Digital Twins to BIM Object Library – A Top-Down Modeling Approach

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Abstract

As the demand for affordable housing rapidly increases, researching methods to provide affordable residential buildings are of prime importance. As part of the digital platform "Housing 4.0" we aim to develop a BIM4D2P (BIM for Design to Production) tool that enables stakeholders across the value chain to utilize a BIM object library based on modular multi-storey residential buildings to generate affordable and sustainable housing. On the contrary to established methods of Building Information Modeling we were not able to utilize preexistent components or objects for a BIM Object Library - as they hardly exist for our specific purpose. This paper presents a top-down modeling approach and will explain the path from generating twin variants to the decomposition of such, to the generation of the data for the BIM object library.

Keywords: BIM, Digital Twin, Object Library, Top-Down Modeling, Digital Platform, Housing

1 Introduction

As the demand for affordable housing rapidly increases, researching methods to provide affordable residential buildings are of prime importance. Modular off-site construction is a promising approach due to its potential to generate accelerated, cost and material efficient residential projects. The ongoing research within the funded research project "Housing 4.0" (Housing 4.0: Digital Platform for affordable housing - FFG Austrian Research Funding agency, 2019) aims to develop an integrated framework for a BIM-based digital platform for modular affordable housing as a support-tool for designers, planners, developers, housing associations and users.

The construction industry is currently undergoing a digital transformation. Processes in the real estate industry (planning, construction, operation) are becoming increasingly digitized along the value chain. However, in order to be able to exploit the full potential of information and communication technology (ICT), it is necessary to integrate and link the individual digital processes as well as all stakeholders. The coupling of planning and construction - from design to production - has the potential to support the creation of affordable housing. By using Building Information Modeling (BIM) and digital tools in design and industrial construction production, it will be possible to significantly reduce construction costs and construction time, as well as to ensure the necessary flexibility and adaptability of floor plans and buildings, which will become increasingly necessary in the future.

In order to be able to guarantee an efficient, digital data chain, special focus must therefore be placed on the interface between planning and production in the early planning phase. This can be achieved through 3D models and a BIM planning approach, as all building elements to be produced can be directly forwarded to digital production (Matcha 2010). There is still little research on BIM application and implementation in manufacturing in the construction industry and a knowledge gap of BIM for production (off-site production). Previous research focused on BIM objects and their graphical and non-graphical content. The BIM application and workflows within manufacturing companies, interfaces, and data exchange with other corporate functions have not been addressed to date (Dawood et al. 2016).

The digital platform Housing 4.0 interlinks various digital tools and databases with the aim to generate modular affordable multi-storey residential spaces while integrating numerous stakeholders throughout the whole process from design to construction and life cycle. The project supposes an open modular building system with various stakeholders and manufacturers and an open source integrated data transfer approach and data structures. Housing 4.0 as a digital platform has to be described as two co-dependent tools that are interlinked with a joint digital knowledge data base. The application BIM4D2P, Building Information Modeling for Design to Production, is the base for the design-build-operate process. Therefore, data structure and approaches for data transfer from design to production is its main goal. Furthermore, BIM4D2P inherits a BIM object library that contains the BIM objects which are digital elements of either 2D or 3D modules. The primary aim is to create data structures to enable interdisciplinary data exchange of the digital object libraries (digital BIM modules and components). The digital object libraries for planners and construction production are intended to support optimized and semi-automated production of residential modules and components to the greatest extent possible. Currently, data structures for BIM objects are hardly available. A framework for data structures, which is being developed as part of the project, is intended to enable the transfer of data from planner to building production in a system-independent manner. This study focuses on the top-down approach to generate the platform’s information rich BIM object library by utilizing digital twins.

2 State of the Art and Literature Review

2.1 BIM, Digital Twins and Modularity

The original meaning of the term, introduced by the Grieves in 2003 in the field of manufacturing engineering, transformed over time so that today, according to Batty (2018), the concept of 'digital twin' is understood to mean a variety of digital simulation models that are executed alongside real-time processes and that relate to social and economic systems as well as physical systems. According to Boje et al (2020), by creating digital twins in the construction sector, this adds another, temporal dimension to BIM modeling. There is still little research on BIM application and implementation in manufacturing in the construction industry and there is a knowledge gap for the use of BIM for production (off-site production). Mostafa et al (2018) find that while BIM is having a huge impact on the construction industry, the use of BIM for prefabrication is minimal. According to the study authors, minimization of design errors, consistency between design and execution, early involvement of key stakeholders in the processes, and mass customization are the key benefits of BIM use in prefabrication (Mostafa et al. 2018). The study, based on interviews with key stakeholders in Australia, also found that in prefabrication of residential buildings in Australia, BIM has already been recognized as a visualization tool and a knowledge base (2018).

