Open BIM-based LCA of HVAC and circularity assessment using the Madaster platform

Theißen Sebastian [a], *Pelzer* Björn [c], *Höper* Jannick [a], *Drzymalla* Jan [c], *Frank* Claudius [b], *Bergmann* Patrick [b], *Meins-Becker* Anica [a]

[a] Institute of Building Information Modeling, Faculty of Architecture and Civil Engineering, Wuppertal, Germany, sebastian.theissen@uni-wuppertal.de.

[b] Madaster Germany GmbH, Berlin, Germany.

[c] Institute of Building Services Engineering, Faculty of Process Engineering, Energy and Mechanical Systems, TH Köln (University of Applied Sciences), Cologne, Germany.

Abstract. In Life Cycle Assessments (LCA) of buildings and circularity assessment, Heating Ventilation and Air-Conditioning (HVAC) systems are almost completely ignored due to the lack of regulation requirements, simplified consideration in green building certification and high complexity. Therefore, there is a lack of relevant information that enables a comprehensive whole building LCA and a circularity assessment of materials in HVAC. Using a digital Material Passport (MP) for buildings enables combining whole building LCA with qualitative and quantitative assessments of circularity. The open Building Information Modeling (BIM) method and the open data exchange format Industry Foundation Classes (IFC) offer a high potential for the efficient creation and management of a MP, as data can be integrated, linked and exchanged in 3D models with a high degree of semantics. This work analyses the life cycle assessment and circularity of two design variants of Ventilation and Air-Conditioning (VAC) systems of an office building within an open BIM-based process. Thereby, the embodied carbon of the VAC design variants was analyzed within an open BIM-based LCA. As a second step, the VAC models were assessed regarding their circularity using the Madaster Circularity Indicator (MCI) and detachability index within the Madaster platform as a case study. The results show that the impact of VAC materials is very important to consider within a whole building LCA, as VAC cause high material-related embodied impacts. In addition, the circularity assessment, using MCI and Detachability index, shows that the reduction of material mass does not influence the assessment. Instead, Design for Disassembly (DfD) turns out as a very important factor, which can also provide information for a more realistic assignment of end-of-life scenarios, effecting LCA results interpretation in the future. However, therefore various competencies in planning, data modelling and sustainability assessment need to be more connected. The open BIM approach already offers the tools to make this more efficient and automated. The research shows advantages and obstacles of open BIM based LCA and circularity assessment of HVAC and provides insights for further research regarding a more holistic assessment of buildings.

Keywords. LCA, Circularity Assessment, MCI, detachability, technical building services, HVAC, open BIM, IFC, material passports.
DOI: https://doi.org/10.34641/clima.2022.184

1. Introduction

The decision of the Paris Climate Agreement of 2015 and the climate goals agreed in December 2019 have intensified the requirements for the reduction of greenhouse gases (GHG) emissions at both European and national levels. The European Green Deal sees a sustainable transformation in the most GHG-intensive sectors in terms of climate protection, resource conservation and digitalization as important solutions. The construction and building sector plays a key role in this context, as it is the world's largest consumer of materials and the largest emitter of GHG emissions, and also generates the largest share of global waste production [1]. The EU Taxonomy Regulation, as a part of the European Green Deal, is a classification system for sustainable financial products. In this context, pressure is also exerted on real estate industry players through the fulfillment of sustainability requirements as well as their transparent

Copyright ©2022 by the authors. This conference paper is published under a CC-BY-4.0 license.

disclosure. For example, Life Cycle Assessment (LCA) of buildings is required. As a standardized method LCA is used. This method has already become established in certification systems for sustainable buildings. Thereby, a whole building LCA is used to evaluate environmental impacts and resource consumption over the entire life cycle of the building. However, technical building services (TBS), meaning Heating Ventilation and Air-Conditioning (HVAC) electrical and plumbing systems, is usually only included in a simplified way and therefore usually insufficiently evaluated. TBS is not only an underestimated part within whole building LCAs. It is also usually not considered in circularity assessments [2], although TBS contains strategically and economically valuable raw materials, such as copper, aluminum, steel and rare earths [3]. Since LCA is only partially suitable for assessing circularity, further evaluation methods are needed. For example, installation situation and the accessibility as well as the connection to other building elements are not covered or considered using whole building LCAs. However, these are crucial for the Design for Disassembly (DfD) and the assignment of a correct possible End-of-Life scenarios within whole building LCAs [4]. Methods, such as the Madaster Circularity Indicator (MCI) or the Urban Mining Index (UMI), represent initial approaches in this regard. However, these circularity assessment methods focus on structural elements and do not consider TBS so far.

