MATERIAL EFFICIENCY INSIGHTS WITH BIM-BASED CIRCULARITY ASSESSMENT: A DESIGN SCIENCE RESEARCH STUDY

Li Jiang[1], Marc van den Berg, Hans Voordijk and Arjen Adriaanse

Department of Construction Management and Engineering, University of Twente, Drienerlolaan 5, 7522NB, Enschede, the Netherlands

The construction industry is in the process of becoming circular where economic growth is decoupled from materials extraction. Several assessment methods are being developed to measure the circularity, but no practical tool is available yet for understanding material efficiency in construction projects. Designers and other stakeholders, accordingly, have limited understanding about how circular their projects are. Through building on the potentials of Building Information Modelling (BIM) as a digital whole life-cycle methodology, this research, therefore, aims to iteratively develop a BIM-based circularity assessment tool. A design science research methodology was adopted during a large-scale renovation project with circularity ambitions in the Netherlands. Following the steps of design science research, the research identified the stakeholders' problem, defined a design objective, designed a circularity assessment tool, demonstrated its usage in a BIM environment, evaluated the user experiences and communicated possible future improvements. It thus provides new opportunities for project stakeholders to gain (circular) material efficiency insights.

Keywords: BIM; circularity assessment; design science; project; renovation

INTRODUCTION

As a resource- and waste-intensive sector, the construction industry is responsible for an estimated 50% of materials depletion and 30% of total waste generation in the European Union (European Commission, 2022). Moreover, there are no signs of a decrease in materials extraction and waste production (Coenen *et al.,* 2021). This is attributed to a ‘linear’ model, where materials are taken, consumed, and eventually disposed of. The concept of a Circular Economy (CE) has emerged aiming to decouple economic growth from materials extraction (EMF, 2019), through long-lasting and continuously resource reuse in a closed loop. Recognizing the benefits that the CE can make towards creating a resilient and sustainable future, the Netherlands sets targets for the country: 50% less primary raw material consumption in 2030 and a fully circular economy by 2050. However, the transition to circular construction brings about complex challenges and difficulties which urgently require theoretically grounded and empirically validated insights and tools (Van den Berg *et al.,* 2020).

One of the growing interests and methodological debates concerns how to quantify, attribute the benefits and identify opportunities in circular strategies (Walker *et al.,*

[1] l.jiang@utwente.nl

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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). Moreover, an upswing in information-centric approaches has encouraged the development of Building Information Modelling (BIM) in the construction industry (Akanbi *et al.,* 2018). 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). Because of this, researchers have emphasized the advantages of BIM utilization in measuring circularity (e.g., Akanbi *et al.,* (2018)).

Several different circularity assessment methods at the building-, component-, or 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), high uncertainties are embedded in the process of determining the end-of-life 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.

Hence, existing methods fail to measure the degree of material efficiency in construction projects, and accordingly, designers and other stakeholders have limited insights into the circularity performance of their projects. 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 and Nadler, 1978). Because of this, construction projects require a practical method with actual circularity insights to facilitate resource efficiency in practice rather than inflated assessment results attributed to an over-optimistic estimation.

In sum, research has overlooked the urgent need for insights into (circular) material efficiency in construction projects. Recognizing the potentials of BIM in circularity assessment, this paper, hence, tries to provide new insights into how to measure project-based circularity performance by using BIM. Different from a building/product circularity assessment, where estimations must be made over the expected life cycle of the building/product, a project-based method aims to provide circularity insights by narrowing its focus to the actual material flows coming in and out of construction sites. The next section presents a design science research methodology for the topic. The authors then present a prototypical BIM-based circularity assessment tool and reflect on its implementation during a faculty building renovation project in the Netherlands. The paper concludes with insights into users' perceptions and other circularity-related information needs to foster iterative design.

METHOD

Except for contributing scientific knowledge to construction projects, this study also focuses on designing practical artefacts (a BIM-based tool). Hence, a research approach based on design science was selected. Design science is a form of research that supports the discipline-oriented creation of successful artefacts (Peffers *et al.,* 2007). This study was thus designed as design science research and conducted in an actual project concerning the renovation of a large university building located in the eastern part of the Netherlands. Originally built in 1968, this building with a gross floor area of almost 19000 m2 had been abandoned since 2003 and was renovated to house a new faculty. Following the overall design ambition of "a healthy, green, and sustainable building", many existing building elements (e.g., structural components) were preserved to the largest extent.

