level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Remanufacture</td>
<td></td>
</tr>
<tr>
<td><strong>Linear economy</strong></td>
<td>Increasing circularity</td>
<td>Rule of thumb: Higher level of circularity = fewer natural resources and less environmental pressure</td>
<td></td>
</tr>
</tbody>
</table>
As a general term based on Ladder van Lansink, “Reuse” represents different scenarios including “repair before reuse, refurbish before reuse, remanufacture before reuse and repurpose before reuse” based on the definition of Coenen (2019). Hereby, in this study, it is assumed that if the tighter reuse-related cycles could not be satisfied at product-level, the remaining possibility is material recycling. When the case of recycling could not be guaranteed, the remaining materials will be regarded as “unrecoverable waste” either going to a landfill or energy recovery in a linear economy.

Furthermore, this study considers reuse or other reuse-based strategies (e.g., remanufacture and refurbish) are a status considered on or above product level (e.g., elements or structures), while recycling is applied at material-level as the worst option in a CE, as presented in Table 6. Taking an example from Sandin and Peters (2018), if a material of a product is recovered and reused in a new product, it was categorized into “material recycling”. This is because this option is applied at material level rather than product level. Furthermore, the status of upper levels can be inherited by lower levels, for example, reusing a product implies the materials of the product are also reused, or so-called material reuse by some scholars (e.g., Van den Berg et al. (2019)). However, to clarify, this report uses the term “reused/reuse products” and “recycling/recycled materials” to emphasize their differences from the perspective of the level of scale.

4.1.1.2 Circular project model
A model so-called Circular Project Model (CPM, as visualised in Figure 16) developed by Van den Berg et al. (2019) can be used to enhance “circular materials flow” in construction projects, by capturing different R strategies. As introduced by Van den Berg et al. (2019), a linear procedure is modelled from transporting new materials to a construction site (arrow 1) to depositing waste from the site (arrow 2). By adopting the concept of CE, materials are recovered from an old building and reused in a different project (arrow 3), or in a more effective way, old materials are collected and reapplied at the same construction site without extra transporting (arrow 4). Circular attempts can be also observed in an EoL scenario, where waste represented by arrow 2 can be reused as a material input for another new building (arrow 5). The model can be applied to provide insight into the degree of circularity for different types of projects like a new-built and renovation one, by modifying the arrow thickness to represent the amount of relevant material flow (Van den Berg et al., 2019). Furthermore, although only reuse scenario is modelled, the CPM can be used to represent other R strategies (Table 6). For example, remanufacturing can be understood as reusing a product (arrow 3) and adding new materials/products (arrow 1) to create a new object for a construction project. However, the recycling scenario is not incorporated into the model.
4.1.2 Circular design
According to EMF (2013), circular design is defined as “i.e., improvements in material selection and product design (standardization/modularization of components, purer material flows, and design for easier disassembly)”. If a great deal of effort is made for the circular design by keeping further profits in mind, the material value can be maintained maximally (Akanbi et al., 2018). According to Amory (2019), value retention and value recovery can be achieved through the implementation of a clear and anticipating design referred to as Design for Circularity. The circular performance of a building is enhanced through various aspects of circularity, referred to as Design for X (DfX). Amory (2019) highlights that there is no established standard set of DfX among scholars and that these strategies overlap or complement each other rather than being mutually exclusive.

van Vliet (2018) proposes that the utilization of Design for Disassembly or Detachability (DfD) aligns closely with different principles of CE. Similarly, Jiang, Bhochhibhoya, et al. (2022) also stated that the design strategy DfD is the core circular strategy with a far-reaching consequence, since its application guarantees or complements other design strategies represented as Design for X. For example, the concept of Design for Maintenance is a circular strategy that has been proposed by scholars such as Abdullah et al. (2017). The aim of DfM is to ensure that buildings are easily repairable and that replacement parts can be obtained at reasonable costs during the operational phase (Amory, 2019; EMF, 2014). Buildings that have incorporated DfD strategies are more likely to have good inspectability and modularity, which in turn enhances their maintainability without encountering significant difficulties. Furthermore, EMF (2014) asserts that the reuse potential of materials is largely dependent on the ease of disassembly, making DfD a critical precondition of the Design for Reuse.

Besides, Webster (2007) highlights that, in addition to environment benefits such as reduced energy consumption, the implementation of DfD can also yield economic benefits for construction companies.

4.1.2.1 Design for disassembly at product-level
The concept of Design for Disassembly (DfD) aims to optimize material utilization and waste reduction from building EoL management. This is achieved through the implementation of design strategies that allow for the disassembly of building components and enable their replacement and reuse (van Vliet, 2018).
The ultimate goal is to create an adaptable building to avoid building deconstruction and removals, as a more sustainable approach to construction and building management.

Durmisevic (2006) presents a visual representation of the various levels of disassembly in buildings (Figure 17) and highlights the distinction between a total totally fixed, partially opened and fully opened structure. The fully opened structure presents the ideal scenarios where buildings’ materials, components, and systems can be easily separated and disassembled at different building levels. In other words, the author introduces that disassembly should be attainable at all scales from materials to entire buildings. Verberne (2016) adapts DfD to build a product circularity indicator, to assess interfaces and connections at product-level, and a similar methodology can be found among scholars (e.g., van Vliet (2018) and Zhai (2020)).

Refer the definition of van Vliet (2018), this study considers DfD can guarantee the possibilities of disassembly at product or product-above level, enabling disassembly for prevention and disassembly for reuse (Table 7). This is because, recycling does not need careful disassembly, as long as the recyclable materials can be separated (Coenen, 2019) and it largely depends on recycling techniques (e.g., van Vliet (2018)) and the choice of material (e.g., Coenen (2019)), rather than DfD. By contrast, the requirements for reuse have been acknowledged to be more stringent, as they necessitate the capability to disassemble components without causing damage to either the elements themselves or their connections. Damage, however, is not a significant issue in the context of recycling when the level of contamination and deterioration are accepted.

<table>
<thead>
<tr>
<th>Circular material usage</th>
<th>Circular design</th>
<th>Level of scale (Platform CB’23, 2020)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevention</td>
<td>Design for disassembly (DfD)</td>
<td>Structure-level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Element-level</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Product-level</td>
</tr>
<tr>
<td>Reuse-based strategies (e.g., reuse, repair, refurbish, remanufacture and repurpose)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Recycle</td>
<td></td>
<td>Material level</td>
</tr>
</tbody>
</table>

4.1.2.2 Assessment methods of Design for Disassembly
Numerous studies have explored the principles, factors, and guidelines for DfD, which seeks to facilitate the disassembly of buildings at the EoL stage rather than demolition (van Vliet, 2018). To achieve a CE, van Oppen (2017) developed an IPF model, which emphasizes the significance of technical, process, and financial aspects of building development. The concept of detachability is central to these three aspects, which can be analyzed as follows (van Vliet et al., 2021; van Vliet, 2018):
- Technical aspects: concern factors that determine whether products/elements can be physically disassembled such as the connection between products and their surroundings.

- Process aspects: concern those aspects during the design and construction process like disassembler experience and deconstruction safety.

- Financial aspects: address the financial feasibility of developing a detachable building and implementing disassembly at EoL, which influences the choice of disassembly instead of demolition. In other words, the value of a disassembled product must be greater than the disassembly costs from a financial aspect.

van Vliet (2018) proposed that these three aspects-related factors can be understood as technical requirements, preconditions and drivers respectively. Technical disassembly factors are used to assess circularity performance, while process-based factors serve as preconditions that influence organization options in their procurements process. Financial-based factors act as drivers, to understand how financial aspects can simulate the transition from linear to circular. This study focuses on the circularity assessment, and hereby, aims to determine the technical detachability potential: to what physical extent products and elements can be disassembled.

The Disassembly Determining factors (DDF) is regarded as one of the popular methods, which assess the technical detachability potential (Durmisevic, 2006). A follow-up study was conducted by van Vliet (2018), who determined and categorized the most important DDF, by focusing on the disassembly capabilities of a product and its related connections. Afterwards, a program – the DGBC circularity program is established in collaboration with different organizations (e.g., Alba Concepts, Dutch Green Building council and W/E adviseurs), aiming to investigate and describe how to make a circular building more measurable with an emphasis on disassembly or detachability aspects. Two major indexes are built, namely, a releasability index of the connections (LIC) and a releasability index of the composition (LIs).

Specifically, the former concerns the ability to disassemble a product or elements by considering the connection type and the accessibility of the connection. The latter represents how easily a product can be disassembled in the meantime, to assess a situation where surrounding products or elements are preserved. It includes two factors: intersections and edge confinement.

For each factor (connection type, accessibility of the connection, intersections and edge confinement), a different numerical value ranging from 0.1 to 1 is assigned to different scenarios, to represent the level of ease of disassembly (Table 8).

<table>
<thead>
<tr>
<th>Factors</th>
<th>Sub-factors</th>
<th>Description</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Releasability index of the connections</td>
<td>Type of connection (TV)</td>
<td>Dry connection</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Connection with added elements</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Direct integral connection</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Soft chemical compound</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard chemical compound</td>
<td>0.10</td>
</tr>
<tr>
<td>Accessibility level (ToV)</td>
<td>Freely accessible without additional actions</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accessible with additional actions that do not cause damage</td>
<td>0.80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accessible with additional actions with fully repairable damage</td>
<td>0.60</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accessible with additional actions with partially repairable damage</td>
<td>0.40</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Not accessible – irreparable damage to the product or surrounding products</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Crossings (DK)</td>
<td>No crossings – modular zoning of products or elements from different layers</td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

van Vliet (2018) proposed that these three aspects-related factors can be understood as technical requirements, preconditions and drivers respectively. Technical disassembly factors are used to assess circularity performance, while process-based factors serve as preconditions that influence organization options in their procurements process. Financial-based factors act as drivers, to understand how financial aspects can simulate the transition from linear to circular. This study focuses on the circularity assessment, and hereby, aims to determine the technical detachability potential: to what physical extent products and elements can be disassembled.

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Specifically, the former concerns the ability to disassemble a product or elements by considering the connection type and the accessibility of the connection. The latter represents how easily a product can be disassembled in the meantime, to assess a situation where surrounding products or elements are preserved. It includes two factors: intersections and edge confinement.

For each factor (connection type, accessibility of the connection, intersections and edge confinement), a different numerical value ranging from 0.1 to 1 is assigned to different scenarios, to represent the level of ease of disassembly (Table 8).
Releasability index of the composition

| Occasional crossings of products or elements from different layers | 0.40 |
| Full integration of products or elements from different layers | 0.10 |

Edge confinement (RO)

| Open, no obstacle to the (interim) removal of products or elements | 1.00 |
| Overlap, partial impediment to the (interim) removal of products or elements | 0.40 |
| Closed, complete obstacle to the (interim) removal of products or elements | 0.10 |

Hereby, the calculation method for determining the detachability potential of a product/element is (van Vliet et al., 2021):

\[
\text{disassembly potential } = \frac{4}{TV + \frac{1}{ToV} + \frac{1}{DK} + \frac{1}{RO}}
\]

Where TV is Type of connection; ToV is Accessibility level; DK is crossing and RO is edge confinement as shown in Table 8.

Note that for enabling the feasibility of the calculation method, the minimum value (to describe the worst scenarios) is set as 0.1 out of 1. The assessment of a building’s disassembly performance is derived from the cumulative disassembly potential of its constituent products/elements. To determine this score, a weighting factor known as the Environmental Costs Indicator (MKI) is employed. The higher the MKI value of a given product, the more impact the product has. This is because this method has been designed to directly correlate with the MPG calculation.

4.2 Circularity assessment

This section aims to review existing methods to understand to what extent the existing methods are applicable to measure the circularity performance of construction projects.

To align with the project goals and deliverables as outlined in sub-section 1.3, three essential criteria have been identified for evaluating other existing methods. These criteria, namely reliability, operability, and intuitiveness, are intended to ensure consistency with the project objectives and deliverables relating to calculation models (with a focus on reliability), information management (with a focus on operability), and the BIM-based circularity assessment tool (with a focus on both operability and intuitiveness). There are some other desirable quantities proposed by some scholars. For example, both Linder et al. (2017) and Saidani et al. (2019) suppose that a generic method has the potential to apply to various industrial sectors given its high adaptivity and flexibility, and a high degree of generality is regarded as a desirable quality. However, in this study, the focus remains on the project goals and deliverables, and hence, criteria that are deemed "irrelevant" to the project goals, such as generality, have been excluded. This targeted approach ensures that the identified criteria are aligned with the project's specific scope and objectives and that the evaluation process is customized to the needs of the project. However, it is important to note that the narrow focus of the evaluation criteria may be subject to criticism from readers who advocate for a broader assessment approach, but it can enable a more efficient and effective evaluation process in the context of this study.

Specifically, Reliability examines if a metric is able to provide similar results under consistent conditions, by reducing the possibilities of subjective judgments. Additionally, the availability of information represents a crucial aspect during the application of circularity assessments. Thus, the reliability criterion encompasses an evaluation of whether a circularity assessment accounts for variations in information availability across different phases and is capable of conducting an assessment using available information, thereby limiting the need for estimation or assumption. Furthermore, one
of the main difficulties of measuring circularity performance is associated with the ability to gather adequate information and an ideal method should contribute to information collection (Saidani et al., 2019). In this light, BIM is a useful tool in support of information collection and management, to smoothen the process of circularity assessment. In addition, Saidani et al. (2019) introduce a standardized input datasheet that is useful for facilitating the process of data collection, for example, documenting technical data (e.g., bill of materials) and organizational data (e.g., EoL materials treatment) into different sections. Hence, this study refers to operability in terms of data construction and information management, which is necessary to be a critical criterion. Finally, methods with an intuitive user interface are useful for fostering understanding for non-experts in the circular economy. Hence, intuitive examines if a method enables a comfortable visualization with a proper GUI.

The review process allows for exploring a list of methods originating from grey literature and academic papers, as reported in Table 9 and Table 10 respectively. Note that all reviewed methods are classified as “Low”, “Medium” and “High” based on their level of reliability, operability and intuitiveness. Referring to the definition by Roos Lindgreen et al. (2021), grey literature represents those studies published by non-academic bodies like consultancy organizations and policy institutes. The inclusion of grey literature is motivated by the fact that companies are increasingly interested to know to what extent they have achieved circular transition, and about 74% of them utilize their self-developed frameworks for measuring circularity (WBCSD, 2018). Based on the research scope, these existing methods all aim to assess circularity performance with regards to materials efficiency, either can be used generally (e.g., MCI and CTI) or specific for the construction sector (e.g., BCI, CCEF).

It is important to note that extensive methods (specifically from grey literature) are available at the micro-level for assessing to what extent a company has realized circularity transition while being excluded from the review process. For example, EMF (2020) published Circulytics to examine a company’s potential for achieving circular in the future, and the current level of circularity. As a highly comprehensive method, company ability is examined not limited to products and materials but only includes strategy, innovation, people, operations, water, energy and etc. Similarly, Circular Economy Toolkit (Evans & Bocken, 2013) was designed for the company to explore business opportunities for creating value under the context of CE throughout the whole supply chain from design, usage, and maintenance to reuse, remanufacture and recycling. As introduced before, this study narrows itself at the nano-level (for building, components and materials), and comparisons with higher-level methods (e.g., at micro) may lose fairness given the different focuses. Furthermore, some methods are adaptable to different levels. For example, the MCI can be applied at the company level (at the Micro level) by aggregating the circularity value of the company’s products (at the Nano level) based on the mass-weighting method (EMF, 2019). Furthermore, Global Sustainable Enterprise System (2021) (GSES) covers all facets of substitutability at the organization level and product/project level, and each of them can be assessed separately. Inside the product/project level, one pillar so-called circular footprint puts emphasis on how products and projects can become more circular at the nano level. These methods which can be applied at multi-levels (e.g., MCI and GSES) will be reviewed in this study with the main focus on their application at the nano level.

4.2.1 An overview of existing circularity methods
According to EMF (2015), a method for evaluating the effectiveness of a product in transitioning from linear to circular has yet to be established. To address this gap, the MCI was created by EMF (2015) as a means of assessing product-level circularity. The MCI is based on the principle of lifecycle thinking and takes the inputs, utility, and outputs of a product into consideration. It uses three key indicators, which are the amount of virgin materials used, the amount of unrecoverable waste produced, and the product’s lifetime, to provide a preliminary assessment of a product’s circularity performance. The MCI is user-friendly and can be utilized by individuals without expertise in CE (Saidani et al., 2017), making it a valuable tool for understanding the impact of different material combinations on product performance and helping companies make informed decisions (Saidani et al., 2017).
As a result of its advantages, the MCI is considered as one of the most promising frameworks for measuring circularity performance (WBCSD, 2018) and offers a helpful starting point (Linder et al., 2017). Because of this, according to Jiang, Bhochhibhoya, et al. (2022), many other methods have been developed utilizing the MCI and customized for the construction industry. A pertinent illustration of such adaptations is offered by Verberne's (2016) Building Circularity Indicator (BCI), which leverages MCI as a foundation for quantifying the circularity performance of buildings. Subsequent developments pertaining to the digitalization of BCI through the utilization of BIM have been undertaken by Zhai (2020). Another advancement is about the Predictive Building Circularity Indicator (PBCI) (Cottafava & Ritzen, 2021) to predict the circularity value when some of the information is unavailable (e.g., the unrecoverable waste percentage). Additionally, the MCI-based methods have been used as a foundation for the assessment of material efficiency not only for buildings (Zhang et al., 2021) but also for infrastructure projects (Coenen et al., 2021). Similarly, the MCI has been customized by non-academics for the development of methods like the Building Circularity Index (Alba, 2015), the Madaster Circularity indicator (Madaster, 2018) and the core measurement method (Platform CB'23, 2020) in the construction industry. An updated version of the MCI was published in 2019 (EMF, 2019) with its high popularity. Except for examining the extent of circular material usage, there are some methods designed for evaluating specific circular design aspects including the BIM-based Whole-life Performance Estimator (BWPE) (Akanbi et al., 2018) and Diassessmlability, Deconstrucstability and Resilience (3DR) (O'Grady et al., 2021), as presented in Table 10.

4.2.3 Summary
This study provides a review of existing methods applied for nano-level originating from academia or industry, encompassing the examination of MCI, MCI-based methods, and other methods which consider the aspects of circular material usage and circular design. Three criteria are employed to delineate the degree to which they conform to the objectives of "reliability, operability, and intuitiveness".

As indicated in Table 9 and Table 10, the majority of these methods are rated as "Low" in terms of reliability, as they require lifecycle information of assets, which is frequently unavailable in construction projects. Additionally, these methods fail to account for the variability of information availability across different construction phases and offer only a fixed solution for all scenarios (with different amounts of available information). As a result, project stakeholders are required to make numerous assumptions to conduct a circularity assessment using these methods. Furthermore, in the realm of circularity assessment, there is limited attention given to the construction and support of data. This deficiency can be attributed to several factors, including the focus of academic methods on the calculation aspect, which often neglects the importance of data construction and user experience. Regarding intuitiveness, existing industrial and company practices, as illustrated in Table 9, demonstrate a high degree of intuitive functionality through their utilization of GUIs such as those found in excel, web, and application-based platforms. Conversely, most reviewed academic methods tend to neglect the significance of user experience.

Although all methods have been examined to be unsatisfactory in terms of their reliability (with “Low” or “Low to Medium”), there are some methods that have demonstrated comparatively better performance in other two aspects: operability and intuitiveness. Specifically, the Madaster circularity indicator (Madaster, 2018), BIM-based Whole-life Performance Estimator (Akanbi et al., 2018) and Building circularity assessment scoring tool (Zhang et al., 2021) have shown superior performance (highlighted in green in Table 9 and Table 10), attributed to their consideration on operability by leveraging the capabilities of BIM for data construction, regardless of whether IFC or Revit-based solutions (plug-in or Dynamo) are utilized. Additionally, these three methods are designed to offer a user-friendly and intuitive GUI, making them accessible and easily usable for various end-users. More information about these methods will be introduced in the next chapter.
### Table 9. Overview of existing industries/company circularity methods (the green cell represents the methods with better performance with “High” operability and intuitiveness)

<table>
<thead>
<tr>
<th>Existing industries/company methods</th>
<th>Description</th>
<th>Desirable qualities</th>
<th>Operability</th>
<th>Intuitiveness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material Circularity Indicator (MCI) (EMF, 2019)</td>
<td>Measuring how well a product/company performs in the context of circularity considering the materials input, output and utility</td>
<td><strong>Low</strong> Requires building lifecycle information (e.g., EoL materials treatment); Ignore the variability of information availability</td>
<td><strong>Low</strong> No support for data construction</td>
<td><strong>High</strong> An Excel-based GUI enables easy and fast understanding for non-experts</td>
</tr>
<tr>
<td>Circular Transition Indicator (CTI) (WBCSD, 2020)</td>
<td>Assessing a company’s circular performance</td>
<td><strong>Low</strong> Requires building lifecycle information (e.g., actual recovery percentage); Ignore the variability of information availability</td>
<td><strong>Low</strong> No support for data construction</td>
<td><strong>High</strong> A web-based GUI is available</td>
</tr>
<tr>
<td>The core measurement method (CMM) – stock of materials (Platform CB’23, 2020)</td>
<td>Measuring circularity and sustainability of buildings and infrastructure sectors</td>
<td><strong>Low</strong> Requires building lifecycle information; Ignore the variability of information availability</td>
<td><strong>Low</strong> No support for data construction</td>
<td><strong>Low</strong> No GUI</td>
</tr>
<tr>
<td>GPR Building (W/E Adviseurs, 2017)</td>
<td>Evaluating project performance in a comprehensive way concerning energy, environment, health, user quality and future value</td>
<td><strong>Low</strong> Requires building lifecycle information; Ignore the variability of information availability</td>
<td><strong>Low</strong> No support for data construction</td>
<td><strong>High</strong> A simple GUI is available</td>
</tr>
<tr>
<td>Madaster Circularity indicator (MCI’) (Madaster, 2018)</td>
<td>Customizing MCI for assessing construction projects and supporting to develop a material passport</td>
<td><strong>Low</strong> Requires building lifecycle information (e.g., EoL materials treatment); Ignore the variability of information availability</td>
<td><strong>High</strong> Support uploading IFC files (BIM data) or Excel files. A standard Excel format is provided. Material passport is available.</td>
<td><strong>High</strong> A web-based GUI is available</td>
</tr>
<tr>
<td>Building Circularity Index (BCI’) (Alba, 2015)</td>
<td>Assessing the circularity performance of a real estate object and generating a material passport in collaboration with Madaster</td>
<td><strong>Low</strong> Requires building lifecycle information; Ignore the variability of information availability</td>
<td><strong>Medium</strong> Material passport is available; Lack BIM application</td>
<td><strong>High</strong> An application is available</td>
</tr>
<tr>
<td>Existing academic methods</td>
<td>Description</td>
<td>Desirable qualities</td>
<td>Operability</td>
<td>Intuitive</td>
</tr>
<tr>
<td>----------------------------</td>
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</tr>
<tr>
<td>Building Circularity Indicator (BCI) (Verberne, 2016) (further modified by van Vliet, 2018)</td>
<td>Measuring how well a building performs in the context of circularity based on MCI</td>
<td>Low Requires building lifecycle information; Ignore the variability of information availability</td>
<td>Low No support for data construction</td>
<td>Low No GUI</td>
</tr>
<tr>
<td>Building circularity assessment scoring tool (BCAS) Zhai (2020)</td>
<td>Digitalizing the BCI in a BIM environment</td>
<td>Low Requires building lifecycle information; Ignore the variability of information availability</td>
<td>High Make usage of BIM open standard (NL-SfB) to organize information</td>
<td>High Dynamo for Revit is provided</td>
</tr>
<tr>
<td>Predictive Building Circularity Indicator (PBCI) (Cottafava &amp; Ritzen, 2021)</td>
<td>A predictive version of BCI</td>
<td>Low-Medium All required data are available within project boundary; Ignore the variability of information availability</td>
<td>Low No support for data construction</td>
<td>Low No GUI</td>
</tr>
<tr>
<td>Circular Construction Evaluation Framework (CCEF) (Dams et al., 2021)</td>
<td>Assessing circularity performance of buildings based on international design code</td>
<td>Low Requires building lifecycle information (e.g., % of elements which can be reused/recycled); Ignore the variability of information availability</td>
<td>Low No support for data construction</td>
<td>Low No GUI</td>
</tr>
</tbody>
</table>