At this point, the method of open Building Information Modeling (BIM) offers a high potential for the detailed consideration of TBS in whole building LCAs and the assessment of circularity. It also reduces the manual effort of the necessary data collection and calculation processes compared to day-today planning. Through the lifecycle, open and transparent exchange of data within the open BIM approach, data of architecture, structural engineering, TBS as well as LCA and circularity can be linked. In addition, it can be evaluated as well as communicated and documented. In this way, the open BIM-based calculation of LCA and circularity creates many added values for sustainable design, construction, operation, renovation and deconstruction. However, only two works in the field of open BIM-based LCA including TBS are known [5,6]. Work on open BIM-based assessments of circularity of TBS is not known. In this paper, an open BIM-based LCA and circularity assessment of two design variants of a Ventilation and Air-Conditioning (VAC) system of an office building is presented. The aim is to investigate the importance of VAC for whole building LCAs and circularity assessments. In addition, the challenges and potentials that arise during the modeling and data exchange within an open BIM process were identified.

LCA in the building and construction industry is standardized in EN 15978 and EN 15804. While EN 15978 defines for example the general scope and system boundaries, EN 15804 standardizes which types of environmental impacts must be considered in which phases of a life cycle. A total of 38 different environmental indicators are currently defined, such as the Global Warming Potential (GWP), which need to be indicated in the life cycle phases: Product phase (A1-A3), Construction phase (A4-5), Use phase (B1-7) and End-of-Life (C1-4) phase. The phases are supplemented with a module D, which indicate benefits resulting from reuse, recovery or recycling outside of the life cycle and system boundaries. Currently, whole building LCA finds its main application in the assessment of environmental quality within green building certification systems, such as the one of the German Sustainable Building Council, called DGNB. These systems define currently the only (voluntary) requirements that offer the possibility of taking HVAC into account.

DGNB provides a simplified or complete calculation approach, based on the standards of EN 15978 and 15804. In practice, however, HVAC is currently only represented using the simplified approach [7]. The main reasons for this in early project phases are that the design progress of HVAC for whole building LCA is too poorly developed. In late project phases, incomplete LCA data of HVAC make a detailed LCA more difficult. Also, the additional manual effort required for a detailed assessment of the various HVAC system components based on 2D planning documents is very high. Therefore, the simplified procedure is preferred in certification systems like DGNB. In more detail, it is only necessary to include the generator systems, e.g., the air handling units of a VAC system, in whole building LCA. The remaining system infrastructure and components are therefore only included as an additional share of 20%, meaning a factor of 1.2 is multiplied with LCA results. This means that the environmental impacts and resource consumption of, e.g., piping, air ducts and outlets, are not considered in detail. Instead, their embodied impacts are represented by the factor of 1.2 depending on the LCA results of the building structure.

However, studies show that TBS, including HVAC, can cause significantly higher environmental impacts [8]. For example, GHG emissions of HVAC are higher than 20% or 30%. Depending on the building type and energy standard, GHG emissions can cause up to 80% in special cases [9]. However, a detailed assessment of the environmental impacts and resource consumption of HVAC using only LCA is not sufficient to show the true environmental impacts. Also, it can lead to incorrect statements when optimizations are made. For example, if piping for an underfloor heating system is selected only on the basis of embodied carbon, plastic pipes (PEX) account for about the half of the embodied carbon as copper pipes. This is shown by a functionally equivalent comparison based on ÖKOBAUDAT datasets [10]. However, it is unlikely that plastic pipes are (up-)cycled at the end of their service life. Instead, often only incineration takes place. As an opposite, copper is very likely to be materially recycled. In addition, composite pipes made of PEX will incur high disposal costs at the end of their service life, while copper promises an increasing raw material value in the future. Therefore, a combined assessment of environmental impacts as well as circularity is very important in the environmental selection of building construction and HVAC materials and products in order to provide a more holistic decision support.

There is currently no standard for the assessment of circularity that unifies the currently different methods that assess circularity for the building and construction sector. However, one of the first and so far best known methods was developed by Madaster [11]. It is a validated scientific method, called the Madaster Circularity Indicator (MCI). This method is based on the Material Circularity Indicator developed by the Ellen MacArthur Foundation [12]. The MCI measures the quality of circularity, score from 0-100%, in three different phases:
(1) Construction phase: What is the ratio between the volume of “virgin” materials and the volume of “recycled, reused or renewable” materials?
(2) Use-phase: What is the expected functional lifecycle of the products used, as opposed to the average functional lifecycle of similar products?
(3) End-of-life: What is the ratio between the volume of "waste", and the volume of "reusable and/or recyclable" materials and products derived from a building when it is refurbished or demolished?
To calculate the MCI-score, the measurement method uses the weighted average. The weighted average is based on the mass of the materials and products used. In addition, in calculating the MCI-score, the result is multiplied with a correction factor. This factor is based on the comprehensiveness of the model in terms of the percentage of the mass for which the materials are known.

