Doctoral Thesis

Process-Design for the semi-automated generation of BIM-based Material Passports for buildings

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Dissertation

Prozess-Design für die semi-automatisierte Generierung von BIM-basierten Materiellen Gebäudepässen

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This doctoral thesis presents the results of the research carried out at the Institute for Interdisciplinary Building Process Management, Department for Integrated Planning and Industrial Building. The conducted research project "BIMaterial: Process-Design for a BIM-based Material Passport" builds the fundament of this thesis.

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Abstract

Concerns about shortage of primary resources as well as the increase of CO_2 emissions, are nowadays relevant topics in sustainable development. The construction sector, as the largest consumer of raw materials, needs urgent optimization of resources consumption as well as minimization of environmental impacts such as CO_2 emissions. Since the population is expected to grow from 7 billion today up to 9 billion in 2050, sustainable solutions regarding the optimization of resources consumption and harmful emissions of buildings are required. Existing concepts, such as Circular Economy and Urban Mining – are claiming the reuse and recycling of buildings and their elements. However, currently knowledge about the existing stock and embedded materials in buildings is lacking, which is the main obstacle in the recycling of existing stocks. New digital tools and methods such as Building Information Modeling (BIM) for design optimization together with methods for the material documentation of buildings, such as Material Passports (MP) offer potentials to enhance Circular Economy in the AEC-industry (Architecture, Engineering and Construction).

The main research question of this cumulative PhD thesis is how to enable an automated BIM-based generation of MPs. Thereby the MP serves as optimization tool of resources consumption as well as of environmental impacts in early design stages and moreover as a document that shows the material composition of buildings. Within this thesis, the concept, scope as well as relevant parameters for the MP are defined. Further the potential of BIM as knowledge-base and optimization tool for resources consumption and emissions is investigated as well as its potential for the automated generation of MPs. Finally, a data- and stakeholder management framework is presented, which serves as basis for the implementation of the developed BIM-based workflow for MPs.

The developed BIM-based workflow is tested on two use cases, and the proof of concept for the usability of the developed BIM workflow for a semi-automated compilation of MPs is provided. However, optimization of the workflow is necessary, since a fully automated process is still not possible due to inconsistent parametrization of materials in BIM as well as inconsistent data within various eco-data repositories. The thesis proposes a harmonization of MP-relevant data within the industry, supported by policy making and introduction of a new stakeholder – an MP consultant to successfully standardize and implement the BIM-based process for the generation of MPs.

The MP shows large potentials for the optimization of resources consumption as well as environmental impacts in early design stages. Thereby the MP also represents a crucial step towards the enhancement of Circular Economy and Urban Mining strategies, through supporting recycling and reuse of existing stocks.

This dissertation was conducted within the research project *BIMaterial* (grant No. 850049), which was funded by the Austrian Ministry for Transport, Innovation and Technology (BMVIT) through the Austrian Research Promotion Agency (FFG).

Zusammenfassung

Derzeit stellt Ressourcenknappheit sowie die signifikant steigenden CO2 -Emissionen relevante Themen in der nachhaltigen Entwicklung dar. Der Bausektor, als größter Verbraucher von Rohmaterialien, benötigt eine dringende Minimierung des Ressourcenverbrauchs, sowie der ökologischen Umweltfaktoren wie z.B. CO2 – Emissionen. Durch den zu erwartenden Bevölkerungswachstum von 7 Milliarden bis zu 9 Milliarden im Jahr 2050, sind nachhaltige Lösungen in Bezug auf Optimierung des Ressourcenverbrauchs und der schädlichen Emissionen von Gebäuden notwendig. Bestehende Konzepte wie Circular Economy und Urban Mining fordern die Wiederverwendung und das Recycling von Gebäuden und ihren Elementen. Jedoch besteht derzeit kein Wissen über den Baubestand und den eingebauten Materialien, was eine große Herausforderung für das Recycling des Bestands darstellt. Neue digitale Werkzeuge und Methoden wie z.B. Building Information Modeling für Design-Optimierung gemeinsam mit Werkzeugen für die Materialdokumentation von Gebäuden wie z.B. der materielle Gebäudepass (MGP) haben das Potential die Kreislaufwirtschaft in der AEC-Branche zu fördern.

Die Forschungsfrage dieser kumulativen Dissertation ist, wie eine automatisierte BIM-basierte Generierung eines MGP ermöglicht werden kann. Dabei dient der MGP als Optimierungswerkzeug für den Ressourcenverbrauch sowie für die ökologischen Umweltfaktoren in frühen Planungsphasen und darüber hinaus als Dokument, welches die materielle Zusammensetzung von Gebäuden darstellt. In dieser Dissertation wird das Konzept, der Umfang sowie die relevanten Parameter für den MGP definiert. Darüber hinaus wird das Potential von BIM als Wissensbasis und als Optimierungswerkzeug für den Ressourcenverbrauch und schädlichen Emissionen untersucht, sowie das Potential für die automatisierte Generierung von materiellen Gebäudepässen analysiert. Schließlich wird ein Daten- und Stakeholder Management Rahmenwerk präsentiert, welches als Basis für die Implementierung für den entwickelten BIM-basierten Workflow für MGPs dient.

Der entwickelte BIM-basierte Workflow wurde an zwei Use Cases getestet, und der Proof of concept für die Anwendbarkeit des entwickelten BIM-Workflows für eine semi-automatisierte Erstellung von MGPs ist gegeben. Trotzdem ist eine Optimierung des Workflows notwendig, da ein vollautomatisierter Prozess aufgrund von inkonsistenter Parametrisierung von Materialien in BIM sowie durch Dateninkonsistenzen in unterschiedlichen Öko-Repositorien immer noch nicht möglich ist. Diese Dissertation schlägt eine Harmonisierung von MGP-relevanten Daten innerhalb der Industrie vor, welche durch Regulationen der öffentlichen Hand unterstützt werden können. Zudem wird

ein neuer Stakeholder, der MGP-Konsulent, für die Standardisierung und Implementierung des BIM-basierten Prozesses zur Generierung von MGPs benötigt.

Der MGP zeigt großes Potential für die Optimierung des Ressourcenverbrauchs sowie der ökologischen Umweltfaktoren in frühen Planungsphasen. Dabei repräsentiert der MGP auch einen wesentlichen Schritt in Richtung Verstärkung der Circular Economy und Urban Mining Strategien durch Unterstützung von Recycling und Wiederverwendung der Bestandsgebäude.

Diese Dissertation wurde im Rahmen des Forschungsprojekts *BIMaterial* (Projektnummer 850049) durchgeführt und vom Bundesministerium für Verkehr, Innovation und Technologie (BMVIT) durch die österreichische Forschungsforderungsgesellschaft (FFG) gefördert.

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List of abbreviations

AEC	Architecture, Engineering and Construction
AP	Acidification Potential
BIM	Building Information Modeling
BO	BuildingOne
CE	Circular Economy
EU	European Union
GIS	Geographical Information System
GWP	Global Warming Potential
IBO	Austrian Institute for Building and Ecology
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
MP	Material Passport
PEI	Primary Energy Intensity

Structure of the work

This dissertation is structured in two main sections:

Synthesis (Section I)

Research Papers (Section II)

- **Section I** summarizes the research objectives and results of the thesis. It presents the state of the art review of the main topics related to MPs, such as Circular Economy, Urban Mining, Material Flow Analysis, Material Passport for buildings, Recycling Potential, Life Cycle Assessment, Building Information Modeling as well as policy making and regulations. Subsequently, the objectives of the thesis are outlined and followed by the presentation of the used methodology. Finally, the summary of research papers is presented, followed by a conclusion and future outlook.
- **Section II** presents the original research papers as well as the translation of the 4th paper, which originally was written in German.

Section I

Synthesis

1 Introduction

1.1 Problem Statement

According to the WWF's living planet report (World Wildlife Fund), more than two planets will be needed to meet humans' demands of natural resources by 2030 [McLellan et al., 2012]. The Sustainable Europe Research Institute claims that worldwide resource extraction of metals and minerals will rise from 19 billion tons in 1980 to approximately 54 billion tons in 2030, which accounts for a growth of over 180% within 50 years. [Giljum et al., 2009] Accordingly, concerns about increasing global consumption of non-renewable resources as well as shortages of primary raw materials and reduction of space available for final disposal of wastes are becoming important topics for the society [Mining, 2015]. These concerns are strongly intensified by the expected population growth from 7 billion today to 9 billion persons in 2050 [UNEP 2011], which will consequently lead to an increase in raw materials consumption as well as to an upcoming of large amounts of waste.

The construction industry is the world's largest consumer of raw materials and accounts for 25-40% of global carbon emissions, facts that are underlining the urgent need for improvement of the habits in the construction industry, such as wasteful consumption of raw materials [WEF, 2016]. In the existing building stock, a large amount of materials are incorporated, which mostly lead to waste at the end of the life-cycle. Research about the existing stock shows, that for many materials, the secondary stock is even larger than the primary resources, as for example in Austria, which is a country that strongly depends on imports. In many European countries, the situation is similar to Austria: due to a low amount of primary resources, an import of raw materials is necessary [Brunner and Rechberger, 2016]. As the raw materials consumption is increasing, the challenge of raw materials supply will continue in future. Since the construction industry is the largest consumer of resources worldwide, whereby only 20-30% of Construction and Demolition Waste (CDW) is recovered, new strategies dealing with wasteful processes are necessary [WEF, 2016]. Therefore, the European Union (EU) has developed several approaches in their resources strategy. With this strategy, the supply of raw materials should be guaranteed for the upcoming years in the European industry. One approach is to increase recycling rates in order to reduce the consumption of primary materials, which is also associated with Circular Economy (CE) strategies. A concept within CE is Urban Mining, which is promoting a systematic reuse of anthropogenic materials from urban areas. In contrast to usual recycling, Urban Mining includes, apart from mining of waste, also the exploration and observation of materials in buildings and infrastructures [Klinglmair and Fellner, 2010]. At present, there is a lack of knowledge on the material composition and construction of building stocks, which represents a major obstacle for realizing the Urban Mining strategy and therefore for increasing recycling rates [Brunner, 2011]. The recycling potential is apart from technological developments, also determined through design. As planners and architects are the major decision makers regarding design and materials, they play a crucial role in the recycling potential of buildings. Thereby, the early design stages are very important, as in these stages, materials and constructions as well as assembly methods are defined. Constructive criteria such as accessibility and separability of building elements and its parts are determining the recycling potential of buildings. Hence, there is need for new design-centric methods and tools, allowing optimization in the planning stage and compilation of deconstruction concepts, as well as inventory methods for the creation of urban material cadasters, which would finally contribute to the development of a secondary raw materials cadaster. Therefore, in this PhD thesis, the Material Passport, which should serve as optimization of resources consumption as well as documentation of the materials composition of buildings is proposed. Building Information Modeling (BIM), as emerging tool, has the potential to serve as knowledge database and design optimization tool, as it enables detailed modeling of building elements including materials information as well as masses and quantity determination [Eastman et al., 2011; Bazjanac 2006; Azhar, 2011]. However, there does not exist any standardized methodology neither for the Material Passport, nor for the integration of the Material Passport into BIM. Therefore the aim of this thesis is to develop a BIM-based workflow for the generation of automated Material Passports.

1.2 Research question

The focus of this PhD thesis is process-development for an automated generation of a BIM-based MP.

This thesis is structured in three parts: The first part focuses on the development of a methodology to compile an MP. The second part is dedicated to the generation of a BIM-based, automated workflow for the compilation of MPs and represents the core of this research. The third part of this thesis deals with the creation of a framework for the implementation of the developed BIM-workflow into the AEC (Architecture, Engineering and Construction) industry. Thereby the main research question of this thesis is:

Is an automated, BIM-based generation of Material Passports possible and what type of process is required for the compilation of Material Passports?

In order to answer the main research question, several sub-questions will be explored, as illustrated in Fig. 1:

What kind of input-data is needed for the generation of MPs?

How should BIM modeling be conducted?

Is an automated generation of MPs possible?

What methodology is needed for the compilation of the MP?

What content should the MP comprise of in order to generate appropriate results?

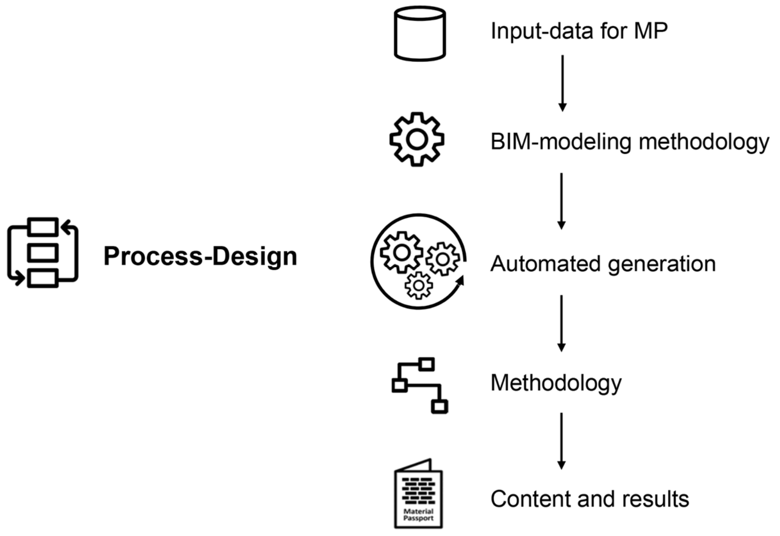

Figure 1: Research question and sub-questions

2 State of the art

Material Passports are closely related to the topics of Circular Economy, Urban Mining, Material Flow Analysis and Life Cycle Assessment, since their common aim is to reduce the extraction of raw materials, reuse and recycle urban stocks as well as to minimize environmental impacts. On the other side, upcoming of computational tools in the AEC industry offers new possibilities for prediction and optimization of the material consumption of buildings. Tools such as BIM enable modeling of detailed material composition of buildings as well as data management. However, the link between Material Passports, which could offer optimization of materials consumption of buildings and BIM, which could serve as modeling tool and knowledge-base, is still lacking.
In the following, MP-related topics are introduced.

2.1 Circular economy

The term Circular Economy (CE) is becoming very popular as it is also promoted by several national governments, businesses as well as by the European Union (EU) [Korhonen et al., 2018] and should enable consumers, countries and firms to close the loop of a products' lifecycle by simultaneously reducing negative impacts to the environment [European Commission, 2015; Murray et al., 2017]. In contrast to CE stands linear economy with a "take-make-waste" approach [Mining, 2015], which began during the industrial revolution, where long-term damage was caused through exploitation of resources and ignorance of the environmental limits [Prieto-Sandoval et al., 2018]. Furthermore, mass production of goods was enabled by new manufacturing methods, leading to frequent supply of low-cost products and accordingly to significant solid waste generation and landfill. Moreover, the strong growth of the world population lead to a high demand of resources, wherefore Meadows et al. [1972] proposed first solutions to minimize raw materials consumptions already in the early 70s of the 20th century [Lieder and Rashid, 2016]. The main aim of CE is to move away from linear processes by maintaining the value of materials, resources and products within the economy as long as possible, as illustrated in Fig. 2. Thereby environmental impacts, energy consumption, as well as the upcoming of waste should be reduced by maximizing recycling rates, which is within the scope of the EUs action plan for CE [European Commission, 2015]. CE, as concept dealing with wasteful industrial and production processes, is currently a subject of interest for many projects. One project that intensively deals with the wasteful processes as well as with the implementation of CE into the AEC industry is BAMB (Buildings as Material Banks) [BAMB, 2019], which is described in chapter 2.4.