Table 10. Overview of existing academic circularity methods (green cells represent the methods with better performance with “High” operability and intuitiveness)
<table>
<thead>
<tr>
<th>Method</th>
<th>Description</th>
<th>Complexity</th>
<th>Data Requirements</th>
<th>GUI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diassembly, Decomstructability and Resilience (3DR) (O'Grady et al., 2021)</td>
<td>An index for the built environment by considering design for disassembly, deconstruction and resilience</td>
<td>Low</td>
<td>No support for data construction</td>
<td>Low No GUI</td>
</tr>
<tr>
<td>BIM-based Whole-life Performance Estimator (BWPE) (Akanbi et al., 2018)</td>
<td>Estimating the recoverability of structural components of buildings</td>
<td>Low</td>
<td>Requires infinite circular lifecycle information (e.g., the number of materials are reusable up to three times or an infinite number of times); Ignore the variability of information availability</td>
<td>Low No GUI</td>
</tr>
<tr>
<td>Resource Efficiency Assessment of Products (REAPro) (Ardente &amp; Mathieux, 2014)</td>
<td>Assessing the resource efficiency of products of EoL treatments</td>
<td>Low</td>
<td>No support for data construction</td>
<td>Low No GUI</td>
</tr>
<tr>
<td>Building circularity calculation method (BCCM) (Zhang et al., 2021)</td>
<td>Assessing the circularity performance of buildings</td>
<td>Low</td>
<td>Requires building lifecycle information; Ignore the variability of information availability</td>
<td>High No GUI</td>
</tr>
<tr>
<td>A bridge circularity assessment framework (BCSF) (Coenen et al., 2021)</td>
<td>Assessing resource efficiency of infrastructure projects (bridges)</td>
<td>Low - Medium</td>
<td>Considers the inability of determining the EoL destinations; Assumptions are still required like the recyclability scale of products, and design robustness; Ignore the variability of information availability</td>
<td>High An Excel-based GUI is available</td>
</tr>
<tr>
<td>Circularity and longevity indicators (CLL) (Figge et al., 2018)</td>
<td>Assessing the resource efficiency with the combination of a circular indicator (times of usage) and a longevity indicator (length of time)</td>
<td>Low</td>
<td>Require information on multiple lifecycles (e.g., the lifespan of initial use and second-hand use); Ignore the variability of information availability</td>
<td>Low No GUI</td>
</tr>
</tbody>
</table>
4.3 BIM integration in circularity assessment

The preceding sections present circularity indicators and existing circularity methods, which make circularity becomes quantifiable, albeit with certain limitations. These insights are useful in facilitating the development of a new circularity calculation method, corresponding to the generation of ancillary knowledge (see Figure 1). Another focus of this project is to digitize the circularity method inside a BIM environment, in the form of a BIM-based circularity assessment tool (see Figure 1). Therefore, the objective of this sub-section is to examine the potentialities of BIM in the process of circularity assessment. With a focus on the project's goal of evaluating circularity under varying degrees of information availability, this sub-section initially scrutinizes the different project phases and the corresponding information availability, categorized according to BIM's "level of development (LoD)". Subsequently, diverse BIM integration methodologies proposed by scholars are evaluated in terms of their strengths and limitations.

4.3.1 Project phases and BIM levels

The construction industry is characterized as project-based. In the Netherlands, the building process and project phases are described in the New Rules Standard Task Descriptions (DNR-STB), which defines 10 phases from project initiation to final use and exploitation. These phases can align with the information requirements of the “Level of development” (LOD) defined by the American Institute of Architects (AIA), as shown in Table 11. In BIM, LOD describes the level of development, concerning more detailed geometry and semantic information (in BIM models) throughout project phases (Schaubroeck et al., 2022). The information levels should correspond to the design and engineering processes to operate effectively.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiative and feasibility (IH)</td>
<td>Decide whether to execute or not</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Project definition (PD)</td>
<td>Understand stakeholders requirements</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Schematic design (SO)</td>
<td>Develop the first representation of the project</td>
<td>LOD 100</td>
<td>Develop graphical models using a symbol or other generic representation</td>
<td></td>
</tr>
<tr>
<td>Preliminary design (VO)</td>
<td>Develop an overall representation of the project (e.g., locations, functional and spatial structure, facilities for use, architectural appearance, etc.)</td>
<td>LOD 200</td>
<td>Develop a generic system or object with approximate quantities, shape and size.</td>
<td></td>
</tr>
<tr>
<td>Definitive Design (DO)</td>
<td>Develop a detailed representation of the project (e.g., the internal and external structure, the use of materials, the finish detailing, etc.)</td>
<td>LOD 250/300</td>
<td>Develop a specific system or object regarding quantities, shape and size.</td>
<td></td>
</tr>
<tr>
<td>Technical Design (TO)</td>
<td>Develop and specify the design technically (e.g., specifying the construction design, etc.)</td>
<td>LOD 350</td>
<td>Develop a specific system or object regarding quantities, shape, size, and interfaces with other systems.</td>
<td></td>
</tr>
<tr>
<td>Pricing and contracting</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Execution Ready Design (UO)</td>
<td>Make design execution ready</td>
<td>LOD 400/450</td>
<td>Develop a specific system or object regarding quantities, shape, and size with detailing, assembly, fabrication and installation information.</td>
<td></td>
</tr>
<tr>
<td>Execution management</td>
<td>Monitor implementation progress</td>
<td>LOD 500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Use and Exploitation</td>
<td>Maintain and manage the building</td>
<td>-</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
4.3.2 BIM integration techniques

With the increasing use of BIM in construction phases, opportunities arise to integrate sustainability (e.g., LCA analysis) and circularity assessment in a BIM environment and many methods have been developed or are being developed for this purpose. Different integration ways are envisaged and this sub-section focuses on the possible workflows for realizing BIM-based circularity assessment, by evaluating existing tools or relevant research work. The evaluation includes the BIM integration either in circularity or sustainability/LCA analysis, given both methods share similar characteristics: requiring relevant product/material information of a building (Zhai, 2020). Moreover, as discussed before, the assessment of sustainability performance is (relatively) completed and mature in the Netherlands. This means those BIM-based sustainability methods may provide more insights into integration possibilities.

Wastiels and Decuyper (2019) identified comprehensive classification by dividing BIM-LCA integration into five types, as presented in Figure 18. The first strategy is to extract the building information based on a bill of quantities (BoQ) from a BIM model, in the form of a spreadsheet. In the second strategy, an open exchange format (e.g., IFC) works as a transmission of a BIM model containing geometric information, which is exported and aligned with predefined LCA profiles (from an LCA-related database) by an LCA practitioner. The third strategy uses a BIM viewer as an intermediate step to attribute LCA profiles to building components. By doing this, the attribution of LCA profiles can be realized in a 3D environment and maintain an LCA assessment in LCA software. For speeding up the assessment processes, the fourth strategy introduces a plug-in in BIM authoring software, where LCA profiles can be directly attached to BIM objects. The authors award the last strategy (or strategy 5) which proposes that relevant LCA information (non-geometric) can be inserted into BIM models, together with geometric information. Moreover, they highlighted that the information should be either generic or specific based on the level of BIM objects (a generic object or a manufacturer-specific object). However, these BIM objects do not have to contain all details, instead, use a reference to link to an LCA tool or database, where the data is stored. By doing this, data can be centralized with BIM models to potentially support real-time analysis, although more laborious is required when changing data/information associated with BIM objects.

![Figure 18: BIM-LCA integration ways](Potrč Obrecht et al., 2020)
In the field of circularity, Zhai (2020) stated that there is no study has systematically investigated the possibilities of linking BIM to circularity assessment and three directions were summarized in her study. The first stream lies on a data exchange standard (e.g., IFC) to store the information of BoQ, which is analyzed in an external software or online platform. The concept of the first stream corresponds to the second strategy mentioned in Wastiels and Decuyper (2019)’s study (2019) (Figure 18). Zhai (2020) introduced two more streams, following the same idea of strategy 5 presented in Figure 18. One of the approaches involves all circularity-related information inside BIM objects by introducing custom parameters in BIM-associated software. Another integration possibility is to establish an automatic and efficient link between BIM models and external databases through a reference (for example, using NL-SfB classification code in Zhai’s study (2020)).

Although different BIM integration techniques are categorised either for circularity or sustainability assessment among scholars (e.g., Marrero et al. (2020)), the main differences lie in two aspects, namely information and assessment environment, as presented in Table 12 and Table 13.

Table 12. Different ways of storing information.

<table>
<thead>
<tr>
<th>A: Information (where that circularity-related information is stored)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1: BIM models only involve BoQ, and are complemented by circularity/sustainability profiles stored in an external database.</td>
</tr>
<tr>
<td>A2: All information is inserted into BIM models.</td>
</tr>
<tr>
<td>A3: BIM models contain BoQ and references to link to circularity/sustainability profiles stored in an external database.</td>
</tr>
</tbody>
</table>

Table 13. Different environments of a circularity assessment

<table>
<thead>
<tr>
<th>B: Assessment environment (where a sustainability/circularity assessment should be conducted)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1: Conduct assessment in an external tool (e.g., standalone software or online platform) with an input file (e.g., IFC and Excel) as the information carriage.</td>
</tr>
<tr>
<td>B2: Conduct assessment in a BIM authoring software in the form of a plug-in.</td>
</tr>
</tbody>
</table>

In the previous chapter, three methods were appraised after reviewing current developments in both academic and industrial realms, as they take the operability of their techniques by leveraging the capabilities of BIM for information management. These methods are classified based on their information storage location and assessment environment (labelled as A1/A2/A3 and B1/B2), as illustrated in Figure 19. The remaining portion of this section will introduce them.

The BWPE was developed for forecasting the whole-life salvage performance of structural components in a building. Akanbi et al. (2018) appraised the BIM’s feature of Intelligent modelling, which allows additional information can be integrated within BIM objects together with 3D geometric data. Accordingly, the authors developed the BWPE in the form of an add-in in Autodesk Revit (B2, see Figure 19), through Application Programming Interface (API), Visual Studio and C# programming language. For the functionality of the BWPE, all required circularity-related information is stored inside BIM objects (A1, see Figure 19) by creating custom parameters such as the identification of toxic content and secondary finishes (Figure 20).

To demonstrate how BIM can foster and automate the building circularity assessment, Zhai (2020) developed a BIM-based scoring tool. Dynamo for Revit (B2, see Figure 19) was employed for establishing automatic information integration between two sources: a Revit model and an external database (self-developed) and supporting an assessment inside Revit as a plug-in. A reference link (based on NL-SfB classification schema) was set for enabling information matches from two information sources (A3, see Figure 19), as shown in Figure 21.

Figure 21. Example of Dynamo for Revit in support of circularity assessment (Zhai, 2020)


The Madaster platform can be used for storing the information of a new/existing building and generating circularity scores (ranging from 0-100%) of buildings, with the help of the Madaster database. As an independent digital platform, the Madaster is able to process two types of source files, either IFC files (B2, see Figure 19) or a Madaster Excel template (when no BIM model of the building is available), as illustrated in Figure 22. It was acknowledged that the universal IFC file format allows communication between various 3D CAD applications in which information is stored using their own file format. The Madaster platform asks for the completeness of source files regarding 1) material description (e.g., NL-SfB table 3); 2) classification code (e.g., NL-SfB table 1); 3) geometric data.

Figure 22. Example of a standalone application in support of circularity assessment (Madaster, 2021)
Furthermore, the Madaster Platform can realize automatic elements matching between the uploaded IFC file and the Madaster platform by comparing the material designation (A3, see Figure 19). Specifically, the match is based on some reference codes (of an element stored in an IFC file) like product code, GTIN code or EAN code, which are used to structure product/material information in the Madaster database. A priority principle over the matching is also embedded in the platform when exact matches are found. In sum, as one of the most popular digitized circularity assessment tools in the Netherlands, it is appraised with several highlights:

- The platform is capable of categorizing and summarizing the information contained in the IFC file(s), to provide users insights into where and how much of which materials are used in a building.
- The platform was developed by taking common Dutch standards into account (e.g., NL-SfB) and it aligns well with the current working mode in a Dutch construction project.
- An effective assessment score can be provided with limited user input: only requiring information of product classification, material description and geometric information.

However, regarding the circularity assessment, the Madaster Platform is based on MCI, and in other words, it inherits the limitation of the MCI: based on subjective estimations and adjustments throughout the whole lifecycle of a building and ignoring the differences of information availability in different project phases (Table 9). The aforementioned two methods, as presented in Table 10, share the same issue. Furthermore, based on the limited information (published by Madaster), the material classification is mainly based on NL-SfB (table 3). More insights are required to understand how a tool can support the utilization of other common Dutch or even international standards.

4.3.2.1 Strengths and weakness of the BIM integration techniques

Different integration ways and their examples are introduced previously, with different strengths and weaknesses. For example, regarding the assessment environment, one key aspect of BIM focuses on interoperability (Soust-Verdaguer et al., 2017), considering how to promote collaboration among various stakeholders and information exchange between different software (Cheung et al., 2012). Hence, Soust-Verdaguer et al. (2017) criticized the development of plug-ins which restrict themselves to individual software and proposed the need of utilizing an open BIM schema, specifically in IFC data format. By contrast, some studies (e.g., van Eldik et al. (2020)) revealed the limitations of the IFC-based solutions given extra work is required for exporting IFC files, and hence, propose their preference to perform assessments in real-time inside BIM-aided software. The strengths and weaknesses of the BIM integration techniques regarding information and assessment environment are summarized in Table 14 and Table 15 respectively. These provide a theoretical foundation for selecting an appropriate pathway for the development of the BIM-based circularity assessment tool in this study. The selection process should consider their strength and weakness, and more importantly, the specific requirements of stakeholders (for further details, see sub-section 5.3.2). However, it is important to note that each of the evaluated approaches has its own set of advantages and limitations, and the solution developed in this study may not fully satisfy all usage scenarios and requirements. As such, further discussion is provided in subsection 8.4.2.
Table 14. Strengths and weaknesses of different ways of storing information

<table>
<thead>
<tr>
<th>Information (where information is stored)</th>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1: BIM models only involve BoQ, and are complemented by circularity/sustainability profiles stored in an external database via Excel/IFC/plug-in/BIM viewer</td>
<td>- Less work for model producers (e.g., designers, contractors)</td>
<td>- Manual work for linking BoQ and profiles (Wastiels &amp; Decuyper, 2019) - Iterative design might not be supported since it is not possible to preserve already defined links (Wastiels &amp; Decuyper, 2019)</td>
</tr>
<tr>
<td>A2: All information is inserted into BIM models by adding additional parameters</td>
<td>- All data can be centralized within the BIM objects (Wastiels &amp; Decuyper, 2019) - Iterative design could be supported with all information coming from one source</td>
<td>- More laborious are required to change information in each BIM object (Wastiels &amp; Decuyper, 2019)</td>
</tr>
<tr>
<td>A3: BIM models contain BoQ and reference to link to circularity/sustainability profiles stored in an external database</td>
<td>- Iterative design could be supported through automatic linkage with the references - Although the information is stored separately, they can link to each other through the standard reference link</td>
<td>- Agreements should be achieved regarding the usage of standard reference(s) - Communication should be enabled among different references</td>
</tr>
</tbody>
</table>

Table 15. Strengths and weaknesses of different assessment environments

<table>
<thead>
<tr>
<th>Environment (where assessment conducts)</th>
<th>Strength</th>
<th>Weakness</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1: conducting assessment in an external tool (e.g., standalone software or online platform)</td>
<td>- Support the assessment in an open BIM environment, where different 3D CAD applications are applicable.</td>
<td>- Manual steps to export an intermediate file (e.g., IFC) (van Eldik et al., 2020) - Cannot assess design alternatives in real time (Zhai, 2020)</td>
</tr>
<tr>
<td>B2: conducting assessment inside a BIM authoring software in the form of plugin</td>
<td>- Real-time assessment (Bonnema, 2008)</td>
<td>- Issues on interoperability and data exchange (Soust-Verdaguer et al., 2017)</td>
</tr>
</tbody>
</table>

4.4 Information management in BIM

In the context of supporting a circularity assessment, it is essential to consider the utilization of open BIM standards as means of semantic information storage and seamless information exchange. This is in line with two BIM characteristics as highlighted by Van Nederveen et al. (2010): 1) the exchange of semantic information; 2) the use of open standards. The former concerns that a BIM model should incorporate semantic information beyond geometric information, encompassing material properties and functional information. The latter underscores the imperative use of open standards within a BIM environment, as introduced in sub-section 1.2.2, to facilitate unambiguous information exchange and sharing. A standard is a collection of central information and process agreements, recorded in a
The critical role of open standards stems from the lengthy lifespan of buildings which requires long-term data storage and management of assets (Patacas et al., 2015). Open standards can be used to structure information processing needs, so this information can be collected and verified at the early stage, and managed throughout the whole building life cycle.

BIM Loket initiated acceleration projects, one of which (the Roadmap standards, see Spekkink (2022)) concerns the development trajectory for open BIM (and GIS) standards, with the objective of the realization of a coherent ‘ecosystem’ of standards. Moreover, this roadmap concerns how to achieve better harmonization and cooperation among different standards, to support data to flow in and between various chain partners in a system-independently way (Spekkink, 2022). In support of the objective, the roadmap starts to provide an overview of open standards and guidelines relevant to the digitalization of the Dutch construction and infrastructure sector. Three types of standards are distinguished and correspond to the process, semantics and exchange. Process-related standards work for achieving collaboration and communication throughout project processes. Moreover, semantic standards concern the meaning of information considering, for example, naming, definition and relationship, while the last group of standards (exchange) are primarily related to the system-independent exchange of digital information. Note that the distinction between these categories is not always clear. In other words, an exchange standard (e.g., IFC) can also be a semantic standard (IFC includes many definitions of object types, properties and relationships). Figure 23 provides indications of which standards and guidelines can be applied in which phases of the life cycle of assets in the built environment. This study focuses primarily on investigating the semantic (depicted in blue and pink in Figure 23), and exchange standards (depicted in orange in Figure 23), aiming to comprehend their potential to facilitate the storage and exchange of semantic circularity information throughout different project phases. Considering the project focuses on BIM and buildings, some standards related to other domains (e.g., “IMGeo” for GIS or “BIM basic infrastructure” for infrastructure) are excluded. Hence, the rest of this sub-section will introduce the application of BIM-related semantic and exchange standards including BIM basic ILS, IFC, NL-SfB, NLRS, NAAK.T and ETIM.

![Figure 23. Standards application throughout project phases (blue and pink primarily represent semantic standards)](translated from Spekkink (2022))
4.4.1 BIM Basic ILS
BIM Loket has asserted that the provision of a collaborative environment is contingent upon the availability of “exchangeable, structured, unambiguous, correct, complete and reusable” information and has developed the BIM basic ILS as an initial attempt (BIM Loket, 2021a). ILS stands for information delivery system (or Informatie Leverings Specificatie in Dutch), which is an important contract document which stipulates the desired (BIM) data to support use, management, and maintenance.

Specifically, the BIM Basic ILS addresses several practical questions related to information exchange. Firstly, it clarifies the need for information exchange, which is to enable unambiguous information about an asset in an effective and efficient way. Secondly, it specifies how information should be exchanged, and encourage the utilization of the IFC open data standard to support software-independent exchange. This ensures that information can be exchanged across different software platforms without losing data or requiring manual translation. The BIM Basic ILS also outlines what stakeholders should agree on to ensure an unambiguous exchange of information. This includes agreeing on a common language for object and property naming and using a shared project coordinate system. Additionally, the ILS prescribes the minimal required information for each object, such as assigning materials to all objects and using the IFC schema (IfcMaterial) to store this information.

4.4.2 IFC
The Industry Foundation Classes (IFC) represents an open international standard for exchanging and sharing BIM data among software applications used by different stakeholders within the construction or facility management industry sector (ISO, 2018). Its idea was initialized and developed by buildingSMART, aiming to break down the silos of information and enhance seamless information sharing throughout the whole lifecycle of construction projects or assets (buildingSMART, 2013).

The inception of the IFC marked a significant milestone in the evolution of the building industry’s quest for an open data model standard that could address the need of BIM interoperability (Laakso & Kiviniemi, 2012). The implementation of open interoperability for BIM could generate substantial productivity gains: facilitating the seamless transmission of design, cost, project, production and maintenance information, thereby reducing redundancies and improving overall efficiency throughout the building’s lifecycle (Laakso & Kiviniemi, 2012). Additional information about the hierarchical structure of IFC and how different semantic information is stored can be found in Appendix B.