At a higher level, such as the building product, component or building level, additional attention must be given to DfD and deconstruction in terms of circular construction methods. This means that information on the installation situation, accessibility or detachability with other materials must also be available. In this respect, the detachability index, also 0-100%, has recently been added to the MCI method to better evaluate the DfD and deconstructability [13]. The index is based on the revised version of the report "Circular Buildings - a measurement method for detachability 2.0". The following criteria are taken into account [14]:
(1) Connection type: dry connections are preferred over connections with added elements and direct, integral connections take precedence over soft and hard chemical ones.
(2) Accessibility of the connection: how easily one can (physically) reach the connecting elements and to what extent this causes damage to nearby objects.
(3) Intersections: indicates the extent to which products overlap or are integrated with each other. The higher the integration, the more actions required to disassemble an element at the end of its life.
(4) Product edges inclusion: assessment of how products are placed in a composition and whether it is open or closed. A 'locked up' product can only be dismantled in the reverse order of construction.

The Madaster platform is also the only known solution to date that enables open BIM-based assessments of the circularity of entire buildings and individual building products [15].

The BIM method integrates different actors and software systems. This requires an exchange of data between the individual software systems. Open BIM describes the exchange of data between different programs using open data formats. This is intended to ensure that no manufacturer-specific application restrictions prevail in the projects. The basic data model in the open BIM method is the non-proprietary data exchange format IFC, which is standardized in ISO 16739. IFC is an object model and represents more than 700 classes. The classes are technically defined and are formally mapped via object-related relations to other classes, in addition to the inheritance relations. These definitions are generally concretized in the IFC data model by so-called entities, functions, rules, attributes as well as relations. In addition, there are the functions of quantity sets and property sets (Psets), which can be used to define dynamically expandable property sets in a modular way.

So far, only a few options are available in the current IFC4 standard via IfcClasses and Psets that represent information of LCA or circularity assessment in a standardized way. For example, in the field of LCA, service life can be covered by the previous structure of Pset_EnvironmentalImpactIndicator and Pset_EnvironmentalImpactValues. In general, however, these are outdated and not EN 15804 compliant [16]. In the field of circularity, the fastener type can be described and exchanged in a standardized way via IfcFastener as a relevant criterion of circularity. Nevertheless, there is a lack of possibilities to describe the accessibility and installation situation. Furthermore, it is not possible to exchange information on the disassembly effort, the reuse potential, or the disposal path of a material in a standardized way via the IFC model. The information must therefore be created and exchanged as user-defined Psets. For example, a "Pset Madaster" can be used to enrich various information and transfer them using IFC. Thereby, third-party software, in this case the Madaster platform, can read and process the information. Currently, the Madaster platform can read the following important properties from the IFC file via the Pset_Madaster and process them for circularity assessments:

- GUID, Volume, Area, Length, Width, Height, Type, Building phase, Classification, MaterialOrProductName, GTIN, Product code, Building Number, Flooring, IFC-type
- DetachabilityConnectionType, DetachabilityConnectionTypeDetail
- DetachabilityAccessibility
- DetachabilityIntersection
- DetachabilityProductEdge

2. Method

In pursuing the objectives of this paper, a BIM-based LCA was performed, followed by the circularity assessment. Due to the limited scope of this paper, only a part of the HVAC was considered. Since VAC accounts for the largest mass and embodied carbon share with over 55% of the total HVAC in office buildings [8], we focused on VAC only. The approach starts in the first step with the design and creation of a VAC BIM model based on a reference office building. Based on this, a second VAC variant was created in which optimizations were made with regard to the volume flow rate due to a reduced occupancy rate. When dimensioning the VAC models, all necessary calculations and designs were carried out according to German standards and legal requirements. Subsequently, the LCA for the two variants was performed using an open BIM-based LCA software program. Both BIM models were then uploaded to the Madaster platform via IFC upload to evaluate the variants from a circularity perspective. Finally, the results of the circularity assessment were compared with the LCA results and discussed.