The methodology of Integral Planning is missing in the planning practice and processes for the development of industrialized construction production (off-site production, prefabrication) and are not yet established. Industrialized construction and prefabrication are currently experiencing a renaissance due to increasing urbanization and the growing need for affordable housing in central urban locations. Industrial housing has gone through five generations in its development (Ågren and Wing 2014). Philipp Meuser identified the first four generations as building, building section, housing unit, and component catalog (Meuser 2019). According to Meuser, the last, fifth generation of industrial housing production is based on individual design, which is then subdivided into prefabricated elements (Meuser 2019).

3 Method

3.1 Research Design

As part of the digital platform "Housing 4.0" we aim to develop a BIM4D2P (BIM for Design to Production) tool that enables stakeholders across the value chain to utilize a BIM object library based on modular multi-storey residential buildings. On the contrary to established methods of computer aided design or Building Information Modeling we were not able to utilize preexistent components or objects for a BIM Object Library - as they hardly exist for our specific purpose. To develop and test the BIM4D2P tool in the first place, we had to generate our own test data. To determine what parameters and input data the BIM object library of a modular multi-storey housing project based on modular construction has to inherit we propose following reverse engineering driven top-down modeling approach.

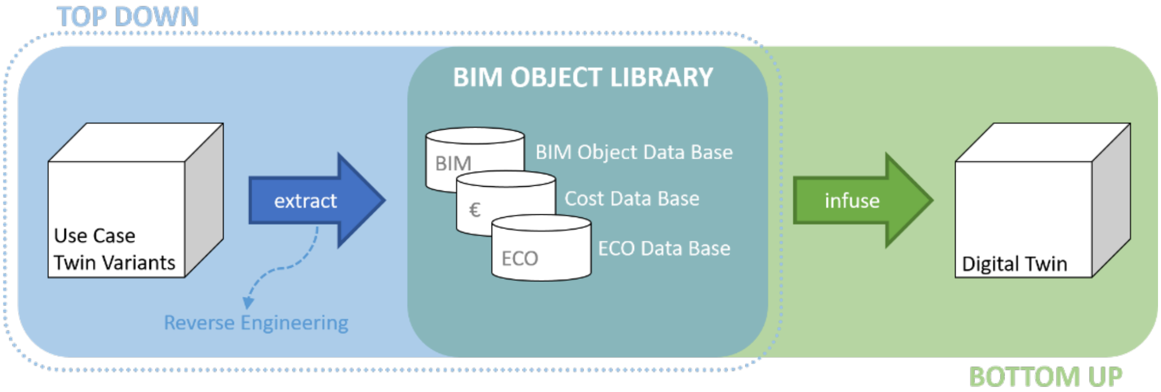


Figure 1. Combined Top-Down Bottom-Up Modeling Approach

To specify the top-down and bottom-up combinatory modeling approach (fig. 1) we need to clarify these two approaches within our context. We use top-down modeling to decompose and extract the data needed for the library out of the specifically for this purpose generated digital twin variants and we intend to apply bottom-up modeling to utilize the BIM object library to generate novel BIM-based twins.

This paper focuses specifically on the top-down modeling approach and will explain the path of generation of the twin variants to the generation of the test data for the BIM object library. Therefore, the aim has been to explore to what extend can a top-down modeling approach be utilized to generate a generic BIM object library for modular multi-storey residential buildings? We hypothesize that generic test data can be derived by decomposing specifically generated digital twins of modular buildings.

3.2 Methodology

Top-down modeling, from specific to generic, is a promising approach when hardly any test data is available. The phases (fig. 2) from defining the design space to the preliminary version of the BIM object library are characterized by an iterative method of data generation and reduction of data, which are interlinked by a reverse engineering driven decomposition (extraction) approach. Following phases of this methodology are described in this section: Design Space Exploration, Modeling of Twin Variants, Quality Gate, Post Processing, Preliminary Component Generation, Generic Object Generation.