Furthermore, for achieving a higher level of quality, BIM has been adopted in the project, where corresponding protocols generated by the design teams were provided to record the minimal agreements of BIM, for example, a standardized way for 3D modelling and document sharing. Stakeholders from different design disciplines and client representatives have collaborated over the course of the design science project. These stakeholders mainly include two project managers, a sustainability consultant, a BIM expert, and a design engineer. Several meetings took place in an informal setting meant for reviewing current circular solutions. Moreover, follow-up individual semi-structured interviews and evaluation sessions were organized to deeper understand and evaluate stakeholders' needs and requirements. The leading researcher also collected project data, including construction drawings, circularity reports and documentation concerning BIM applications, which are closely related to the study's interests.

Following the science research methodology (DSRM) proposed by Peffers *et al.,* (2007), this study was taken with several interrelated steps. Specifically, the study first identified the problem regarding the lack of a project-based circularity method. Then, a circular project model developed by Van den Berg *et al.,* (2019) was referred as a baseline for assessment in Objective Definition. It was customized as a BIM-based tool, driven by several design requirements of a "digitized tool" collected in Design and Development. The step of Demonstration was followed and the renovation project with floor components was assessed through the tool. In the step of Evaluation, the first-mentioned author conducted a user-based evaluation regarding usability aspects with the stakeholders. The lessons learned from the evaluation were thus generated as new design requirements in the step of Communication, to foster iterative design.

Regarding the step of Evaluation, a standardized method recommended by ISO 9241-11 (1998) was employed for assessing the major aspects of 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. 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. A post-interview was followed with structured questions, evaluating users' satisfaction concerning tool design and other circularity requirements. The step of Evaluation ended with a standardized questionnaire named Usability Metric for User Experience provided by Finstad (2010), using a four-item Likert scale to evaluate users' perception of outcome, interaction process and experiences with a high-reliability degree of 0.94 (out of 1) (Assila and Ezzedine, 2016).

This (one-off) design science research cycle with six steps worked from high-level requirements/needs and provided an innovative solution for circularity assessment of construction projects associated with BIM, which facilitates in-depth discussions regarding circularity-related information needs to foster iterative design.

FINDINGS

This section will demonstrate how the steps of DSRM led to a BIM-based tool for providing circularity insights in any design and construction project.

I - Problem Identification: Lack of a Practical Tool

The faculty building renovation project lacks a practical tool to get insights into circularity. Presently, the project has chosen to conduct a GPR Building (GPR Gebouw in Dutch) calculation to gain insight into the degree of sustainability of the designs. 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. 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 involve materials used within the environmental domain, subjective estimations still could not be avoided. 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. 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.

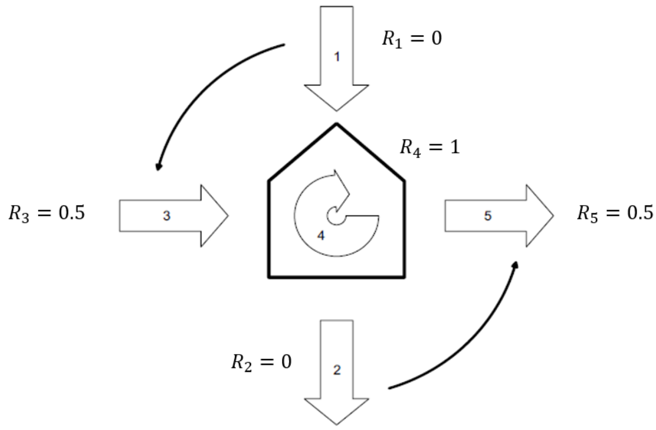
II - Objective Definition: A Circular Project Model

Project stakeholders are unable to monitor their project performance regarding circularity. Hence, a new assessment method is necessary to measure and visualize the degree of circularity. A circular project model developed by Van den Berg *et al.,* (2019) was taken as a basis to develop such an assessment method (Figure 1).

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 (about material efficiency in construction projects), but it had not yet been digitized in a BIM environment.

As these material flows are modelled, a simplified indicator of material efficiency is developed as presented in Equation 1, where F_i is the mass-based percentage of each material flow and R_i represents the weighting of each of the factors. R_i shows the preference of material flow within a circular project. For example, the attempt of recovery and reuse at the same site (arrow 4 in Figure 1) has the highest circular level, as it means that the old building products/materials can be reused directly without requiring additional transportation.