2.1 Implementation Case Study MH Software/DESITE BIM/Madaster

The planning and dimensioning of the VAC models in terms of air volumes, sound protection, central unit dimensioning was performed with Microsoft Excel and manufacturer-specific dimensioning software. The subsequent modeling of the ventilation and air conditioning system was done with the software solution MH-Software in version 6.0 BIM. DESITE BIM from thinkproject GmbH was used as an information management program to enrich the VAC models with additional information. Unlike MH software, this tool cannot be used for geometric modeling. Instead, semantic information can be enriched, modified and individually evaluated by DESITE BIM allowing holistic access to all data and information in the model. For example, models imported in IFC format can be checked, analyzed and extended in many ways on the basis of self-programmed analysis rules. Based on the results of the research project "Life Cycle Assessment and BIM in sustainable construction" [16], Höper [17] developed a EN 15978 compliant BIM & LCA tool within DESITE BIM, which can also conduct a whole building LCA including TBS. In addition, it is possible to combine different sub models, e.g.. architecture and TBS, into one coordination (linked) model. Furthermore, external databases such as ÖKOBAUDAT can be integrated. In addition to the dynamic calculation of the LCA of the VAC models, DESITE BIM was also used for the data enrichment of the Pset_Madaster. Madaster is a central platform where the identity, quality and location of materials and components in buildings can be registered. It has an Excel as well as IFC import interface. The goal of the platform is to store information about materials and components over the lifecycle of a building, even with changing owners, and make it available during renovation and deconstruction. The platform can combine multiple IFC models. Uploaded BIM models can be subsequently edited and linked to other databases to perform circularity assessments.

2.2 Data for LCA and circularity assessment

The data basis for whole building LCA is ÖKOBAUDAT (version 2021-I) and IBU.data as well as additionally developed TBS LCA data extensions. For example, the service lives of standard VDI 2067 for TBS were added. The Madaster database has been individually adapted to the country-specific situation of the circular economy for each country in which the platform is available. In Germany, the data comes mainly from databases provided by Madaster, producers or public databases (e.g. ÖKOBAUDAT). One Madaster database provides data that consists of primary raw materials and no recycling is assumed. The second Database is a "C2C database" within Madaster that contains ideal scenarios for the same building products. These ideal scenarios are based on the technically best possible reuse and recycling processes today. They are based on the WECOBIS database provided by the federal government.

2.3 Modeling of a reference and optimized VAC model

For the planning and modeling of the VAC model, a reference building based on standard VDI 6009 was used.

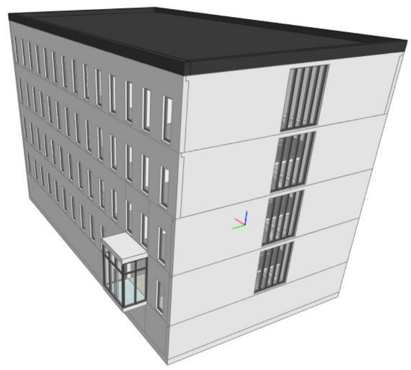

Fig. 1 – BIM model of reference building according to standard VDI 6009.

The office building has five full floors, which are divided into a basement and four above-ground floors. The area according to standard DIN 277 is 2259.36 m^2. The location of the building is assumed to be in Cologne, Germany. This BIM model formed the basis for the design and modeling of the VAC system. Furthermore, an optimized variant for the VAC model was planned and modeled on this basis. Preliminary investigations revealed that a reduction in air volumes can have a positive effect on the total mass and thus the embodied carbon of the VAC. Therefore, for all office and meeting rooms, the approaches of the number of persons related to the floor area were adjusted and the total volume flow for the building was calculated. Based on the adjustment of the person occupancy density, the required outdoor air volume flow could be reduced from 12,370 m^3/h to 9,130 m^3/h. This corresponds to a reduction of 26%. Taking the recalculated outdoor air volume flow as a basis, the entire distribution network as well as all necessary components were redesigned and constructed as an optimized VAC model.

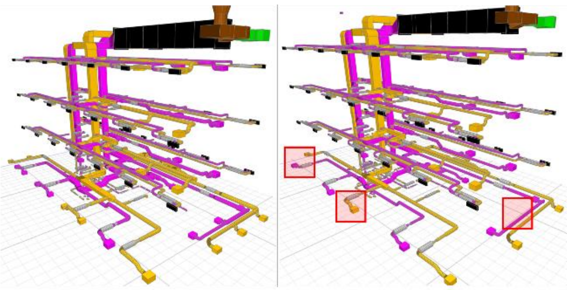

Fig. 2 – Comparison of the reference and optimized VAC model, including exemplary marking of the changes on the first floor.