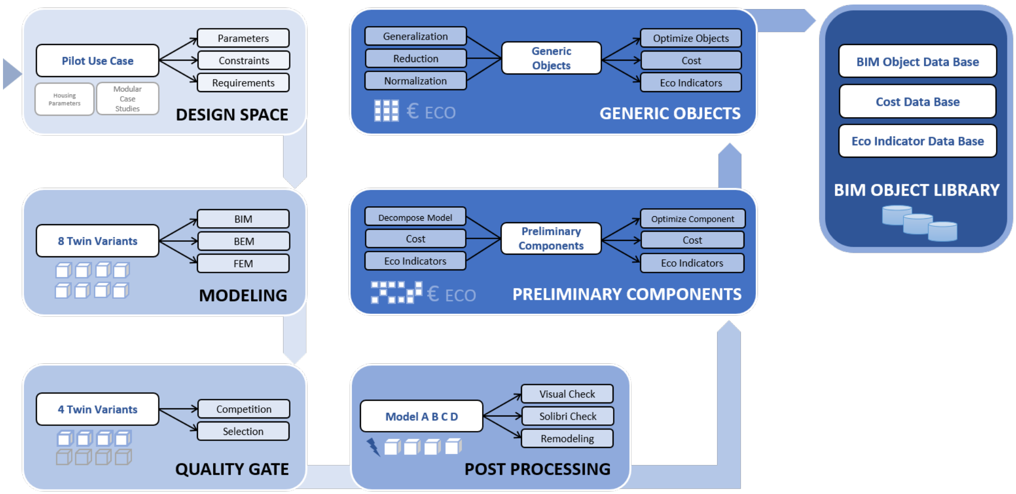


Figure 2. Top-down modeling phases - from specific to generic data

3.2.1 Design Space

The gathering of a large variety of data is essential to develop the generic objects. To ensure diversity and versatility of data to decompose we resolved that the pilot use case of the research project has to be re-generated as digital twin variants. In order to determine its design space (parameters, conditions and requirements) and to identify the conditions of modularity in our specific context, a content analysis of modular multi-storey residential building data has been conducted. Following data of the research project “Housing 4.0” has been utilized: i) a pilot use case of a real built multi-storey residential building, ii) a set of 60 modular housing case studies and iii) a study on housing trends. Since the data collection has been performed prior to this phase a rather large set of modular related data has already been available for the content analysis. Figure 3 shows the input data available for the content analysis and extraction. The method used for content analysis has been qualitative analysis of literature and documents and typological-morphological analysis of plans, photographs and illustrations. In the course of the study, media analysis was used to qualitatively survey housing trends as well as flexibility and adaptability requirements for off-site production, institutions, normative frameworks, actors, materials and technical systems. In this phase our main aim has been to extract the relevant parameters and constraints as well as requirements to define the design space.

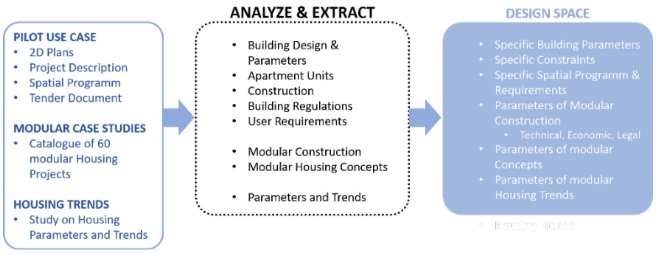


Figure 3. Design Space Phase - Input – Method – Output

3.2.2 Modeling

We aim to generate BIM twin variants, which differ in design and construction but stay inside the pre-defined spectrum of parameters, constraints and requirements derived from the pilot use case. The design space serve as a guideline for the modeling of the variants.

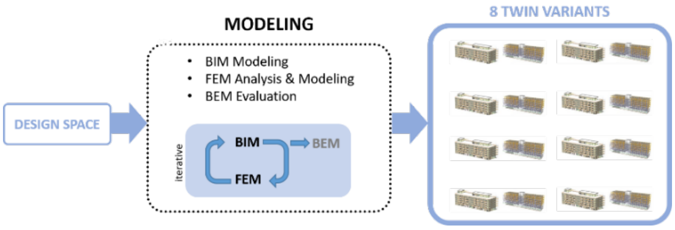


Figure 4. Modeling Phase - Input – Method – Output

In this particular phase, interdisciplinary teams of architecture and civil engineering students developed the projects and interdisciplinary models over the course of one semester. (Pibal et al 2020). The student teams utilized an iterative Building Information Modeling (BIM) to Finite Element Method (FEM) and Building Energy Modeling (BEM) workflow (fig. 4), that has been developed by the Department of Integrated Planning and Industrial Building at TU Wien (Kovacic et al 2014, 2014, 2015). Applying the top-down approach combined with research led teaching we obtained 8 digital BIM twin variants of the pilot use case, which differ in design and construction but stay inside the pre-defined spectrum of parameters, constraints and requirements.