4.4.3 NL-SfB
The NL-SfB classification schema is widely applied in the Dutch construction industry to encode layers and objects in BIM systems (BIM Loket, 2021c). The NL-SfB classification schema is divided into independent groups called tables, namely table 0 to table 4. Table 0 contains the coding for the built environment, including building types, residential areas (e.g., country, province, city) and spaces (e.g., living room, kitchen) (BNA, 2005). Table 1 is used to describe the functional parts of the facility (e.g., outer or inner wall). Table 2 and Table 3 represent the construction method and building materials to be used respectively. While the coding of abstract concepts such as construction process, activities and properties are collected in Table 4. The NL-SfB provides a graphical representation with a different combination of digits and letters following the sequence of Table 0 to Table 4, in which they are placed in fixed places, as shown in Figure 24.
Figure 24. An example of NL-SfB coding system (adapted from BNA (2005))

4.4.4 NLRS

The NLRS (Dutch Revit Standard) is an open standard that lays down agreements about the use of naming, model structure, use of parameters, etc. for the Autodesk Revit software package (BIM Loket, 2022). It ensures that all parties (working with Revit) structure their information in the same way. Furthermore, the NLRS allows the use of other open standards, such as IFC and NL-SfB (BIM Loket, 2022). For example, the entity classification of NL-SfB (Table 1) and its description are asked to be filled in the parameter of ‘Assembly” and “Assembly Description”. Similarly, the material classification of NL-SfB (Table 3) is suggested to be included when naming materials in Revit using a standard naming system as follows: \(<LCSRStl>_<classification code>_<material description>_<characteristics>_<generic or supplier>_<content creator>\). The explanation of the material naming format is presented in Table 16.

Table 16. Material naming system in Revit (Pijffers, 2016)

<table>
<thead>
<tr>
<th>Definition</th>
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<tbody>
<tr>
<td>&lt;LCSRStl&gt;</td>
</tr>
<tr>
<td>&lt;classification code&gt;</td>
</tr>
<tr>
<td>&lt;material description&gt;</td>
</tr>
<tr>
<td>&lt;characteristics&gt;</td>
</tr>
<tr>
<td>&lt;generic or supplier&gt;</td>
</tr>
<tr>
<td>&lt;content creator&gt;</td>
</tr>
</tbody>
</table>

4.4.5 NAA.KT

As introduced before, NL-SfB is mainly applied for encoding layers and objects in BIM systems, and only the classification code in table 3 can be used to record material-level information. Because of this, in the NLRS, users can provide deeper material insights in <material description> complemented with the classification code (Table 16). However, design engineers could not describe their materials unambiguously without standard formats. Instead, NAA.KT is an industry-wide standard to ensure unambiguous material designation, by maintaining a fixed order in naming: NAAm_Kenmerk_Application (name_attribute_application) (BIM Loket, 2021b). NAA.KT provides a list of standard material descriptions in each position regarding name, attribute, and application as shown in Figure 25.
4.4.6 ETIM
The European Technical Information Model (ETIM) provides an open standard for the clear classification and specification of products in the installation industry through a uniform product categorization model. This classification employs product classes, features, values, and synonyms, facilitating the efficient identification of appropriate products (Figure 26). All classes, features, values, and units are distinctly and unambiguously identifiable via a language-dependent unique coding (Habets & Pappas, 2013).

![Figure 25. NAA.KT generator overview](image)

![Figure 26. Example of ETIM classification for a lamp (Appleton, 2021)](image)

The report of the “UOB content guide” has specified how NLRS and ETIM should be applied for Revit users when modelling their objects in the installation sector (see G.M.OudeLashof, 2020). Specifically, UOB standards for uniform objects library, which is a standard library for Revit-modeler. For example, it encourages users to group all ETIM-class features under “Model Properties” in Revit and use the format of “EC_Feature code_Feature description” to name a Revit parameter, as an example represented in Figure 27.
4.5 Activity theory and implementation plan

The previous sections aim to provide theoretical background for the development of design solutions or end products in this study. Upon completing the development, it becomes necessary to assess the tool’s potential for implementation in the problem context. As discussed in sub-section 3.3.3, the step of treatment implementation entails analyzing the tool’s ability to function alongside the existing tool employed in the case project, with the ultimate aim of enhancing the decision-making process. Hereby, a systematic and dynamic mechanism is necessary to support the integration of the new tool and the existing one. Activity theory can be used to provide a theoretical framework for understanding the performance problems and corresponding solutions when integrating the new tool (proposed in this study) in a complex system (the environment of the case projects).

The usefulness of activity theory is concretized by its ability to examine and understand object-oriented and motive-driven collective human activities (Akintola et al., 2020). Originally designed for analyzing human-computer interaction, activity theory works as a cross-disciplinary theoretical basis for aiding the understanding of different forms of human practices (Lu et al., 2018). In the construction industry, activity theory has been used as an analytical framework for understanding the complexity and interaction of actions in projects and analyzing and interpreting the evolvement of a new tool (Lu et al., 2018). For example, Lu et al. (2018) conducted activity theory-based analysis of BIM implementation in building Operations & Maintenance. Akintola et al. (2020) applied activity theory as a theoretical standpoint to spotlight BIM’s impact on professional work practices. van den Berg et al. (2021) explored how BIM reorganizes deconstruction practices from an activity-theoretical perspective. In their study, activity theory was used to visualize how additional problems are triggered given the introduction of new (BIM-based) tools in successive steps.

According to a well-known triangular graphic created by Engeström (1987), every activity can be interpreted by understanding how a subject (an actor performs an activity) uses tools (meditation of the object) to achieve an object (immediate goal) and outcome (long-term results), as shown in Figure 28. Three more elements (rules, community, and division of labour) are incorporated at the bottom of the triangle, in order to interpret human activities in a consistent and systematic way (Lu et al., 2018). Specifically, the Community represents involved actors engaging in the activity, whose interactions are restricted and guided by rules (laws, norms and agreements) and division of labour (the way of arranging work in an activity), as visualized in Figure 28. Tensions exist within and between these elements in a dynamic activity system. As explained by van den Berg et al. (2021), the changes in one element (such as the integration of a new tool) trigger clashes (so-called contradictions) of those previously established elements. The phenomenon of clashes, known as contradictions, can give rise to disruptions and performance problems, necessitating the identification and implementation of solutions (Cole, 1996;
These contradictions can be classified into four types: primary, secondary, tertiary, and quaternary. Primary contradictions occur within a specific element of an activity system, while secondary contradictions arise between different elements within the system. Tertiary contradictions manifest between an established activity and a more advanced one, and quaternary contradictions occur between a given activity and a neighbouring one (Engeström, 1987; van den Berg et al., 2021).

![Triangular activity system model](image)

**Figure 28. Triangular activity system model (Lu et al., 2018)**

### 4.6 Conclusion and findings

In this chapter, the theoretical background regarding the topics addressed in this study is presented. In accordance with the project’s scope of material depletion in the environmental domain, this chapter first delves into circularity indicators which make circularity become measurable from a technical perspective. Specifically, two aspects including circular material usage and circular design were examined respectively. The former encompasses material selection, with a view to facilitating materials regeneration and restoration in either the technical or biological cycle. Several strategies for circular material usage, such as reuse and recycling, were defined. The latter (circular design) concerns how to design products and components in a way to guarantee future usage to facilitate a tighter restoration cycle like reuse. This chapter emphasizes the examination of the design strategy – Design for Disassembly (DfD), as one of the core strategies which guarantees or complements other design strategies. The methods of how to assess the disassembly potential of products/elements from a technical aspect were also examined. Consequently, this study posits that a circularity measurement method ought to encompass (at the very least) two facets of circularity performance, including the degree of circular material usage and circular design.

This study further provides a review of contemporary methods employed for nanoscale research, derived from both academic and industrial sources. Specifically, this study examines the MCI, MCI-based method, and other related methods that are customized to gauge the efficiency of circular material and design. The review procedure is underpinned by three criteria, namely: reliability, operability and intuitiveness and several findings are listed as follows:

- The majority of the methods are categorized as low reliability due to their dependency on lifecycle information, which is often not available in construction projects. Moreover, these methods do not consider the variability of information availability during different construction phases.
and offer a fixed calculation method for different phases, necessitating subjective assumptions by project stakeholders.

- There is a dearth of attention given to the construction and support of data in the domain of circularity assessment.
- Industrial and company practices exhibit a high degree of intuitive functionality through the use of GUIs such as those found in excel, web, and application-based platforms. In contrast, academic methods tend to overlook the importance of user experience.

Therefore, this study deduced that (most) existing methods are inadequate in providing actual circularity insights into construction projects for stakeholders. Additionally, the Circular Project Model developed by Van den Berg et al. (2019) was introduced with several highlights in tandem with the project’s goals and interests:

- Different material flows (in both a linear and circular procedure) flowing in/out construction sites are visualized.
- It provides insight into the degree of circularity for different types of projects like a new-built and renovation ones.
- Although only reuse scenario is modelled, the CPM can be leveraged to embody other R strategies like remanufacturing or refurbishing.

Thus, the CPM is proposed as a commendable starting point for designing a "reliable, operable, and intuitive" circularity assessment method for construction projects, despite certain limitations (such as the inability to capture recycling scenarios), which may necessitate refinement. These aforementioned discoveries have the potential to make valuable contributions towards the development of calculation models (ancillary knowledge 2) and a new BIM-based circularity assessment tool (end product), as illustrated in Figure 1.

Subsequently, an analysis is conducted on different BIM techniques that aid in facilitating circularity assessment. The integration techniques are categorized based on two primary factors: information and assessment environment. The former concerns the location of storing circularity-related information store, while the latter focuses on where a circularity assessment should take place. Three existing tools (with different combinations of BIM techniques) are introduced, including the Madaster circularity indicator (Madaster, 2018), the BIM-based Whole-life Performance Estimator (Akanbi et al., 2018) and the Building circularity assessment scoring tool (Zhang et al., 2021). This section is concluded with an overview of the strengths and weaknesses of each integration way, which provides a theoretical foundation when selecting an appropriate pathway for the development of the main end-product of this study (see Figure 1). The selection process should weigh the trade-offs associated with these integration methods, while also taking into account the specific requirements of stakeholders (for further details, see subsection 5.3.2).

The chapter also delves into the possibilities of utilization of open BIM standards as means of storing and exchanging semantic information in the context of circularity assessment. Several well-developed standards were investigated including BIM basic ILS, IFC, NL-SfB, NLRS, NAA.K and ETIM within the Dutch construction industry. These insights contribute to the generation of ancillary knowledge regarding information management (see sub-section 5.1).

Last but not least, activity theory is introduced to serve as a theoretical framework for understanding the possible contradictions that may arise from integrating the new tool (proposed in this project) with the existing tool (used in the case projects). This provides valuable knowledge background towards the development of the byproduct pertaining to the implementation plan (see Figure 1), and the utilization of activity theory is presented in sub-section 7.2.
5. Treatment Design

As outlined in sub-section 1.3, the primary objective of this project is to develop an end-product in the form of a prototypical BIM-based circularity assessment tool, supplemented by ancillary knowledge related to information management and circularity assessment (Figure 1). Each of these outcomes will be introduced in this chapter. Note this report mainly represents the design results on the final iteration (after three design cycles), especially about the end-product (the BIM-based circularity assessment tool).

5.1 Ancillary Knowledge 1 – BIM standards and information management

5.1.1 Current situation and challenges

To effectively capture circularity-related information through the utilization of (open) standards, the present study first relies on the case projects as practical examples to investigate how stakeholders employ standards or guidelines in the execution of construction projects.

As the most widely used BIM guideline in the Netherlands, the ILS provides a framework of essential agreements necessary for the efficient and effective exchange of digital building information. To guarantee the quality of BIM models, the client of the case projects (UT) prescribed the use of ILS (version 2), which offers a clear answer regarding interchangeable and unambiguous information exchange. In accordance with ILS, an international open data structure, IFC was applied to realize information exchange in a software-independent way, although different software was used in the case projects (e.g., Revit, Naviswork and Tekla). Furthermore, NL-SfB (Table 1) was utilized by designers and contractors to establish uniform object identification. In addition, the NLRS lays down agreements about the creation of Revit objects and encourages the use of other open standards like IFC and NL-SfB (Table 1 and Table 3). In the case projects, the entity classification of NL-SfB (Table 1) and its description were asked to be filled in the parameter of “Assembly” and “Assembly Description” in a Revit environment (Figure 29). Furthermore, design engineers were required to adopt a standard material naming system based on NL-SfB table 3 as follows: <LCRStl>_<classification code>_ <material description>. Here, <classification code> conforms to table 3 of the NL-SfB (letter and number combination) based on material type, as an example shown in Figure 30. However, in practice, NL-SfB is mainly employed for encoding layers and objects in BIM systems, and only the classification code in table 3 can be used to record material-level information. Because of this, one BIM expert expressed: “The NL-SfB is not enough” and “NAA.K.T is gradually asked by our clients”. The utilization of NAA.K.T was also incorporated in the lastest version of the ILS.

Figure 29. Assembly code in Revit (23.21 represents constructive floors)

Figure 30. An example of materials naming in the case project (Langezijds): I4 and M1 represent wood laminate and mineral wool respectively.

In relation to the construction phase of the case project (Langezijds), there is a multitude of sub-contractors and manufacturers involved (more than 40), with the main contractor responsible for quality control and (BIM) model consolidation. Based on one BIM specialist involved in the construction team, all (sub-) contractors/manufacturers follow the minimum guidelines provided by the ILS, ensuring a certain level of consistency in the models, whilst granting flexibility for the inclusion of additional
information with customized formats. This, however, has led to the use of different dialects to document material information in aspect models developed by subcontractors/contractors/manufacturers, which differs from the design phase, where NL-SiB (recommended by NLRS) or NAA.KT is commonly used for material designation as discussed before. Furthermore, it was observed that despite the presence of certain circularity-related information (e.g., products’ weight and installation methods), it was not included in BIM objects and was stored in different places, such as sheets of product information developed by manufacturers, in a customized manner.

In addition to stakeholders involved in construction projects (designers, contractors and manufacturers), external databases like the National Environment Database (NMD) were also investigated for their potential to support a circularity assessment. The NMD, which works closely in the field of circular construction, provides standardized circularity-related information and values to ensure transparency and comparability of the circular performance of construction products. In order to classify products in the NMD database, the NL-SiB is used as a basis (the first three digits of NL-SiB and supplemented by a proprietary classification method). However, it was observed that, similar to the issue identified among contractors and manufacturers, no standardized method for material designation is available.

5.1.2 Potential solutions
Upon investigating various semantic and exchange standards (as presented in sub-section 4.4), ETIM has shown the potential to facilitate the storage and exchange of semantic circularity information in a structured manner. Firstly, while ETIM is rooted in the electrotechnical and installation sector, it is rapidly gaining acceptance in the construction industry. The construction industry, and specifically installation companies, have widely adopted the ETIM classification system to structure information relating to "off-the-shelf" installation products (Spekkink, 2022). ETIM has become a standard communication tool between installation companies and their suppliers. To facilitate the effective utilization of ETIM, guidelines such as the UOB content guide (as outlined in sub-section 4.4) have been developed to assist users in modelling objects and structuring relevant information, particularly by relevant manufacturers/suppliers. This adoption of ETIM within the construction sector, particularly in the installation sector, sets a good example for wider sector implementation.

Secondly, the ETIM follows a standardized structure, which documents different information of a product by capturing its classes, features, and values, as illustrated in Figure 26 in sub-section 4.4. ETIM International has also designed a Classification Management Tool (CMT), which records various classifications for supporting practical usage. With those advantages, the ETIM system has demonstrated considerable potential in facilitating standard information. Accordingly, this study proposes the integration of ETIM within construction phases, specifically between contractors and manufacturers, to support information management in a structured manner. Specifically, the study proposes the usage of ETIM classification for structuring information at the feature/parameter and value level, as illustrated in Figure 31. This is because the presence of NL-SiB (Table 1) for capturing information at the level of product group (e.g., 21 for presenting external walls) and product class (21.1 for presenting non-loading bearing external walls) based on the ETIM classification structure (Figure 31). While there is potential for the implementation of the ETIM classification system at the product level as a replacement or link to the NL-SiB system (Table 1), there remain considerable challenges to be addressed. The Roadmap Standard report prepared by BIM Loket (see Spekkink (2022)) highlights that, despite the frequent use of ETIM by installation companies, the construction sector as a whole involves a great deal of customization rather than reliance on "off-the-shelf" products. As a result, the widespread adoption of the ETIM standard, particularly at the product level, is hindered. Consequently, this study proposes a more feasible approach that combines the NL-SiB system at the product level with the ETIM system, which can be initiated at the feature or value level (see Figure 31). More detailed information regarding the utilization of ETIM is presented in sub-section 5.4.2.1.
Additionally, the study recommends that the NMD should refrain from using its own proprietary dialects and instead embrace established standards for material designation. To support a circularity assessment during project phases, the NMD database can align with the standards used by designers, contractors, and manufacturers such as NL-SfB (Table 3), NAA.KT, or ETIM. The subsequent chapter provides further details and examples on this subject.

However, the incorporation of the ETIM into BIM can result in a situation where multiple stakeholders apply different standards (for material designation) within the same models. To address this issue, the present study proposes the development of standard mapping tables, which would allow for unambiguous communication between different material standards. In other words, the tool should be designed in a manner (with the help of mapping tables) that allows for the recognition of various material designations structured according to different standards like NL-SfB, NAA.KT and ETIM, to facilitate a circularity assessment at different phases of a project (as illustrated in Figure 32). This strategy aligns

**Figure 31. The proposal of adopting ETIM for structuring information at the level of feature and value**

**Figure 32. Mapping tables for material designations structured by different standards**
with one of the potential initiatives of BIM Loket, which involves conducting research into the connection between NAA.KT and ETIM (Spekkink, 2022).

Taking an example as shown in Figure 33, starting from design phases, a standard classification system NL-SfB (Table 1) is used to provide objects with a four-digit code (e.g., 23.21 for a constructive floor). NL-SfB (Table 3) or NAA.KT is also encouraged to apply for structuring materials information during design phases. When approaching construction phases, a new standard – ETIM can be used by contractors and manufacturers with specific codes (e.g., EV004820 and EV000079 for mineral wool and concrete respectively). These ETIM classification codes can be translated to NL-SfB or NAA.KT code. For example, the ETIM classification of EV004820 corresponds to M1 (based on NL-SfB) or Isolatie_mineral wol_ntb (based on NAA.KT), which are equivalent designations for the same material (i.e., mineral wool) and fall under the category of Inorganic Materials. Despite the fact that different project phases use different standards, the same is meant with the help of automatic mapping inside the tool.

5.1.3 Summary
The present study initiates by scrutinizing current approaches employed by project stakeholders (e.g., design and construction engineers) and their associated challenges in the case projects, with the primary aim of providing illuminations into the realms of information management and open standards. The current approaches and challenges encompass the following:

1. The NL-SfB (Table 1) has emerged as a widely used standard among various stakeholders involved in the construction industry for product classification, providing a common ground for communication and collaboration.
2. With the ILS as the guiding principle and leveraged by other standards (e.g., NAA.KT) and software standards (e.g., NLRS), design teams have been able to adopt a structured approach to managing information related to circularity, such as product classification and materials designation.

3. The absence of a standard for materials designation among contractors, manufacturers, and external databases like the NMD has created unambiguous communication at the material level, hindering effective collaboration and transparency (Figure 34).

4. Despite the availability of some required information during the construction phase, such as material composition and installation methods, it is documented in a customized way in different places, further impeding efficient circularity assessment in a BIM environment.

Figure 34. Different standards used among construction stakeholders (adapted from (Cleijpool et al., 2022))

Correspondingly, the study proposes:

1. ETIM is proposed to be involved in construction phases for contractors and manufacturers to support information management in a structuralized way (Figure 35).

2. To ensure consistency and comparability across different stakeholders, the material information in the NMD database or other similar databases can be organized according to the standards used by designers, contractors, and manufacturers such as NL-SfB (Table 3), NAA.KT, or ETIM.

3. To facilitate clear communication between different standards at the material level, it is recommended to create standard mapping tables. These tables would enable unambiguous mapping between the language used by different standards and thus enhance the exchange of material information between different stakeholders, as shown in Figure 35.
5.2 Ancillary Knowledge 2 – Tailor-made calculation models

In current practice, many existing methods for assessing circularity performance show insufficient flexibility in accommodating the varying degree of information availability during different phases of construction projects. This commonly yields a fixed calculation model that may rely upon subjective estimations by users, especially during early phases where information is normally limited. In contrast, this project proposes a new approach that accounts for the variability of information availability throughout the project lifecycle, resulting in three tailor-made circularity calculation models. This approach enables project stakeholders to use the available information at different stages of the project to gain an overview of their circular performance and acquire deeper material insights as more information becomes available in the later project phases. Specifically, this approach categorizes a construction project into three phases based on the level of information availability: initial phases, design phases, and construction phases (as detailed in Table 17).

<table>
<thead>
<tr>
<th>DNR-STB</th>
<th>Comparable with LOD</th>
<th>Categories defined by this EngD project</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiative and feasibility (IH)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Project definition (PD)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Schematic design (SO)</td>
<td>LOD 100</td>
<td>Initial phases</td>
</tr>
<tr>
<td>Preliminary design (VO)</td>
<td>LOD 200</td>
<td></td>
</tr>
<tr>
<td>Definitive Design (DO)</td>
<td>LOD 250/300</td>
<td>Design phases</td>
</tr>
<tr>
<td>Technical Design (TO)</td>
<td>LOD 350</td>
<td></td>
</tr>
<tr>
<td>Pricing and contracting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Execution Ready Design (UO)</td>
<td>LOD 400/450</td>
<td>Construction phases</td>
</tr>
<tr>
<td>Execution management</td>
<td>LOD 500</td>
<td></td>
</tr>
<tr>
<td>Use and Exploitation</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The CPM developed by Van den Berg et al. (2019) was taken as a basis to develop the assessment methods (Figure 16). As summarized from the literature review (sub-section 4.6), this simple model makes a distinction between new materials, waste and recovered materials within CE from a project-based perspective. The model, hence, fits with the aforementioned study’s scope (focusing on material depletion in construction projects), but it had not yet been digitized in a BIM environment. As introduced before (Table 6), this study considers reuse as a status considered on or above product level (e.g.,...
elements or structures). Therefore, from a resource perspective, the CPM model can be used to visualize to what extent new resources (e.g., materials and products) or reused products are used in a construction project. Here, the term “resource” is used to describe all objects at different levels of scale (e.g., materials, products and elements). In addition, the words “reuse/reused products” are used instead of “materials” to clarify that reuse strategies are applied at product-level, as shown in Figure 36. Note that the status of upper levels can be inherited by lower levels; therefore, this study implies reusing a product implies all materials of the products are also reused (in arrow 3 in the CPM, see Figure 16). Furthermore, as stated in sub-section 4.2.1, the CPM can be used to represent other R strategies (e.g., remanufacture), although only the reuse scenario is modelled. However, the current CPM fails to capture recycling scenarios and should be improved. Note that this study explicitly focuses on how to measure circularity performance regarding material depletion from two aspects, namely, circular material usage and circular design, as summarised in sub-section 4.6. The former considers how to encourage material regeneration and materials restoration, while the latter aims for designing products/components in a way to enable future usage, such as following the principles of DfD. Those design strategies contribute to close material loop by facilitating material reuse; hence, is important to be considered under the domain of material depletion. Other aspects (e.g., energy, water and emission) are excluded from this study (as introduced in sub-section 2.2).