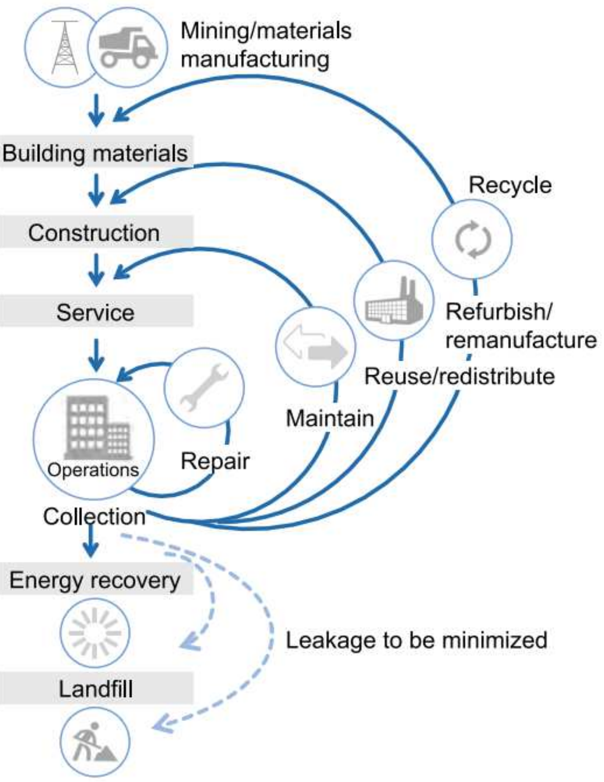

Figure 2: Circular Economy Principles in the Construction Value Chain [WEF, 2016 based on Ellen MacArthur Foundation and Boston Consulting Group]

2.2 Urban Mining

A large amount of materials is incorporated within the built environment, thus representing a significant stock. The existing stocks, or parts of it, have large potentials to be reused or recycled at the end of the life-cycle. The systematic reuse of anthropogenic materials from the existing stock is a new approach towards recycling, a strategy labelled as "Urban Mining". Urban Mining is one main strategy within Circular Economy, among some others such as landfill mining and waste minimizing, dealing with mining of waste as well as with the exploration and observation of materials in the built environment, which makes Urban Mining different to usual recycling [Klinglmair and Fellner, 2010]. According to the World Economic Forum report, only 20-30% of all CDW is recovered or reused, neglecting the opportunity to use these materials as e.g. wooden flooring material, road-building materials, fertilizer additive etc. as shown in Fig. 3. The 70-80% discarded materials mostly consist of lumber (40%), followed by asphalt products (14%) and soil/fines (11%) [WEF, 2016]. Several studies were conducted, trying to determine the urban stock: By using macroeconomic and statistical data (top-down) and coupling with bottom-up analysis of buildings, building elements and materials, Kohler and Hassler [2002] determined the material flows of the German building stock. Lichtensteiger and Baccini [2008] explored the urban material storages in Switzerland using the ARK-Haus method, whereby buildings were categorized according to their age and typology. “Christian Doppler Lab for Anthropogenic Resources” at TU Wien used a similar method, in order to analyse buildings and infrastructures in terms of recyclability [Kleemann et al. 2016]. The main obstacle, which makes urban mining challenging, is lack of information about materials and substances embedded in buildings [Brunner, 2011], as well as methods and tools to display the material composition of buildings.

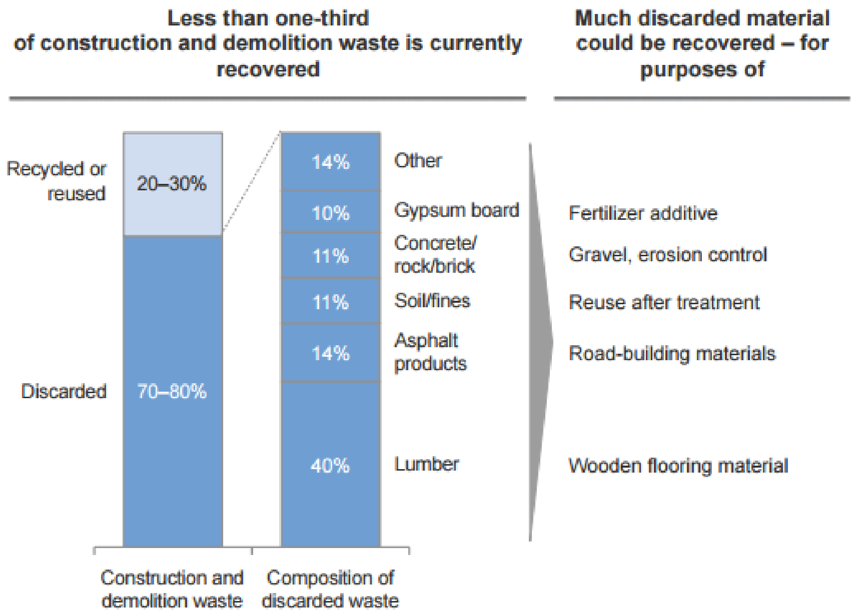

Figure 3: Construction and demolition waste [WEF, 2016 based on Ellen MacArthur Foundation and Boston Consulting Group]

2.3 Material Flow Analysis

The Material Flow Analysis (MFA) is a systematic assessment of the state and changes of flows and stocks of materials within a defined system of space and time. Moreover, the MFA connects the sources, pathways as well as the intermediate and final sinks of a material. By a simple mass balance all inputs, stocks and outputs, the results of an MFA, can be controlled. The MFA is used as decision-support tool in resource, waste and environmental management as well as for policy assessment [Brunner and Rechberger, 2016]. Huang et al. [2013] defined the MFA as an estimation of the material demand and the environmental impact of a system. For the building stock of Rio de Janeiro; Condeixa et al. [2017] carried out an MFA, based on which they estimated the building age and the remaining lifetime in order to make assumptions for environmental impact assessments and planning strategies for efficient use of materials.

2.4 Material Passports for buildings

The EU-wide project BAMB defines an MP as an electronic set of data that describes characteristics of materials in products that give them value for recovery and reuse. According to Madaster, which is an independent public platform for private individuals, businesses and public, the MP is a digital document that records the identity of all construction materials used, documenting the products and raw materials used in a building or project. Madaster is a platform with an online library of materials in the built environment and has the mission of reducing waste by providing materials with an identity. Thereby Madaster is facilitating the registration, storage, organisation and exchange of data [Madaster, 2019].

Within the project PILAS, a research was conducted by Markova and Rechberger [2011] who analysed the generation of a Material Passport through three use cases based on which they proposed a concept. In their research Markova and Rechberger used the top-down and bottom-up approach. In the top-down approach, the building is investigated from the highest level to the lowest level. The highest level are the functional elements and the lowest level is the specific material in a building element. In the bottom-up approach, the analysis starts at the materials of each element in the building, and are scaled up in order to reach the building level.

The EU-funded project BAMB brought practice and academia together in order to create circular economy solutions. The Horizon 2020 project consisted of 15 partners from all over Europe and aimed to implement Circular Economy strategies into the AEC industry in order to reduce waste and use less virgin materials. One tool to achieve this aim, among many others such as the reuse potential tool created by the BAMB consortium, is the Material Passport [BAMB, 2019]. BAMB is also aiming to use BIM for the generation of MPs, but so far BIM was only used as material repository database without an implementation of a BIM-based workflow for the compilation of the MP.

2.5 Determination of buildings' recycling potential

Buildings with a high recycling potential could support circular economy through reuse or recycling of embedded material or components. However, so far, there are not so many studies that consider the recycling potential of buildings. In a case study, Thormark [2006] showed the importance of producing buildings with high recycling potential in order to reduce energy and raw material extraction over a long time. Thereby the recycling potential was expressed as the amount of embodied energy as well as the natural resources used in a building that could be recycled after demolition. The results of the study show, that the embodied energy could be decreased by 17% through substitution of building materials and components. Since recycled materials do not undergo the extracting-process which primary materials do, they have a lower embodied energy, than non-recycled components. However, the final embodied energy is depending on the form of recycling, disassembly as well as maintenance of materials and building components, important aspects that should not be neglected [Thormark, 2006]. Another study, conducted by Blengini [2009], examined the recycling potential of a residential building in Turin. Results showed that the recycling potential was assessed by 29%, considering the materials embodied in the building shell.

2.6 Life Cycle Assessment

The need for sustainable buildings in terms of energy and resources consumption has been recognized by planners, investors and principle decision makers [König et al. 2012]. In order to optimize building performance, an assessment of the environmental performance of buildings and their sub-components is necessary in the planning phase [Srinivasan et al., 2014]. Since the construction sector is concerned with improving the environmental impacts of buildings, several tools and methods are used to support the implementation of sustainable development into the sector [Alwan et al., 2017]. One method to assess the environmental performance of resources and materials is Life Cycle Assessment (LCA), which is carried out by aggregation and analysis of the flows throughout the life cycle of products from cradle to grave, or even better from cradle to cradle. Moreover, an LCA evaluates direct and indirect energy inputs in product processes, as defined by the International Organization for Standardization (ISO) - Standard 14040:2006 [ISO, 2006]. Various LCA tools exist on the market, dealing with the conduction of LCAs, such as the commercial tools LEGEP [LEGEP, 2019] or SimaPro [SimaPro, 2019]. Furthermore there exist freely accessible calculation templates from building certification systems DGNB [DGNB, 2019], BREEAM [BREEAM, 2019] or LEED [LEED, 2019], as well as assessment methods by GaBi [GaBi, 2019] and SimaPro [Kovacic et al., 2018]. A basic evaluation methodology is provided by the Austrian Institute for Building and Ecology (IBO) [IBO, 2019] which is supported by the free tool eco2soft [eco2soft, 2019], where calculation templates are embedded. The IBO methodology only considers three main indicators in the LCA: Global Warming Potential (GWP), Acidification Potential (AP) and Primary Energy Intensity (PEI). As in early design stages information about the embedded materials in buildings is not available yet, carrying out LCAs is a challenging task [Ramesh et al., 2010].The methodology for the generation of an MP stands in close relationship to the LCA, since the MP tool generates not only recycling relevant indicators, but moreover assesses the environmental impact of buildings.

2.7 Building Information Modeling for MPs and LCAs

International standards define a BIM-model as “a shared digital representation of physical and functional characteristics of any built object…”, which is created with object-oriented software, consisting of parametric objects that represent building components [ISO, 2010; Volk et.al, 2014]. Moreover, BIM is a shared knowledge resource consisting of information about a facility, representing a basis for decisions throughout the whole life-cycle from the conceptual phase to the demolition of a facility [buildingSMART, 2019]. BIM stands for the model itself – Building Information Model or for the process - Building Information Modeling [Lévy, 2011]. In this dissertation the term BIM is used for Building Information Modeling and BIM-model for Building Information Model. Since a BIM-model consists of information about the geometry, spatial relationships, quantities and properties of building elements as well as cost estimates and material inventories, it contains relevant data, which is required for design, fabrication and construction activities [Eastman et al., 2011; Bazjanac, 2006; Azhar, 2011]. Apart from that, BIM shows large capacity regarding process-automation and data management and therefore acts a potential game-changer for most stakeholders within the AEC industry [Sebastian, 2011]. OpenBIM is, in addition to BIM, a comprehensive approach to the collaborative design, realization and operation of buildings, supporting open standards and workflows. Moreover, openBIM intends to enable the participation of all project members within the BIM, by providing data for use throughout the entire life-cycle of a facility, thereby avoiding multiple input of data and consequential errors. For enabling data exchange between various project members and accordingly disciplines, the IFC (Industry Foundation Classes) standard is proposed by buildingSMART, which is the only widely accepted open standard data exchange in the AEC industry [buildingSMART 2019].

In a study, Rajendran and Gomez [2012] found, that there is growing interest in the use of BIM for waste reduction as well as for design for deconstruction concepts. A BIM-enabled decision support method for early design stages in order to carry out an LCA, was developed by Basbagill et al. [2013], however, a fully automated exchange between BIM and LCA applications is still not developed, as Soust-Verdaguer et al. [2017] identified by analyzing BIM-based LCA methods for buildings in a critical review. Reisinger et al. [2014] conducted a comparative study where they analyzed documents similar to MPs. Thereby they developed a building-material-data sheet, which was created without the support of a BIM-model and compared it to one that was generated with a BIM-based system. As a result they found that the BIM-based system has more potential. In order to automatize the application of LCAs in the AEC industry, there are still some steps required such as an improvement of data exchange between BIM and LCA. As the MP requires the same BIM modeling methodology as the LCA by only providing additional indicators regarding recycling potential, the BIM-based MP could profit from the ongoing developments regarding BIM-based LCA. Existing LCA plug-ins have the advantage of immediate results, but are restricted to the indicators provided by the LCA plug-in, which cannot be changed for a specific purpose in BIM and are only applicable for specific BIM-software. In order to conduct a more comprehensive analysis, a combination of different tools could be used. However, this is a very time-consuming process, due to the required manual steps to edit data, such as use of BIM (for quantification of building materials), environmental databases as well as LCA tools. Therefore Soust-Verdaguer et al. [2017] propose to adapt material properties from BIM-software to the LCA data structure. IFC has the potential to be used for MPs and LCAs, however currently the IFC schema is not sufficient for the automated generation of MPs and LCAs, as only general properties are provided [buildingSMART, 2019; Pinheiro et al., 2018]. Therefore, the first step would be to standardize materials and their properties in order to implement them into the IFC schema, followed by an optimization of interpretation and automated data exchange. There exist many object libraries, e.g. NBS library [NBS Library, 2019], BIMobject [BIMobject, 2019] etc., which are used as information base for the design stage and deal with the standardization of materials. Nevertheless, material information conforms either only to national standards or to intrafirm regulations, therefore its applicability in the international BIM community is limited.

2.8 Policy making and regulations

The waste-intensive construction industry raises the attention of public policy, and is accordingly leading to new policies. Public policy plays an important role in driving recycling practices through regulations, since the extracting and processing of materials is related to economic aspects [Mining, 2015]. As one of the main strategies of the European Union (EU) is to maximize recycling rates in order to minimize environmental impacts and energy consumption caused by extraction of primary materials, an action plan for CE has been developed [European Commission, 2015]. Building up on that strategy, the EU claims an increase of recycling and other material recovery of construction and demolition waste to a minimum of 70% by weight by 2020 [European Union, 2011]. Austria sets regulations for demolition of buildings, due to which the toxicity content of materials has to be analyzed before demolition as well as recycling materials have to be categorized according to their quality after demolition [Recycling-Baustoffverordnung, 2015]. Belgium sets regulations for a mandatory conduction of an inventory for materials in buildings before their demolition, in order to identify the waste fractions. By analyzing policies and regulations regarding recycling, Giorgi et al. [2018] figured out that recycling and waste prevention is achieved through defined legislative frameworks, that support conditions for a sustainable management of CDW among operators and consumers (designers, planners, public administration, construction companies). One of the guidelines proposed by Giorgi et al. [2018] proposed guidelines for the improvement of sustainable management of CDW, whereby among some others, the mandatory use of MPs and LCAs were also part of it.

A Material Passport is a document that displays the materials embedded in a product or system, and consists of set of data that describes the characteristics of materials in products [BAMB, 2019]. In this research the scope of the MP was increased through integrating the recycling potential and the LCA into the MP-concept, such that it not only serves as document, but moreover as an optimization tool. Moreover a process to generate automated Material Passports – a tool that enables optimizations of resources consumption, recycling potential as well as LCA in early design stages - was developed through the use of BIM technology. The developed BIM-based MP bridges a research gap, since there exists no BIM-based process for the automated generation of MPs BIM so far.

3 Objectives

The main objective of this thesis is to create the process for an automated compilation of a BIM - based Material Passport. The Material Passport enables the assessment of materials embedded in buildings, showing large potentials to evaluate and increase the recycling potential of buildings as well as to serve as basis for a secondary raw materials cadastre. To enable circularity, and in consequence high recycling rates, material information about the existing building stock is necessary, wherefore a Material Passport (MP) should serve as an important aid. As potential game-changer for most AEC actors [Sebastian, 2011] as well as information rich knowledge-base, BIM shows large capacity regarding process-automation and data management. Even though BIM consists of large potentials to document the material consumption of buildings, there exists no BIM-based workflow for the automated generation of MPs BIM so far.