2.4 Conduct of LCA using specific open BIM-based LCA tool

The basis for the LCA of the two VAC models is described by the following:

Tab. 1 – Summary of LCA framework conditions

Life span	50 Jahre
Data basis	ÖKOBAUDAT 2021-I, IBU.data and VDI 2067
Calculation method	EN 15978 und DGNB ENV1.1 (version 2018, 8. edition), without module B6. complete calculation approach for VAC system
Life cycle impact assessment	CML; Global Warming Potential

The ÖKOBAUDAT provides the parameters for the environmental impacts per unit and specified smallest nominal size. Using the weight information from the LCA data, the conversion to the defined functional unit was performed. This is the reason why the number of units of the components is partly listed as rounded values in the following.

Tab. 2 – Summary of Life Cycle Inventory

Part of VAC system	Material and type	Amount	FE	Service life
Duct segment	Angular, steel	428.25	[m^2]	30 a
Duct fitting	Angular, steel	166.10	[m^2]	30 a
Duct segment	Spiral duct round, steel	425.65	[m^2]	30 a
Duct fitting		83.56	[m^2]	30 a
Insulation	Mineral wool, aluminium-covered	42.97	[m^3]	30 a
Fire damper	Angular, stainless steel,	19.96	Pcs.	20 a
Fire damper	Round, steel, plastics	10.37	Pcs.	20 a
Volume flow controller	Constant, round, plastics, steel	17.13	Pcs.	20 a
Volume flow controller	Variable, angular plastics, steel	2.00	Pcs.	20 a
Volume flow controller	Variable round, plastics, steel	102.35	Pcs.	20 a
Silencer	Angular steel plastics,	2.00	Pcs.	20 a
Silencer	Round, steel plastics,	132.50	Pcs.	20 a
Air handling unit	Steel, plastics, aluminium	1.237	Pcs.	20 a
Air outlet	Slot diffuser plastics, steel	42.00	Pcs.	20 a
Air outlet	Poppet valve plastics, steel	38.35	Pcs.	20 a
Air outlet	Swirl outlet, plastics, steel	71.78	Pcs.	20 a
Air outlet	Deflector hood	1.00	Pcs.	20 a
Air outlet	Grid, steel	1.00	Pcs.	20 a

The LCA was conducted using the open BIM&LCA tool by Höper. A full description how this tool works can be found be found in [5].

2.5 Conduct of a circularity assessment using Madaster

Both models, with the identical information of table 2, form the basis for the evaluation of circularity using the Madaster platform. Beforehand, the VAC models were additionally enriched with properties described in 2.4 and assigned to Pset_Madaster.

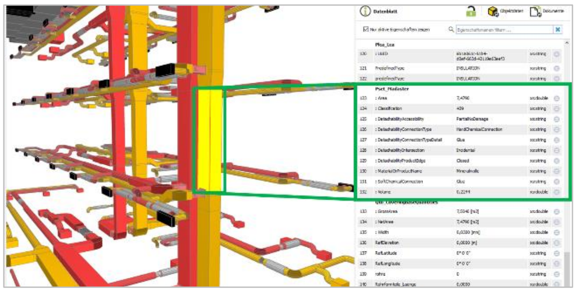

Fig. 3 – Enrichment of Pset_Madaster

Subsequently, an IFC export was performed, which was uploaded to Madaster.

Fig. 4 – Conduct of a circularity assessment using the Madaster platform

Based on the previously fulfilled modeling requirements, Madaster automatically assigns the VAC model to the materials of the Madaster database as far as possible.

3. Results

3.1 LCA results

Figure 4 shows the GWP of the VAC system in kg CO_2-equivalent/m²/a. The components shown in Table 2 were grouped into five categories: air ducts total without insulation, insulation total, components, air handling unit, air outlets. The sixth column shows the total GWP of the VAC system. Each column is subdivided into the different life cycle modules according to EN 15804 and focused on the relevant life cycle modules according to DGNB: A1-A3, B4, C3, C4 as well as D. Overall, a saving of 19% was achieved for the optimized variant compared to the reference. With regard to the individual components of the VAC system, it is clear that the air ducts have the largest share in the reference and the optimized variant. The reason for this is the generally large total area of the air ducts and the resulting total weight. Therefore, significant GWP savings could be achieved, especially in reducing the mass of the air ducts. Furthermore, there was a shift from the square designed fire dampers to the round design. The reason for this is the reduction of the volume flow at the shaft outlet, which made it possible to dimension the fire dampers smaller resulting in material and thus GWP savings. The same applies to the volume flow controllers. Since the outdoor air volume flow of the meeting rooms and open-plan offices was generally reduced due to the occupant density, the diffusers could be reduced in number or size. With focus on the differentiation of life cycle modules, it was shown that B4, i.e., the GWP due to replacement, had the highest impact in each group. This can be explained by the relatively short replacement cycles of the VAC components compared to a life span of 50 years according to DGNB.