Figure 1: Circular Project Model: 1=new materials; 2=waste; 3=reuse of recovered materials (from an old building); 4=recovery and reuse (from and in the same building); 5=recovery of materials for reuse (in another building). R represents the weighting factor of each arrow (adapted from Van den Berg et al., (2019)).



To show the implication of Equation (1), the following assumptions are made: weighting factors located in a linear procedure from transporting new materials to a construction site (R_1) to deposit waste from the site (R_2) are assigned a zero value. On contrary, the most preferable solution (R_4) is given a full score of 1. A middle score of 0.5 is assigned to less effective circular actions (R_3 and R_5), in which reused materials 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 visualised in Figure 1 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. Moreover, this study is narrowed to materials flow analysis and other aspects (e.g., embodied energy and emission) are not considered.

$$\text{Circularity value} = \sum_{i=1}^{5} R_i * F_i \quad (1)$$

III - Design and Development: A BIM-Based Circularity Assessment Tool

Design requirements of a "digitized circularity tool" in a BIM environment were identified based on several interviews and meetings with the stakeholders. BIM had not been applied for sustainability or circularity-related assessment in the case project. The sustainability consultant introduced: "I manually enter the required information into the GPR" when calculating the environmental impact of the project. When talking about the possibilities of BIM integration, all participants affirmed its potential in supporting circularity assessment.

The first major design requirement concerns the interoperability between different BIM-associated software. One project manager mentioned that various software was used in the renovation project. "The design teams started with Sketchup and produced a detailed design in Revit", he said. Afterwards, the BIM expert explicitly called for "an open and neutral information exchange format" for supporting circularity assessment between different software, as he said: "instead of a Revit plug-in, I would suggest using interoperable IFC files". Hence, driven by the requirement, a stand-alone BIM-based circularity assessment tool was developed using IFC files as the information carrier, rather than a software plug-in. To conduct the assessment of building model(s), the corresponding IFC files must be properly generated from BIM-associated software with correct information. The BIM feature of intelligent modelling allows additional information to be integrated with geometric data in a 3D model. In this case, one common IFC parameter so-called "Status" was introduced to BIM-associated software to carry the material information of each building element based on Figure 1. PyCharm and Python programming language were used to realize automatic extraction and analysis of information stored in IFC file(s).

Furthermore, the BIM-based tool should provide not only a single circularity value but also other insights. These related insights include for example, "how many new/reused materials are involved in the floors or other building entities" as the BIM expert introduced. A similar view was also expressed by other participants: "I would like to know what kind of materials are involved in each arrow" and "how they influence the overall circularity value", the project manager and sustainability consultant said. Driven by this design requirement, the BIM-based tool can present an overall circularity score, and more importantly, provide some deeper insights. Similarly, correct information should be contained inside IFC (files). Hence, before starting an assessment, users are asked to provide information on materials and entities based on the NL-SfB classification, which is an open standard used in the Dutch construction industry to encode entities and materials in BIM systems using different digits and letters (e.g., "23" represents floors and "f" describes wood materials).

Last but not least, a graphic user interface (GUI) was developed to make the tool "easier to show or visualize the information", as one participant expected. Specifically, the tool was developed to enable the visualization of material information by colour-coding the elements' geometry in a 3D view. It also provides other circularity insights using 2D charts. Furthermore, inheriting the characteristic of the circular project model, the tool supports the visualisation of the degree of circularity for any type of project including a new-built, demolition or renovation one. 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 renovation projects. In addition, the tool allows the assessment from the beginning stage of a project (approximately with a BIM Level of Detail (LOD) of 200) when basic geometry and material information are available.

IV - Demonstration: Material Efficiency Assessment in the Renovation Project

The prototypical BIM-based circularity assessment tool was implemented on the case project, of which the phase of selective demolition had finished, and renewing and construction had begun. Two IFC files - named Faculty Floor (New) and Faculty Floor (Existing) in this case were generated from Revit, holding the information of existing building and new construction respectively. When choosing the project type as Renovation, the tool supports the analysis of both IFC files (Figure 4), conducting the circularity assessment of the whole construction project. Based on Equation (1), the final circularity value was assessed as 0.47 (Figure 4).

Except for providing detailed mass numbers, the amount of material flow can be reflected through the relative arrow thickness. Furthermore, a 3D model was visualized in the GUI and a set of colours was applied to distinguish materials origins or waste scenarios (Figure 4).