3.2.3 Quality Gate

To guarantee the quality and feasibilty of the twin variants an independent jury of experts from the AEC Industry assessed the projects according to a pre-defined set of criteria during a competition as an installed quality gate. The projects and models have been evaluated regarding the criteria catalogue shown in figure 5.

Figure 5. Quality Gate Phase - Input – Method – Output

Out of eight submitted projects, five projects have been assessed as suitable. Out of these submissions, four twin variants were further on post processed for this study and one variant will be utilized for future verification and the bottom-up approach.

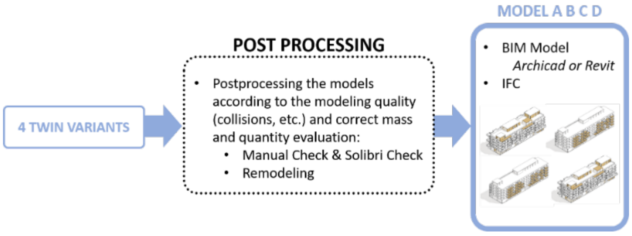


Figure 6. Post Processing Phase - Input – Method – Output

3.2.4 Post Processing of Variants

The post-processing (fig. 6) has taken place to ensure the overall quality of the BIM models and to secure quality of the later on generated data. We conducted a manual check and software-based SOLIBRI model check followed by post-processing of the twin variants inside ARCHICAD 23. The manual check of models was conducted to review plausibility of components and component layers, exportability of lists, clearly assignable designations and correct layers. The rule-based verification utilizing the SOLIBRI Model Checker was conducted to review correct assigned floors to objects, unclassified objects, material information, duplicates and overlapping elements etc. The post-processed twins were stored as native ARCHICAD models and IFC files.

3.2.5 Preliminary Component Generation

To determine the affordability and sustainability of objects and consequently digital twins via the digital platform, costs as well as ecological indicators need to be assigned to the twin-specific objects. Since test data and such objects themselves are hardly available we, in this phase, aimed to decompose the post-processed models and generate their preliminary information-rich components (fig. 7). To ensure a large variety of test data 11 teams of civil engineering students generated the preliminary data (Schützenhofer et al 2020). The post-processed twin variants, in the form of native ARCHICAD models and IFC files, were decomposed into components and component-layers. To store and enrich components, calculate cost and determine ecological indicators we used a specific research led teaching method (Schützenhofer et al 2020). Ecological indicators have been collected via Austrian Institute for Building and Ecology, more exactly baubook-eco2soft, the calculation is based on the Material Passport by Honic et al (2019). Benchmarks for cost calculation were collected from the Baukosteninformationszentrum Deutscher Architektenkammern (BKI) of 2017 and 2020 for residential buildings. As the result, we received 11 optimized component catalogues with cost and ecological indicators for each specific twin variant.

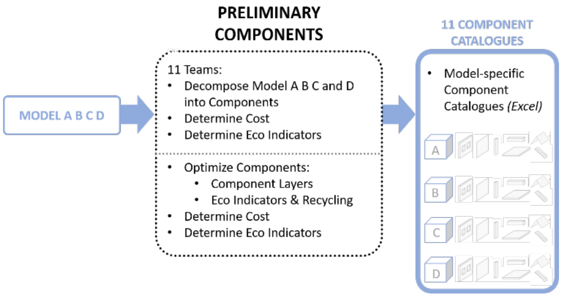


Figure 7. Preliminary Component Generation Phase – Input – Method – Output

3.2.6 Generic Object Generation

During the verification of the component catalogue, following issues arose: i) lacking scalability of project specific components, ii) numerous identical or highly similar components, iii) uncertain quality of components. As a result we have undertaken a circular process of generalization, reduction and normalization (fig. 8) to generate the generic object catalogue: we decomposed the 11 catalogues into single components. During generalization, components were firstly clustered into horizontal and vertical components and secondly into types of components (e.g. walls, slabs, columns) and more detailed sub-types. During reduction, identical or highly similar components have been identified and merged. During normalization, the requirements (independence, functional dependency, and freedom from redundancy) for the individual information of the normalized components were assured. The generic components have then been optimized and enriched with cost and eco indicators with the same method explained in section 3.2.5.