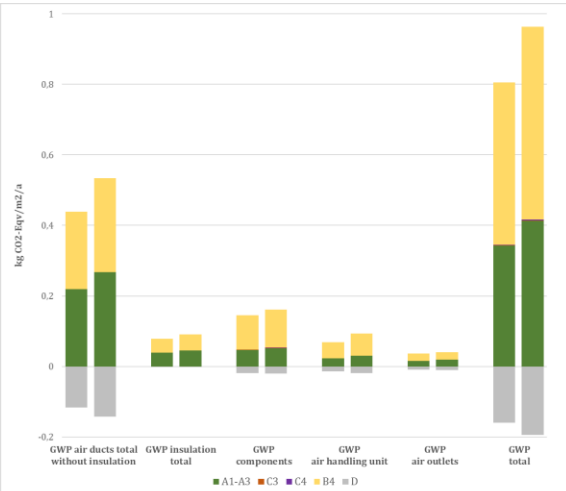

Fig. 5 – Comparison of the GWP of the optimized and the reference VAC model

3.2 Circularity assessment results

As there is currently no possibility to directly compare variants in Madaster, the results of the two VAC variants were compared in a separate overview. For this purpose, the MCI and the circularity in the construction, use and end-of-life phase were compared. Furthermore, the detachability index was presented. All values are between 0 and 100%, with 100% representing the target value. The evaluation of the MCI and its three indicators shows no changes for the reference as well as for the optimized variant. This can be explained by the fact that no other materials with different circularity properties were used. Only the quantities and masses changed. Therefore, the detachability index did not change either.
The reduction of material masses, e.g., galvanized steel, can be observed via a detailed overview of the materials used in Madaster. Thus, there is only an influence on LCA and raw material values.

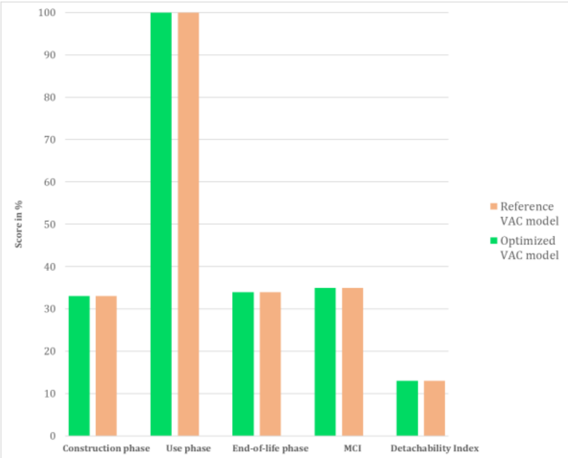

Fig. 6 – Comparison of MCI, consisting of construction, use and end-of-life phase, as well as Detachability Index of the optimized and the reference VAC model

4. Discussion

The discussion focuses on four main points: (1) Importance of VAC for whole building LCA. (2) Suitability of MCI and Detachability Index to assess circularity of VAC (3) Effects of circularity assessment on LCA. (4) Challenges and further potentials.

4.1 Importance of VAC for whole building LCA

As other studies on whole buildings LCAs have already shown, the simplified approach representing TBS with an additional factor of 20% is not sufficient to consider the TBS adequately in a whole building LCA. This paper confirms this finding when the following reference is made to the DGNB LCA benchmark for new construction of office buildings: Multiplying the benchmark of 9.4 CO_2-Eqv/m²/a, which only includes embodied impacts of TBS generator plants, by the factor of 1.2 leads to a total value of 11.28 CO_2-Eqv/m²/a. This corresponds to a premium of 1.88 kg CO_2-Eqv/m²/a as an absolute value for all components of TBS. The LCA of the air ducts as well as the other components of the reference VAC system of this work show an absolute value of 0.87 CO_2-Eqv/m²/a. In relation to the absolute value of 1.88 kg CO2-Eqv/m²/a, of the DGNB LCA Benchmark, 46% would already be covered by the materials of the VAC system and the replacement cycles. Against the background of a 50 year DGNB life span of an office building even higher environmental impacts are to be expected, while the building construction, especially in the support structure, generally does not require any costly material replacements. In addition, further material related embodied carbon from heating, sanitary, electrical and other TBS systems, which also have large distribution networks and short replacement cycles, can be expected to have significantly higher GWP impacts than the remaining 1.01 kg CO_2-Eqv/m^2/a. Thus, it become clear that TBS is underrepresented using just a factor of 1.2. The importance of TBS needs to be considered in whole building LCAs more. This can be achieved if, on the one hand, an increased factor is introduced within the framework of the simplified approach or, on the other hand, the effort for detailed consideration of TBS is further simplified.