3. 1 MP-concept

For the realization of the main aim, which is the development of a BIM-based process for the automated compilation of an MP, first, the conceptual representation of the MP is defined. The objective is to determine the content of the MP and the materials that have to be considered in any case in the MP. A further aim is to develop the structure of the MP, which consists of the typical building components of a building and the type of the required information of the components and materials. The information can contain the location of the components in the building, the type of connection between materials and components as well as the parameters to evaluate the recycling potential. The common norms ÖNORM 1801-1 [ÖNORM 2015] (construction structure 1., 2., 3. level) or DIN 276 [DIN 2008] (1., 2., 3. level, gross element/element/…) are tested regarding their usability for the MP-structure. The structure should serve as basis for developing the modeling methodology in BIM. Apart from that, the relevant life-cycle stages as well as the required information and BIM-modeling methodology for these stages has to be determined. The MP should have different roles throughout the life-cycle, as illustrated in Fig. 4. In early design-stages it serves as an optimization tool, in the tendering phase it is used to capture the execution-relevant material composition and in the end-of-life it acts as qualitative and quantitative documentation of the material composition of the building as well as basis for a secondary raw materials cadaster. In this thesis the aim is to focus on the conceptual (MPa) and preliminary design stage (MPb) and define the modeling methodology for these stages.

A further aim within the MP-concept is to determine the indicators that should be included in the MP-concept in any case as well as their relevant life-cycle stage by literature review as well as by knowledge gathered in former projects. Existing methodologies for the generation of MPs and LCAs, as well as existing databases and their contents are analyzed. Since there exist numerous databases, which all provide different data within different nomenclature, their applicability has to be tested in order to prevent difficulties.

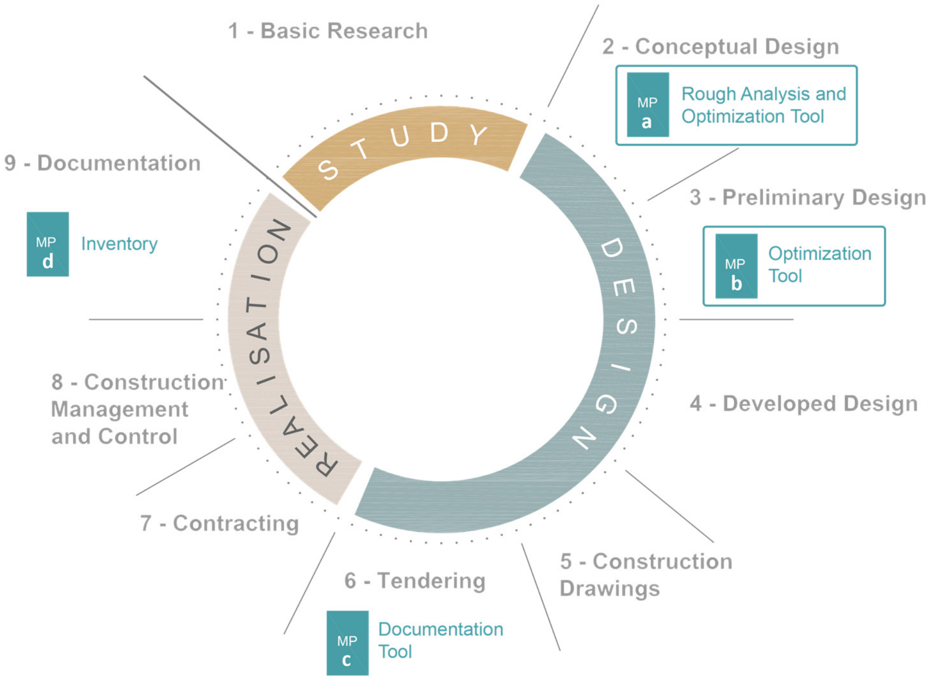

Figure 4: Relevant life-cycle stages for the MP

3.2 BIM-based workflow for the automated generation of MPs

BIM shows large potential in gathering material and other relevant information of buildings, since in BIM very accurate modeling with e.g. detailed material composition and thicknesses of each layer of a component is possible. Therefore BIM can serve as knowledge-basis for follow-up assessments such as the MP and LCA. However, a BIM-based workflow for the automated compilation of MP does not exist according to our knowledge so far. The objective of this thesis is to develop a BIM-based process for the automated generation of MPs. Therefore, existing BIM-software, tool chains and databases are tested regarding their interfaces as well as their applicability for the MP. The BIM-based workflow is developed based on the structure and defined parameters. A further aim thereby is to create a modeling guide for architects, which is used by architects in order to create an MP-suitable BIM-model, as well as templates which should serve as a basis for modeling in BIM.

3.3 Framework for the implementation of the MP in the AEC industry

For enhancing the recycling potential and decreasing environmental impacts of buildings, a wide-spread use of MPs is necessary. Therefore, the MP-concept and BIM-based workflow should be implemented into the AEC industry. The aim is to create a framework to enable the implementation of BIM-based MPs, showing the role of various stakeholders, such as architects, planners, BIM-managers, public policy, industry etc., as well as displaying the required collaboration between the relevant stakeholders for a successful integration of the BIM-based MP.

4 Methodology

In this dissertation, a BIM-based process for generating semi-automated MPs is developed in order to assess and optimize the recycling potential and environmental impact of buildings. A fully automated process is not possible due to low maturity of building projects in early design stages and data inconsistencies within eco-repositories. The obstacles in the generation of an automated process are further explained in chapter 5.1 (summary of P3). The methodology for the compilation of the MP is based on coupling of digital tools (BIM) with building catalogues and eco-repositories to enable the assessment of the recycling potential and environmental impacts of the planned building. The MP acts as optimization and decision tool in early design stages, in order to find the most suitable design variant regarding resources efficiency and environmental impacts. Apart from that, the MP also serves as documentation tool in the end-of life stage of buildings, where it acts as an inventory and basis for a secondary raw materials cadastre, to enable circularity through recycling of materials of the existing stocks.

The research has been conducted by following these steps: First, a basic research about existing methodologies for creating Material Passports without BIM are analysed. Based on the initial research as well as through knowledge gathered from former projects, relevant parameters for the MP are defined. Second, an appropriate methodology for the compilation of the MP is created. Third, the BIM potentials and existing workflows are explored in order to generate the workflow for the semi-automated compilation of the BIM-based Material Passport, which is the key contribution of this dissertation. Forth, institutional theory is used for analysing the implementation potential of the developed BIM-workflow into the AEC industry. Finally, the BIM-workflow is tested on use cases and a semi-automated MP is generated on a use case.

4.1 Relevant parameters

Through literature review, as well as through knowledge gathered in former projects, parameters and requirements, which are relevant for the MP, are identified. The determination of relevant parameters for the MP also builds up on existing methodologies for assessing the recycling potential and LCA from the Austrian Institute for Building and Ecology (IBO) [IBO, 2019].

According to waste management and within material flow analysis (MFA), the mass (in tons) is considered as the relevant parameter [Brunner and Rechberger, 2016]. As materials with a low recycling potential lead to significant masses of waste, the recycling potential is a relevant parameter, which has to be integrated into the MP-concept. The recycling potential is depending on the material itself and also on the connection type to other materials, since materials which are connected to each other through glue (e.g. load-

bearing element with the insulation layer), require an effortful demolition process and cause unclean fractions, consequently leading to a lower recycling potential. The accessibility and therefore the material distribution within the building is important, since materials, which are located in high floors are difficult to access and dismantle. The lifespan of materials has to be considered and plays a very crucial role, since materials with a short lifespan have to be replaced more often throughout the life-cycle of a building. E.g., a material with a lifespan of 30 years has to be replaced 3 times in the total lifespan of a building, which is considered as 100 years usually.
The assessment of ecological impacts, such as the CO_2 emissions, energy consumption etc., are standardized impact categories used for the LCA. In this thesis, the basic LCA-methodology from the Austrian Institute for Building and Ecology is used and integrated into the MP-concept. The basic methodology considers three indicators: GWP (Global Warming Potential), AP (Acidification Potential) and PEI (Primary Energy Intensity) of buildings. Since the focus of this study is on resources efficiency, only the embodied energy was assessed and the operational energy was neglected.

The main results obtained from an MP can be summed up as:

- Total mass of the building
- Material distribution within the building
- Recyclable mass and waste mass of the building
- Environmental impacts (GWP, AP, PEI)

4.2 Data and framework for the creation of the MP

The framework for the generation of the MP is developed based on the proposed methodology from IBO, as mentioned above. Thereby baubook [Baubook, 2019] and the eco2soft-tool [eco2soft, 2019] from IBO are used in order to obtain building components and their relevant parameters. Baubook is a building components catalogue, providing information about building components, such as the detailed material composition and layer thicknesses. Eco2soft provides LCA-data (GWP, AP, PEI) as well as the recycling potential of each material, expressed as recycling grade from 1 to 5, whereby 1 is the best grade and 5 the worst. Recycling grade 1 means that this material has a recycling potential of 75% and that 25% of this material becomes waste. Recycling grade 4 stands for 0% recycling and 100% waste and recycling grade 5 for 0% recycling and 125% waste. The additional 25% in case of grade 5 is due to auxiliary materials, which are necessary for demolition. In the IBO-methodology, the connection type between two materials is not considered, since all properties are given for the material itself and not for whole structures. Therefore it is proposed to downgrade the recycling grade, if two materials are glued to each other.

The recyclable mass (in kg or tons) is assessed through linking the mass and recycling potential of a material. The following example displays the assessment of the recyclable-mass for a concrete (recycling grade 2) wall with 10 m²:

Recyclable mass =
density *(eco2soft) ** ***thickness*** *(baubook/BIM) ** ***area*** *(BIM) ** ***recycling potential*** *(eco2soft)*
2300 *[kg/m³] ** ***0,18*** *[m] ** ***10*** *[m²] ** ***50%*** *=* ***2070 [kg]***

Table 1: Assessment of the recyclable mass

The assessments for the MP can be conducted manually in MS Excel (or similar spreadsheet software) or through a semi-automated process with BIM. The assessment with BIM is the focus of this thesis. As shown in the example above, from BIM the thickness and area can be obtained, which are required to assess the mass of a layer. The density and recycling potential is obtained from eco2soft. Since BIM is a tool used by architects and planners for design and modeling, where changes can be conducted easily, it is useful for the compilation of an MP, as described in the next chapter.

4.3 BIM-workflow for the semi-automated generation of the MP

For the semi-automated generation of the MP, first, a tool chain is built up. The tool chain consists of coupling digital tools and databases, as shown in Fig. 5. BIM-software [Graphisoft Archicad 21 and Autodesk Revit 2018] is used for creating the BIM-model of the building and the Material Inventory and Analysis Tool – BuildingOne (BO) [One Tools, 2019] for data management and assessment of the final MP-results. BO is an SQL (structural query language) - based database, originally developed as building information system for property management. For this purpose, it was used for gathering MP-relevant information, data management and finally as MP-generator. BO is an Add-On for BIM-software, enabling a bi-directional synchronization of data between the BIM-model and BO. As every change in the BIM-model is automatically synchronized in BO and all assessments are recalculated, it is an indispensable tool for the semi-automated MP-creation, since tracking every change in the BIM-model manually is a difficult and error-prone task. Apart from that, a parametrization of materials, which is necessary for the MP-assessment, is burdened with various difficulties in BIM, such as lack of consistency, large data amounts etc. making direct data handling in BIM challenging. Therefore BO is a useful tool for the semi-automated generation of the MP, as it provides higher flexibility by enabling a parametrization of materials and addition of required material properties.

For the generation of the BIM-model, a modeling guide ("Modeling guide for the generation of a BIM-model for a follow-up generation of a Material Passport"; attached in Appendix) and a BIM-template (the BIM-template is an Archicad template file; the content is described in the modeling guide) has been created, enabling the generation of an MP-appropriate BIM-model. The modeling guide describes the modeling methodology in BIM and e.g. claims that building elements from the BIM-template have to be used. In the BIM-template predefined elements from baubook are modelled as BIM-objects and are available for modeling a building. Thereby the designation of the materials and elements, as well as thicknesses of the layers are modelled according to baubook. The BIM-template consists of 43 different elements such as walls, slabs, foundations etc. with load-bearing materials out of timber, concrete or brick. In the BIM-template the materials are not parametrized through MP-relevant properties, for reasons such as large data-sizes etc., as mentioned above.

The third important tool, besides BIM and Material Inventory and Analysis Tool BO, is the control tool Solibri Model Checker [Solibri Model Checker, 2019]. The control tool makes a general BIM-check and also controls, if the predefined elements, which are provided as a BIM-template, were used. Therefore, specific rule sets were generated in the control tool, which are available in a Solibri file (.smc).

Through the bi-directional connection between BIM-software and the Material Inventory and Analysis tool BO, data of the building elements such as walls, slabs, windows and doors from BIM is transferred to BO. For walls and slabs, the information about the volume, material and thickness of each layer and for doors and windows the area and material information is transferred to BO. In BO, the predefined elements are parametrized through the MP-relevant parameters through linking recycling- and LCA-data from the IBO database to BO. All predefined building elements are provided in the BO-template, which is a BO project file. The content of the BO-template as well as a description of how to use BO for the generation of an MP are available in the roadmap ("Roadmap for the generation of a Material Passport; attached in Appendix). Through assignment of predefined materials from BIM to those from BO, the assessment is enabled. As the designation of the elements in the BIM-template and BO-template is consistent, matching the elements from BIM to those from BO for follow-up assessment is easily applicable. Apart from predefined elements, the BO-template also consists of all relevant calculations and SQL-queries for the compilation of the MP. In BO, also the final MP-results are created. The developed BIM-workflow is tested on two use cases and described in the summaries of the research papers as well as in the original research papers.

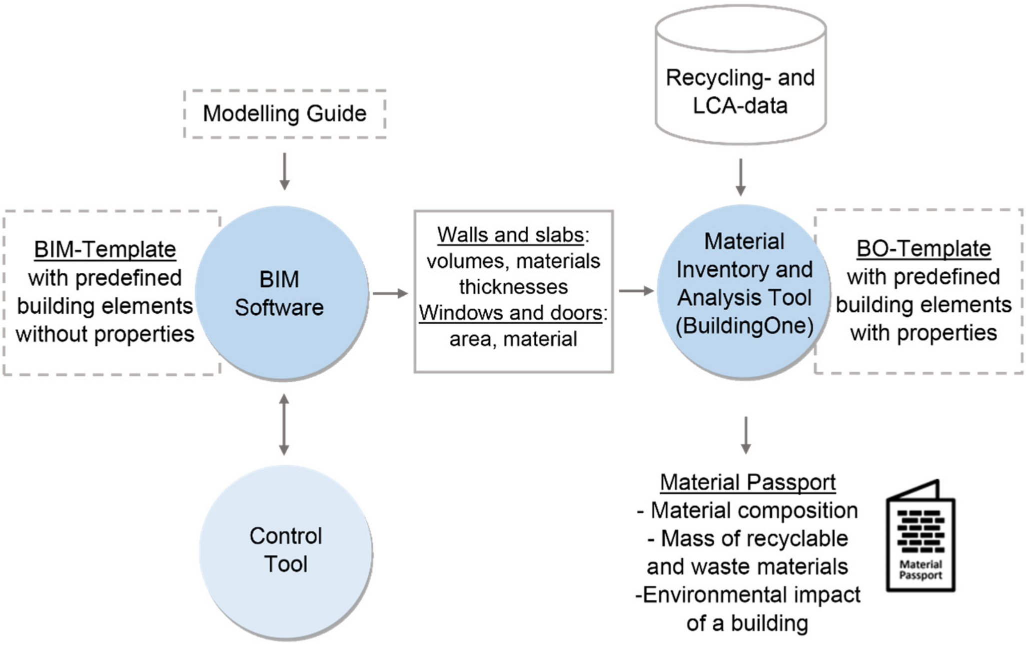

Figure 5: BIM-based workflow for the compilation of the MP

4.4 Implementing to the practice

For the transition of the BIM-based workflow for generation of MP in the AEC practice, institutional theory was used for the implementation of the BIM-based process of generating the MP, since this theory plays a crucial role in the implementation of new concepts. Thereby the interaction of various stakeholders within different domains (AEC industry, regulative body and industry) was analyzed based on institutional theory. The institutional theory consists of the so-called “three pillars”, which are the regulative, normative and cultural-cognitive elements [Scott, 2005]. The three pillars contribute to the construction, maintenance and change of institutions. Thereby regulative elements represent the rule-setting activities, which create a system of control by constituting and strengthening areas of control. Values and norms are part of the normative pillar, which present a prescriptive and obligatory dimension into social life. The cultural-cognitive elements are e.g. shared beliefs within community and their relation to cognitive elements such as feeling, acting and thinking [Scott, 2012; 2014]. The regulative, normative and cultural-cognitive elements can be found in construction project organizations and seldom occur isolated [Henisz et al., 2012]. The institutional theory has been used as basis for the development of the data- and stakeholder management framework, which should support the implementation of the MP by showing the required collaboration of various stakeholders within three domains (regulative body, industry and AEC organization).