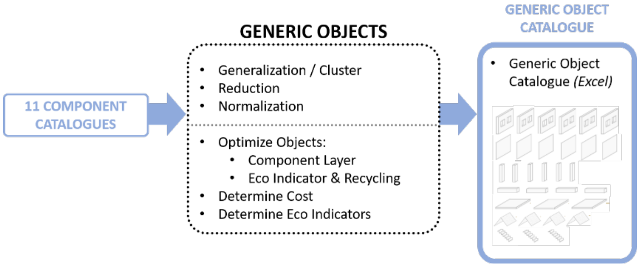


Figure 8. Generic Object Phase - Input – Method – Output

4 Findings and Discussion

As the result, the generic BIM object catalogue, the cost repository (data base) and ecological indicator repository (data base) as the main findings of this study have been generated. These form the test data for the BIM Object Library. The method resulting from the top-down modeling approach is a secondary finding and is intended to be reworked as a guideline in prospective.

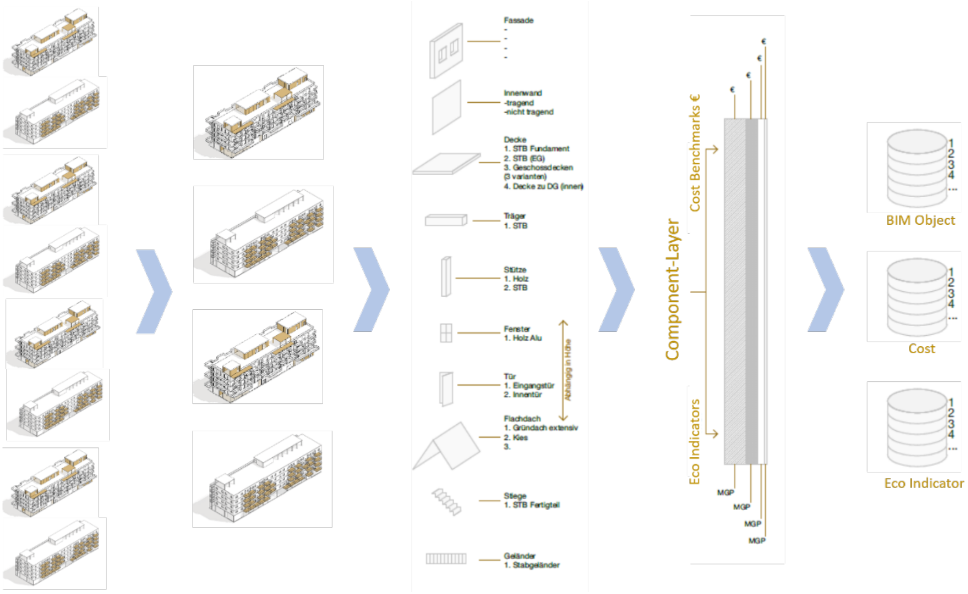


Figure 9. Findings of the Top-Down Modeling Approach

4.1 BIM Object Library

The BIM object library contains the component catalogue, its component layers, costs and eco-indicators based on a material passport. In a broader sense, it is part of the platforms' knowledge base and main input for the BIM4D2P tool. The test data is stored within a template (fig. 10). For future utilization within the platform, this template has to be filled with design-specific data. Thus, the development of the BIM4D2P had the creation of a generic template of the BIM object library as a sub objective.

The BIM object library has to be understood as a knowledge base and inherits:

- BIM Object Catalogue
- Cost Repository
- Eco Indicator Repository

We are aiming at the data management approach of linking the platform with the external cost and eco-repository, instead of integrating the data in the BIM objects itself. Hence, in its preliminary design, the BIM Object Library is structured as a template in the form of a spreadsheet (fig. 10).

The top-down modeling approach provides the basis for the framework of the preliminary BIM object library. The received project-specific digital twin variants were analysed and decomposed. The objective was to identify all existing components and their layers and material, costs and ecological indicators and to prepare them as test data for the generic library. The layers of components were checked for completeness and feasibility in an iterative process. If necessary, the superstructures were supplemented or exchanged. repetitive components were combined into a generic component with sub-types and provided with corresponding information.