5.2.1 Initial phases (LoD <= 200)
As these resource flows are modelled in Figure 36 based on the CPM, a simplified indicator of material efficiency is developed as presented in Equation 1, where $F_i$ is the volume-based percentage of each resource flow and $R_i$ represents the weighting of each of the factors. Note that the central unit of measurement adopted in this stage (initial phase with approximately LOD level lower than 200) is “volume”. This is because, during this stage, the referred 3D model is only a graphic representation of an object rather than a BIM model, without involving other information but only geometric information. Besides, $R_i$ shows a preference of resource flow within a circular project. For example, the attempt of recovery and reuse at the same site (arrow IV in Figure 36) has the highest circular level, as it means that the old building products/materials can be reused directly without requiring additional transportation.

$$Material\ circularity = \sum R_i \times F_i, \text{ where } i = 1,2,3,4,5$$

(1)

To show the implication of Equation (1), the following assumptions are made:

1. Weighting factors located in a linear procedure from transporting new resources to a construction site (R1) to depositing waste from the site (R2) are assigned a zero value.
2. On the contrary, the most preferable solution (R4) is given a full score of 1.
3. A middle score of 0.5 is assigned to less effective circular actions (R3 and R5), in which reused products are transported to and away from a construction site.
With Equation 1, the level of circularity can be quantified in the range 0 to 1, where 0 represents a purely linear procedure while 1 is a fully circular project. Note that the calculation model only differentiates the materials flows visualized in Figure 36 without distinguishing different materials within the same flow. In other words, the reused gravel, concrete or wood (in the same building) are regarded as the same. For enabling usability, Table 18 can be used for supporting circularity assessment in initial phases.

Table 18. The calculation table for initial phases

<table>
<thead>
<tr>
<th>Resource flow</th>
<th>Ri</th>
<th>Fi (0–100% volume-based)</th>
<th>Circularity value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – New resources</td>
<td>0</td>
<td>e.g., 50% or 0.5</td>
<td>$F_1 R_1$</td>
</tr>
<tr>
<td>2 – Waste</td>
<td>0</td>
<td></td>
<td>$F_2 R_2$</td>
</tr>
<tr>
<td>3 – Reused products from an old building</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 – Reused products in the same building</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 – Reuse products in another building</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material circularity</td>
<td></td>
<td></td>
<td>$\sum R_i F_i$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Where i = 1,2,3,4,5</td>
</tr>
</tbody>
</table>

5.2.2 Design phases (200 < LoD <= 350)

Various material flows can be further distinguished to provide a more complete circular scenario (Figure 37), given additional information, such as material designation (structured based on NL-SfB or NAA.KT), which is typically provided during design phases with approximately LOD levels between 200 and 350. By providing detailed material information, it becomes possible to identify the presence of renewable resources (e.g., wood) as well as non-renewable materials (e.g., concrete) of a given product. Additionally, it is also feasible to differentiate unrecoverable waste based on their EoL processing options (recycling, incineration and landfill), by utilizing the standard value provided by the NMD database (refer to sub-section 5.4.2.1 for more information). In summary, from a resource...
perspective, the model (of design phases) aims to visualize to what extent primary/renewable materials or reused products are used in a construction project. Specifically, compared with the previous one (Figure 36), the model is updated by:

1. Differentiating resources going to the reuse/recycling cycle or ending up in incineration/landfill
2. Dividing resources feedstocks into renewable and non-renewable materials

![Figure 37. The calculation model used in the project phases](image)

Similar to Equation 1, the material efficiency is calculated by multiplying the mass-based percentage of each resource flow \(F_i\) and the weighting of each of the factors \(R_i\). The percentage of resource flows refers to material/product/element mass, rather than volume. This is because mass is proposed as a more suitable measurement unit for differentiating materials’ relative importance compared to volume since volume is largely determined by production technologies and the processing materials used (Coenen et al., 2021). During design phases, manufacturers/suppliers of construction elements are generally unknown and elements are modelled as “global/general” rather than “specific”. Therefore, the information on mass or products’/materials’ weight is regarded as “unavailable”. For guaranteeing the mass-based metric is easily applicable in practice, the BIM-based circularity assessment tool was designed in a way to obtain mass information by depending on the project-specific data (geometric information like volume, area or material thickness) and general data (materials average density). More details are provided in the next chapter.

Different weighting factors \(R_i\) are given to each resource flow for outcome aggregation (as presented in Table 19) and the following assumptions are made:

1. Inheriting the characteristic of the circular project model, the reuse strategy is taken as the highest priority compared with consuming new resources (no matter whether it is renewable or not). In other words, the model encourages using technical/biological products (arrow 3 with a weighting factor of 0.5) rather than; for example, depleting renewable materials (arrow 1.2 with a weighting factor of 0.25).
2. Similarly, the reuse strategy is the most appraised; hence, the actions of reusing materials in another building (arrow 5 with a weighting factor of 0.5) were appraised compared with recycling materials (arrow 2.3 with a weighting factor of 0.25).

Note, although the crushed concrete can be reprocessed to asphalt debris, the construction projects themselves are unclear about what percentage of concrete can be recycled in most cases. “We pay for the recycling factories to collect the construction waste”, one project manager said, while the processing scenarios (recycling, landfill or energy recovery) are dependent on different factors (e.g., recycling techniques and materials characteristics), which are difficult to estimate. However, the estimated EoL processing options should be modelled in the BIM-based tool, given that “it is interesting to see how many materials can be recycled”, as the project manager said. For supporting practical usage, the standard value of materials’ EoL scenarios (presented as a percentage) will be embedded inside the tool. The value is extracted and restructured from the NMD database and more details will be introduced later. Table 19 can be used for supporting the circularity assessment during design phases.

Table 19. The calculation table for design phases

<table>
<thead>
<tr>
<th>Resource flow</th>
<th>Ri</th>
<th>Fi (0~100% mass-based)</th>
<th>Circularity value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.1</td>
<td>0</td>
<td>$F_{1.1} \times R_{1.1}$</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>0.25</td>
<td>$F_{1.2} \times R_{1.2}$</td>
</tr>
<tr>
<td>II</td>
<td>2.1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>3</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>4</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>5</td>
<td>0.5</td>
<td></td>
</tr>
</tbody>
</table>

Material circularity

$$\sum R_i \times F_i$$

Where $i = 1.1, 1.2, 2.1, 2.2, 2.3, 3, 4, 5$

5.2.3 Construction phases (LoD >350/400)

When projects go, more information can be obtained when contractors and manufacturers are involved in construction projects, and deeper circularity insights can be provided with this available information correspondingly. As introduced in sub-section 2.2, the circularity performance is embodied through the extent of circular material usage and circular design. Regarding circular design, DfD contributes reusability and recyclability of products/materials from a technical perspective and gained ground in the construction industry (Geldermans, 2016). Furthermore, Detectability is an important factor which essentially enables efficient reuse and potentially increases the amount of reused products (either arrow 3, 4 or 5 in the CPM) in a new building. Hereby, the overall circularity value is weighted with the considerations of two indexes so-called: Material Circularity (about circular material usage) and Detachability Potential (about circular design). The model used in this phase is presented in Figure 38.
Material circularity

Instead of only considering the usage of renewable materials (Figure 37), the positive effect of recycled input (flow 1.2) is included in the calculation model with available information in construction phases, as shown in Figure 38. Note that recycled materials are regarded as “new” in arrow I, given the fact that those secondary materials are produced into new products, and for the project, it is not different to use products produced by secondary materials or new materials, as one project manager mentioned. Here, the same weighting factor (0.25) is given to the material flow of renewable and recycled materials. In other words, it is assumed that the usage of circular materials (either renewable or recycled) is taken as the same effect on the circularity performance of construction projects.

Same with the previous stage, the material circularity is calculated by multiplying the mass-based percentage of each resource flow ($F_i$) and the weighting of each of the factors ($R_i$), using Table 19. The only difference lies in F1.1, which presents the percentage of circular materials in this stage instead of the percentage of renewable materials. Note that during this stage, relevant contractors and manufacturers are encouraged to include precise mass information inside BIM objects, rather than estimations based on general density information (in design stages).

Detachability potential

The index of detachability potential is used for providing an indication of how easily a (new) building and its products can be disassembled or released when a building approaches its EoL. Differing from the material circularity (at the material level), the detachability potential is considered at product level. The effectiveness of material separation (mainly for material recycling) is ignored in this study.
The detachability measurement method is referred to the report “Circular Buildings – a measurement method for detachability 2.0” (van Vliet et al., 2021), considering the ability to disassemble a product or element at the end of a building life. To enable usability, this project starts with two main factors: connection type and accessibility level. Specifically, the factor of connection type concerns the various types of connections used for connecting objects, which affect the ability to disassemble a product or element at the end of a building’s life. The second factor of the detachability measurement considers the accessibility level, which measures how easily a demolition contractor can reach the connecting elements and to what extent will it damage surrounding objects. The higher the score is, the earlier a demolition contractor can reach the connecting elements without damaging the surrounding objects. The level of detachability potential of a product (in a new building) is expressed as follows:

\[
D_{P(a)} = \frac{2}{\text{Connection type} + \text{Accessibility level}}
\]  \hspace{1cm} (2)

Where \(D_{P(a)}\) is the detachability potential of product a.

As listed in Table 8, a quantitative assessment is enabled by translating the descriptive values of connection type and accessibility level into numerical values. Note that for a renovation project, the measurement is used to assess the detachability potential of a new building, without considering products/materials flowing out of the building. In other words, only products located in arrow I, III and IV are counted when assessing products’ detachability potential.

**Overall circularity value**

Since material circularity and detachability potential are applied to the different levels of scale (at material and product levels respectively). Therefore, for calculating the overall circularity value in this phase, products serve as a minimum assessment unit. In other words, the material circularity of a product is first evaluated through its material composition (e.g., the relative percentage of circular/uncircular materials in arrow I). Afterwards, the product is assessed on how easily it can be separated from surrounding products and represented by an index of detachability potential. The assessment of a building’s disassembly performance is predicated upon the cumulative disassembly potential of its constituent products/elements. To determine this score, a mass-based weighting factor is applied (instead of the MKI-based one proposed in the original method). By doing this, it enables the assessment of two aspects, namely material circularity and detachability potential, using a consistent unit of measurement (mass).

The assessment process is presented as follows:

1. Obtain the information of products ‘weight in each flow.
2. Obtain the information of material composition of each product based on Figure 38. For example, if a product is regarded as “new” in arrow I, more information regarding the weight or relative percentage of circular materials (renewable and recycled) and non-circular materials is required.
3. Calculate the material circularity of each product using Equation (3):

\[
M_{P(a)} = \frac{\sum_{b=1}^{n} M_{m(b)} \sum_{b=1}^{n} R_i (b) \times M_{m(b)}}{\sum_{b=1}^{n} M_{m(b)}}
\]  \hspace{1cm} (3)

Where:
\(M_{P(a)}\) is the material circularity of product a
\(M_{m(b)}\) is the weight of a material b involved in the product a
\(R_i (b)\) is the weighting factor of the material b, as presented in Table 20.

Table 20. Weighting factors of each resource flow

<table>
<thead>
<tr>
<th>Resource flow</th>
<th>Ri</th>
</tr>
</thead>
<tbody>
<tr>
<td>I 1.1 – Non-renewable primary materials</td>
<td>0</td>
</tr>
<tr>
<td>I 1.2 – Renewable or/and recycled materials</td>
<td>0.25</td>
</tr>
<tr>
<td>II 2.1 – Energy recovery</td>
<td>0</td>
</tr>
<tr>
<td>II 2.2 – Landfill</td>
<td>0</td>
</tr>
<tr>
<td>II 2.3 – Recycling</td>
<td>0.25</td>
</tr>
<tr>
<td>III 3 – Reused products from an old building</td>
<td>0.5</td>
</tr>
<tr>
<td>IV 4 – Reused products in the same building</td>
<td>1</td>
</tr>
<tr>
<td>V 5 – Reused products in another building</td>
<td>0.5</td>
</tr>
</tbody>
</table>

For example, if a new product (in arrow I) is composed of 50% primary materials and 50% recycled input, the material circularity of the product is: 0.5 * 0 + 0.5 * 0.25 = 0.125.

4. If a product is part of flow I, III or IV, obtain the information of connection type and accessibility
5. If a product is part of flow I, III or IV, calculate the detachability potential of the product using Equation (2)
6. Calculate the product circularity value of each product using Equation (4)

\[ P_a = M_{p(a)} \cdot (D_{p(a)}) \]  

Where:
- \( P_a \) is the product circularity value of product \( a \)
- The brackets represent the detachability potential of a product that will be only considered when the product is in the new building (arrow I, arrow III and arrow IV).
7. Calculate the overall circularity value of all products in different flows using Equation (5)

\[ \text{Overall circularity value} = \sum_{a=1}^{n} \frac{W_{p(a)}}{\sum_{a=1}^{n} W_{p(a)}} \cdot P_a \]  

Where \( W_{p(a)} \) is the product weight of a product \( a \)

Table 21 can be used for conducting the assessment.

Table 21. The calculation table for construction phases

<table>
<thead>
<tr>
<th>Resources flow</th>
<th>Products</th>
<th>Product weight</th>
<th>Material circularity</th>
<th>Detachability potential</th>
<th>Product Circularity value</th>
</tr>
</thead>
<tbody>
<tr>
<td>I 1.1 (Non-renewable primary materials) = 0</td>
<td>Product I₁</td>
<td>( W_{p(I₁)} )</td>
<td>( M_{p(I₁)} )</td>
<td>( D_{p(I₁)} )</td>
<td>( P_{I₁} = M_{p(I₁)} \times D_{p(I₁)} )</td>
</tr>
<tr>
<td>I 1.2 (Renewable or/and recycled materials) = 0.25</td>
<td>Product Iᵣ</td>
<td>( W_{p(Iᵣ)} )</td>
<td>( M_{p(Iᵣ)} )</td>
<td>( D_{p(Iᵣ)} )</td>
<td>( P_{Iᵣ} = M_{p(Iᵣ)} \times D_{p(Iᵣ)} )</td>
</tr>
<tr>
<td>II 2.1 (Energy recovery) and R 2.2 (Landfill) = 0</td>
<td>Product II₁</td>
<td>( W_{p(II₁)} )</td>
<td>( M_{p(II₁)} )</td>
<td>-</td>
<td>( P_{II₁} = M_{p(II₁)} )</td>
</tr>
<tr>
<td>II 2.3 (Recycling) = 0.25</td>
<td>Product IIᵣ</td>
<td>( W_{p(IIᵣ)} )</td>
<td>( M_{p(IIᵣ)} )</td>
<td>-</td>
<td>( P_{IIᵣ} = M_{p(IIᵣ)} )</td>
</tr>
<tr>
<td>III 3 – Reused products from an old building</td>
<td>Product III₁</td>
<td>( W_{p(III₁)} )</td>
<td>( M_{p(III₁)} )</td>
<td>( D_{p(III₁)} )</td>
<td>( P_{III₁} )</td>
</tr>
</tbody>
</table>
5.3 End-product – A BIM-based circularity assessment tool

This sub-section provides the system requirements and system architecture of the BIM-based circularity assessment tool. As discussed in sub-section 3.3.1, the development of the tool was aided by the Python programming language. The programming code for the tool can be found in the GitHub repository\(^1\).

### System requirements

**System requirements are derived from two sources:** the literature (or existing methods) and stakeholders (involved in the case projects). In terms of the literature (as learned in sub-section 4.3), three desirable quantities (or system needs) of circularity methods are identified, namely reliability, operability and intuitiveness, and reveals that most existing methods fail to meet these requirements. Hereby, this study proposes to design a “reliable, operable and intuitive” BIM-based circularity assessment tool. Considering the project goal in support of a circularity assessment throughout different project phases where different BIM-authoring software may use, an IFC-oriented circularity assessment tool may be more feasible rather than restricting the assessment inside a single software. This requirement is consistent with the stakeholders’ needs, as documented in Table 23. Therefore, regarding the need of “Reliability”, one requirement concerns the tool’s capabilities of extracting and analyzing the information contained in the IFC file(s) (Table 22). In sub-section 4.2, the aspect of operability pertains the BIM utilization and information management. The existing methods, such as Madaster (see details in sub-section 4.3.2), provide valuable insights for improving operability, through the use of open standards for information storage and exchange. Moreover, learning from those methods, the commonly used Dutch open standards can reduce additional efforts by users for information preparation. The aspect of intuitiveness focuses on enhancing the user experience through the use of 2D charts/graphs and 3D colour coding, as recommended by Di Biccari et al. (2019). The EngD candidate identified additional requirements based on a review of existing literature and methods. In sub-section 4.6, the candidate highlighted the need to consider two aspects of circularity performance, specifically circular material usage and circular design, to improve material efficiency. Furthermore, the candidate proposed that the CPM could be designed as a circularity assessment method for construction projects, aligning with the project’s goal. To this end, the EngD candidate established a requirement for visualizing materials flow (e.g., new, reused, or discarded) based on the CPM. There are some other requirements identified by the candidate, such as providing a quantitative result and processing data stored in an external circularity database, which are presented in Table 22.

---

\(^1\) https://github.com/Jiang013/EngD-project
<table>
<thead>
<tr>
<th>System needs</th>
<th>System requirements (learned from the literature and existing methods (e.g., Madaster))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td>The tool should be designed in a way to consider the variability of information availability of different project phases, avoiding subjective assumptions by end-users and providing similar results under consistent conditions. The tool should be capable of extracting and analyzing the information contained in the IFC file(s).</td>
</tr>
<tr>
<td>Operability</td>
<td>The tool should utilize the BIM ability in support of information collection and management, to smoothen the process of circularity assessment. The tool should be developed by taking common Dutch standards (as those standards listed in sub-section 4.4) into account and it should align well with the current working mode in a Dutch construction project.</td>
</tr>
<tr>
<td>Intuitiveness</td>
<td>The tool should exhibit a high degree of intuitive functionality through the use of GUIs such as in the form of excel, web, and application-based. The GUI should show circularity performance (including the overall score and score of each indicator) with a combination of text and 2D charts/ graphs. The tool should visualize the circularity level through 3D colour-coding, to guide users about the poor performance of circularity or imply that results are good using a set of different colours (Di Biccari et al., 2019).</td>
</tr>
<tr>
<td>Others</td>
<td>The tool should encompass (at the very least) two facets of circularity performance, including the degree of circular material usage and circular design. Regarding circular material usage, the tool should (at least) provide information about the flow of new, reused/recycled, and discarded materials, based on the circular project model created by Van den Berg et al. (2019). The tool should provide a quantitative result with a range of 0 to 1. The score 0 represents an entirely linear project while 1 means a fully circular project. The tool should perform an assessment (after uploading all required files/information) automatically with a simple click. The tool should enable an effective assessment with limited user input. The tool should process data stored in an external circularity database (in an Excel form) The tool should link the information stored in the IFC schema and circularity database with open standards or references.</td>
</tr>
</tbody>
</table>

Simultaneously, as elucidated in sub-section 3.3.1, this study has followed an iterative design cycle that progressed from high-level needs to a more detailed examination of stakeholder requirements. This progression was driven by the treatment validation in each iteration of the design cycle, as presented in Table 23. Table 24 provides additional information regarding each requirement and corresponding stakeholders’ representative quotes summarized from the treatment validation, and more detailed will be introduced in sub-section 6.3. It is important to note that the first-round design cycle of the BIM-based circularity assessment tool is primarily driven by the requirements obtained from the literature, rather than stakeholder inputs, although the initial version of the prototypical tool failed to meet all the requirements outlined in Table 22. The reason for this is that, during the early design phase, the EngD candidate focuses on developing a limited prototypical tool (as illustrated in Figure 60 in sub-section 6.3), which can be utilized by stakeholders to generate requirements through user-based evaluation sessions (refer to sub-section 6.3 for more details). This is mainly due to the fact that, at this stage, stakeholder requirements tend to be too broad without a physical artefact, resulting in only two overarching needs being identified in this study's initial phase (as shown in Table 23). Therefore, the EngD candidate adopted a strategy to first develop a physical prototypical tool and enhance stakeholder
discussions to generate more detailed requirements, which can facilitate subsequent design cycles (as depicted in Table 23).
### Problem Investigation (see Chapter 1)

**Problem:** lack of a tool for assessing the actual circularity performance of construction projects in different project phases  
**Goal:** develop a prototypical BIM-based circularity assessment tool

<table>
<thead>
<tr>
<th>Requirements</th>
<th>First design cycle</th>
<th>Second design cycle</th>
<th>Third design cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-level requirements:</td>
<td>1. The tool should use an IFC file(s) as an information carrier instead of a plug-in in BIM-associated software. 2. The tool should enable an intuitive and easy interface.</td>
<td>The second round of design requirements: 1. The tool should provide deeper material-level information. 2. The tool should provide a property window to show the information of each building entity. 3. The tool should integrate the scenario of using bio-based materials. 4. The tool should integrate the recycling scenarios. 5. The tool should support NL-SfB (Table 3) and NAA.KT. 6. The tool should provide circularity-related suggestions and explanations, as a “design tool” rather than a “checking app”. 7. The tool should use multiple units when presenting the information. 8. The tool should improve usability aspects.</td>
<td>The third round of design requirements: 1. The tool should integrate detachability assessment. 2. The study should provide guidelines on how to use the BIM-based tool together with the existing method (in the case projects). 3. The tool should be demonstrated with multiple object groups.</td>
</tr>
</tbody>
</table>

#### The ancillary knowledge and end product
1. A general calculation model based on the circular project model (see Figure 36)  
2. A standalone BIM-based circularity assessment tool with basic functions (e.g., IFC analysis, 3D visualization)  
3. A calculation model by deeper distinguishing material origins and waste scenarios (see Figure 37)  
4. An improved BIM-based circularity assessment tool with deeper circularity insights (e.g., deeper material-level information; estimated EoL scenarios)  
5. A circularity assessment model considering material circularity and potential detachability (see Figure 38)  
6. An improved BIM-based assessment tool with deeper circularity insights (e.g., detachability potential) (see sub-section 5.4.2.3)  
7. Guidelines of information management with the utilization of different open standards in different project phases (see sub-section 5.4.2.1)

### Treatment Validation (see Chapter 6)

<table>
<thead>
<tr>
<th>User-based evaluations</th>
<th>User-based evaluations</th>
<th>User-based evaluations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case demonstration</td>
<td>Case demonstration</td>
<td>Requirements evaluation Case demonstration</td>
</tr>
</tbody>
</table>