5. Results

This cumulative dissertation builds up on the research project “BIMaterial: Process-Design for a BIM-based Material Passport”, which was funded by the Austrian Ministry for Transport, Innovation and Technology through the Austrian Research Promotion Agency (FFG, grant number: 850049, 2. Ausschreibung “Stadt der Zukunft”), and was conducted with the project partners ATPsustain and A-NULL.

The conducted research is documented in four peer-reviewed papers and structured as following:

The first paper (**P1**), presents the general **MP-methodology** (without BIM support). The methodology is tested on use case 1, where results are assessed and presented. The second paper (**P2**) presents the developed **BIM-based workflow**, which is tested on use case 1 in order to validate the developed BIM-workflow. The third paper (**P3**) describes the final BIM-workflow, which was applied to use case 2 and displays the developed data- and stakeholder management framework for the **workflow-implementation** of BIM-based MPs in order to make them applicable in the AEC-industry. The fourth paper (**P4**) summarizes the results and shows the final MP-document, which was created based on use case 2. P4 is also representing the **proof of concept** for the developed BIM-based workflow. The focus areas of this thesis as well as their associated research papers are illustrated in Fig. 6.

- **P1** Honic Meliha, Iva Kovacic and Helmut Rechberger: “Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study.” *Journal of Cleaner Production* (2019).

- **P2** Honic Meliha, Iva Kovaci, and Helmut Rechberger: “BIM-Based Material Passport (MP) as an Optimization Tool for Increasing the Recyclability of Buildings.” *Applied Mechanics and Materials*. Vol. 887. Trans Tech Publications (2019).

- **P3** Honic Meliha, Iva Kovacic, Goran Sibenik and Helmut Rechberger: “Data-and stakeholder management framework for the implementation of BIM-based material passports.” *Journal of Building Engineering* (2019).

- **P4** Honic, Meliha, Iva Kovacic and Helmut Rechberger: "Der BIM-basierte materielle Gebäudepass als Optimierungswerkzeug." *Bautechnik* 96.3 (2019): 219-228.

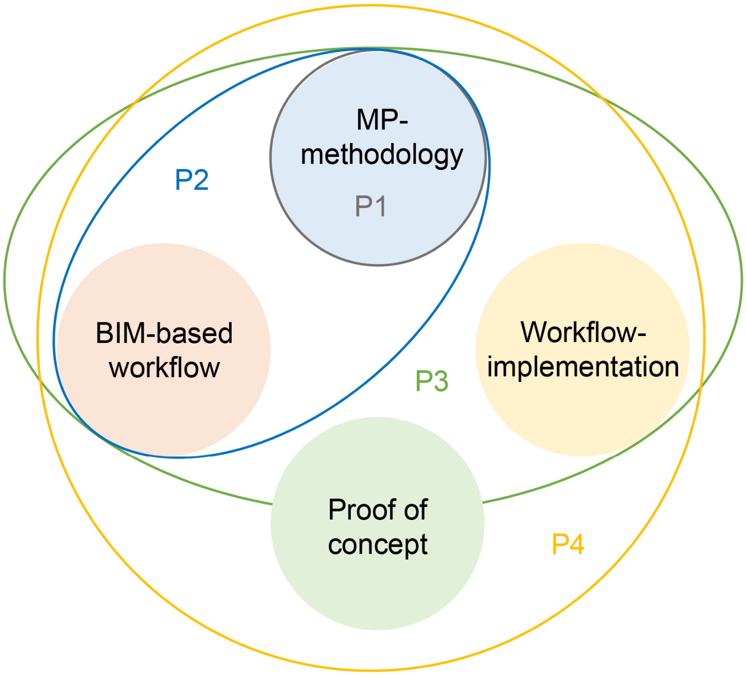

Figure 6: The focus areas of this thesis as well as their associated research articles

5.1 Summary of research papers

The first paper (**P1**) gives an overview about the current situation in the construction industry, shows the developed structure as well as the relevant parameters for the MP and describes the used MP-methodology. In this paper the manual generation of an MP is displayed, whereby BIM was only used to obtain the geometry of the building elements, and was not integrated into the MP-generation process. The MP-methodology was tested on a residential building out of cross laminated timber (CLT) construction, wherefore the BIM-model was already existing from a previous work [Honic, 2016]. The conceptualized building was generated with the use of building components from the database dataholz [dataholz, 2019]. Dataholz provides detailed information about the material composition of building components, but does not offer MP-relevant information such as density, recycling-potential etc., thus complicating the generation of the MP. In order to enable the generation of the MP, relevant parameters from eco2soft were assigned to the materials from dataholz. This process has been conducted manually in MS Excel [MS Excel, 2019], by assigning similar materials to the materials from dataholz. Since the designation and the units in which data is provided in eco2soft and dataholz is varying, the assignment process was a challenging and error-prone task. Apart from the information from eco2soft, information about the geometry of the building (area of building components) was obtained manually from the BIM-model and gathered in MS Excel. Even though eco2soft provides all MP-relevant data, it does not consider the separability of two materials. As the separability is influencing the recycling grade, expressed in numbers from 1 to 5, IBO proposes to downgrade materials which are glued to each other, due to unclean fractions that occur when separating two materials which are e.g. glued to each other. Changing the recycling grade is not possible in eco2soft, which is why this step was conducted in MS Excel, where all building components including their connection type were generated. The final MP-assessment was carried out in MS Excel. A variant study was also scope of this paper, therefore the MP assessment was carried out for a second variant of the same building out of concrete. The building components for the variant out of concrete were obtained from baubook. As baubook and eco2soft belong to IBO, they have the same designation for materials, therefore it was easy to carry out the MP-assessments. The two variants were kept comparable through persisting the same u-value (=thermal transmittance: rate of heat transfer through a structure) for both variants. A detailed description of the two variants and the manual MP-assessment is part of paper P1. Results show that the variant out of concrete construction has a higher recycling potential than the variant out of timber construction (concrete: 52% and timber: 34% recycling potential). However, due to the high mass of concrete, in total, the amount of waste is higher in the concrete variant than in the timber variant (concrete: 1797 tons and timber, 1123 tons of waste). The results of the case study showed, that the developed MP-methodology provides valuable results as well as displays the optimization potentials of constructions, therefore the MP-methodology was used for developing the semi-automated BIM-workflow, as described in the second paper (P2).

In **P2**, a proposal for the semi-automated BIM-based generation of the MP is shown. Therefore, the same use case as in P1 was used, in order to have a comparison between the manual (P1) and semi-automated (P2) workflow. In this paper only the flat roof (again in two variants: concrete and timber) was considered for the assessment in order to make a first test of the developed BIM-based workflow. The proposed BIM-workflow couples BIM-software with the eco2soft tool and the Material Inventory and Analysis Tool, thus creating a tool-chain. Building elements were obtained from dataholz (for timber variant) and eco2soft (for concrete variant). As mentioned above, the building components from dataholz do not consist of the MP-relevant properties, therefore they were created manually in eco2soft. However, even though eco2soft provides all MP-relevant data, it does not consider the separability of two materials, therefore an Excel sheet, consisting of the entire building components including their connection type, was generated. The Excel sheet also serves as basis for modeling in BIM and matching the MP-relevant data in the Material Inventory and Analysis Tool (BO). For BIM-modeling, the modeling guide was used, a document that describes e.g. the designation of building components and materials. As the BIM-model out of timber construction was already existing, for the assessment of the concrete variant, the timber components were replaced by components made from concrete. Model data, including the geometry as well as layers (materials) and their thicknesses were transferred to BO, where to each material from BIM, the MP-relevant data was assigned. As a parametrization of materials and layers is not possible in a consistent way in BIM, BO was used as database, gathering all relevant MP-information from BIM and eco2soft. Apart from that, managing data in BIM in general is difficult due to large data sizes. All assessments were based on the developed methodology in P1, wherefore the required properties, calculations and queries were created in BO. The main findings of this research paper are, that the bi-directional data exchange between BIM and BO works very well and that the proposed BIM-workflow enables a semi-automated generation of an MP. However, the BIM-workflow requires a workaround - an effortful manual step, where MP-relevant data from eco2soft has to be assigned to the building components from dataholz. Therefore, an improvement of the BIM-workflow, such as using only one database is crucial, in order to enable a wide spread application.

In **P3**, the optimized BIM-based workflow for the generation of the MP is presented, as well as a data – and stakeholder management framework for the implementation of MPs in the AEC industry. As data inconsistencies, as described in the summary of P2, lead to an effortful process, for an easy application of the BIM-based workflow, one database – IBO – was used. The final workflow for the compilation of the BIM-based MP consists of three tools, two templates and a modeling guide. The tools and the modeling guide are described above. Two templates (BIM-template and BO-template) are provided in order to enable the generation of MPs for new building projects. Thereby, for the BIM-template, building components from eco2soft (baubook), with a manual step in Excel for evaluation of the separability, where created in BIM-software. The BIM-template consists of various building components such as walls and slabs as well as of different materials such as timber and concrete. These building components, with the same designation and with enrichment through MP-relevant data from eco2soft, were generated in BO and are available in the BO-template. Through the consistent designation in the BIM- and BO-template, matching of components from BIM with those in BO is easily conducted. As in BO all components and their related layers are parametrized through MP-relevant information, the assessment is carried out in a smooth way. The optimized BIM-based workflow was tested on a new use case (use case 2), which is an office building in concrete construction. The BIM-based workflow turned out as a very useful, not only for a basic assessment, but moreover for compiling variant studies in order to define the best variant regarding resources efficiency and ecological impact. In P3 also the roles of various stakeholders within the BIM-based MP-generation process were investigated through application of the developed workflow on the use case. As the MP is used as a design optimization and documentation tool regarding material composition of a building, thus supporting Urban Mining and CE strategies on the macro-economic scale, it addresses a wide range of stakeholders, such as designers and planners, BIM managers, building owners, policy makers, product manufacturers, etc. These stakeholders were grouped into three domains: AEC organization (designers, planners, BIM managers, MP consultants), industry (product manufacturers-EPDs, product database providers-eco-inventories) and regulative body (institutions regulating the environmental protection, resources efficiency and CE, etc.). The final result of this research paper is the developed data- and stakeholder management framework, showing the required collaborations between the domains and the roles of each domain, in order to enable the implementation of MPs. Thereby, regulative bodies are responsible for setting regulations such as "70% recycling by weight of construction and demolition waste by 2020", as claimed by the EU [European Commission, 2011]. The industry is in charge of providing harmonized and standardized data, since this data inconsistencies are a big challenge in the application of the developed BIM-based process. The main finding is, that in AEC organization an MP consultant is required, who is in charge of integrating recycling and LCA-data into the BIM-process by linking databases to the Material Inventory and Analysis Tool, and moreover for the final MP-generation, since the BIM manager himself, does not possess the required knowhow about materials and databases. The developed framework serves as basis for a wide spread implementation of the MP concept into the BIM process. A further finding is that due to high level of implicit knowledge, and low level of development in terms of BIM information in early design stages, a fully automated generation of BIM-based MPs is not possible. As building elements in the design stages are mostly modelled with mono-layered elements for keeping the design space as open as possible, the conduction of MP assessments is faced with challenges, since it requires the material composition and respective indicators. Therefore the use of predefined elements is proposed, which narrows the design space of architects and planners. Moreover, the varying designation of databases causes difficulties in data management, which is another reason why predefined elements are used, since matching data from various databases is a time-consuming and error-prone task. Due to the required use of predefined elements and manual assignment of elements from BIM in BO, a fully automated generation of an MP is not possible.

The last research paper (**P4**) is a summary of all achieved aims, showing the content, structure and scope of the MP throughout the life cycle, as well as the results created for use case 2 within the final MP document. Through this paper, the **proof of concept** for the developed BIM-based workflow is given. Moreover, this paper provides a detailed description of the stage oriented modeling methodology. The MP-concept considers four life cycle stages: the preliminary design stage, conceptual design stage, tendering stage and documentation stage, but the focus lies on the conceptual and preliminary design stages. As in the conceptual design stage the detailed material composition is not defined yet, though necessary for the compilation of the MP, assessments are carried out through matching the mono-layered building components from BIM to the parametrized components available in BO. For this stage the BO-template is configured, such that only the area and classification (classification of a modelled wall in BIM = “wall”) is obtained from the BIM and all other information is assigned to the building components from BO, thus enabling the conduction of variant studies e.g. timber vs. concrete construction. In the preliminary design stage, the BIM- model is generated based on the selected variant and with building components from the BIM-template. In this stage it is important, that the BIM-model is created precisely, since the volumes, layers and their thicknesses are obtained from BIM and assigned to components and their MP-relevant information in BO for follow-up assessments. The modeling methodology was the basis for the generation of the MP-document, which is presented in this paper including tables that show the recycling grade and potential, the amount of recycling and waste on material level, as well as the accruing masses throughout the life cycle and the LCA-results. This paper has been published in German, the original as well as the translated version is attached in Section II.

6. Conclusion

The main contribution of this thesis is development of a semi-automated BIM-based workflow for the generation of Material Passports. As the MP aims to document the materials embedded in buildings and moreover to minimize the resources consumption as well as the environmental impacts, it represents an important instrument for the implementation of Circular Economy and Urban Mining strategies into the AEC sector.

Within this research an MP-concept and -structure, a BIM-based workflow for the semi-automated generation of MPs as well as a framework for the implementation of the MP to the practice was developed.

The conceptual framework for the proposed MP is based on the life cycle assessment and recycling assessment methodology of the Austrian Institute for Building and Ecology (IBO) as it was found as the most suitable methodology by not only providing building component catalogues but moreover consistent MP-relevant data. The IBO-methodology proposes the linking of recycling grades from 1 to 5 as well as LCA-indicators such as GWP, AP and PEI to materials within a building element. Through applying the methodology for each material of a building element and up-scaling from the material-level to the building-level within the developed MP-structure, results on building-level as well as the levels with largest optimization potential regarding resources efficiency and LCA are obtained.