4.2 Suitability of MCI and Detachability Index to assess circularity of VAC

The circularity assessment shows that the MCI as a single indicator is not sufficient to meaningfully evaluate circularity for TBS. While the C2C database within Madaster can be used to simulate material optimization through alternative materials and/or different material circularity properties for the VAC system, this is not sufficient without more information on how materials are connected or installed. Evaluations of service life show that if a TBS material has a longer service life than the reference service life of 15 years of TBS, 100% can already be achieved in the use phase. This standardization is to be regarded as critical, since TBS can have very different service life spans, e.g., ranging from one year of fine filters up to 40 years of pipelines in accordance with VDI 2067. In addition, problems arise if the installation situation is not considered. In the example of the air duct, a 100% evaluation within the use phase can be considered with a standard service life of 20 years. However, since the ducts run above an attached plasterboard ceiling, destruction must be planned for maintenance or replacement in order to achieve accessibility to the ducts.

The Detachbaility index therefore provides a starting point to include the DfD, too. However, it is necessary to enrich the data using the Pset_Madaster and a BIM coordination model as well as simultaneous expertise in the planning and execution of the VAC system. However, when assigning these properties, it is not possible to specify the project-specific installation or connection to another element/component. This means that it can be defined for mineral wool insulation that an adhesive connection is present, but it is not possible to further define to which component, e.g. ventilation duct, the mineral wool is glued. So, the (quantitative) assessment of the DfD of HVAC systems provide research potential. In addition, this qualitative assessment of defining properties of detachability and accessibility within the Pset_Madaster results in subjective influence, e.g., in the assessment of accessibility and the extent to which damage can occur in preceding structures. The detachability index is therefore dependent on the subjective evaluation of the planner. Quantitative evaluations will be important in the future and represent also a need for further research, e.g., to what extent installation situations can be (automatically) analyzed from coordination models. This combination of necessary competencies for this also shows how new tasks and new job profiles for sustainable design and construction will arise in the future, in which BIM, HVAC design and sustainability assessment must be considered holistically.

4.3 Effects of circularity assessment on LCA

While Madaster has so far been used primarily as a documentation tool after the completion of a building, the use of the tool in early phases has proven useful in the course of conducting the assessments in this work. In particular, conclusions for a better DfD understanding, e.g., in the suspended ceiling, could be identified during the evaluation of the installation situation and accessibility. Thus, the circularity assessment in the open BIM process can be used as an optimization tool already for earlier planning phases by ideally influencing how VAC is accessible as well as connected and installed already before execution. This can provide important decision-making support, e.g., when choosing a fully revisable metal ceiling instead of plasterboard. Another point of interest is that the assessment of DfD can help to identify the end-of-life scenario for LCA in module D. By having the information whether materials are readily separable from each other, it is possible to assess to what extent direct reuse, recycling, incineration, or landfilling are possible. However, therefore it is useful to know the specific installation situation and connection to other elements/materials. If this is possible in the future, this could mean that findings from the circularity assessment must ideally be available at the same time or prior to LCA in order to select realistic scenarios in Module D for the LCA. This is particularly relevant for the DGNB LCA, since the benefits from Module D are included here. However, there are currently only a few LCA datasets where several scenarios are already available, as required by EN 15804:2020.