### Treatment Implementation (see Chapter 7)

A verified new workflow with the integration of the new tool and the existing tool (the GPR) from activity theory perspective
<table>
<thead>
<tr>
<th>Design cycles</th>
<th>Requirements</th>
<th>Representative quotes from interviews/meetings</th>
</tr>
</thead>
</table>
| First-round   | The tool should use an IFC file(s) as an information carrier instead of a plug-in in BIM-associated software. | “For calculating the environmental impact of the project, I have to wait for architects to provide all of the required information and then I fill them into a program to do a calculation.”  
“The design teams use different software, normally start with Sketchup and produce a detailed design in Revit.”  
“Instead of a Revit plug-in, I would suggest using neutral and open sources like IFC files.” |
|               | The tool should enable an intuitive and easy interface.                        | “We should make it easier to show or visualize the information.”                                              |
| Second-round  | The tool should provide deeper material-level information.                    | “Instead of only providing a single number, I would like to know, for example, how many new materials are involved in the floors, walls or stairs.”  
“I would like to know what kind of materials are involved in each arrow.”  
“I do not know what materials are inside the floor and how they influence the overall circularity value.” |
|               | The tool should provide a property window to show the information of each building entity. | “Instead of only showing a 3D model, each building component can be clickable to show corresponding properties.” |
|               | The tool should integrate the scenario of using bio-based materials.           | “The model does not include the impact of using bio-based materials.”                                          |
|               | The tool should integrate the recycling scenarios.                            | “Although the ‘waste’ was got rid of from the construction site, they can be recovered in recycling factories”.  
“It is interesting to see how many materials can be recycled.” |
|               | The tool should support NL-SfB (Table 3) and NAA.KT.                          | “We normally talk about its table 1 when we discuss the NL-SfB, but table 3 is rarely referenced”  
“NL-SfB is normally used for product identification, while NAA.KT is gradually applied for standardized material designation.” |
|               | The tool should provide circularity-related suggestions and explanations, as a “design tool” rather than a “checking app”. | “It is good to see what is the specific circularity value of a project, while what should I do next?”  
“You should design “a design tool” instead of “a checking app”.  
“The tool provides a circularity value, but I do not know what the score means and if is it a good score?”  
“The tool shows a score of 0.6, what it meant for us, is it good or not?” |
|               | The tool should use multiple units when presenting the information.           | “I would like to suggest using multiple units (like square meters or cubic meters) when presenting component quantities.” |
|               | The tool should improve usability aspects.                                   | “You should make buttons look clickable.”  
“The tool can become more handy if you add some assistance or navigation.” |
| Third-round   | The tool should integrate detachability assessment.                           | “The disassembly possibility is also important to be considered.”  
“This is not only about what elements are used in the building but also how these elements are assembled and what standards we use in assembly.”  
“It is desirable that at least 30% of the building components are designed to be demountable (in a case project), making it relatively easy in the future building parts can get a second life.” |
<table>
<thead>
<tr>
<th>The tool should be demonstrated with multiple object groups.</th>
<th>“It would be better that you can use the tool to demonstrate with different object groups like walls, floors or columns.”</th>
</tr>
</thead>
<tbody>
<tr>
<td>The study should provide guidelines on how to use the BIM-based tool together with the existing method (in the case projects).</td>
<td>“The tool provides the circularity assessment, while we use other methods like GPR in the project, how they can work together and what we can do if they provide conflict results.”</td>
</tr>
</tbody>
</table>
5.3.2 System architecture

With the aforementioned two deliverables, a prototypical BIM-based circularity assessment tool was developed as a concretized example of how BIM techniques can be integrated into circularity assessment. As discussed in sub-section 4.4.2, the main difference between BIM integration techniques lies in two aspects: assessment environment and information. The former focuses on where a sustainability/circularity assessment should be conducted (e.g., plug-in and external tool) and the latter concerns where circularity-related information is stored (e.g., BIM models and external database).

Regarding the former (assessment environment), one key aspect of BIM focuses on interoperability (Soust-Verdaguer et al., 2017), considering how to promote collaboration among various stakeholders and information exchange between different software (Cheung et al., 2012). Hence, Soust-Verdaguer et al. (2017) criticized the development of plug-ins which restrict themselves to individual software and proposed the need of utilizing an open BIM schema and especially in IFC data format. The client of the case projects (UT) also prescribes the openBIM method in order to be able to exchange information between project partners in a software-independent manner, so that information is not enclosed within a specific software package. Project stakeholders (represented by a BIM expert) further explicitly called for “an open and neutral information exchange format” for supporting circularity assessment between different software. Hence, for this project, a standalone BIM-based circularity assessment tool was developed using IFC files as the information carrier, rather than a software plug-in. To conduct the performance assessment on building model(s), the corresponding IFC files must be properly generated from BIM-associated software with correct information. The BIM feature of intelligent modelling also allows additional information to be integrated with geometric data in a 3D model (Akanbi et al., 2018).

Regarding the latter (information), this project proposes a solution by distinguishing project-specific information and generic information. This approach can combine the advantages of the integration ways (as presented in Table 14), by centralizing project-specific information with the BIM objects and reducing some work for project stakeholders to prepare general information. Specifically, project-specific information represents that information that is only relevant to an individual project, for example, geometric information (volume, areas or material thickness), material flows (new or reused materials input), product connection types, accessibility level and etc. It is proposed that project-specific (non-geometric) can be inserted into BIM models, together with geometric information. The generic information is recorded in an external circularity database in the form of an Excel, including NL-SfB classification schema, general material density, the average material percentage going to recycle/landfill/incineration and etc. This information is useful specifically for a generic object at the early stage of projects when manufacturers are not specific. These data (either project-specific or generic) should be structured in a systematic way (through the usage of open standards) that allows data exchange between the external circularity database and BIM. Based on the availability level of project-specific information, a calculation model will be chosen automatically by the BIM-based circularity tool. Correspondingly, the analysis results (e.g., 3D colour coding and 2D charts) will be presented based on the chosen calculation model.

This section gives an overview of the development process of the prototypical BIM-based circularity assessment tool. Figure 39 depicts the system architecture, according to the Input-Processing-Output (IPO) model. In the IPO model of this project (Figure 39), three major components are interlinked: 1) Input: a combination of input sources from BIM models (exported to IFC file(s)) and an external circularity database; 2) Processing: an assessment module in which three different circularity calculation models are available; 3) Output: 3D colour coding and 2D analysis charts presented in a GUI. Note that in principle, the external database should be well-organized, with comprehensive information that is seamlessly integrated with the tool. End-users are, therefore, not required to devote their effort to preparing the “general information” in the database. However, this study only serves as a proof of concept regarding BIM technologies in facilitating circularity assessment across various phases. It does not seek to develop a tool that can be directly implemented in practical scenarios, and the EngD candidate only prepared (a small amount of) information to demonstrate a part of the case project, as presented in sub-section 6.1 later.
Figure 39. The system architecture of the BIM-based circularity assessment tool
5.4.2.1 Input – Information preparation

The step of input concerns the identification and structuring of information for the circularity assessment. As introduced before, in order to reduce the need for subjective estimations, an assessment model where three different calculation models are developed, in line with different levels of information availability during different project phases: initial phase (LOD < 200), design phase (200 < LOD ≤ 350) and construction phase (LOD > 350/400). The required information is categorized into product-specific information (stored in BIM models) and generic information (extracted from an external database), as presented in Table 25.

<table>
<thead>
<tr>
<th>Information needs</th>
<th>Initial phase (LOD &lt; 200)</th>
<th>Design phase (200 &lt; LOD ≤ 350)</th>
<th>Construction phase (LOD &gt; 350/400)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product-specific information (from BIM models)</td>
<td>Status (distinguish materials originals and waste scenarios based on the CPM)</td>
<td>Geometric information (volume, area, material thickness)</td>
<td>Materials designation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product classification &amp; description</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product weight</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Percentage of recycled materials input</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Connection type</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Accessibility level</td>
</tr>
<tr>
<td>Generic information (from an external database)</td>
<td>Mapping tables between the standard of NL-SfB and NAA.KT</td>
<td>Mapping tables between the standard of NAA.KT, NL-SfB and ETIM</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Material average density</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Material average EoL scenarios (the percentage of going to landfill, incineration and recycling)</td>
</tr>
<tr>
<td>Standards/Guidelines</td>
<td>IFC parameters</td>
<td>IFC parameters; NLRS; NL-SfB/NAAK.T</td>
<td>IFC parameters; NLRS; NL-SfB/NAAK.T; ETIM</td>
</tr>
</tbody>
</table>

Project specific information

**Initial phases**

Starting with the initial stages (approximately LOD lower than 200), a 3D model can be developed to represent the information on a basic level with approximate geometric information like area, height, and volume. Non-geometric information can be also attached to the model elements. One common IFC parameter so-called “Status” is introduced to BIM-associated software to carry the material information of each building element based on the CPM (Figure 16). Users should differentiate materials originals (New materials, Reused materials from an old building or Reused materials in the same building) and waste scenarios (Waste or Reuse materials in another building), as an example presented in Figure 40.
Design phases

When a project moves to design phases, more information (including entity classification and material designation) can be added and structured by open standards including NL-SfB (Table 1 & Table 3) or/and NAA.KT. Taking the example of Revit, the required information should be prepared with standard formats based on the NLRS, which documents how projects can apply open standards when modelling BIM models. Specifically, the entity classification of NL-SfB (Table 1) and its description are asked to be filled in the parameter of “Assembly” and “Assembly Description” (Figure 29). Similarly, the material classification of NL-SfB (Table 3) or NAA.KT is suggested to be applied when naming materials in Revit (Figure 30). As introduced in sub-section 5.1.1, construction projects (taking the case projects as typical examples), commonly utilize the aforementioned standards to structure information during the design phases, specifically during the DO (definitive design) or TO (technical design) stages. The incorporation of a BIM-based circularity assessment tool aligns with the current working mode, to avoid extra manual input. With these standard preparations, the BIM-based tool is able to extract the corresponding information from IFC file(s) and provide deeper material insights.

Construction phases

The LOD 350/400 is the stage moving from design to construction phases, where more detailed information becomes available with the high level of design models including materials information (e.g., recycled materials composition) and connections/support. Based on the assessment model (Figure 38), stakeholders are encouraged to provide information such as product weight, the percentage of recycled materials, connection type and accessibility level. For supporting information management in a structurized way, several customized parameters should be introduced to BIM-associated software as a Revit example shown in Figure 41. These parameters and corresponding values should be filled based on ETIM standards, for achieving an unambiguous information representation. Specifically, the name of parameters is structured as follows: EC_ETIM features coding>_<ETIM naming>. The parameters of “EC_EF002169_Material”, “EC_EF000124_Connection type” and “EC_EFXXXXXX_Accessibility” respectively. The value of these parameters should be put in a way like <ETIM value coding>_<ETIM naming>. The classification coding of ETIM’s features and values can be searched from the Classification Management Tool (CMT) provided by ETIM International. However, rooted in the electrotechnical and installation sector, ETIM has not specified for construction products and materials and currently, it is not complete for containing all the required information used in this study. Hence, those unavailable classification codes are presented by EFXXXXXX or EVXXXXXX, and it is proposed that more effort should be put into ETIM classification in the construction industry for practical usage. The ETIM classification of connection type and accessibility level are presented in Table 26 and Table 27 respectively.
Table 26. Connection types and detachability level (adapted from Durmisevic (2006))

<table>
<thead>
<tr>
<th>Connection type</th>
<th>Classification (based on ETIM)</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Dry connection</td>
<td>EVXXXXXX: Loose (no mounting material)</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>EV019152: Stacking</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EV010162: Interlock panel</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EV006116: Magnetic</td>
<td></td>
</tr>
<tr>
<td>B: Connection with added</td>
<td>EV020482: Bolt and Nut Connection</td>
<td>0.80</td>
</tr>
<tr>
<td>elements*</td>
<td>EVXXXXXX: Ferry connection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EVXXXXXX: Corner connections</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EV000173: Screw connection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EVXXXXXX: Connections with added connection elements**</td>
<td></td>
</tr>
<tr>
<td>C: Direct integral connection</td>
<td>EV000158: Pin connections***</td>
<td>0.60</td>
</tr>
<tr>
<td></td>
<td>EV003638: Nail connection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EVXXXXXX: Anchored cladding</td>
<td></td>
</tr>
<tr>
<td>D: Soft Chemical Compound</td>
<td>EVXXXXXX: Kit connection</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>EVXXXXXX: Foam compound (PUR)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EV016070: Tape connection</td>
<td></td>
</tr>
<tr>
<td>E: Hard Chemical Compound</td>
<td>EV003046: Glue connection</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>EVXXXXXX: Collapse connection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EV010232: Weld connection</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EV021773: Cement Bonded Compound</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EVXXXXXX: Chemical anchors</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EV001391: Cast-in-situ concrete</td>
<td></td>
</tr>
</tbody>
</table>

Table 27. Accessibility level and corresponding score (adapted from Durmisevic (2006))

<table>
<thead>
<tr>
<th>Accessibility level</th>
<th>Classification (based on ETIM)</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freely accessible without extra actions</td>
<td>EVXXXXXX1</td>
<td>1.00</td>
</tr>
<tr>
<td>Accessible with additional actions that do not cause damage</td>
<td>EVXXXXXX2</td>
<td>0.80</td>
</tr>
<tr>
<td>Accessible with additional actions with fully repairable damage</td>
<td>EVXXXXXX3</td>
<td>0.60</td>
</tr>
<tr>
<td>Accessible with additional moves with partially repairable damage</td>
<td>EVXXXXXX4</td>
<td>0.40</td>
</tr>
<tr>
<td>Not accessible – irreparable damage to the product or surrounding products</td>
<td>EVXXXXXX5</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Generic information
The generic information is collected in the form of an Excel, including NL-SfB classification, mapping tables, EoL scenarios and etc.
The NL-SfB classification schema is collected (as shown in Figure 42) from BNA (Dutch: Branchevereniging Nederlandse Architectenbureaus; English: The Royal Institute of Dutch Architects) and users feel free to download it. Note that the category column is customized and created in this project. For simple analysis, the materials are grouped into eight categories including 1) clay/concrete; 2) stone; 3) metal; 4) organic material; 5) inorganic material; 6) aggregates; 7) glass and 8) other materials. The unrecognized classification code or non-standard formats will be categorized as “unknown”.

**Mapping tables among standards**

Multiple standards are used in the design and construction processes. In other words, a BIM model or IFC file may involve different material designations structured based on different standards like NL-SfB, NAA.KT and ETIM. One solution proposed in the previous chapter is to create mapping tables at material-level, to enable unambiguous communications among standards inside the BIM-based circularity tool. Figure 43 and Figure 44 provide examples of how such mapping tables establish the relationship between NL-SfB and ETIM, and between NL-SfB and NAA.KT, respectively. Given varying focuses and usage scenarios, different standards adopt different classification schemes. For instance, softwood is commonly designated as “i2” based on NL-SfB, whereas there is no corresponding ETIM code for this material. While this project highlights the potential of mapping tables in circularity assessments, further work is required to develop a comprehensive framework that supports a practical application.

**EoL scenarios**

EoL scenarios have been considered crucial for evaluating the circularity performance of construction products/materials. To achieve this, the NMD database has been used as a source of information, and
the EoL processing options have been extracted and reorganized. As depicted in Figure 45, the NMD database provides standard values for different processing options, such as landfill, incineration/energy recovery, and recycling/reuse, which are expressed as percentage breakdowns (NMD, 2022). However, as previously discussed, the NMD database utilizes its own language for material description, which may not be compatible with the commonly used standards in construction projects. Therefore, efforts have been made to map the NMD material classifications to these standards to ensure consistency in the circularity assessment.

![Figure 45. EoL scenarios in the NMD database (NMD, 2022)](image)

For enabling automatic assessment, the breakdown percentage of EoL scenarios should be restructured based on either NL-SfB (Table 3), NAA.KT and ETIM. For example, the material named “beton, cellenbeton (o.a. elementen, blokken)” (see number 9 in Figure 45) will be translated into “beton_cellenbeton_blok” based on NAA.KT or “f2 (all-in-aggregate concrete)” based on NL-SfB (Table 3), and expected that most of these materials (99%) will be released for recycling. Note that the fraction of similar materials is chosen when the material is not presented in the NMD database. Figure 46 and Figure 47 show examples of the value of different EoL scenarios based on NL-SfB and NAA.K.T respectively.

![Figure 46. EoL scenarios based on NL-SfB (Table 3)](image)

![Figure 47. EoL scenarios based on NAA.K.T](image)

### 5.4.2.2 Processing – Calculation models

As introduced before, a prototypical BIM-based circularity tool has been developed that includes an assessment module with three different calculation models tailored to align with information availability in different project phases and LOD levels. However, although different project phases and LOD levels
are categorized in this report, the tool is unable to distinguish at which project stages IFC files originate from or which LOD levels BIM models belong to. Instead, the tool attempts to extract or estimate the required information for the calculation models in the later project phases, such as the construction phase. If (part of) the information is unavailable, the tool will reduce the amount of required information by resorting to a calculation model designed for early project phases (e.g., initial phase or design phase). For example, if there is no information regarding connection types and accessibility levels stored in the uploaded IFC file(s), the tool will settle for less and try to use the calculation model of design phases. If information is still limited (e.g., without material information), the simplest model (for the initial phase) will be used. To guarantee usability, users are not required to provide information for each element, but if no value of a certain parameter can be found, a default value will be used. The default value is the worst-case scenario for a circular design. For example, if a construction object is not assigned information regarding recycled input or connection type, it will be assumed that the object is produced with purely primary materials and is connected by hard chemical compounds. Appendix B contains supplementary details regarding the methodology employed by the tool for extracting required data from an IFC file.

Furthermore, considering the usage of different standards and design rules among stakeholders, the tool extracts required information based on priority from specific to global (general). For example, the tool employs a mechanism of prioritizing mass-based calculation models, whereby the value of materials’ weight is sought through the parameter of EC_EF000167.Weight. In cases where the weight of a material is not specified, it is determined through a process of multiplying the materials’ volume by its general density information. If the volume information of a given material layer remains unavailable, the tool utilizes other geometric information of the layer, including its area and thickness, to calculate the volume information and thereby calculate the corresponding material weight. This is because, detailed information on material weight is normally clear after entering construction phases and choosing specific products, while only rough geometry information (such as volume, area and layer thickness) is available during design phases.

5.4.2.3 Output – Graphic user interface

A graphical user interface (GUI) was developed (Figure 48 to Figure 54). The GUI is designed to be easy, efficient and intuitive to use so that project stakeholders can quickly comprehend the circularity performance of their design of construction projects. The corresponding circularity insights presented in the GUI (slightly) vary as the calculation model. More circularity insights can be provided with more available information as a project progresses. Appendix D presents examples of the GUI and explains the GUI's differences performed by different calculation models.

The GUI consists of different components as shown in Figure 48 to Figure 54.

(1) Main window: the main window explains the background of the BIM-based circularity assessment tool, emphasizing the utilization of the CPM. Inheriting the characteristic of the CPM, the tool supports the visualization of the degree of circularity for any type of project including a new-built, demolition or renovation one. Users need to choose one specific project type before starting a circularity assessment. Furthermore, as explained in Figure 48, this BIM-based circularity assessment tool is the product of the EngD project, which received sponsorship from the University of Twente and DigiGo.
(2) File tab: The most important functionality of the File tab is to upload IFC (files). Specifically, a renovation project normally experiences two phases from the existing building to new construction, of which information is normally stored in two IFC files respectively. Hence, the tool supports uploading two IFC files when assessing a renovation project. By contrast, only one IFC file is required when performing a circularity assessment of a new-built or demolition project.

(3) Overview of project information: This part presents the general project information and overall assessment results. Once an IFC file is imported, the file’s base name appears in the IFC file label. This
functionality lets the user know that IFC file(s) have been uploaded. As introduced before, based on the project type, one or two IFC files are required to upload. In the example shown in Figure 49, two IFC files – named Test (construction new) and Test (construction existing) were used, holding information of new construction and existing building respectively. When choosing the project type of Renovation, the tool supports the analysis of both IFC files, conducting the circularity assessment of the whole construction project. The value of material circularity (MC) is calculated based on the volume-/mass-based percentage of material flows and their weighting factors, depending on the selected calculation model as discussed before. When the information of connection type and accessibility is available, the value of disassemble-ability potential (DP) will be calculated and presented (e.g., 0.12 in the example). The overall circularity value (0.439 presented in Figure 49) is assessed by considering the effect of MC and DP. It should be noted that the score generated from the tool is a relative value, rather than an absolute value. As such, the score is meaningful when comparing two or more design alternatives of the same construction project. In this context, it can be concluded that the higher the score, the better the circularity performance. However, it is not appropriate to use the score to compare two different projects, such as a new construction and a renovation project. Since it would be unfair to make such comparisons, given a renovation project may always achieve a higher score, given its higher possibilities and opportunities to reuse old materials and products.

(4) Overview of product information: This part presents the circularity-related information of a specific construction product/element (when the product/element is chosen in the 3D model in Component 5). Expect for the information directly extracted from BIM model(s) or IFC file(s), the product’s material circularity, detachability potential and overall circularity value are also assessed respectively.

(5) – (6) Overview of material flow: Inheriting the characteristics of the CPM, the amount of material flow can be reflected through the relative arrow thickness supplemented by detailed quantity numbers. Depending on the selected calculation model, the quantity numbers are either presented based on volume (square meter) or mass (ton). A 3D model was visualized in the GUI and a set of colours are applied to distinguish materials’ origins or waste scenarios based on the CPM. The window of 3D color coding supports the functionality of translating, rotating, zooming in and zooming out.

(7) Filter: This function enables flittering building elements categorized based on the CPM. For example, Figure 50 shows the example of highlighting those reused elements (in the same building) in green when pushing the button of “reused products in the same building”.

(8) – (9) Overview of disassemble-ability potential: Similar to material circularity, different colours are used for visualizing the level of disassemble-ability potential in a 3D model. The value of disassemble-ability potential ranges from 0 to 1 and is differentiated into five categories with 0.2 as the interval, representing the different levels of disassemble-ability potential (low, low-medium, medium, medium-high and high).

(10) Material overview: Component 10 to Component 12 will be enabled when material information is known (moving from initial phases to design/construction phases). The pie in the middle (as shown in Figure 52) presented an overview of the relative quantities of different material flows based on the CPM. Furthermore, one main material stream (waste) is differentiated between different EoL scenarios: going
to recycling/reuse or ending up in incineration/landfill. The tool will automatically check if the information of recycled input is known from the uploaded IFC file(s). If known, new materials will be divided into circular (recycled or/and renewable materials) or non-circular materials (non-renewable primary materials). Otherwise, based on the calculation model developed for design phases, only renewable/non-renewable materials can be separated from new materials.