The developed conceptual framework was implemented into the BIM-based workflow for the generation of MPs. A BIM-tool, control tool, as well as the Material Inventory and Analysis Tool were used for building up the workflow as well as for generation of the final MP-document. The BIM-tool (Graphisoft Archicad) is used for creating the BIM-model, based on the developed modeling guide and the BIM-template. The control tool (Solibri Model Checker) is used for checking the created model regarding e.g. MP-appropriate BIM-model, correct designation of materials and is based on pre-defined rule sets. The Material Inventory and Analysis Tool is used for generation of the final results and is built up with queries required for the MP-generation as well as with the predefined building elements which are enriched with MP-relevant properties.

The proposed workflow serves as design optimization tool as well as material repository thus supporting material and resources optimization throughout the life cycle. It simultaneously offers the conduction of LCAs, the assessment of the recycling potential as well as the accumulation of masses and waste throughout the lifecycle.

The proof of concept was generated on two use cases (a residential building and an office building). The analysis shows that the mass of a building plays the most important role for the optimization of the recycling potential and minimization of waste. The proposed form document for the Material Passport, comprising of the recycling potential, the recycling grade and the share of recycling and waste, together with the appropriate grading system is illustrated in Figure 7.

Finally a proposal for the successful implementation of MPs in the AEC practice was developed (Fig. 8). Through application of the BIM-based workflow on use cases, as the main domains playing a crucial role for the implementation of the MP, AEC-companies, industry and regulative bodies were identified. The proposed data and stakeholder management framework suggests a strong collaboration of these domains in order to harmonize data and standardize processes and moreover defines regulations for the improvement of recycling rates of buildings as well as for the implementation of the MP in the construction sector.

It has to be stated that the main focus of this thesis was to demonstrate the proof of concept for the semi-automated BIM-workflow for the generation of a Material Passport. Existing recycling- and LCA-data as well as methodologies were used, though not analyzed deeply, since the focus lied on developing a BIM-workflow which enables the integration of any data and methodology. The assessment of data quality, uncertainties dealing with LCA methodology and variability of results were not primary focus of this thesis, yet some limitations regarding data and methodology were identified. These limitations are: the existing data on recycling and LCA is not consistent in various databases (designation of materials, considered life durance and transportation emissions, etc.), the used IBO-methodology is a very basic methodology which does not consider e.g. the connection type of two materials and is restricted to a grading system with grades from 1-5, as described above. In a further step, the proposed methodology needs optimization.

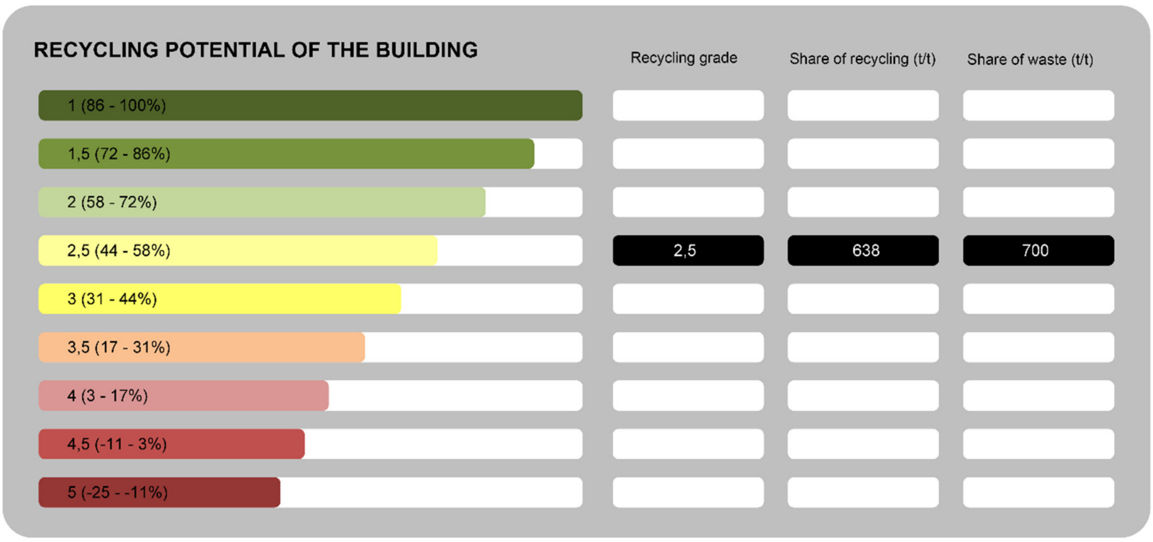

Figure 7: One part of the MP-document - recycling potential of use case 2

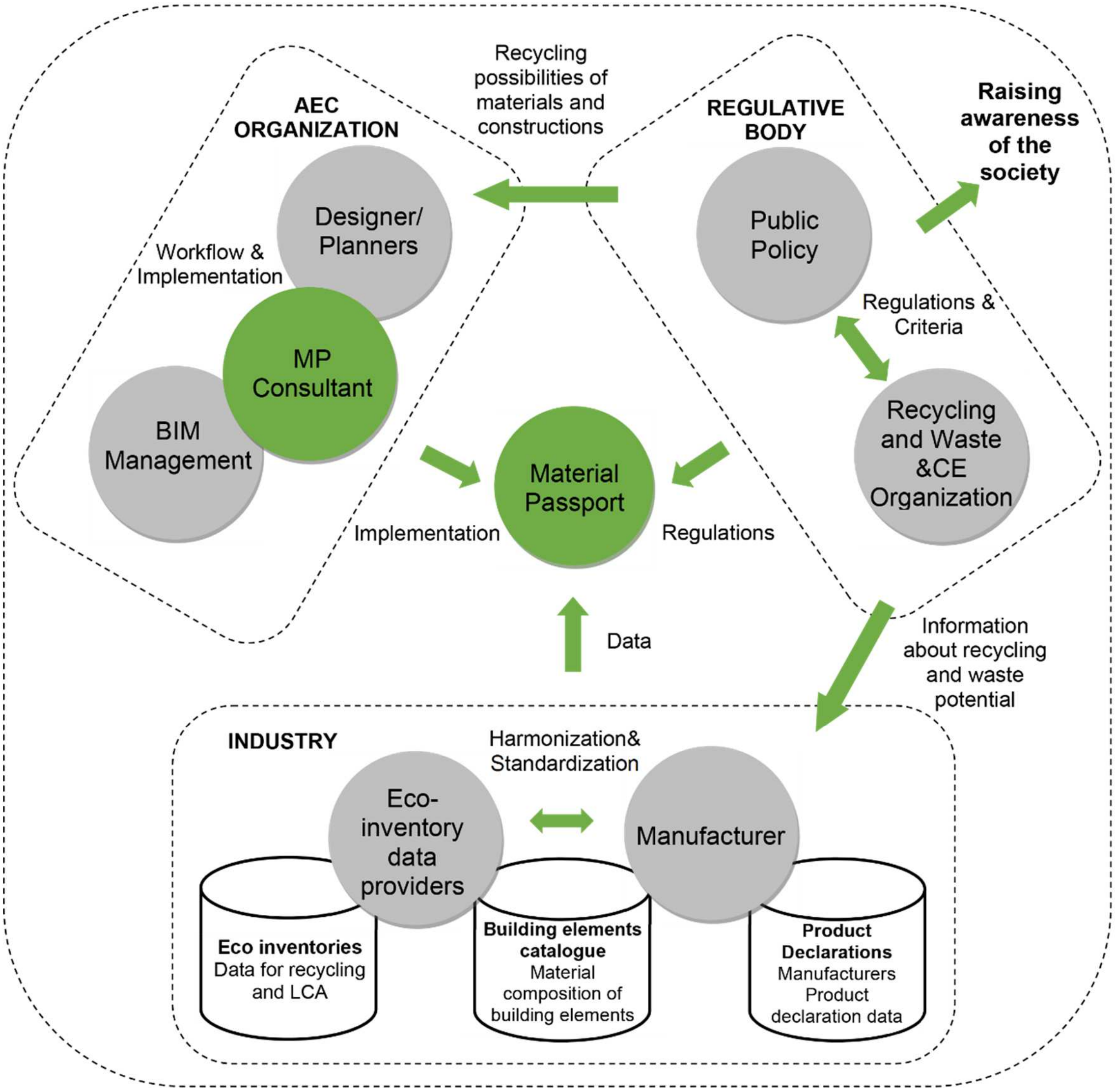

Figure 8: Data- and stakeholder management framework

7. Outlook

The presented BIM-based MP acts as decision support for designers and planners for optimizing the resources efficiency as well as for minimization of environmental impacts such as CO_2 emissions in the early design stages. However, new construction rate across Europe is only 3% [Euroconstruct, 2018] and only 20-30% of construction and demolition waste is recycled or reused [WEF, 2016], underlining the potential of the existing stock. To increase recycling rates, it is necessary to analyze the existing building stock as well as determine the incorporated materials in buildings. For this purpose, the developed methodology for the generation of Material Passports serves as important support since it enables the assessment of materials embedded in buildings and moreover evaluates their recycling potential and environmental impacts. In order to apply the developed BIM-workflow for existing buildings, it is necessary to first obtain information about the geometry and incorporated materials of the existing building stock, wherefore new methods are needed. The obtained information about geometry and materials would enable the creation of an information rich BIM-model which would serve as basis for the generation of a Material Passport. The generated Material Passport for the existing building (MPd) would act as inventory and provide information about the remaining life time of incorporated materials as well as their recycling potential, condition and time when they would be available for recycling. For increasing recycling rates, the developed MP-methodology is a good basis, however an adoption of the methodology for the end-of life stage is necessary.

The developed BIM-based workflow for the compilation of the MP has already found implementation in the follow up research project “SCI_BIM: Scanning and data capturing for Integrated Resources and Energy Assessment using Building Information Modeling”, which uses the method in a larger context. SCI_BIM is an ongoing research project that received funding by the Austrian Ministry for Transport, Innovation and Technology (BMVIT). Within the research project a use case is captured through laser and ground penetration radar scans in order to obtain the geometry and the material composition for the generation of a BIM-model and follow-up compilation of a BIM-based MP as well as for the prediction of the energy consumption of the building. The BIM-model and accordingly the MP is kept up to date through the innovative gamification approach, which enables tracking of changes through user participation. On urban level, the MP of existing building stocks will serve as basis for a secondary raw materials cadaster for Vienna.

As future outlook for the implementation of BIM-based MPs three fields can be identified:

- Secondary raw material cadaster
- Integration of MPs of building stocks in a public digital information platform
- MPs as foundation for cost assessment

A potential use of the MP is for the generation of a **secondary raw materials cadaster** for the city of Vienna. The first step therefore is the creation of a BIM-based catalogue with typical building elements. First, buildings from different time periods need to be scanned with a GPR (ground penetrating radar) in order to define the typical material composition of buildings from a specific time period. By coupling the obtained materials information through scans with the information about the geometry and height from GIS (geographical information system), a BIM-model for follow-up generation of a Material Passport is created. The assessed information through the MP can be up-scaled on city-level and serve as basis for a secondary raw materials cadaster. For the generation of a BIM-based catalogue with typical building elements of existing buildings the gained insights on the MP-methodology as well as on the use of BIM for the generation of the MP acts as a fundament.

A further potential is a **public digital platform** for MPs on existing building stocks. This platform can be a new created online platform or the existing GIS, which is being updated in real-time in order to make the existing material stock including the information about the time when the recyclable materials will be available and the place where the materials or elements exist accessible for the recycling industry and public. It would also be necessary to consider the transportation routes of the recycling materials since too long transportation routes lead to high CO_2 emissions. It is necessary to find the right balance and to decide if recycling is beneficial in each case. Considering this, it can be useful to create a platform on a smaller scale such as on area or city level. The existence of such a real-time and public platform with embedded information from the MP might significantly improve recycling rates.

The developed semi-automated BIM-workflow for the generation of Material Passports also shows potential for **cost assessments** as well as for precise mass and quantity analyses of buildings. Due to the bi-directional connection of the BIM-model with the BuildingOne database, changes are synchronized automatically. The developed workflow enables a smooth and error-free data exchange as well as the conduction of changes in the model without any additional effort, underlining it`s significance for obtaining reliable results.

The developed MP-methodology has already been applied on a real use case - an industrial building for the automotive production consisting of an office, production and storage part. The investors underlined the importance of sustainability in the design brief, therefore a sustainable design proposal was developed using MPs. Several variants were generated and evaluated using the MP-methodology - one based on timber and the other using concrete structure. Regarding recycling potential and CO_2 emissions the timber variant delivered better results. All results were presented for the investors of the project. Even though sustainability was labeled as important in the design brief, the investors did not decide in favor of the design proposal. The application of the MP-methodology on a real use case showed, that it is of significant importance to raise awareness in the society towards adoption and acceptance of not only energy efficiency, but also of resources and material efficiency which requires the consideration of a much longer time horizon. Moreover, terms such as Circular Economy as well as recycling and waste minimization should be more present in media in order to enable the implementation of sustainable solutions in the AEC-industry.

8. Literature

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9. Acknowledgements

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The BIM-templates, BO-templates and the Solibri file are available on request (meliha.honic@tuwien.ac.at). A description on how to use them is available in the modelling guide (Appendix 1) and in the roadmap (Appendix 2).

Section II

Peer-reviewed papers

P1

Honic Meliha, Iva Kovacic and Helmut Rechberger:
"Improving the recycling potential of buildings through Material Passports (MP): An Austrian case study." *Journal of Cleaner Production* (2019).

P2

Honic Meliha, Iva Kovacic and Helmut Rechberger:
"BIM-Based Material Passport (MP) as an Optimization Tool for Increasing the Recyclability of Buildings." *Applied Mechanics and Materials*. Vol. 887. Trans Tech Publications (2019).

P3

Honic Meliha, Iva Kovacic, Goran Sibenik and Helmut Rechberger: "Data-and stakeholder management framework for the implementation of BIM-based material passports." *Journal of Building Engineering* (2019).

P4

Honic, Meliha, Iva Kovacic and Helmut Rechberger:

"Der BIM-basierte materielle Gebäudepass als Optimierungswerkzeug." *Bautechnik* 96.3 (2019): 219-228.

Appendices

Appendix 1:
Modeling guide for the generation of a BIM-model for a follow-up generation of a Material Passport

Appendix 2:
Roadmap for the generation of a Material Passport

Modeling guide for the generation of a BIM-Model for a follow-up generation of a Material Passport

The modeling guide serves as instruction for the generation of qualitative BIM-Models in order to enable the creation of Material Passports. Within this guide, the modeling methodology for the conceptual design stage as well as for the preliminary design stage is described, within which the Material Passport serves mainly as optimization tool. Thereby it is distinguished between modeling of walls/slabs and single elements such as windows, doors, facades and columns. The modelling guide is provided for BIM-modeling in Graphisoft Archicad only, since there exist data-exchange problems between Autodesk Revit and BuildingOne, which lead to incorrect results for MPb. The generation of the MPa is possible with Revit.

Stages

The Material Passport is available for two life-cycle stages (see fig. 1): as rough analysis and optimization tool in the conceptual design stage (MPa) and as optimization tool in the preliminary design stage (MPb). The BIM-Model for MPa is created with mono-layered elements, whereby the materials are not defined yet in this stage. The BIM-Model for MPb is generated with multi-layered elements. The generation of the MPb is not possible in Revit due to data-exchange problems with BuidlingOne and is therefore only feasible with Archicad.