4.1.1 BIM Object Catalogue

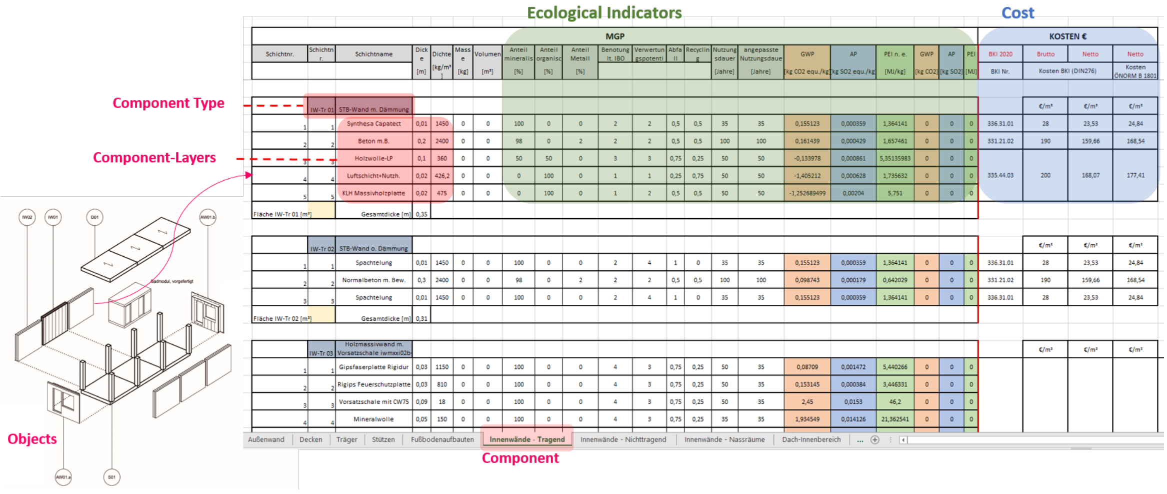
By top-down modeling, the data that was available from the twin variants and the enriched information was integrated into the catalogue (component type, location, static properties, construction, layer, material, etc.). The object catalogue clusters the vertical and horizontal components by types. These types consist of different sub-types and variants. The sub-types are defined by their specific component layers (fig. 9). Since we are aiming at the data management approach of linking the platform with the external cost and eco-repository, instead of integrating the data in the BIM objects itself, this collection of data inside the template (fig. 10) will further be linked to the platform and digital BIM objects inside common Software such as REVIT or ARCHICAD.

4.1.2 Cost

Benchmarks for cost calculation were collected from the Baukosteninformationszentrum Deutscher Architektenkammern (BKI) of 2017 and 2020 for residential buildings. These are either assigned to single component-layers or layer packages (fig. 10).

4.1.3 Ecological Indicators

The ecological indicators contain the three most important indicators of environmental impacts: Global Warming Potential (GWP)—CO equivalent, Acidification Potential (AP) and Primary Energy Intensity (PEI), consisting of non-renewable and renewable parts. Based on the MP by Honic et al (2019), additional indicators such as reusability, recyclability and separability can be assessed.