Figure 52. GUI overview IV

(9) Materials insights based on material categories: Based on standards (NL-SfB, NAA.KT and ETIM) used in construction projects, the BIM-based tool provides deeper material insights based on different material categories. Figure 53 shows that the case example mainly contains clay/concrete and aggregate materials. Specifically, aggregate contributes a higher circularity value (1) because all of them originate from the existing building (i.e., arrow 4). When materials were not entered correctly based on the standards, they will be grouped into “Unknown”. Furthermore, users are able to check detailed materials composition inside each category; for example, the example project includes 0.335 tons of aggregates and 100% of them are natural fills, as shown in Figure 53.

Figure 53. GUI overview V
(10) Material insights based on entity categories: Component 12 presents a similar analysis as Component 11 but for different entity categories (e.g., floors and floor finishes). When the mouse hovers over the graph, the corresponding information regarding material composition can also be shown. As shown in Figure 54, the floor finishes involve a high proportion of reused clay/concrete or aggregate coming from the same building.
6. Treatment validation

6.1 Requirements evaluation

Before starting to design the BIM-based circularity assessment tool, system requirements were first defined as a guideline (see sub-section 5.3.1), to consider the question “what does the system need to fulfil” in order to satisfy stakeholders. In return, the set of requirements can serve as a valuable evaluation tool for the EngD candidate. Based on the requirements listed in Table 22 and Table 23 (learned from literature and stakeholders), Appendix C employs “Yes/No” to indicate if each requirement has been satisfied or not. As a result, two requirements are not fulfilled. Specifically, regarding the requirement of “The tool should use multiple units when presenting information”, the tool selects either “square meter (to represent volume)” or “kilogram/tons (to represent weight)” depending on the level of information availability. This is because the tool is primarily intended to emphasize the use of volume or mass as the main unit of measurement when calculating the circularity value, and the use of diverse units to represent different objects may lead to confusion among users. The present study falls short of meeting the requirement of developing a "design tool" rather than a "checking app." This is due to the challenging nature of providing tailored suggestions or recommendations for each project, which must consider a range of factors, including circularity, cost, and schedule, among others. As outlined in sub-section 6.3, this limitation is acknowledged, and it is deemed necessary to address it through future research efforts.

6.2 A case project demonstration

The prototypical BIM-based circularity assessment tool was implemented on the case project (Langezijds project), of which the phase of selective demolition had finished, and renewing and construction had begun during the period of this EngD period (see Table 4). In the design phase, Revit is the main BIM-authoring software used for the creation of 3D models, which were received and updated by different sub-contractors/contractors in different software (e.g., Revit, Navisworks and Tekla). The researcher collected models from both the design phase and construction phase and modified them inside a Revit environment (e.g., adding customized parameters) for the purpose of demonstration. Considering the limited processing power of the prototypical tool, only a small amount of building entities (as shown in Figure 55 and Figure 57) are selected for demonstration and visualization. Importantly, the objective of the demonstration is to illustrate and validate the tool’s potential for supporting circularity assessments in different project phases, rather than providing definitive answers regarding the performance of the case project. As a renovation example, two IFC files of the case project were generated, holding the information of the existing building and new construction respectively.

6.2.1 The case demonstration in design phases

The building entities chosen for the purpose of demonstration are situated on the first floor and comprise various structural components, namely the constructive columns, floors, ceiling, and internal walls, as visualized in Figure 55. Most of the entities were assigned with standard product classification and material designation based on NL-SfB by architects during the design phase. The researcher introduced one IFC parameter so-called “Status” to capture material origins or destinations based on the CPM, as introduced in sub-section 5.4.2.1.
When choosing the project type as Renovation, the tool supports the analysis of both uploaded IFC files, conducting the circularity assessment of the whole construction project during its design phase. Based on Table 19, the final circularity value was assessed as 0.507 (Figure 56), contributed by a high proportion of reused materials. During the design stage, the detachability potential is “Unknown” given unavailable information (Figure 56).

### 6.2.2 The case demonstration in construction phases

A decorative floor finish was added by subcontractors above the constructive floor based on designers’ models (Figure 57). The researcher updated the BIM model by complementing additional information through the development of ETIM-based parameters. This information includes connection type, accessibility, material designation, weight and percentage of recycled materials of each building entity, as shown in Figure 57. Sub-section 8.2 also summarized additional information that should be prepared by users.
The decorative floor layer has been produced by "primary resources" (arrow 1.2 in Figure 38), which have a detrimental effect on the material circularity value of the project. Specifically, the material circularity value has decreased from 0.507 (Figure 56) to 0.452 (Figure 58) due to the inclusion of this layer. However, it is important to note that the overall circularity value of the project was assessed not only based on material circularity but also on disassembly/detachability potential. In this case, the detachability potential was evaluated to be 0.1 (Figure 59). The value is attributable to the adoption of conventional construction practices by the contractors, which entails the usage of irreversible chemical connections and the inaccessibility of many building entities. The demonstration of the case project serves as an example of the tool’s capability to offer actual circularity insights in different project phases.
6.3 User-based evaluations

This study progressed from high-level needs to a more detailed examination of design requirements. This progression was achieved through the Treatment Validation through stakeholders-based evaluation in each iteration of the design cycle, as presented in Table 24. To obtain a more comprehensive understanding of stakeholders’ perspectives and requirements regarding the tool, the evaluations were designed to allow users to interact with the tool themselves. As introduced in sub-section 3.3.2, by using the evaluation tests with users, participants are engaged in the evaluation sessions, and encourage them to share their thoughts by allowing them to “think aloud”. These participants include project managers, sustainability consultants, BIM experts, and design and construction engineers. A total of 12 individual evaluation sessions were conducted with these stakeholders, with approximately 4 sessions taking place in each evaluation round. As discussed in sub-section 3.3.2, the user-based evaluation sessions aim to evaluate the usability of the BIM-based circularity assessment tool regarding its effectiveness, efficiency and satisfaction. Furthermore, except for focusing solely on usability aspects, the EngD candidate aims to examine stakeholders’ information needs in relation to circularity-related decision-making. By proposing questions like “what kind of additional circularity insights/information do you need” in the post-interview, the participants were invited to elicit their perspectives on other information needs regarding material efficiency. Furthermore, as introduced in sub-section 3.3.2, supplementary evaluation channels such as scheduling periodic meetings, conducting a workshop, participating in a research day, and presenting at a conference, complement the aforementioned individual evaluation sessions to provide further valuable insights.

Regarding effectiveness and efficiency, the results of user evaluations indicated that users were able to successfully complete most tasks within a minute without encountering significant difficulties across all evaluation rounds, although in the initial round of evaluation, users reported minor difficulties in exploring the predefined tasks (see Appendix A for detailed information) due to unfamiliarity with the tool’s interface. For instance, some participants experienced confusion when they were asked to upload two IFC files when using the tool for the first time, although they were able to resolve this issue within a few seconds. Furthermore, a sustainability consultant highlighted the importance of designing clickable buttons in a more visually distinct manner, “you should make buttons look clickable”, she added. Specifically, participants (represented by the sustainability consultant) suggested that certain functions, such as the Filter function (as depicted in Figure 50), were not designed in a clear way and could benefit from more noticeable visual cues. For example, “highlighting the areas where users can interact with the tool”, could potentially encourage users to explore the functions more actively. In light of these usability issues, one participant further suggested that the tool could benefit from minor hints/assistance
and additional navigation features to enhance its usability as a "handy tool". It is worth noting that these usability issues were not evident in subsequent evaluation rounds when the tool was updated in the later phases.

Regarding satisfaction, the EngD candidate observed that user satisfaction increased with each iteration round. In the initial evaluation sessions, all participants agreed that the tool is easy to use without frustrating experiences. “It is indeed simple to use and you can see very quickly what the result is”, one participant added. A project manager also expressed his admiration, stating that “it is good for me to see how circular my project is from a big picture”. However, many concerns were raised during the first and second evaluation sessions regarding the limited insights provided by the earlier version of the tool, aside from its usability aspects. For example, in the first evaluation round, the EngD candidate only presented a simple tool which mainly consisted of the Component 5 and 6 (as shown in sub-section 5.4.2.3). This version is only able to reflect the amount of material flow and distinguish between materials' origins or waste scenarios using a set of colours. Figure 60 presents an example of this earlier version of the BIM-based circularity assessment tool. During the first-round evaluation, participants expressed concerns regarding the material quantities displayed in the earlier version of the tool (as shown in Figure 60), specifically regarding their confusion as to whether the quantities represented cubic meters or kilograms. Moreover, another project manager argued that the prototype (in the first design cycle) failed to distinguish the technical and biological material cycle, and their attempt to “use as many bio-based materials as possible” in the renovation project could not be awarded correspondingly. Furthermore, the CPM was criticized for its narrow focus, which only modelled two waste scenarios (unrecoverable waste or being reused): “although the ‘waste’ was got rid of from the construction site, it can be recovered in recycling factories”. He exemplified this with asphalt debris, which is made up of crushed concrete from other construction projects. Therefore, the project manager proposed that further design is needed to create a more complete circular scenario. In the second-round evaluation sessions, stakeholders emphasized the significance of the disassembly potential of a building. A design engineer stated that their project aims for at least 30% of the building components to be demountable, allowing for easier reuse of building parts in the future. Furthermore, a project manager emphasized that it is not only the building elements that matter but also how these elements are assembled and the standards used in the assembly process. These valuable insights provided by the stakeholders served as a source of inspiration for the EngD candidate to enhance the original CPM model. The candidate improved the calculation models employed in the design phases (as depicted in Figure 37) by incorporating the ability to differentiate materials based on their EoL scenarios, and by classifying resource feedstocks into renewable and non-renewable categories. Additionally, the feedback regarding the disassembly potential of buildings was also integrated into the latest version of the tool (as illustrated in Figure 38).

In addition, a BIM expert highlighted the need for more detailed information beyond a single number when analyzing a building's circularity performance. Rather than simply adding up material quantities from different entities (as shown in Figure 60), the expert suggested providing data on the specific types of materials used in various building components such as floors, walls, and stairs. This would help stakeholders gain a better understanding of the meaning behind the circularity values. “I can have more feeling about what these numbers mean”, he added. This viewpoint was expressed by other participants, including a project manager and sustainability consultant, who emphasized the importance of understanding how different materials contribute to the overall circularity score, as: “I would like to know what kind of materials are involved in each arrow” and “how they influence the overall circularity value”, said by a project manager and sustainability consultant. As a result, Component 11 (as illustrated in Figure 53) was added to the latest version of the tool to provide more detailed information on material flows and their impacts on circularity performance.
The efforts made to incorporate stakeholder feedback into the development of the tool resulted in a significant increase in user satisfaction, as expressed by a design engineer who stated that “the tool made a big improvement compared to the old one”. Similarly, one project manager acknowledged, “it is great that you incorporated my concerns”. For the final version of the tool, a design leader expressed her optimism about its potential and suggested that it could be utilized to validate whether a construction project is still aligned with the expectations or requirements set out during the design phase. “The performance of a project often declines during the construction phase and your tool may help to evaluate whether they (construction teams) are meeting the expectations set by us (design teams)”, she explained. This feedback highlights the potential usage case of the tool to aid in monitoring and evaluating the construction process, ensuring that the project remains on track with the original goals and objectives. Furthermore, during a discussion about the circularity score, a project manager raised his perspective about the value of the tool in other usage scenarios. Specifically, the project manager questioned the meaning of the circularity score: “the tool shows a score of 0.6, what it meant for us, is it good or not?”. Another participant encoded this concern, expressing “what is the value of the value”. Subsequently, the EngD candidate further clarified the concept of the score, emphasizing that it is a relative rather than an absolute value. Accordingly, the score is primarily relevant when comparing two or more design alternatives of the same construction project. In this context, it is possible to draw a conclusion regarding the material efficiency of the designs, based on the score obtained. Specifically, a higher score indicates a better circularity performance. The project manager further considered the potential usage scenarios of the tool, noting its potential usefulness during the tender phase of a project to aid in selecting a design that considers circularity. Because of this, the project manager praised the tool for its potential to facilitate the decision-making process.

The evaluation sessions shed light on the participants’ concerns regarding varying levels of information availability throughout different project phases. For example, the discussions with stakeholders firstly covered the possibilities of using the measurement unit of mass, which was not prepared in the case project and “have to define this requirement at the beginning while it is still difficult”, one designer engineer said. He took the example, where structural engineering can only provide general density information for “a single floor” in the design model and have to depend on suppliers to provide “detailed information of each layer in the floor” in the construction phase. This implies that mass information is only available when suppliers become involved in construction projects. Furthermore, in the second-round evaluation, one BIM expert further elaborated on the different phases and the associated information, as he said: “we assign the information of product classification (normally represented by NL-SfB (table 1)) and material designations when moving to the phase of DO (definitive design) or TO
(technical design)” and “we normally know the detailed recycled percentage when choosing specific manufactures”. These discussions provided inspiration to the EngD candidate to consider the different levels of information availability during different project phases.

Furthermore, the evaluation sessions also brought light to the stakeholders’ concerns regarding information specification. A smooth assessment is guaranteed with the correct information and some participants realized this required information was not collected in the case project. One stakeholder mentioned that some building components were removed while reused in another part of the (same) building, which implies that these parts were “new-built” in the later phase while they should have been labelled as “recovery and reuse in the same building” based on the CPM. However, “in the model, the existing elements are those at the same place with the same functions, and others were recognized as new”, he said. The design teams only differentiate materials as new or existing, since “it is not a requirement” and “no one asks for it”, resulting from no clear requirements for information preparation from the perspective of circularity. However, “it is not difficult” and can be realized for example, by “defining multiple phases (like a “reuse phase”)” in design models, the participant added.

During evaluation sessions, the topic of standard utilization was also highlighted. Despite the case projects utilizing the NL-SfB (table 3) to support material designation, one participant highlighted that it is still not commonly used in practice despite being developed over a decade ago. “We normally talk about its table 1 when we discuss the NL-SfB, but table 3 is rarely referenced”, he explained. Furthermore, a BIM expert also emphasized the importance of information management and raised concerns about the tool’s reliance on NL-SfB (table 3) in its earlier version, noting that the standard is primarily intended to support product designation rather than materials description. To address this limitation, the expert introduced a more advanced development called NAA.KT, has gradually gained attention in the Netherlands as a means of unambiguous material designation in construction projects. Additionally, another participant raised concerns regarding the amount of information required for using the tool and she questioned whether a significant amount of information needs to be prepared to utilize the tool effectively. In response, the EngD candidate clarified that the tool’s information requirements are aligned with current design processes (e.g., encouraging material designation using NL-SfB (table 3) and NAA.KT), and also saving user input by embedding most general information, such as density, in an external database. Despite some concerns being dispelled after this explanation, a project manager repeatedly stressed the significance of highlighting or making it clear what kind of additional information should be prepared by users. As the project manager stated, “by making clear the specific information that is needed, I can request that design teams prepare the necessary information to enable the utilization of your tool in my next project.”

In addition to the concerns mentioned earlier, the evaluation sessions for the BIM-based circularity assessment tool also brought to light other pertinent issues. For example, participants expressed the difficulties of preparing IFC files for old buildings where BIM models do not exist, and professionals typically rely on original 2D drawings, field visits, or 3D scanning techniques. Remodelling these buildings poses significant challenges as many assumptions have to be made, particularly regarding material layers in building elements. Another concern was raised about the practicality of using the tool in construction practices or the extent to which the proof of concept can be translated into a tool that supports construction practices. Last but not least, a design engineer pointed out that the current tool limits itself as “a checking app” instead of “a design tool”. “It is good to see what the specific circularity value of a project is, but what should I do next?”, he said. He further explained that design teams normally assess project performance at a certain point (e.g., finishing the preliminary design) and stop using a “checking app” when they have the circularity value, but “how can you use the tool in a period between design changes?”. Instead of providing a conclusion, a “design tool” can encourage users to move toward a more circular design; for example, by replacing concrete with renewable materials. However, this study fails to provide specific answers or solutions in response to those concerns and revealed the need for further research.
6.4 Summary

The step of Treatment validation is mainly composed of three parts: requirements evaluation, the demonstration of a case project and user-based evaluations. Firstly, the EngD candidate utilizes a set of pre-defined requirements as an evaluation tool to conduct a self-assessment of the tool's performance, determining that the majority of the requirements have been met. However, it is acknowledged that two specific requirements have not been achieved and require further research.

Secondly, this chapter provided a demonstration of the case project during both the design and construction phases, showcasing the BIM-based circularity assessment tool in action. This demonstration allowed users to visualize the impact of providing additional information across different project phases on the material circularity and detachability potential. The results of the demonstration, hence, signify that the tool has the potential to support circularity assessments throughout various project phases.

Lastly, this study incorporated three rounds of evaluation sessions to guide the development and refinement of the tool across successive design cycles. In order to gain a more comprehensive understanding of users' perspectives on the tool, these evaluation sessions were oriented towards user experience, with a focus on three key dimensions: effectiveness, efficiency, and satisfaction. The tool demonstrated clear success in meeting the goals of both effectiveness and efficiency, as evidenced by the successful completion of predefined tasks within the tool in an efficient manner. The tool's effectiveness and efficiency were further proven in the later evaluation rounds, a result of the improvements made to its usability and users' growing familiarity with its interface.

The EngD candidate concluded that user satisfaction increased across each evaluation round, given the tool’s growing capacity to incorporate more insights about circularity performance. Notable improvements included the creation of more comprehensive circular scenarios, the integration of disassembly assessments, and the inclusion of additional material insights. The concerted efforts to incorporate stakeholder feedback into tool development yielded a significant increase in user satisfaction. The final iteration of the tool was commended for its potential to support various usage scenarios, particularly in the evaluation of the alignment of a construction project with the expectations and requirements established during the design phase, as well as its facilitation of design option selection during the tender phase. Furthermore, the sessions affirmed the goal of this project, which emphasizes the importance of considering information availability when designing a circularity assessment tool. This point was underscored by participants’ attention to the specific type of information associated in each project phase.

Additionally, the user-based evaluations underscored the significance of information specification and standard utilization in facilitating circularity assessments. The evaluations identified certain information gaps in the case projects, emphasizing the necessity of clarifying the information needs in support of the utilization of the tool. The evaluations also covered the topic of standard utilization, with the introduction of NL-SfB (table 3) and NAA.KT. However, the evaluations also surfaced other concerns, including the absence of BIM models in older buildings, questions regarding the practicality of the tool, and the need for a 'design tool' rather than a 'checking app', highlighting the need for further development and research in this area.
7. Treatment implementation

Presently, the case projects have chosen to conduct a GPR Building (GPR Gebouw in Dutch) calculation to gain insight into the degree of sustainability of the designs. As introduced in sub-section 1.3, this report aims to understand how the proposed tool (the BIM-based circularity assessment tool) can work with the existing tool (GPR), to help project stakeholders to make better circularity-/sustainability-related decisions. Activity theory is used to serve as a theoretical framework for understanding the possible contradiction caused by the integration of the BIM-based circularity assessment tool.

7.1 An overview of the GPR

As one of the most widely used methods in the Netherlands, GPR tries to evaluate project performance in a comprehensive way concerning energy, environment, health, user quality and future value (Figure 61). Specifically, inside the environment theme, the GPR awards the attempt of limiting harmful emissions and the depletion of raw materials by calculating MPG scores. Moreover, the category of circular material usage concerns resource efficiency by assessing the degree of biobased/recycled materials usage, reuse potential, construction methods etc. However, circularity, taking material efficiency as the highest priority is currently underestimated compared with sustainability-related aspects in the project. Although the GPR tries to quantify the extent of ‘circular material usage’ under the environment domain, subjective estimations still could not be avoided. Because of this, the GPR is labelled as “Low” reliability in Table 9 in sub-section 4.2.2. As introduced by the sustainability consultant: “We expect that we can reuse concrete, steel, glass and part of the insulation”. In other words, they have to estimate the reuse possibilities of building elements roughly based on material characteristics of reusability when performing the calculation. These estimations represent stakeholders’ wishes/requirements instead of actual material performance in construction projects, as one participant expressed: “we agree together with design teams and clients that this may be feasible and should be embedded in the designs”. Similarly, another sustainability consultant mentioned: “the current version of GPR was calculated during the stage of SO,…, and we then keep in mind that it is the clients’ wishes”. Furthermore, at the beginning of the project, stakeholders already thought of some circular principles and measures, such as “reusing the existing elements to close cycles in the building”. However, to what extent those measures contribute to a circular project is unclear. Instead of making educated guesses, project stakeholders require actual information/insights to guide them in the right direction from linear to circular.

![Figure 61. GPR Building Overview (Green blocks represent the scope of categories that are in line with the EngD project)](image)
7.2 Required adjustments from activity theory-based perspective

Within the context of the GPR, the categories of “environment performance” (reflected through MPG scores) and circular material usage, as depicted in Figure 61, are concerned with material aspects that align closely with the focus of the EngD project as described in sub-section 2.2. Therefore, the present report seeks to elucidate how the BIM-based circularity assessment tool can supplement these two GPR categories, with the goal of providing insights into the environmental performance of materials used in a construction project, as exemplified in Figure 61.

As introduced in sub-section 4.5, an activity can be modelled as a triangular graphic created by Engeström (1987) (see Figure 28), which illustrates how a subject utilizes tools to attain a specific goal and outcome, while also being influenced by rules, community, and division of labour. The alteration of any of these elements, such as the tool (e.g., the introduction of a new tool), can destabilize the entire activity system and give rise to contradictions within the other elements. Consequently, any new disruptions or performance issues that arise during the integration of the BIM-based circularity assessment tool into the design and construction process of case projects (as well as in future projects) can be analyzed from activity theory-based perspective utilizing the triangular graphic. Furthermore, these contradictions can be classified into four types, namely, primary, secondary, tertiary, and quaternary (as introduced in sub-section 4.5).

According to activity theory, a (secondary) contradiction (Figure 62 (1)) has emerged between the existing tool (the GPR) and the object (providing actual insights into material performance) of the circularity-related activity. This is because, as previously noted (in sub-section 7.1), GPR has several limitations regarding its ability to assess the extent of material efficiency. The MPG score reflects the extent of the environmental impact of materials, rather than their material efficiency. Despite the fact that GPR incorporates the category of “circular material usage”, it still lacks the ability to provide actual insights into material performance, since it requires subjective estimations. Therefore, in response to this contradiction (Figure 62 (1)), an iterative design and evaluation process was undertaken to develop the BIM-based circularity assessment tool (depicted in Figure 62 (2)). As elaborated in sub-section 3.3.2, to evaluate the tool, the stakeholders were asked to engage with the tool on their own to complete predefined tasks, and subsequently, participate in a post-interview. As noted in sub-section 6.3, stakeholders acknowledged that certain necessary information was not available in the case project (e.g., information pertaining to reuse scenarios) and that there was no agreed-upon standard among (sub-) contractors for recording different information. “Except for the basic ILS, the sub-contractors use their own ways to record different information since we did not ask for it”, one BIM expert (of the construction team) mentioned. This reveals a contradiction pertaining to information requirements arising from the use of the tool. Consequently, this contradiction (as depicted in Figure 62 (3)) required a response. For supporting the demonstration of the case project (as introduced in sub-section 6.2), the EngD candidate collected models from both the design phase and construction phases and supplemented them with additional information inside a BIM environment, to facilitate the circularity assessment supported by the new tool.