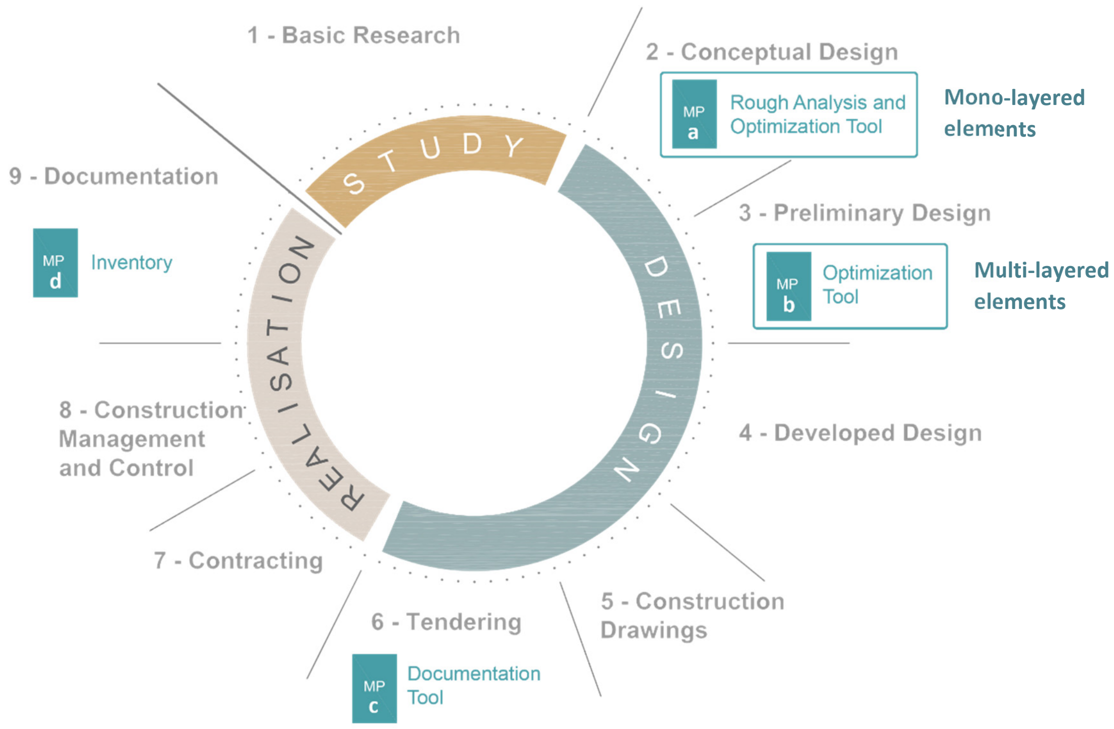


Figure 1: Scope of the MP throughout the life cycle

Modeling methodology

The modeling methodology is based on the Austrian norm [ÖNORM A 6241-2:2015], which prescribes that all horizontal building elements should be modelled as hybrid elements [bimpedia]. Modeling as hybrid elements means that floorings, load-bearing slabs and suspended ceilings are modelled as individual elements in order to enable flexibility in modeling, since these elements are room-specific elements and may change within a building (e.g. flooring of a bathroom and living room of a flat), whereas exterior walls are modelled as one element.

Walls and slabs

For the generation of the MPs, templates for MPa and MPb are available.

For the conceptual design stage, the template for MPa (MPa.tpl) is used, whereby modeling with mono-layered elements is required. It is important that the classification of the elements (e.g. wall has to be modelled as a wall and a slab as a slab) and the geometry is correct.

For the preliminary design stage the template for MPb (MPb.tpl), which consists of predefined elements based on the building catalogue from IBO (Austrian Institute for Building and Ecology), is used. The guidelines for MPb are only suitable for Archicad, since the generation of the MPb is not possible with Revit. All predefined elements have the prefix “XX” and only these elements should be used for modeling (Fig. 2).

By applying the parameters (tool in Archicad „apply parameters“) from the predefined elements to new elements, generation of the BIM-Model is easily conducted, since all parameters are copied from the existing elements to the new created ones (Fig. 3). As mentioned above, for the MPb each element has to be created according to its function (wall as wall and slab as slab). In the preliminary design stage, all layer-thicknesses can be adapted individually. The replacement of a material by another one can be conducted, though the effect on the connection type and recycling potential has to be considered and if required adapted in BuildingOne.

In both templates (MPa and MPb) the layer-structure as well as the layer-combination is provided (Fig. 5), which need to be used in order to enable an error-free data-exchange to the BuildingOne database. If materials are changed, the materials from the template with the prefix “XX” need to be used (Fig. 4).

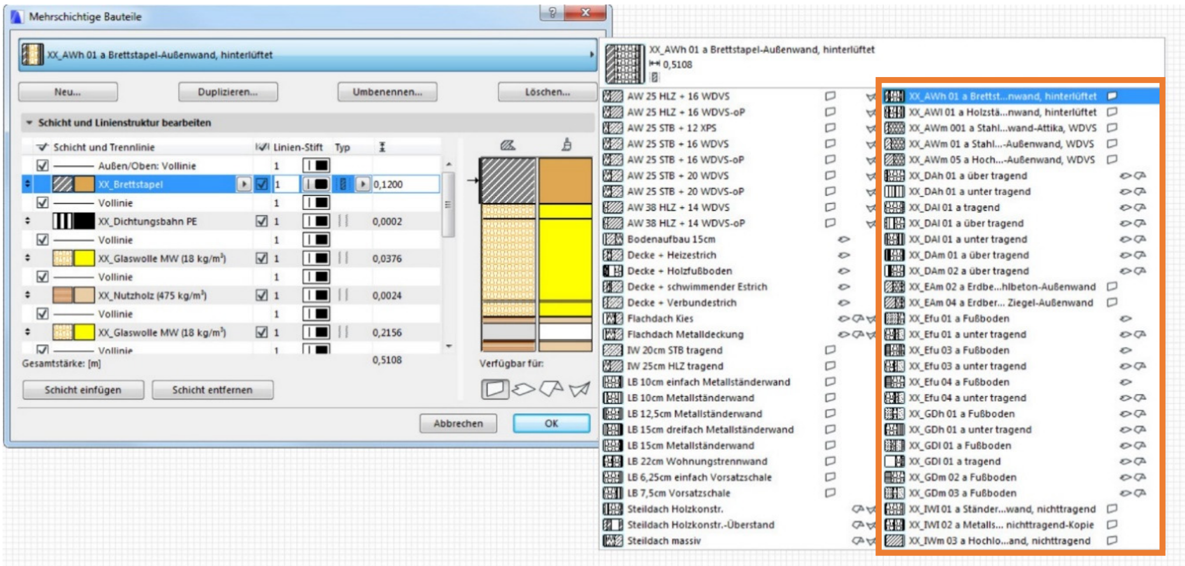


Figure 2: Building catalogue with predefined elements

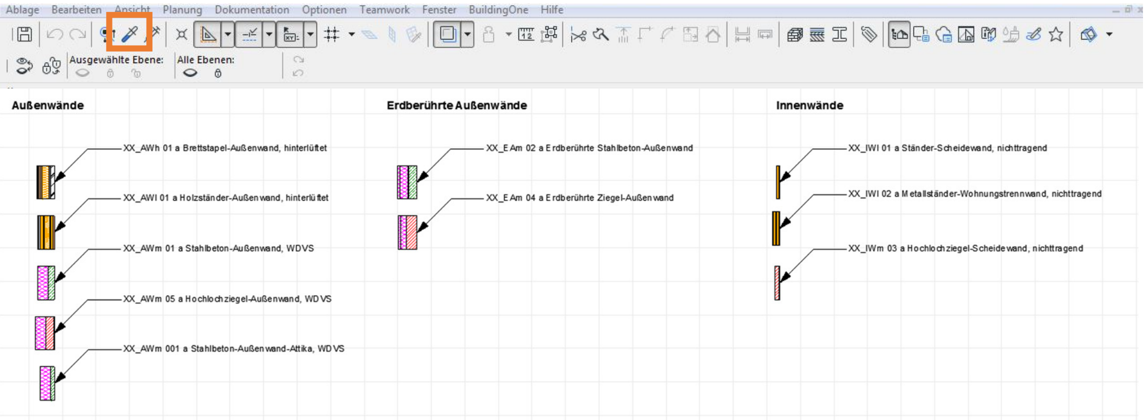


Figure 3: Applying parameters from the predefined elements

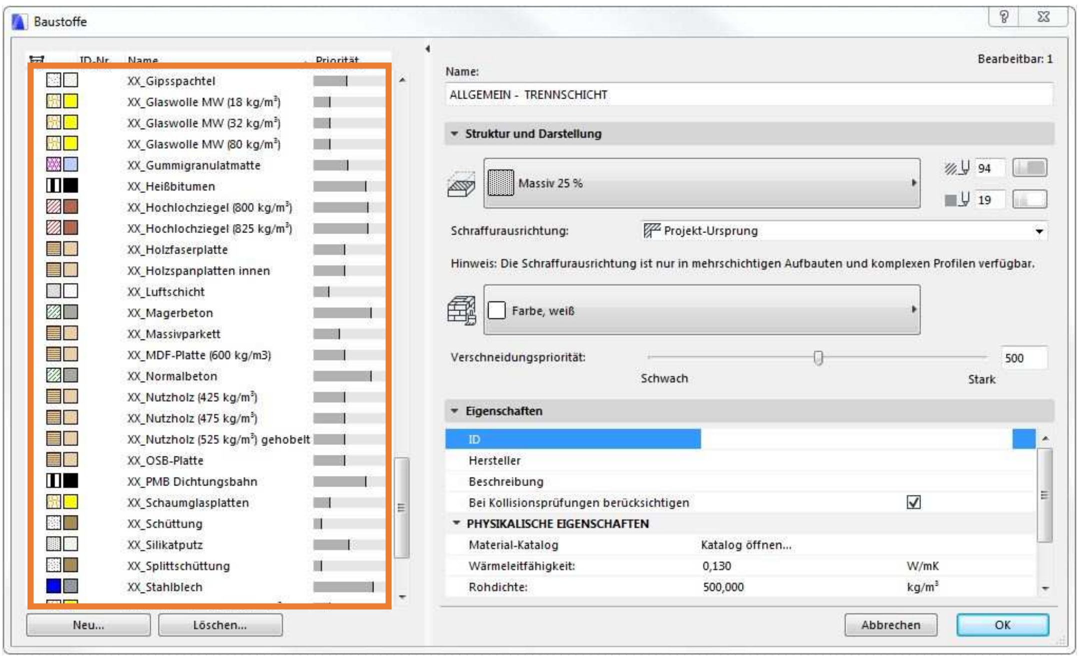


Figure 4: Materials from the catalogue with prefix „XX“

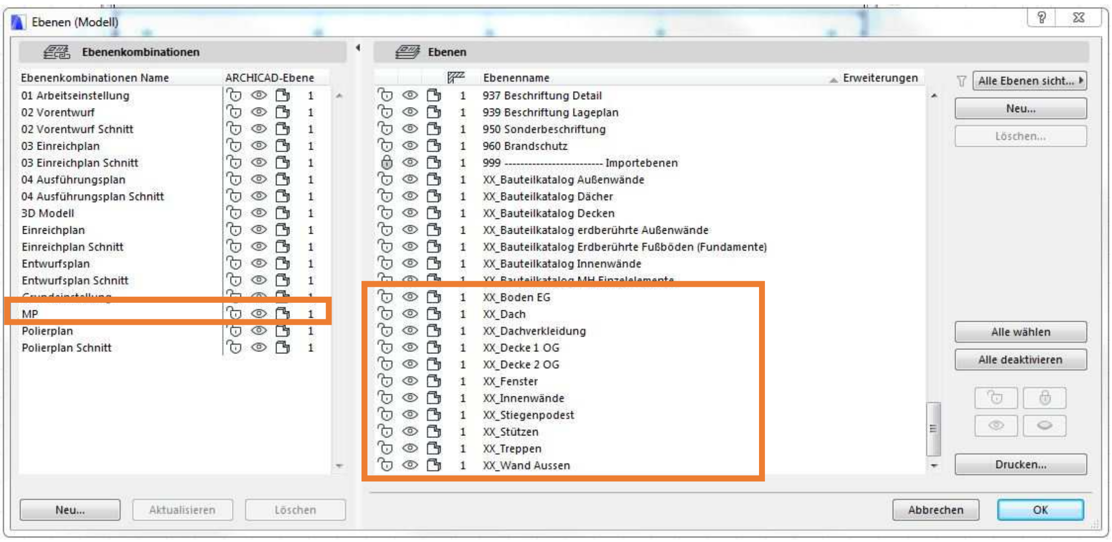


Figure 5: Layer structure and layer combination „MP“

Single elements: Windows, doors, facades and columns

For single elements, it is important to assign the relevant materials. The following properties have to be checked and the relevant materials have to be assigned here: For windows, the glass- and frame-material has to be defined (“Glasmaterial” and “Rahmenmaterial”=frame-material, as shown in Fig. 6). For doors the frame-and panel material, for facades the post- and panel material and for columns the main material has to be defined.

All above mentioned properties have to be defined in order to enable the generation of MPs. After the building has been modelled, the layer-combination “MP” has to be chosen for follow-up data exchange with the database BuildingOne. Further steps are described in the roadmap “Roadmap for the generation of a Material Passport” (Link to the German roadmap: https://nachhaltigwirtschaften.at/resources/sdz_pdf/bimaterial_Roadmap.pdf).

For further information about the modeling guide and templates contact:
meliha.honic@tuwien.ac.at

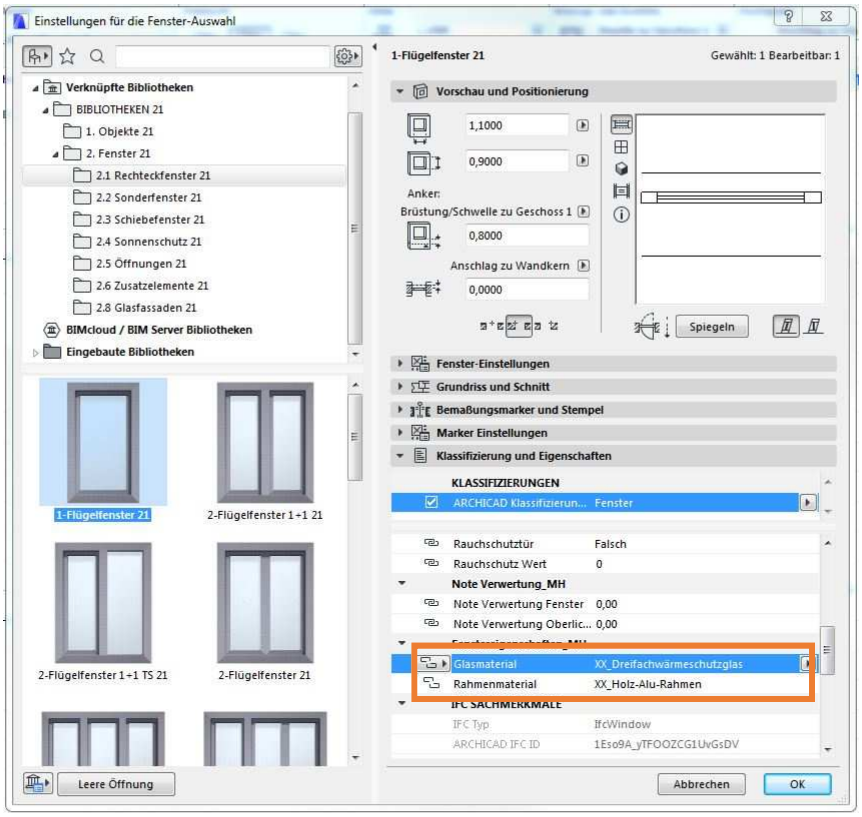


Figure 6: Window material definition for the frame and glass

Literature

ÖNORM (2015), ÖNORM A. 6241-2: 2015-07: Digitale Bauwerksdokumentation–Teil 2: Building Information Modeling (BIM)–Level 3-iBIM. *Österreichisches Normungsinstitut*.

Bimpedia 2019, https://www.bimpedia.eu/welcome (accessed 07 July 2019)

Roadmap for the generation of a Material Passport

The **roadmap** supports and enables the generation of Material Passports (MP) for the conceptual design phase (MPa) and the preliminary design phase (MPb). The generation of the MPb is not possible with Revit due to data exchange issues between Revit and BuildingOne, wherefore only the generation with Archicad is illustrated in this roadmap.