Driven by the aforementioned design requirement, the BIM-based tool is capable of providing other circularity-related insights instead of only a single circularity value, as shown in Figure 5 and Figure 6.

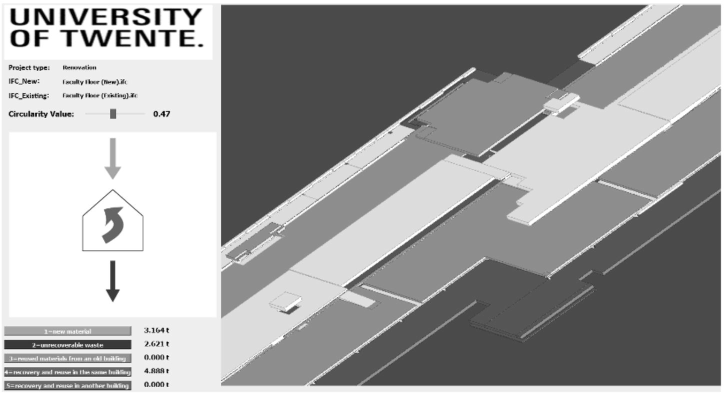


Figure 4: Assessment results of the renovation project (floor components) in the BIM-based tool (red represents waste; green shows reused entities in the same building; pink represents entities that compose of new materials)

Figure 5 shows that the renovation project (floor component) mainly contains clay/concrete and aggregate materials. Specifically, clay/concrete contributes a relatively higher circularity value (0.55) because a high proportion of clay/concrete originates from the existing building (i.e., arrow 4). A small part of the materials is grouped into "Unknown" (Figure 5), given that the information of these materials was not entered correctly based on the NL-SfB classification in the IFC files. Figure 6 presents a similar analysis 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 6, the floor components involve a high proportion of reused clay/concrete coming from the same building.

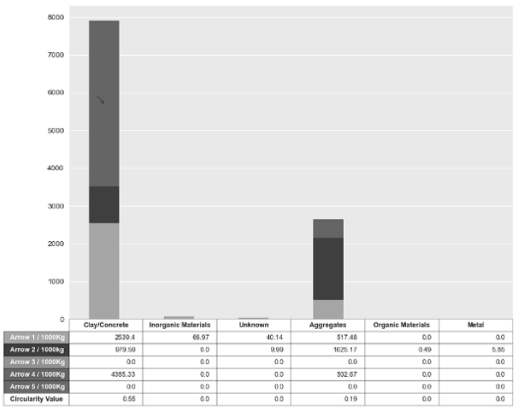


Fig 5: Assessment details at material dimension in the BIM-based tool

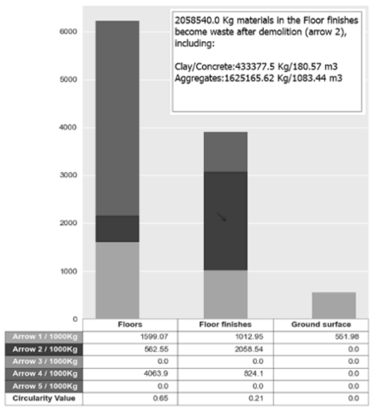


Fig 6: Assessment details at entity dimension in the BIM-based tool

V - Evaluation: User-Based Evaluation

The BIM-based circularity assessment tool was evaluated through tests with users, concerning 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. The required IFC files were prepared for the stakeholders, who are asked to use the tool to perform a circularity assessment. 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 during the post-interview and the questionnaire. By proposing questions like "what kind of additional information do you need", the participants were invited to share their thoughts about other information needs regarding material efficiency.

Regarding effectiveness and efficiency, it was observed that users completed most of the tasks successfully within one minute without obvious difficulties. All participants strongly 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. However, a smooth assessment is guaranteed with the correct IFC file(s) 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 Figure 1.

However, "in the model, the existing elements are those at the same place with 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. Another uncertainty is about preparing the IFC file of (old) buildings when their BIM models do not exist, and they normally rely on original (2D) drawings, field visits or the technique of 3D scanning. However, "many assumptions have to be done" when remodelling these buildings, especially regarding details such as material layers in building elements. These imply an easy and accurate circularity assessment can only be realized if circularity-related information requirements are clearly defined and BIM is applied at a larger scale.