To further enhance the tool’s applicability, it is imperative to specify the necessary information requirements for future projects. This would require the establishment of new rules between subjects (project managers) and the community (design teams and construction teams). It is highlighted in Figure 62 (4) as an unresolved contradiction arises in this regard, necessitating the development of new rules for effective communication and collaboration. As suggested by one of the project managers, design teams can be requested to provide essential information and incorporate them into contractual agreements for future endeavours. Another (unresolved) primary contradiction that has emerged pertains to the division of labour, requiring the allocation of responsibilities to sustainability consultants for conducting the BIM-based circularity assessment alongside GPR calculation and proposing alternatives based on both results (as shown in Figure 62 (5)).

In summary, a contradiction was identified between the existing tool and the object in a circular activity system. In accordance with the principles of activity theory, the study has introduced a BIM-based
circularity assessment tool for evaluating actual material performance and promoting circular building practices. The tool was evaluated with stakeholders’ interaction and revealed another contradiction related to information requirements, which necessitates the introduction of new rules. Additionally, efforts should be directed towards the division of labour to improve the circularity assessment activity. The rest of the chapter will introduce the current assessment process of the existing tool (the GPR), followed by a proposed new workflow that considers the changes in rules and division of labour based on activity theory.

![Diagram of the circularity assessment tool](image)

**Figure 62. Changes and development through the involvement of the BIM-based circularity assessment tool from activity theory perspective:** (1) resolved tool vs. object [secondary] contradiction; (2) resolved tool vs. tool [primary] contradiction; (3) resolved tool-generating activity vs. tool [quaternary] contradiction; (4) unresolved rules vs. rules [primary] contradiction; (5) unresolved division of labour vs. division of labour [primary] contradiction;

### 7.3 Current workflow

To gain insights into the present assessment process workflow, semi-structured interviews were carried out with the sustainability consultants involved in the case projects. These interviews aimed to identify the relevant stakeholders, the sequence of activities involved, and the manner in which information exchange occurs throughout the process. The current sustainability assessment workflow is depicted in Figure 63, comprises several primary steps. These include (1) information collection or estimation; (2) assessment conducted using the GPR tool; and (3) results analysis and recommendation introduction. Note that the assessment process (in Figure 63) only presents the workflow of assessing the categories of “environmental performance (MPG scores) and “circular material usage”. The workflow (in Figure 63) was also verified by the participants.

The calculation of MPG necessitates access to information regarding materials quantities (BoQ), environmental impacts of each material, and other relevant information. The calculation method for MPG involves the summation of the environmental impacts (referred to as shadow costs) of all materials used in a building. Therefore, it is necessary to first identify each material within a design, as well as determine the quantity of each material required (BoQ). Prior to the availability of BIM models, material quantities are measured roughly based on 2D drawings with a focus on major materials, “we only look into those materials with a big contribution on environmental loads, such as façade, glass and concrete”, one sustainability consultant said. As the project progresses with more detailed designs, such as those created using Revit, the design team can export the BoQ from the BIM models and provide it to the sustainability consultant to perform a GPR assessment. According to one participant, "most of the time,
the design teams provide all required information in an Excel file, and I will fill them into the corresponding program to do a calculation.”

Upon obtaining the BoQ information, sustainability consultants commence the search of the environmental information for each material in the existing database. As noted by a participant, relevant information can typically be sourced from the NMD, particularly from suppliers who would like to promote that they can offer environmental-friendly materials. However, it was also highlighted by participants that the NMD database may overestimate the negative environmental impact of certain materials, such as recycled concrete and timber. For example, one participant exemplified this with timber, which “is currently not valued in a way that they should be valued because every tree stores carbon dioxide (which the NMD database ignores)”. Because of this, the environmental impact of certain products/materials is adjusted and updated for achieving fair calculation results. For the unavailable information, the sustainability consultant either seeks the information from corresponding suppliers or uses the information from a similar product (in the database). “Based on the regulation, the MPG should be lower than 0.8, and sometimes, it is hard since you could not specify all the materials, since you could only choose a similar material which may have a worse score.”, one sustainability consultant added.

In terms of assessing the category of circular material usage, the sustainability consultant works in collaboration with the design team and clients to estimate the potential for circularity. “We communicate the choices we made with the design team to check if these choices are feasible,” one participant explained. Once the necessary information, such as the BoQ and environmental performance of materials, and estimations are collected, the sustainability consultant(s) will use the GPR to perform the sustainability assessment. Subsequently, they will analyze the assessment results and propose solutions if the results fail to meet the client’s requirements, which are documented in PvE (Programma van Eisen, Program of Requirements in English), as illustrated in Figure 63.
Figure 63. The current sustainability assessment workflow in the case projects
7.4 Proposed workflow

7.4.1 The sequence of circularity & sustainability assessment

The current assessment method of the MPG primarily focuses on the environmental impact of new/virgin materials entering a building, particularly in the context of new construction. Although the Building Decree mandates statutory MPG requirements for new-built residential buildings and offices, the MPG is not mandatory for projects involving the renovation of old buildings like the case project (Langezijds project). However, the Langezijds project still set ambitious goals by the clients (UT). for MPG (below 0.6€/m2). Sustainability consultants in such renovation projects only consider the environmental impact of new materials in the building, as the impact of old materials is not legally required to be assessed. As a result, the MPG fails to provide information about reuse and disposal scenarios and limits itself to analyzing the environmental performance of new/virgin materials. Under this scenario, the BIM-based circularity tool can work complementary with the MPG, especially for a renovation project. This is because, the BIM-based tool can firstly provide insights into different material flows including new, reused and disposal scenarios, and award those circular actions which limit the number of virgin materials and unrecoverable waste by reusing old materials. Therefore, by starting with the BIM-based circularity tool, project stakeholders are encouraged to reuse different kinds of materials (e.g., reused concrete or wood). A design alternative with relatively higher material efficiency (with a higher circularity score assessment by the BIM-based circularity tool), can be further assessed by the MPG, providing deeper insights into the environmental impact of those non-avoided new materials. In other words, the BIM-based circularity assessment tool provides an overview of different material flows, and MPG can be followed to narrow the scope to new materials and considers what kind of materials are more circular/sustainable for the environment (for example, new wood is awarded rather than new concrete). The sequence of tool usage through different project phases is visualized in Figure 64.

The evaluation of material efficiency in construction projects can be performed in the GPR using the category of circular material usage, which involves a set of five multiple-choice questions. However, to perform such an assessment during initial/design phases when manufacturers and contractors are not involved, estimations such as the expected reuse percentage after EoL and the construction methods tailored to the efficient use of materials are required, as outlined in sub-section 7.1. In contrast, the BIM-based circularity assessment tool aims to provide actual circularity insights by utilizing available information in different project phases. Therefore, it is proposed that the tool can first offer an actual overview of the material used in construction projects and subsequently estimate future scenarios of a building using the five questions involved in the category of circular material usage. Furthermore, currently, GPR is used to enhance design improvements and is not applied to construction phases. Using different calculation models, the BIM-based circularity assessment tool can facilitate a circularity assessment from the design phases to the construction phases. Therefore, the BIM-based tool is proposed to be used as a supplement, especially during construction phases to provide circularity insights regarding material aspects and detachability potential, as illustrated in Figure 64.

In sum, the MPG method is not capable of a renovation or transformation project, where several reuse scenarios may exist. Moreover, the category of circular material usage necessitates estimations about future scenarios during design phases and do not be effectively implemented during construction phases. To address these issues, a BIM-based circularity assessment tool can be used in conjunction with the GPR. Specifically, the BIM-based circularity assessment method can be applied to provide material insights for different types of projects including new-built, demolition, and more importantly, renovation project. Moreover, the tool can provide actual circularity insights (with limited estimations) in different phases with more in-depth assessments becoming possible as additional information becomes available during construction phases. Therefore, it is proposed that the BIM-based tool can be utilized to provide an actual overview of materials performance across various phases. Following this initial assessment, the GPR can be applied to further evaluate the environmental impacts of any newly introduced materials.
using the MPG scores and provide estimations and expectations for future scenarios by using the category of circular material usage (Figure 64).

Figure 64. The sequence of using the BIM-based circularity assessment tool and the GRP

7.4.2 Proposed workflow based on activity theory
After considering the sequence of different assessments supported by the BIM-based tool and GPR, a new workflow has been developed to outline supplementary measures that should be incorporated into the current process to support the adoption of the BIM-based circularity assessment tool (Figure 65). The analysis, illustrated in Figure 62, indicates that two elements need to be altered from activity theory-based perspective, specifically, new rules and new division of labour.

One of the additional measures involves introducing new rules, which specify the information requirements when creating BIM models. As introduced in sub-section 7.2, new rules should be set between clients/project managers and design teams to achieve contractual agreements about information requirements in support of an assessment using the BIM-based circularity assessment tool. Therefore, one supplementary action taken by the architect, construction and MEP engineers is about assigning circularity-related information in different phases (see sub-section 8.2 regarding guidelines of information preparation).

The concept of division of labour pertains to the delegation of duties to sustainability consultants for performing the BIM-based circularity assessment alongside GPR calculation. Therefore, as shown in Figure 65, the sustainability consultant(s) should undertake additional responsibilities, including obtaining IFC files and carrying out circularity assessments using the BIM-based evaluation tool. The aforementioned supplementary actions undertaken by different actors are distinguished in green (Figure 65), as compared with the current workflow (Figure 63).
Figure 65. The proposed workflow with the integration of the BIM-based circularity assessment and GPR method (new actions are colored in green)
8. Conclusion and recommendations

In this chapter, the conclusion is first presented to list some main findings and developments of this study. Subsequently, recommendations and guidelines in support of the utilization of open standards and the BIM-based circularity assessment tool are summarized. This chapter concludes by offering suggestions for future research directions.

8.1 Conclusion

The current economic system is based on a linear model where raw materials are collected, transformed into products, used and then considered as waste. It has increasingly been recognized that this system is unsustainable because raw materials are limited. Hereby, CE offers an alternative and is based on a system in which materials are reused without loss of value. The necessary transition to a CE requires new methods to gain insights into the degree of circularity performance of a structure in construction projects. However, most existing circularity methods fail to provide actual insights for guiding a circular design of construction projects since they require subjective judgments and estimations throughout the whole lifecycle of a structure. Furthermore, there are various BIM integration techniques presented among scholars, and different BIM-based circularity assessment tools have been developed or are under development. However, few studies were found among scholars concerned with different levels of information availability during different project phases with different levels of LOD.

Hereby, this project aims to “develop a prototypical BIM-based tool to assess actual circularity performance of construction projects in different project phases”. Here, the circularity performance refers to the degree of circular material usage and circular design. The former considers how to encourage material regeneration and materials restoration, while the latter aims for designing products/components in a way to enable future usage, such as following the principles of Design for Detachability. The project is executed following the Design Science Research (DSR) approach, which is a domain-independent design strategy focusing on developing practical application design solutions and scientific knowledge under the predefined problem context. Following the design science research methodology proposed by Wieringa (2014), this study follows three iterative design cycles with several interrelated steps, namely problem identification, treatment design, treatment validation and treatment implementation.

Followed by the problem of lacking a circularity method (for providing actual insights into construction projects throughout different phases), the treatment design is a problem-solving process to design one or more artefacts that could solve the problem. Specifically, this project aims to design and develop a prototypical BIM-based circularity assessment tool, which serves as the end-product. In conjunction with this end product, scientific knowledge regarding information management and circularity assessment will also be generated.

The study firstly contributes to scientific knowledge in the domain of information management, indicating that information serves as the core of performing a circularity assessment within this BIM-based tool. Hereby, it is important to understand how relevant (circularity-related) information can be recorded and exchanged in a standardized way to smooth the process of circularity assessment, by utilizing BIM open standards and information structure. Specifically, this study started to investigate how different guidelines and standards are used in the case projects (for storing circularity-related information). Current situations and issues are identified:

- design teams have (relatively) structured manners for managing information with the help of standards and guidelines.
- different languages were observed regarding materials designation among contractors, manufacturers and the NMD database.
- required information is available during construction phases but managed in an unstructured way.
Accordingly, this study proposes:

- the utilization of ETIM;
- the restructuring of information from an external database (like NMD) to be in line with open standards;
- the creation of standard mapping tables among standards

Furthermore, this study contributes additional knowledge about circularity assessment under different levels of information availability. It was concluded that many existing methods for calculating circularity in construction projects are not flexible enough to accommodate the variable availability of information across different phases of construction. This often results in a one-size-fits-all solution that relies on subjective assumptions from project stakeholders. In contrast, this project proposes a new approach that accounts for the variability of information availability throughout the project lifecycle, resulting in three tailor-made circularity calculation models. This approach enables project stakeholders to use the available information at different stages of the project to gain an overview of their circular performance and acquire deeper material insights as more information becomes available in the later project phases. Specifically, this approach categorizes a construction project into three phases based on the level of information availability: initial phases (approximately with LOD <= 200), design phases (200 < LOD <= 350), and construction phases (LOD > 350/400), as defined in Table 11 and Table 17.

Another contribution of this study is a prototypical BIM-based circularity assessment tool for digitizing the calculation models utilizing BIM’s capabilities. An initial step towards the development of the tool involved a literature review to identify and define a set of system requirements that served as design guidelines. The design process was also driven by “design requirements” translated from stakeholders’ needs and progressed from high-level needs to a more detailed examination of design requirements. This progression was achieved through the treatment validation through different channels (e.g., user-based evaluation) in each iteration of the design cycle. Two integration aspects are considered in the development of the tool: 1) Assessment environment: where a circularity assessment should be conducted (e.g., plug-in and external tool); 2) Information: where circularity-related information is stored (e.g., BIM models and external database).

Regarding the “assessment environment”, this study developed an IFC-oriented standalone tool. This design choice is also in line with the project goal: supporting a circularity assessment throughout different project phases (where different BIM-authoring software may use). Therefore, an IFC-based solution may be more feasible rather than restricting the assessment inside a single software. When considering “Information”, this project proposes a solution by distinguishing project-specific information and generic information. Project-specific information represents that information that is only relevant to an individual project, for example, geometric information (volume, areas or material thickness), material flows (new or reused materials input), product connection types, accessibility level and etc. It is proposed that project-specific (non-geometric) can be inserted into BIM models, together with geometric information. The generic information is recorded in an external circularity database in the form of an Excel, including standards classification schema (e.g., NL-SfB and ETIM), general material density, the average material percentage going to recycle/landfill/incineration and etc. This information (either project-specific or generic) should be structured in a systematic way (through the usage of open standards like NL-SfB and ETIM) that allows data exchange between the external circularity database and BIM.

With these considerations, the prototypical BIM-based circularity assessment tool was developed according to the Input-Processing-Output (IPO) model. In the IPO model of this project, three major components are interlinked: 1) Input: a combination of input sources from BIM models (exported to IFC file(s)) and an external circularity database; 2) Processing: an assessment module in which three different circularity calculation models are available; 3) Output: 3D colour coding and 2D analysis charts presented in a GUI.

The Treatment Validation phase started with a self-evaluation (by the EngD candidate) with the help of pre-defined requirements. It also encompassed the demonstration of the tool during both the design and construction phases of a real-world project, coupled with user-based evaluations. The demonstration
highlighted the tool's potential in supporting circularity assessments throughout different stages of a project. The user-based evaluations were centred on three critical dimensions, namely, effectiveness, efficiency, and user satisfaction. The findings revealed that the tool successfully achieved its objectives for effectiveness and efficiency, with users able to carry out tasks efficiently within the tool. Furthermore, user satisfaction progressively increased over time, indicating enhancements in the tool’s usability and integration of feedback from stakeholders. The final version of the tool was recognized for its potential to support diverse usage scenarios. The evaluations also underscored the significance of considering standard utilization, alongside information availability and specification, in facilitating circularity assessments. Thus, sections 8.2 and 8.3 will provide an overview of the necessary standard utilization and information specification required to support circularity assessments by the BIM-based circularity assessment tool.

Furthermore, this study also contributes to the investigation of how the BIM-based circularity assessment tool can collaborate with the existing tool (GPR) in the case projects to enable more effective decision-making processes. As a result, new workflows have been developed as by-products of this study, to facilitate the integration of the new tool into the ongoing project processes of the case projects. Specifically, the study starts to analyze the current workflow of circularity/sustainability assessment in the case projects and identify the issues that need to be addressed to accommodate the integration of the BIM-based circularity assessment tool, adopting activity theory-based perspective.
8.2 Recommendation of information management and standard utilization

This section encapsulates two main recommendations concerning information management and standard utilization: (1) the adoption of the NL-SfB (Table 3), NAA.KT, and ETIM standards for material designation, and (2) the utilization of ETIM as a means of structuring other circularity-related information. These recommendations are grounded in the need for a standardized approach to information management that can enhance the assessment of circularity performance in construction projects.

8.2.1 Material designation

The NL-SfB classification schema is a widely used method for encoding layers and objects in BIM systems in the Dutch construction industry. When talking about NL-SfB, table 1, which outlines the functional components of the facility (e.g., outer or inner wall), is often referenced. Table 3, which describes building materials, is used less frequently than table 1. Several limitations hinder its application in practice including its ambiguous materials description and uncompleted material list. This is why NAA.KT was initialized and also its application is encouraged in the latest version of the basic ILS to enable unambiguous material designation, as discussed in sub-section 5.1.1. Hereby, this study aligns current developments and design practices and further promotes the use of standardized materials designation based on either NL-SfB table 3 (in support of the assessment of some old projects, like the case projects) or NAA.KT for new projects. The recommendation to utilize two standards for material designation is based on the observation, as discussed in sub-section 5.1.1, that both standards are frequently employed in different projects. It was noted that certain older projects (like the case projects) still used NL-SfB (Table 3), while NAA.KT has become increasingly popular for newer projects initiated in recent years. Consequently, to facilitate the practical usage of the BIM-based circularity assessment tool across various projects, both standards are permitted. However, given the advantage of unambiguously designating materials provided by NAA.KT, as discussed in sub-section 4.4.5 or 5.1.1, the utilization of NAA.KT is highly encouraged in this study, as guided by the latest version of the ILS.

However, it has been observed that it is uncommon for contractors and manufacturers to use these standards during construction phases, and different naming conventions are often utilized. Therefore, as introduced in sub-section 5.4.2.1, this study encourages the application of the ETIM system and follows the format of `<ETIM value coding>_<ETIM naming>` to structuralize their material information. However, incorporating ETIM into BIM could result in multiple stakeholders using different standards for material designation within the same models. To address this issue, the present study proposes the development of standard mapping tables that would allow for unambiguous communication between different material standards. The mapping tables should be designed to facilitate the recognition of the same material structured according to different standards, such as NL-SfB, NAA.KT, and ETIM, to enable a circularity assessment at different phases of a project. In the report of “Roadmap standard” (see Spekkink (2022)), BIM Loket also recognizes the potential for conducting research into the connection between NAA.KT and ETIM. In essence, organizations or steering companies such as BIM Loket/DigiGO play a vital role in promoting such initiative and advocating for best practices, and in mandating these practices on a project level.

8.2.2 Other circularity-related information

The active participation of contractors and manufacturers during the construction phases of a project can provide a wealth of information, such as installation methods, which can enhance the understanding of circularity performance in construction projects. To facilitate circularity assessments, it is essential to establish a standardized method for recording and managing relevant information. This study advocates for the adoption of the ETIM standard as a means of supporting information management among contractors and manufacturers. Apart from material designation, this information includes product weight, connection type, and other pertinent information (as summarized in the next section, see Table 28). Stakeholders should prepare additional information, and structure them as parameters of building entities and their value based on ETIM standards, using the format of EC_<ETIM features
coding>_<ETIM naming>, as outlined in sub-section 5.4.2.1. The ETIM coding can be accessed through the Classification Management Tool (CMT) provided by ETIM International. However, it is worth noting that the ETIM standard, which originates from the electrotechnical and installation sector, has not yet specified standards for construction products and materials, and as such, it is incomplete in containing all the required information used in this study. Therefore, this study employs the use of EFXXXXXX (at feature level) or EVXXXXXX (at value level) to highlight those unavailable classification codes in the CMT (see details in sub-section 5.1.2). In conclusion, to encourage the utilization of the ETIM standard in the construction industry, more effort should be invested in developing a practical classification system that includes all the necessary information.
8.3 Guidelines for the utilization of the BIM-based circularity assessment tool

This section summarizes and presents an overview of the preparatory activities necessary to facilitate a circularity assessment within the BIM-based circularity assessment tool. A visual representation of the assessment process is depicted in Figure 66, which delineates the sequential steps involved in executing an assessment using the tool. To initiate the assessment, users should indicate the project type and specify the applied standard for material designation. Here, NL-SfB (Table 3) is the default value. Subsequently, they are required to upload IFC file(s) which involve information of their construction project.

Upon submission of the requisite inputs, the BIM-based circularity assessment tool undertakes an automated process that entails the extraction of pertinent information from the uploaded IFC file(s) and the external database, followed by the selection of a suitable calculation model predicated on the availability of the extracted information. The results obtained from this automated process are subsequently presented in the GUI as illustrated in Figure 66.

The green cells in Table 28 signify the presentation of additional information that is expected to be provided by users (inside IFC file(s)), as compared to the current design ways in the case projects. In sub-section 5.1.1, it was elucidated that the case projects have already incorporated some information in their models, including materials designation (based on NL-SfB Table 3) and product classification (based on NL-SfB Table 1), following the guidelines of the basic ILS and NLRS. As summarized in the previous section, except for NL-SfB (table 3), the BIM-based circularity assessment tool also encourages the use of NAA.KT to provide detailed and specific material designation. More information should be prepared during construction phases using ETIM standards including materials designation, product weight, percentage of recycled materials, connection type and accessibility level (refer sub-section 5.4.2.1 and Figure 41).