The MP generation requires following software:

- Graphisoft Archicad
- Solibri Model Checker
- BuildingOne

Solibri Model Checker does not have a direct connection to Archicad, therefore an IFC-file of the model has to be exported from Archicad, in order to open the model in Solibri. Solibri is used to check if the BIM-Model (in Archicad) has been created correctly and will not be further explained within this roadmap.
BuildingOne is an Add-On in Archicad, which has a bi-directional connection, enabling an automated synchronization of changes within the model (Archicad) and BuildingOne.

Following phases are considered:

- MPa: Conceptual design stage
- MPb: Preliminary design stage

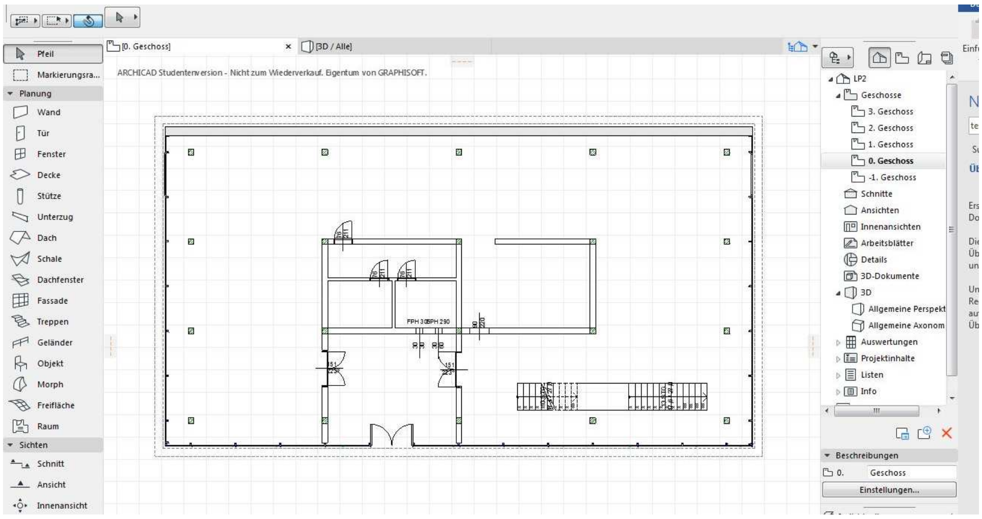
Following building elements are included in the assessment:

- Walls
- Slabs and floorings
- Roofs
- Windows and doors
- Columns
- Facades
- Basement

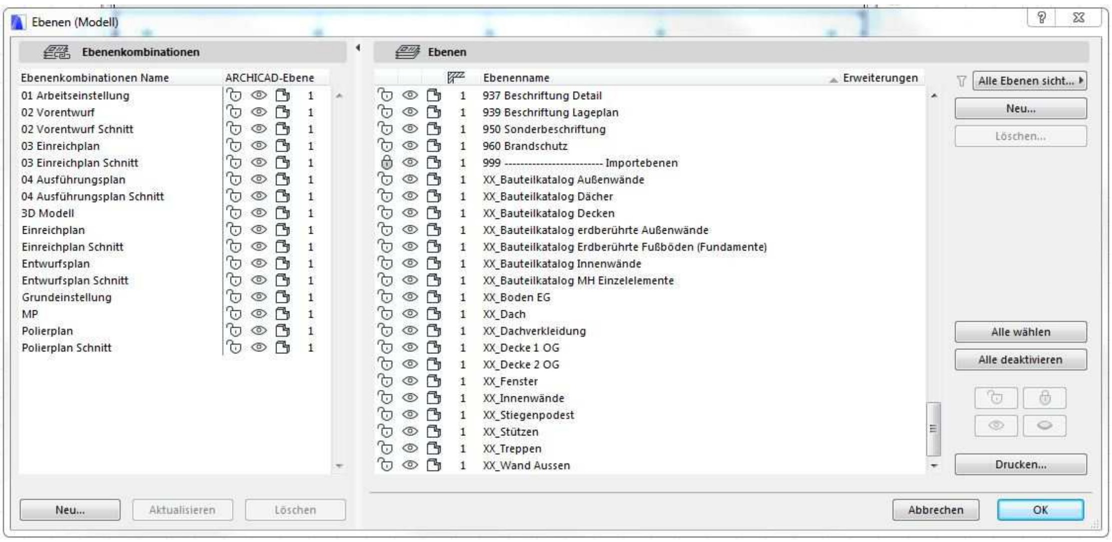
All templates are available on request. Therefore contact:
meliha.honic@tuwien.ac.at

Roadmap – Material Passport for the conceptual design stage (MPa)

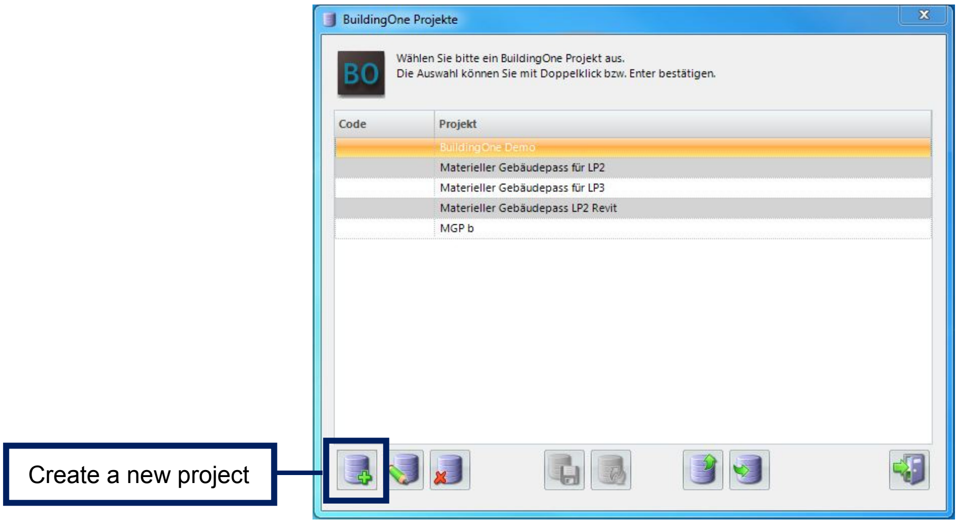
1. **Model** the building by using the Archicad-template (MPa.tpl). Model with mono-layered elements and consider the correct geometry of the building. No definition of materials required.



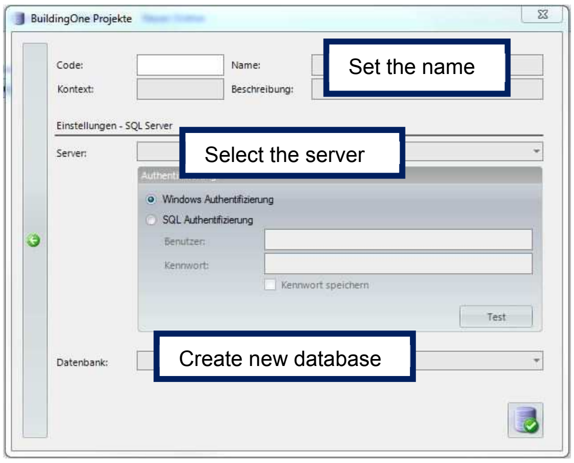
2. Use the **layerstructure** of the template. All elements should be in the correct layer. Therefore the layers with prefix XX should be used (e.g.: XX_Innenwände-interior walls), except the ones from the building catalogue (XX_Bauteilkatalog).

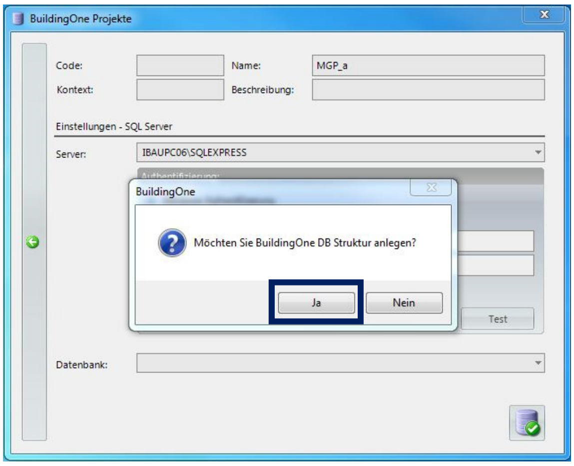


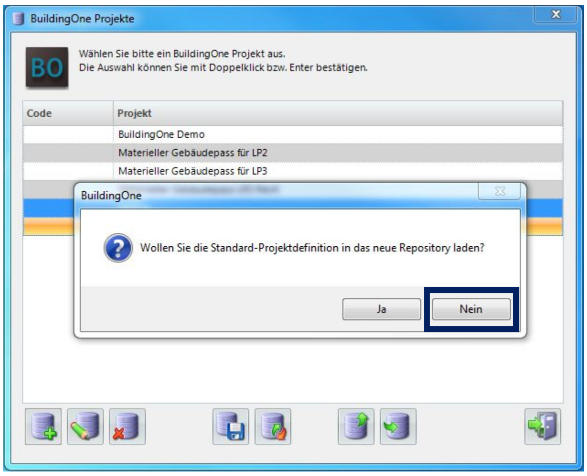
3. Start BuildingOne in order to create a new project. Give the project a name.



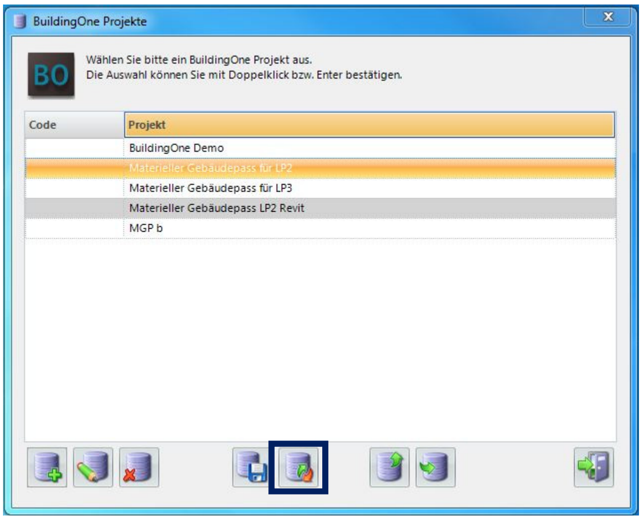
4. Select the SQL-server and establish the connection to the server. Give the project a name and create a new database.