All participants agreed that the results are presented in an easy and intuitive way and the effort of "loading multiple IFC files" to carry information of different phases was praised when performing the assessment of the renovation project. Furthermore, the attempt of utilizing NL-SfB classification as an open standard was also affirmed. However, the BIM expert further introduced a more advanced development called NAA.KT was gradually integrated into projects in the Netherlands in the form of an unambiguous material designation. However, the tool currently fails to support this standard. Furthermore, when discussing which quantity unit(s) is suitable for representing the material flows, one participant supposed "it should depend on the kind of entities". He exemplified that "it is more logical to describe how big the floors are and how many columns we are talking about". The discussion also covered the possibilities of using the measurement unit of mass, which was initially not prepared in the case project and also "it is difficult to obtain the information of materials' density or weight at the beginning", one participant said. He took the example, where structural engineers can only provide general density information for "a single floor" in the design model and have to wait for suppliers to provide "detailed information of each layer in the floor" in the later stage. Hence, it is suggested to use multiple units (e.g., cubic meters and square meters) when presenting the information and considering if the unit of mass is necessary compared with geometry information.

In terms of satisfaction, the participants said that the tool's capabilities met their requirements to a certain degree (with an average score of 4.8 out of 7 based on the questionnaire). One project manager explained: "it is good for me to see how circular my project is from a big picture". However, another project manager argued that the prototype 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 circular project model 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. Further design is needed to create a more complete circular scenario. Another challenge is that the current tool limits itself as "a checking app" instead of "a design tool", the design engineer pointed out. "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.

Overall, the BIM-based circularity tool was affirmed by the potential users, while several limitations include: 1) lack of support with other open standards; 2) incomplete material flows; 3) limits itself as "a checking app".

VI - Communication: Possible Future Improvements

Lessons learned from the previous design science step can be formulated as new design requirements to foster iterative design. To support the circularity assessment, agreements regarding information recording (e.g., in BIM models) must be reached between involved stakeholders. The utilization of NL-SfB was confirmed as a good starting point, while the tool can be strengthened with the involvement of other open standards in the Dutch construction sector (e.g., NAA.KT). Another new design requirement concerns the circular project model, which was criticized for its oversimplification without capturing various material flows within construction projects. It should be improved with a more complete circular scenario in biological and technical cycles, for example, by differentiating materials going to reuse/recycle, or ending up in compost/incineration/landfill. To yield a more complete circularity value, different weighting factors have to be given to show the significance of each material flow. However, the current study is limited to usability testing, and more research is required to validate the proposed calculation model, for example, through an expert validation session. Another challenge of a circularity tool concerns how to make a "design tool" instead of "a checking app", to motivate users to realize a more circular project. The circular project model (Figure 1) provides general design suggestions, for example, by replacing new materials (arrow 1) with reused ones (arrow 3). However, an iterative design is still required to understand how a circularity tool can promote circular designs by providing more concrete suggestions.

CONCLUSION

Circularity gradually becomes an essential aspect in decision-making processes, where project stakeholders require actual circularity insights to facilitate resource efficiency in practice. However, most existing tools require excessive estimations and lead to unreliable assessment results. This study hence was designed as a design science research, aiming to provide an innovative solution for assessing circularity in construction projects. For this purpose, a BIM-based circularity tool was developed and demonstrated in a renovation project. The user-based evaluation confirmed the tool's ability to present a circularity score and also other circularity analyses. Moreover, it uncovered current limitations including incapability of supporting other open standards, incomplete materials flow, limiting itself as "a checking app" etc.

The study firstly contributes to scientific knowledge by complementing a simplified methodology to assess material efficiency and providing actual circularity insights for construction projects. This differs from many existing methods where estimations have to be made during the whole lifecycle of buildings/products. Moreover, this study presents how a design science research methodology with its emphasis on designing, demonstrating, evaluating, and communicating is well-suited in the construction industry for developing theoretically grounded and field-tested prototype artefacts. The study also contributes with a practical tool for digitizing the assessment process utilizing BIM's capabilities of holding customized information. This tool allows the circularity assessment at different project stages with limited manual inputs. Moreover, the tool can present not only the overall circularity value but also more circularity insights at different dimensions in any project including a new-built, demolition and renovation one. However, the study is limited to one complete design science cycle, more research is recommended to improve the BIM-based circularity assessment tool with those new design requirements.

In sum, this study provides an innovative solution to support the circularity assessment of construction projects with BIM integration. Project stakeholders can use actual circularity insights generated by the presented method and tool in their decision-making process, to promote a circular design and construction.

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