Figure 66. The process of an assessment inside the BIM-based circularity assessment tool
Table 28. An overview of information used in support of an assessment in the BIM-based circularity assessment tool (green cells representing those additional information should be prepared by users compared to current design ways in the case projects)

<table>
<thead>
<tr>
<th>Project phases</th>
<th>Parameters name (take Revit as an example)</th>
<th>IFC value type</th>
<th>Parameter value</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial phase</td>
<td>GUID</td>
<td>IfcIdentifier*</td>
<td>e.g., 05Zeg3YKX7fvYIQ$1s_KFm</td>
<td>GUID represents a globally unique identifier, which is a universal identifier to represent each building entity. It will automatically be generated when modelling objects.</td>
</tr>
<tr>
<td></td>
<td>Volume</td>
<td>IfcVolumeMeasure**</td>
<td>e.g., 17.267m3</td>
<td>The volume of a building entity.</td>
</tr>
<tr>
<td></td>
<td>Status</td>
<td>IfcText***</td>
<td>1 or New materials 2 or Waste 3 or Reused products from an old building 4 or Reused products in the same building 5 or Reused products in another building</td>
<td>Distinguish materials/products flow based on the CPM. For example, if one product is reused (in the same building), the value of “Status” is “4” or “Reused products in the same building”.</td>
</tr>
<tr>
<td>Design phase</td>
<td>Material</td>
<td>IfcText</td>
<td>Based on NL-SfB (table 3): &lt;LCRStl&gt;<em>&lt;NL-SfB (table 3)&gt;</em>&lt;material description&gt;</td>
<td>The materials information of a building entity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Based on NAA.KT: NAAm_Kenmerk_Application (name_attribute_application)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Assembly</td>
<td>IfcText</td>
<td>Based on NL-SfB (table 1): e.g., 23.21 (representing “vloeren; constructief, vrijdragende vloeren” or “floors; structural, self-supporting floors”)</td>
<td>The classification code is used to describe a building entity.</td>
</tr>
<tr>
<td>Construction phase</td>
<td>IfcIdentifier</td>
<td>IfcText</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>---------------</td>
<td>---------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>EC_EF000167_Weight</td>
<td>IfcText</td>
<td>e.g., 20.1</td>
<td>The weight of a building entity (represented by kilogram).</td>
<td></td>
</tr>
<tr>
<td>EC_EF017158_Percentage recycled materials</td>
<td>IfcText</td>
<td>e.g., 0.5</td>
<td>The percentage of recycled materials involved in a building entity.</td>
<td></td>
</tr>
<tr>
<td>EC_EF002169_Material&quot;</td>
<td>IfcText</td>
<td>Based on ETIM: &lt;ETIM value coding&gt;_&lt;ETIM naming&gt;; for example, “EV012962_Calcium sulphate”</td>
<td>The materials information of a building entity. The ETIM value coding (part of) can be searched from the Classification Management Tool (CMT).</td>
<td></td>
</tr>
<tr>
<td>EC_EF000124_Connection type</td>
<td>IfcText</td>
<td>Based on ETIM: &lt;ETIM value coding&gt;_&lt;ETIM naming&gt;; for example, “EV003046_Glue”</td>
<td>The connection type of a building entity. The ETIM value coding is presented in Table 26.</td>
<td></td>
</tr>
<tr>
<td>EC_EFXXXXXX_Accessibility</td>
<td>IfcText</td>
<td>Based on ETIM: &lt;ETIM value coding&gt;_&lt;ETIM naming&gt;; for example, “EVXXXXXX2_Accessible with additional actions that do not cause damage”</td>
<td>The accessibility level of a building entity. The ETIM value coding is presented in Table 27.</td>
<td></td>
</tr>
</tbody>
</table>

* IfcIdentifier: a simple text ID string with a mix of symbols and alphanumeric characters
** IfcVolumeMeasure: a number representing the dimension
*** IfcText: a descriptive text field
8.4 Limitations and Recommendations for future work

The present section aims to provide a critical evaluation of the limitations inherent in this study and outline recommendations for future research. The foremost limitations of this study include the questioning about the validity of the calculation methods, the tool’s inability to support circularity assessment in other construction projects and the lack of an integrated decision-making method given the narrow focus of the study.

8.4.1 The validity of the calculation methods

Despite this study processing three design cycles, there were limitations regarding the validity of the calculation methods employed. The user-based evaluation, discussed in sub-section 6.3, generated useful insights and facilitated the development of each new design cycle. However, comparatively less attention was directed toward the calculation methods. Participants were more inclined to reflect on their user experience and requirements for additional circularity insights, such as detachability potential as highlighted in the second-round evaluation. Therefore, future research is recommended to complement this study and improve the validity of the calculation models, rather than focusing primarily on the usability aspects of the BIM-based circularity assessment tool.

With regards to the assessment of material circularity, the EngD candidate, in collaboration with her supervision team, assigned different weighting factors to various materials flows. However, this generated some concerns, as one stakeholder questioned the rationale for choosing specific weighting factors for certain material flows. In other words, the methodology behind the selection of these specific weighting factors was not well-explained. Furthermore, in the context of circular design, this study emphasizes the importance of the DfD strategy as the most crucial circularity strategy. However, the validity of this assumption is still subject to debate. Therefore, further research is required to strengthen the validity of the calculation models by considering each indicator and its corresponding value with greater care. This could be achieved, for instance, through the use of expert panels.

8.4.2 The implementation of the circularity assessment tool in practices

As outlined in sub-section 4.3.2, various options exist to facilitate the integration of BIM in supporting circularity assessments. Each of these approaches has its own set of advantages and limitations. Given the objective of supporting assessment across various project phases (where employing different BIM-authoring software), the current study has opted for an IFC-based solution instead of limiting assessments to a single software. Nevertheless, this approach is associated with certain limitations, such as the need for additional steps to export IFC file(s) and the inability to quantify design alternatives in real-time. In particular, one stakeholder requirement stipulates the need for a “design tool” as opposed to a “checking app” (as introduced in sub-section 6.3), which is not satisfied in the current study (see sub-section 6.1). Therefore, presenting analysis results in their design software (e.g., Revit) and displaying the differences between various design alternatives in real-time may be more convenient than requiring an intimin step to extract IFC file(s). This limitation could be magnified when comparing different design solutions for a renovation project, which may require two separate IFC file(s) and imply additional time and effort when using the BIM-based circularity assessment tool.

Therefore, future research could lead to the development of different types of tools, such as a plug-in tool and a standalone application. Although sharing the same functionalities (e.g., 3D color coding), these tools can support various usage scenarios. An exemplary standalone application is the BIM-based circularity assessment tool (proposed in this study), which can be utilized when multiple stakeholders are involved and have distinct preferences for BIM-authoring software. By relying on a neutral information file(s) (IFC), the tool can facilitate the comparison of design development throughout the entire project phase. When employed for comparing design alternatives in a particular project phase, where specific BIM-based software is commonly utilized, stakeholders such as architects can choose to use a plug-in of the software to visualize the circularity performance within their design environment.
Furthermore, as outlined in sub-section 5.4.2.1, there is a pressing need for further efforts to be invested in the development of an external circularity database to facilitate the implementation of a circularity assessment in real-world construction practices. This study only serves as a proof-of-concept by providing an illustrative example of some general information that ought to be incorporated into an external database, including the EoL scenarios or the mapping tables between different standards (see sub-section 5.4.2.1). Thus, before the tool can be widely adopted and applied in other construction projects, additional resources must be allocated to the development of a comprehensive database, which can be promoted or initiated by some organizations or steering companies such as BIM Loket/DigiGO.

Additionally, this study focuses on the design process and information management practices in two Dutch construction projects, which are considered typical examples in this industry. Moreover, only a small part of one case project (see sub-section 6.2) was utilized as a demonstration and visualization of the tool’s capabilities. It is important to note that the outcomes and insights generated from this study may not be representative of other construction projects due to the limited number of cases analyzed and tested. Furthermore, although Chapter 7 was designed to support the practical implementation of the tool of the case projects, the workflows proposed in sub-section 7.4 are not generalized enough to account for the diverse usage scenarios that may exist in other construction projects. As such, further research is recommended to use more case studies to ensure its applicability and effectiveness in various construction contexts.

**8.4.3 Integrated decision-making method/tool with BIM**

The nine-window diagram is a prominent SE tool that facilitates a comprehensive overview of where and when the end product/system is located, as illustrated in Figure 67. This tool’s primary function is to provide a holistic and dynamic perspective of how the system, particularly the BIM-based circularity assessment tool, evolves over time. The nine-window diagram hence is a valuable aid in guiding future research endeavours by offering a visual representation of the system’s development.

As depicted in Figure 67, one of the supersystems could be the decision-making system – which is an important process before a construction project can start, irrespective of the type, size, or surroundings (Coenen, 2019). While circularity is one critical aspect of this process, it must work in harmony with other aspects, such as the environmental impact of materials. This study starts to explore how the BIM-based circularity assessment tool can be integrated into the current assessment process of case projects (regarding environmental impacts of materials assessed by MPG), as a new workflow presented in sub-section 7.4.2. As illustrated in Figure 65, design teams have to prepare two types of files: an Excel file (for documenting BoQ) and an IFC file (containing geometric and semantic information). However, this approach results in a redundant process, as the IFC file already contains the necessary geometric information to support a GPR calculation. Additionally, although the GPR and the BIM-based circularity assessment tool can work complementary and provide insights from different aspects of the material performance, Sustainability consultants have to receive separate reports from different tools and analyze them manually. Therefore, future research or development should be given to understand how an integrated assessment (e.g., considering MPG and material circularity) can be realized in a BIM environment (Figure 67).

Furthermore, it is important to note that the GPR or MPG calculation heavily relies on the NMD database for providing environmental information of material. As illustrated in Figure 63, given inaccurate and incomplete information in the NMD, corrections and updates of the environmental information of materials supporting the MPG calculation have to be conducted manually. Furthermore, as mentioned in sub-section 5.1.1, the NMD does not support the utilization of different standards (e.g., the material designation based on NAA.KT or NL-SfB (table 3)), creating difficulties in supporting a circularity assessment (e.g., using the BIM-based circularity assessment tool proposed in this study). These challenges indicate the need for a comprehensive database that includes complete and accurate circularity- and sustainability-related information, such as the environmental impact of materials. This database can be regarded as an essential subsystem in the future to support an integrated assessment, as
depicted in Figure 67. Thus, efforts should be made to build such a database that can support circularity and sustainability assessments in the construction industry. Such efforts can significantly enhance the accuracy and completeness of the information and facilitate a more efficient assessment process.

Thus, a more efficient and effective workflow for circularity and sustainability assessments can be envisioned (as depicted in Figure 68) when two key preconditions are met: 1) the development of an integrated BIM-based assessment tool that enables simultaneous assessment of MPG and material circularity and 2) the establishment of a comprehensive and well-developed database that contains all relevant circularity and sustainability-related information. As shown in Figure 68, the workflow involves the preparation of BIM models by design teams that include all necessary information with the help of the integrated database, either directly (inserted into BIM objects) or link to the database. This database can store and structure all relevant circularity and sustainability-related information, making it easily accessible. Afterwards, a sustainability consultant can conduct the circularity and sustainability assessments using the integrated BIM-based tool.

Moreover, in the context of decision-making, the environmental impact (e.g., MPG and material circularity) should not be the sole consideration. A more comprehensive approach would entail the incorporation of additional aspects, including investment costs, schedule, quality, etc. (Figure 67). Thus, a thorough assessment tool must be utilized to account for these multifaceted considerations. In this manner, stakeholders can arrive at informed decisions that weigh the trade-offs between various criteria.
8.4.4 Summary

Three main aspects of this study were criticized and require further research. Firstly, the validity of the calculation methods used in this study has been questioned, which raises concerns about the accuracy and reliability of the results. Secondly, while the tool provides valuable insights into the potential of BIM-based circularity assessment, it is not currently equipped with the necessary functionality to support its practical implementation in real-world construction practices. The tool’s inability to support practical circularity assessment is largely due to its conceptual and theoretical nature. Thirdly, while the tool provides a useful basis for understanding the circularity potential of materials and products, it does not consider other critical decision-making factors such as cost, time, and environmental impact. The lack of an integrated decision-making method or tool poses another limitation to this study.

In light of these limitations, future research should prioritize the validity of the calculation models through expert panels. Moreover, it should consider the development of more operationally-oriented tools by putting effort into the development of a supportive database and analyzing and testing other construction projects. Additionally, the development of an integrated decision-making tool that considers both circularity potential and broader project aspects is essential, for promoting an effective decision-making process by accounting for the trade-off of different aspects.
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Appendix A – The design of User-based evaluation

This session is designed to evaluate the usability of a BIM-based circularity assessment tool (in the second round), aiming to perform the circularity assessment of a construction project from a material perspective. You will first be provided with a few tasks asking you to navigate the app. While doing this, we’d like you to “think aloud” as much as possible. You are welcome to speak your thoughts as often as you can. If there’s something you like, dislike or make you feel confused, please feel free to speak out at any time.

1. Please conduct a circularity assessment for a renovation project. Note: please use the IFC files named “Faculty Floor (New)” and “Faculty Floor (Existing)” located on the Desktop.

2. Please explore some functions like:
   - Colour-coding in 3D visualization
   - The colour filter (material flow filter)
   - Property overview of a single entity (what kind of other information do you would like to have?)
   - Deeper material insights (e.g., about detailed material composition, material circularity value, entity circularity value etc.)

3. Please share your opinion about follow-up questions:
   - How do you feel about the application (in terms of usability)?
     1) colour/layout
     2) analysis graphs
     3) workflow/assistance
     4) etc.
   - Is it useful? At what stage or moment in the project is it useful?
   - What kind of additional information do you need in terms of material aspects?
   - From your perspective, what kind of additional information do other disciplines possibly need?
   - What else functions you would like to have?
   - Is there anything you would like to add?
Appendix B – IFC’s structure and the extraction of semantic information

Following an object-oriented approach, IFC data forms a hierarchical structure of object instances (Theiler & Smarsly, 2018), deriving from the IfcRoot class, as presented in Figure 69. At the first level of IfcRoot hierarchy, three classes are identified: IfcObject definition, IfcPropertyDefinition and IfcRelationship (Gemert, 2019). All semantically treated things or processes are captured inside IfcObject definition, and corresponding characteristics (e.g., property sets) can be found from IfcPropertyDefinition, while IfcRelationship is a place to store information of connectivity among objects (Gemert, 2019). Inside the IfcProduct, all information of building elements is stored inside the class of IfcBuildingElement (Figure 69). Building elements are those elements that physically exist and are tangible things of a built facility. According to Ismail et al. (2017), each IFC class has its attributes which represent either 1) the relationship with other objects or 2) a basic data type containing a corresponding value (e.g., integer and string). One important characteristic of IFC is inheritance, dictating that an IFC class not only associates with its own attributes but only inherits those from its predecessors located at the higher hierarchy level (Gemert, 2019). For example, one attribute of IfcRoot – Global ID has been inherited to IfcBuildingElement or its successor IfcWall. Because of this, each wall can be recognized through an unique identifier stored by this attribute.

The prototypical BIM-based circularity assessment tool is designed in a way to extract circularity-related information of each building element (e.g., wall and floor) stored in different IFC classes. The subsequent sections offer several examples that demonstrate how different information is structured with IFC schema and how Python programming is designed to align with this structure.

Example 1 – the extraction of product classification information

NL-SfB is commonly used in the Dutch construction industry and is also encouraged in this project for providing a unique classification for each building entity. Taking Revit as one example, based on NLRS (as introduced in the sub-section of 4.5.4), entity classification of NL-SfB (Table 1) is filled in the parameter of ‘Assembly”. The parameter will be automatically mapped to one IFC class so-called IfcClassificationReference, as one of the subclasses of IfcRelAssociatesClassification. This is in turn associated with IfcWall class through the relationship of HasAssociations, as illustrated in Figure 70. Based on this hierarchy structure, python language is developed and Figure 73 shows an example of searching the classification code (NL-SfB in this case).
Example 2 – the extraction of quantities information

Taking the extraction of quantities as another example, as introduced in sub-section 5.4.2.2. In situations where the weight of a material is unspecified, a process is employed by multiplying the materials’ volume by its general density information. If the volume information of a given material layer remains unavailable, the tool utilizes other geometric information of the layer, including its area and thickness, in order to determine the volume information and thereby the corresponding material weight.

Therefore, for each building entity (e.g., a wall), multiple loops are created to first get their VolumeValue through IfcQuantityVolume. This particular class is a successor of IfcElementQuantity and IfcRelDefinesByProperties, governed by IfcWall through the relationship of “IsDefinedBy”, as illustrated in Figure 72. In situations where the VolumeValue is not available, the AreaValue property serves as an alternative. Python language is developed and Figure 73 shows an example of searching area information.

Figure 70. IFC’s hierarchy structure from IfcWall to IfcClassificationReference

Figure 71. Python coding designed for searching the information of classification code

Figure 72. The hierarchy structure of IFC schema from IfcWall to IfcQuantityVolume & IfcQuantityArea

Example 2 – the extraction of quantities information

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Therefore, for each building entity (e.g., a wall), multiple loops are created to first get their VolumeValue through IfcQuantityVolume. This particular class is a successor of IfcElementQuantity and IfcRelDefinesByProperties, governed by IfcWall through the relationship of “IsDefinedBy”, as illustrated in Figure 72. In situations where the VolumeValue is not available, the AreaValue property serves as an alternative. Python language is developed and Figure 73 shows an example of searching area information.
```python
for definition in definitions:
    try:
        if definition.RelatingPropertyDefinition:
            property_definition = definition.RelatingPropertyDefinition
            if property_definition.is_a("IfcElementQuantity"):
                for quantity in property_definition.Quantities:
                    try:
                        if quantity.is_a("IfcQuantityArea"):
                            if quantity.Name == "NetSideArea" or quantity.Name == "NetArea" or quantity.Name == "CrossSectionArea":
                                area = []
                                area.append(quantity.AreaValue)
```

*Figure 73. The Python coding designed for searching area information*
## Appendix C – Requirements evaluation

<table>
<thead>
<tr>
<th>System requirements (learned from the literature and existing methods (e.g., Madaster))</th>
<th>Fulfil (Yes/No)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The tool should be designed in a way to consider the variability of information availability of different project phases, avoiding subjective assumptions by end-users and providing similar results under consistent conditions.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should be capable of extracting and analyzing the information contained in the IFC file(s).</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should utilize the BIM ability in support of information collection and management, to smoothen the process of circularity assessment.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should be developed by taking common Dutch standards into account and it should align well with the current working mode in a Dutch construction project.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should be capable of extracting and analyzing the information contained in the IFC file(s).</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should utilize the BIM ability in support of information collection and management, to smoothen the process of circularity assessment.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should be developed by taking common Dutch standards into account and it should align well with the current working mode in a Dutch construction project.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should exhibit a high degree of intuitive functionality through the use of GUIs such as in the form of Excel, web, and application-based.</td>
<td>Yes</td>
</tr>
<tr>
<td>The GUI should show circularity performance (including the overall score and score of each indicator) with a combination of text and 2D charts/graphs.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should visualize the circularity level through 3D colour-coding, to guide users about the poor performance of circularity or imply that results are good using a set of different colours (Di Biccari et al., 2019).</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should encompass (at the very least) two facets of circularity performance, including the degree of circular material usage and circular design.</td>
<td>Yes</td>
</tr>
<tr>
<td>Regarding circular material usage, the tool should (at least) provide information about the flow of new, reused/recycled, and discarded materials, based on the circular project model created by Van den Berg et al. (2019).</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should provide a quantitative result with a range of 0 to 1. The score 0 represents an entirely linear project while 1 means a fully circular project.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should perform an assessment (after uploading all required files/information) automatically with a simple click.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should enable an effective assessment with limited user input.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should process data stored in an external circularity database (in an Excel form).</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should link the information stored in the IFC schema and circularity database with open standards or references.</td>
<td>Yes</td>
</tr>
<tr>
<td>System Requirements (translated from stakeholders’ needs)</td>
<td></td>
</tr>
<tr>
<td>The tool should use an IFC file(s) as an information carrier instead of a plug-in in BIM-associated software.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should enable an intuitive and easy interface.</td>
<td>Yes</td>
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<tr>
<td>The tool should provide deeper material-level information.</td>
<td>Yes</td>
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<tr>
<td>The tool should provide a property window to show the information of each building entity.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should integrate the scenario of using bio-based materials.</td>
<td>Yes</td>
</tr>
<tr>
<td>Requirement</td>
<td>Recommendation</td>
</tr>
<tr>
<td>-----------------------------------------------------------------------------</td>
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<tr>
<td>The tool should integrate the recycling scenarios.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should support NL-SfB (Table 3) and NAA.KT.</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should provide circularity-related suggestions and explanations, as a “design tool” rather than a “checking app”.</td>
<td>No</td>
</tr>
<tr>
<td>The tool should use multiple units when presenting the information.</td>
<td>No</td>
</tr>
<tr>
<td>The tool should improve usability aspects (e.g., provide more navigation, add units).</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should integrate detachability assessment.</td>
<td>Yes</td>
</tr>
<tr>
<td>The study should provide guidelines on how to use the BIM-based tool together with the existing method (in the case projects).</td>
<td>Yes</td>
</tr>
<tr>
<td>The tool should be demonstrated with multiple object groups.</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Appendix D – Circularity insights in different project phases

<table>
<thead>
<tr>
<th>Project phases</th>
<th>Characteristics</th>
<th>Example of results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial phases</td>
<td>1. Overall circularity value depends on the degree of material circularity value based on the CPM.</td>
<td>![Diagram 1]</td>
</tr>
<tr>
<td></td>
<td>2. Volume serves as a central measurement unit, and the quantities of material flows are expressed as square meters.</td>
<td>![Diagram 2]</td>
</tr>
<tr>
<td></td>
<td>3. Limited insights can be provided, with most of the information presented as “Unknown”.</td>
<td>![Diagram 3]</td>
</tr>
<tr>
<td></td>
<td>4. No material information.</td>
<td>![Diagram 4]</td>
</tr>
<tr>
<td></td>
<td>5. Deeper materials insights are not supported, given limited information is available.</td>
<td>![Diagram 5]</td>
</tr>
</tbody>
</table>
1. Overall circularity value depends on the degree of material circularity value; Disassembly potential is unknown.

2. Mass serves as a central measurement unit, and the quantities of material flows are expressed as tons.

3. Material designation is based on standards (NL-SfB or NAA.KT).

4. New materials can be only distinguished into renewable or non-renewable materials, without the information of recycled composition in the project.

5. Waste scenarios can be categorized into landfill, incineration, recycling and unknown based on the standard value from the NMD database.
6. Deeper material insights based on material categories (e.g., clay/concrete and metal).

7. Deeper material insights based on entity categories (e.g., floor and wall).
Most of the results are presented in a similar way compared to the design phases including the 3D colour coding of material circularity, and deeper material insights based on material or entity categories. Some major differences are discussed as follows:

1. Except for the overview of material circularity, a 3D colour coding based on the level of detachability potential is provided.

2. Overall circularity value depends on the degree of material circularity value and disassembly-ability level.

3. More information and corresponding insights are provided.
4. New materials are distinguished as circular materials (recycled or/and renewable materials) and non-circular materials (non-renewable primary materials).