4.4 Challenges and further potentials

The enrichment and analysis of information in a BIM coordination model is essential in order to implement LCA and circularity assessment of HVAC in the open BIM process. Only by using the BIM coordination model could the installation situation and accessibility for the VAC system be evaluated in a meaningful way. This in turn requires the use of open BIM and the data exchange of non-proprietary data formats. In doing so, the different software applications, e.g., BIM authoring tool for architecture and TBS, are able to exchange and read BIM models created by different BIM software. Furthermore, the issue of data quality and quantity is an important point. For example, there is no data set for air handling units in Madaster. This had to be created individually. This in turn was problematic because hardly any manufacturer data on material types and their proportions is publicly available. The quantity of LCA data in ÖKOBAUDAT is also still very low. In the area of quality, image files for conversion of channel sizes and their GWP share complicate machine readability and integration into BIM-based LCA tools. During modeling, not all components of the VAC are usually modeled. Threaded rods and the suspension of air ducts are often not part of the modeling. Accordingly, information on material quantities/masses is also missing here. In addition, there is also a difference between installation and execution planning in the area of modeling. While the suspension structure of air ducts has to be modeled for execution in installation planning, there are usually no more adjustments in the BIM model after execution. This means that the as-built situation is no longer documented. Accordingly, there is no 100% correct digital twin. Reasons for this are often additional and costly efforts. To ensure urban mining in the future, however, it is essential to provide as-built quality with the completion of the building, to make a complete and meaningful basis about material passes for the further life cycle phases of the building available.

5. Conclusion / Outlook

This work has shown that TBS is an important part in the environmental assessment of buildings, which must be considered much more in the future. Open BIM solutions already offer the technical possibilities for this today. Madaster proved to be the only solution that already allows an open BIM-based assessment of circularity of TBS, even if it still needs optimization in many points. From this first investigation, many important insights could be found. For example, how advantages in the combined evaluation of LCA and circularity assessment can be used for a more holistic environmental design support. In this context, also the individual design phases merge into each other, as planning and execution know-how grow together more and more.

Open BIM-based material passports and software make it possible to handle the large amounts of data and to analyze them more easily. However, this also requires connecting different competencies in the planning process, which creates new tasks and processes for planning teams and generates much further need for research.

6. References

[1] Global Alliance for Buildings and Construction, 2020 Global Status Report for Buildings and Construction: Towards a zero-emissions, efficient and resilient buildings and construction sector. 2020.

[2] Cheshire D., Russett S., et al., Resource efficiency of building services: TM56: 2014; Chartered Institution of Building Services Engineers. 2014, Vol. 56.

[3] Köhn A., Urban Mining: Entwicklung einer Methodik zur Ermittlung zukünftiger Rohstoffströme aus Gebäudetechnik. 2018.

[4] Rosen A., Urban Mining Index: Entwicklung einer Systematik zur quantitativen Bewertung der Kreislaufkonsistenz von Baukonstruktionen in der Neubauplanung; Fraunhofer IRB Verlag. 2021.

[5] Theißen S., Höper J., et al., "Using Open BIM and IFC to Enable a Comprehensive Consideration of Building Services within a Whole-Building LCA," Sustainability. 2020, Vol. 12, 5644.

[6] Figl H., Ilg M., Battisti K., "6D BIM–Terminal: Missing Link for the design of CO 2 -neutral buildings," IOP Conf. Ser.: Earth Environ. Sci. 2019, Vol. 323.

[7] Deutsche Gesellschaft für Nachhaltiges Bauen – DGNB, Benchmarks für die Treibhausgasemissionen der Gebäudekonstruktion: Ergebnisse einer Studie mit 50 Gebäuden. 2021.

[8] Lambertz M., Theißen S., et al., "Importance of building services in ecological building assessments,". 2019, Vol. 111, 3061.

[9] Royal Institution of Chartered Surveyors, Whole Life Carbon Assessment for the Built Environment, 1st edition. 2017.

[10] Bundesministerium des Innern, für Bau und Heimat, ÖKOBAUDAT: Informationsportal Nachhaltiges Bauen, http://www.oekobaudat.de/, accessed 22-10-2021.

[11] Rau T., Oberhuber S., Material matters: Wie wir es schaffen, die Ressourcenverschwendung zu beenden, die Wirtschaft zu motivieren, bessere Produkte zu erzeugen und wie Unternehmen, Verbraucher und die Umwelt davon profitieren; Econ. 2019.

[12] Madaster Services B.V., Madaster Circularity Indicator explained: v1.0. 2021.

[13] Madaster, Madaster Release Notes 2021: Version 10.0. 2021.

[14] Dutch Green Building Council, Circular Buildings - a measurement method for detachability 2.0. 2021.

[15] European Commission, Building logbook state of play: report 2 of the study on the development of a European Union framework for buildings' digital logbook; Publications Office.

[16] Lambertz M., Wimmer R., et al., Life Cycle Assessment and BIM in sustainable construction: Final report. 2020.

[17] Höper J., Development of a method for the automation of whole building Life Cycle Assessment using the Building Information Modeling method. 2020.

The datasets generated during and/or analyzed during the current study are not available because they are part of ongoing PhD thesis, but the authors will make every reasonable effort to publish them in near future.