							MGP															KOSTEN €			
Schichtnr.	Schichtnr.	Schichtname	Dicke [m]	Dichte [kg/m³]	Masse [kg]	Volumen [m³]	Anteil mineralis [%]	Anteil organisc [%]	Anteil Metall [%]	Benotung lt. IBO	Verwertungspotenti	Abfall	Recycling	Nutzungsdauer [Jahre]	angepasste Nutzungsdaue [Jahre]	GWP [kg CO2 equ./kg	AP [kg SO2 equ./kg	PEI n. e. [MJ/kg]	GWP [kg CO2]	AP [kg SO2]	PEI [MJ]	BKI 2020 BKI Nr.	Brutto Kosten BKI (DIN276)	Netto	Netto Kosten ÖNORM B 1801
	IW-Tr 01	STB-Wand m. Dämmung																					€/m²	€/m²	€/m²
1	1	Synthesa Capatect	0,01	1450	0	0	100	0	0	2	2	0,5	0,5	35	35	0,155123	0,000359	1,364141	0	0	0	336.31.01	28	23,53	24,84
2	2	Beton m.B.	0,2	2400	0	0	98	0	2	2	2	0,5	0,5	100	100	0,161439	0,000429	1,657461	0	0	0	331.21.02	190	159,66	168,54
3	3	Holzwolle-LP	0,1	360	0	0	50	50	0	3	3	0,75	0,25	50	50	-0,133978	0,000861	5,35135983	0	0	0	335.44.03	200	168,07	177,41
4	4	Luftschicht+Nutzh.	0,02	426,2	0	0	0	100	0	1	1	0,25	0,75	50	50	-1,405212	0,000628	1,735632	0	0	0				
5	5	KLH Massivholzplatte	0,02	475	0	0	0	100	0	1	2	0,5	0,5	50	50	-1,252689499	0,00204	5,751	0	0	0				
Fläche IW-Tr 01 [m²]		Gesamtdicke [m]	0,35																						
	IW-Tr 02	STB-Wand o. Dämmung																					€/m²	€/m²	€/m²
1	1	Spachtelung	0,01	1450	0	0	100	0	0	2	4	1	0	35	35	0,155123	0,000359	1,364141	0	0	0	336.31.01	28	23,53	24,84
2	2	Normalbeton m. Bew.	0,3	2400	0	0	98	0	2	2	2	0,5	0,5	100	100	0,098743	0,000179	0,642029	0	0	0	331.21.02	190	159,66	168,54
3	3	Spachtelung	0,01	1450	0	0	100	0	0	2	4	1	0	35	35	0,155123	0,000359	1,364141	0	0	0	336.31.01	28	23,53	24,84
Fläche IW-Tr 02 [m²]		Gesamtdicke [m]	0,31																						
	IW-Tr 03	Holzmassivwand m. Vorsatzschale iwmxxi02b-																					€/m²	€/m²	€/m²
1	1	Gipsfaserplatte Rigidur	0,03	1150	0	0	100	0	0	4	3	0,75	0,25	50	35	0,08709	0,001472	5,440266	0	0	0				
2	2	Rigips Feuerschutzplatte	0,03	810	0	0	100	0	0	4	3	0,75	0,25	50	35	0,153145	0,000384	3,446331	0	0	0				
3	3	Vorsatzschale mit CW75	0,09	18	0	0	100	0	0	4	3	0,75	0,25	50	35	2,45	0,0153	46,2	0	0	0				
4	4	Mineralwolle	0,05	150	0	0	100	0	0	4	3	0,75	0,25	35	35	1,934549	0,014126	21,362541	0	0	0				

Figure 10. BIM Object Library - Template – Objects, Components, Eco Indicators and Cost

5 Conclusion

Top-down modeling, from specific to generic, as a promising approach to generate a BIM object library by utilizing digital twins is presented in this paper. We aimed at the exploration to what extend a top-down modeling approach can be utilized to generate a generic BIM object library for modular multi-storey residential buildings. We summarise the approach to iteratively compose, decompose, enrich and reduce data of BIM-based digital twins. The method is sequenced into several phases, from design space analysis and definition, to the design and modeling of digital twin variants, and to the decomposition of these twins and enrichment of its components. The phases of design space analysis and modeling of twin variants were installed to generate the largest possible amount of data. To achieve this goal we integrated research led teaching into this approach. A further reason has been the generation and decomposition of components, as also here we aimed at the largest number of data as possible. Of course, since we had to verify the quality and feasibility of named data, post-processing and resulting reduction of data has been inevitable. We hypothesized that generic test data can be derived by decomposing specifically generated digital twins of modular buildings. The chosen approach of this study showed that it is possible to decompose digital twins to generate a preliminary BIM object library, this of course, has its limitations. Since the BIM object catalogue still is quite specific and lacks scalability it will be necessary to apply this proposed method to generate an even larger number of input data. The cost repository needs to be seen as benchmarks. Nonetheless, these are beneficial to either test interfaces developed within the digital platform and of course were necessary for the development of the template. In conclusion we propose this top-down modeling approach to be further implemented as a guideline for future generation of input data for the BIM object library. The gained knowledge will be further utilized to test the usability of the approach when generating novel BIM models and also to verify the proposed bottom-up modeling approach. In our current research, we aim to develop a digital platform for affordable and sustainable multi-storey housing since researching methods to provide affordable living space are of prime importance. This study is one segment of this objective.

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