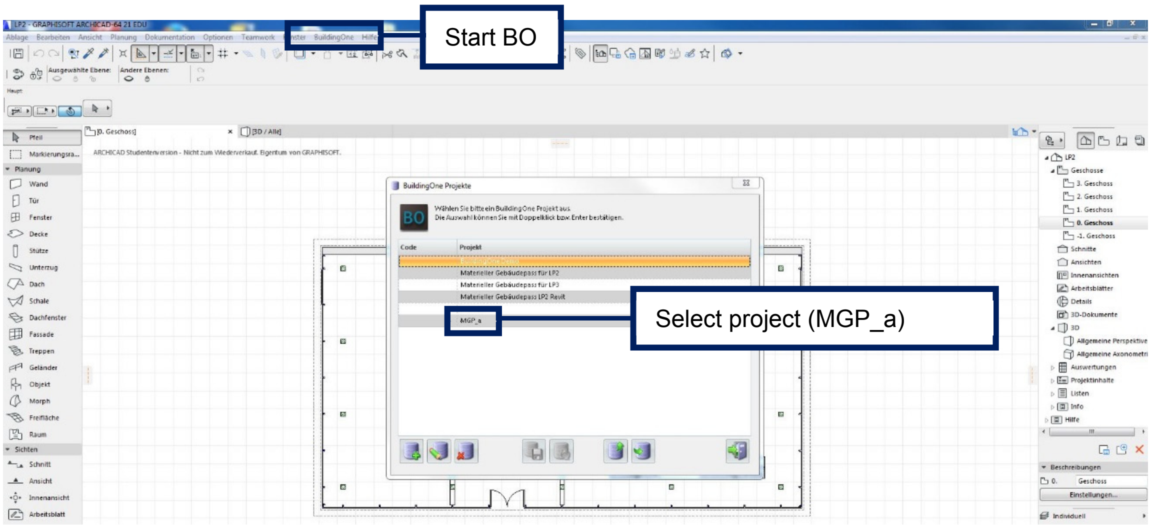




5. Select button „recover project“ and then go to the BO-template file “MPa” (in the figure at point 6.: MGP_a)

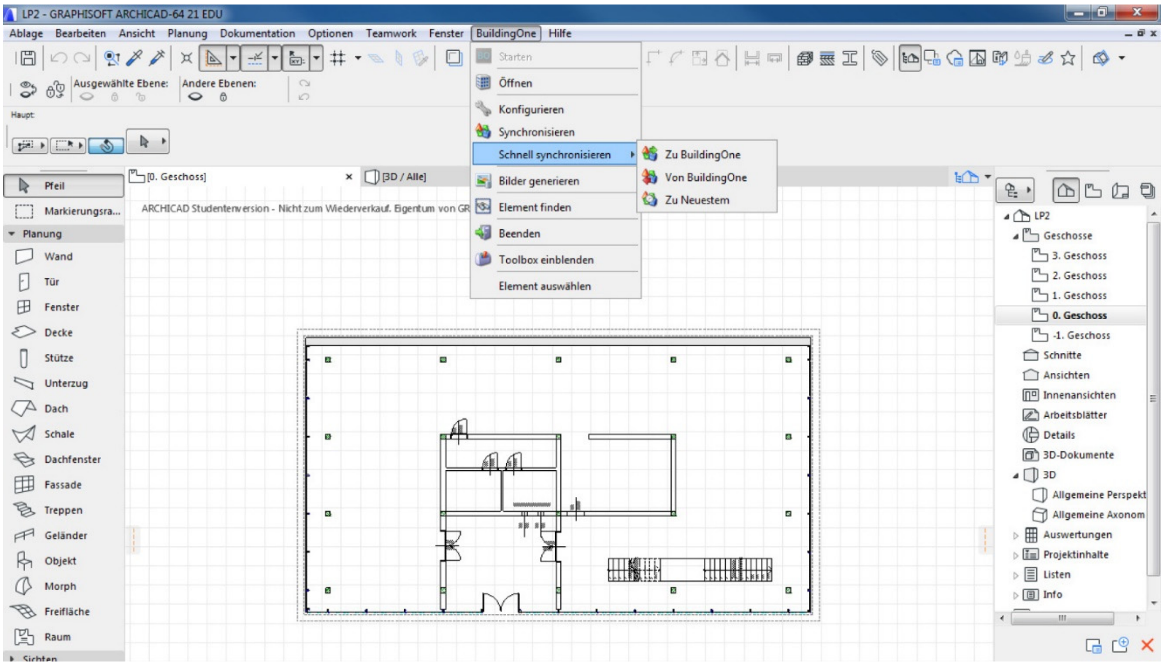


6. Start BuildingOne in Archicad and select the currently loaded project

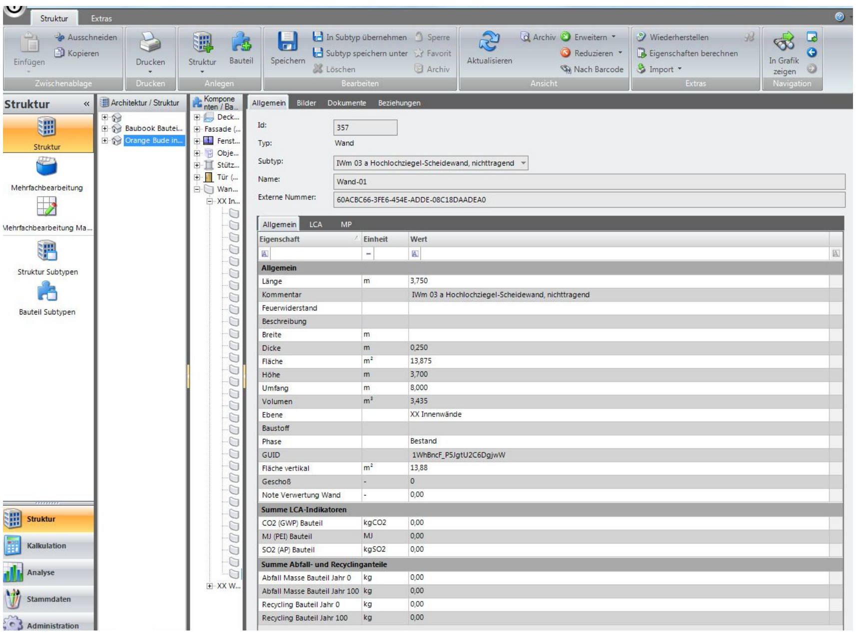


7. Create a new building

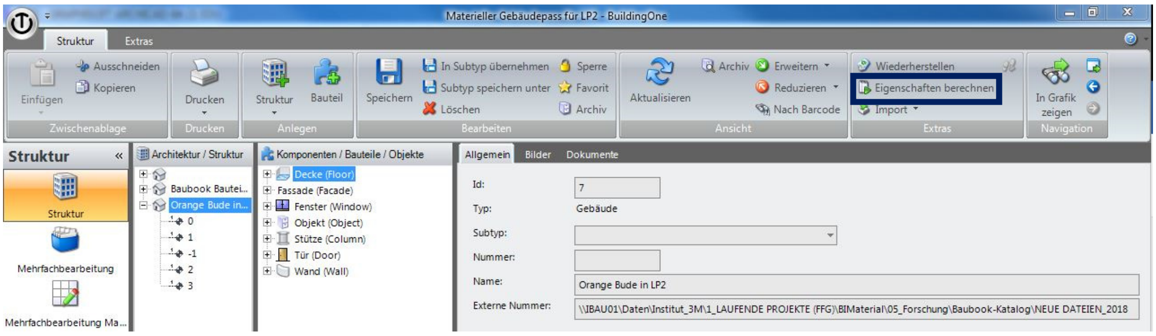
8. Select the layercombination „MP“ in Archicad. Then go to „BuildingOne“- „Schnell synchronisieren“(fast synchronization) – „Zu BuildingOne“(to BuildingOne).



9. All elements are visible in BuildingOne now. Assign subtypes to all elements from the model. Save changes after each assignment.



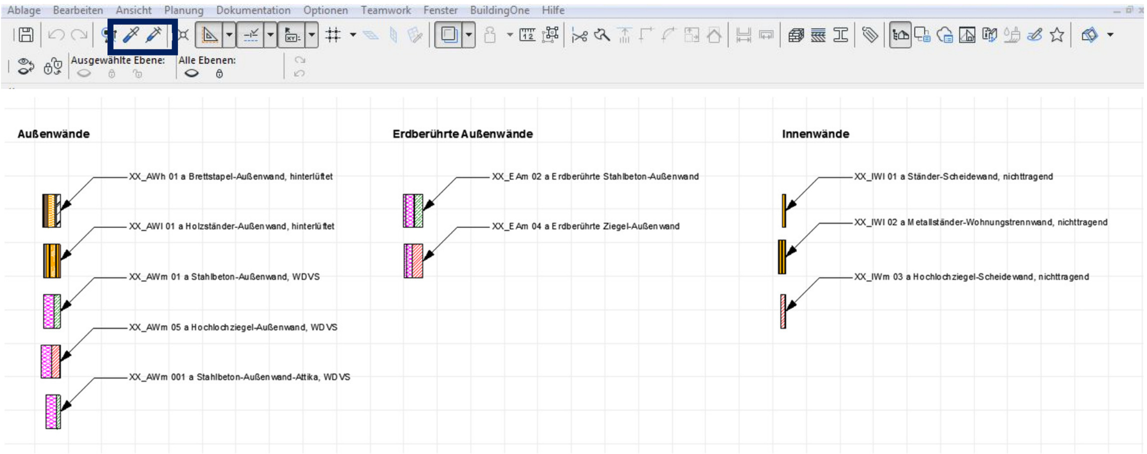
10. Generate the results by selecting “Eigenschaften berechnen” (calculate the properties)

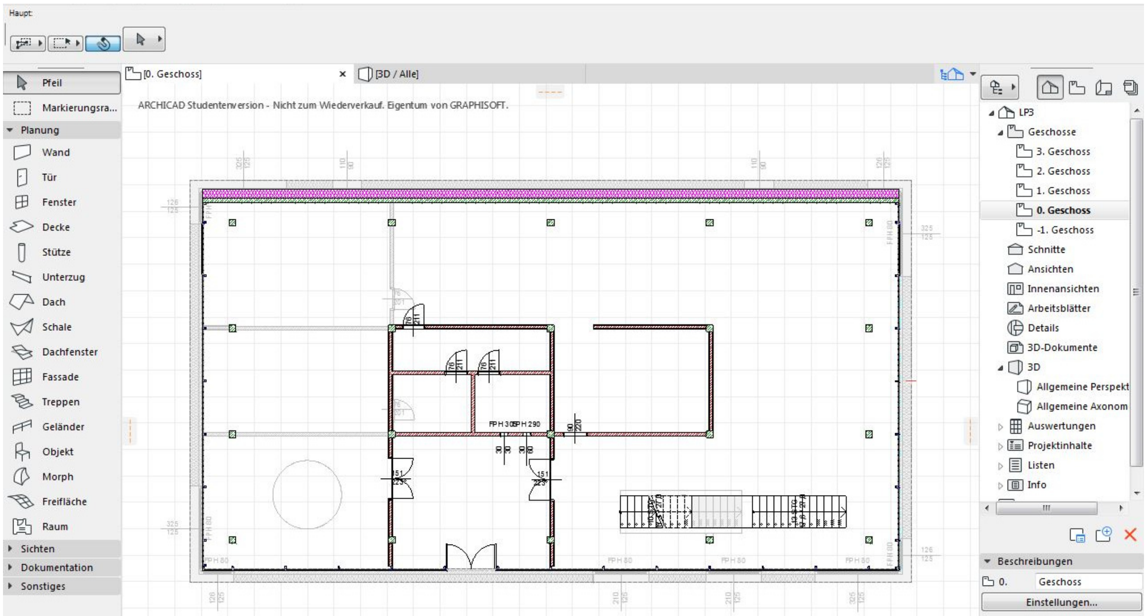


11. Check the results and try out different variants by assigning various subtypes (e.g. timber vs. reinforced concrete construction).

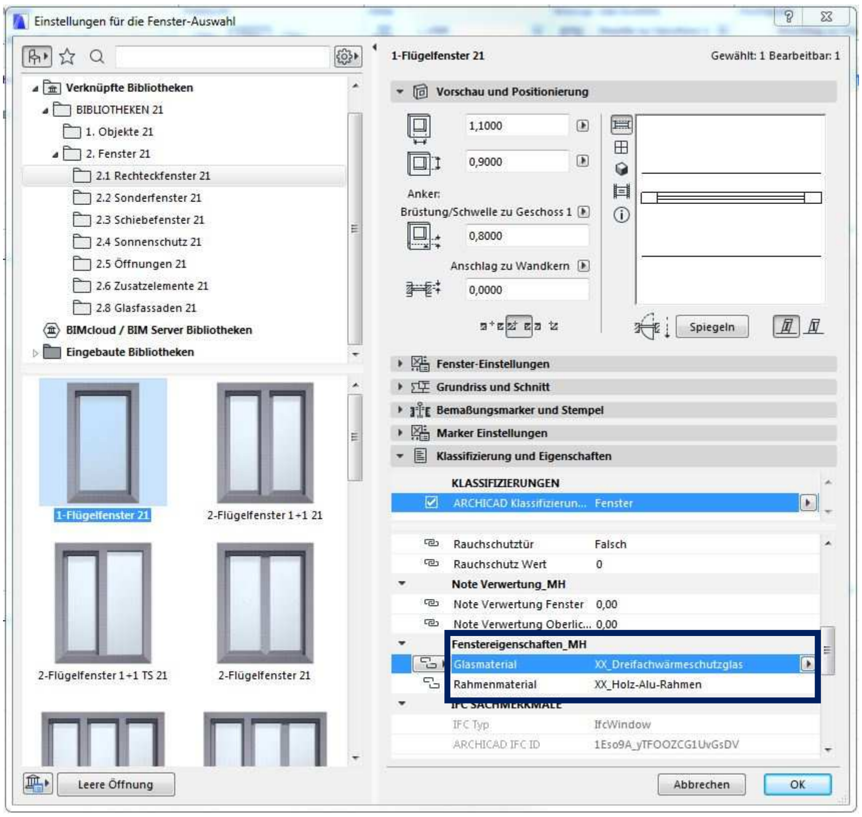
Roadmap – Material Passport for the preliminary design stage (MPb)

1. **Model** the building by using the Archicad-template (MGPb.tpl). Create the model with the elements **walls**, **slabs** and **floorings** from the building catalogue. Use the tool „apply parameter“, in order to copy the element parameters (materials, thicknesses etc.) of the desired element from the catalogue and apply it to the mono-layered element.

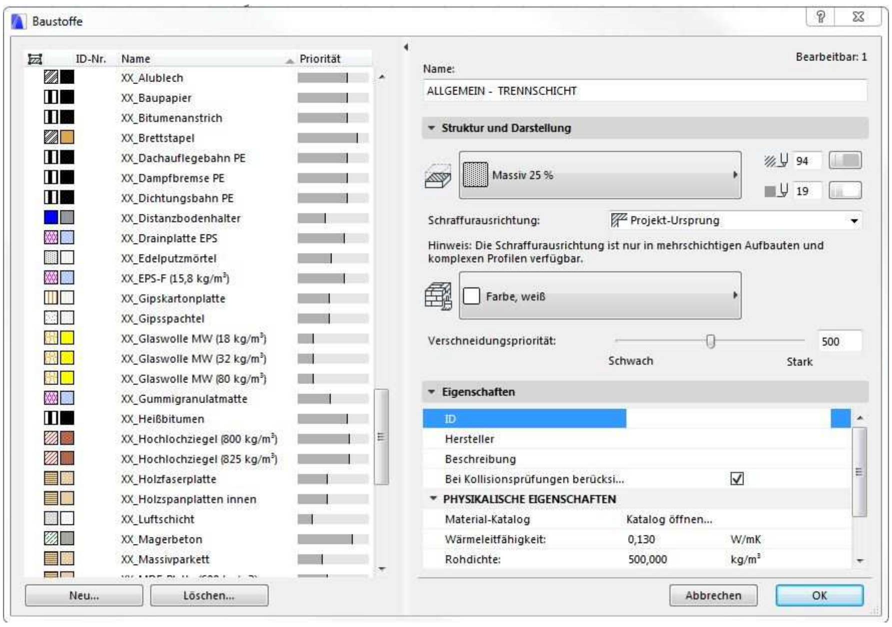




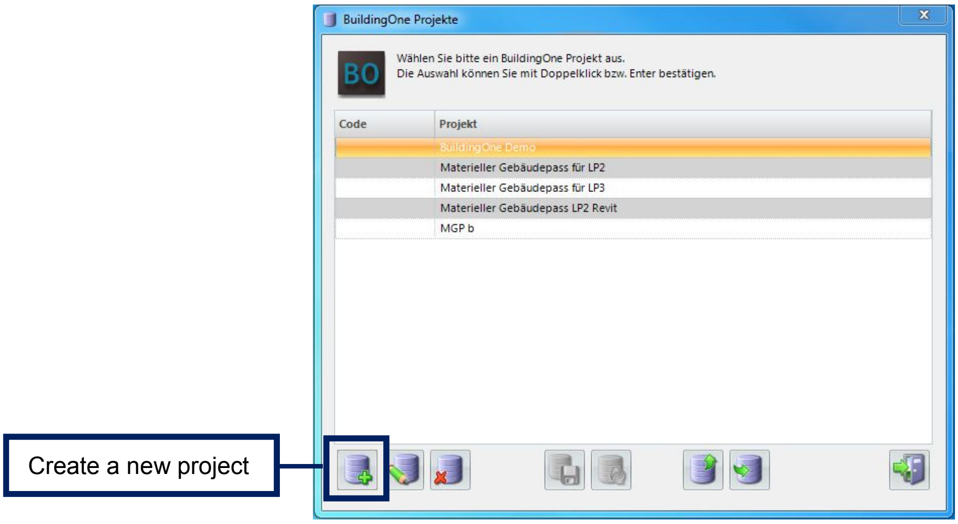
2. For **doors**, **windows, facades** and **skylights** define the material of the frame and the glass/panel. E.g. window: material of the glass „XX_Dreifachwärmeschutzglas“ (high thermal insulation glass) and material of the frame “XX_Holz-Alu-Rahmen” (timber-aluminium frame).



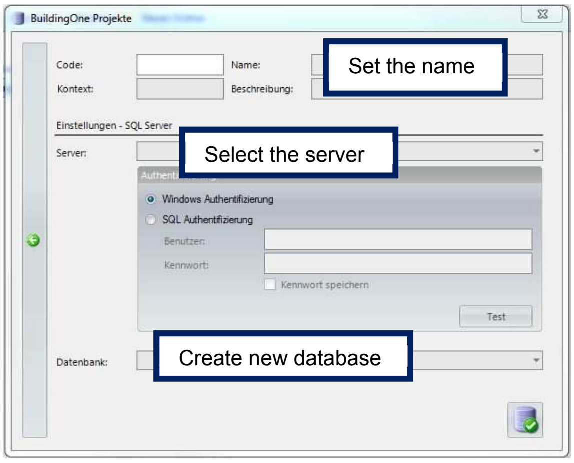
3. Select the materials with the prefix XX for columns and other mono-layered elements from the existing catalogue in the template.

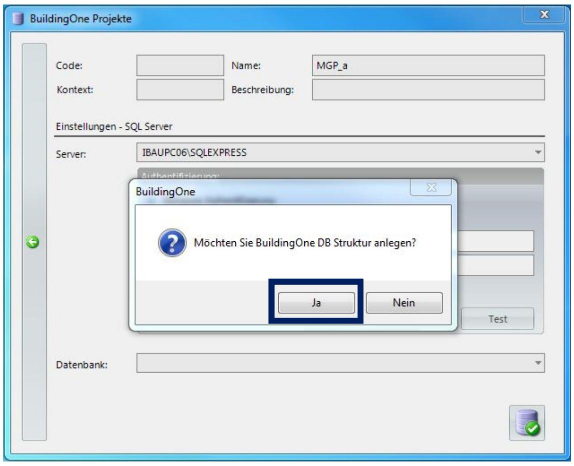


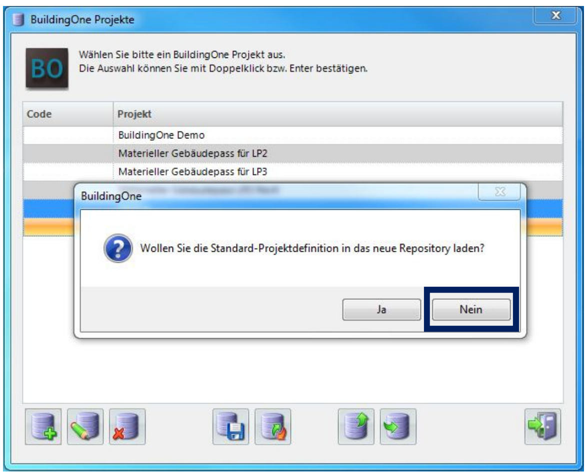
4. Start BuildingOne in order to create a new project. Give the project a name.



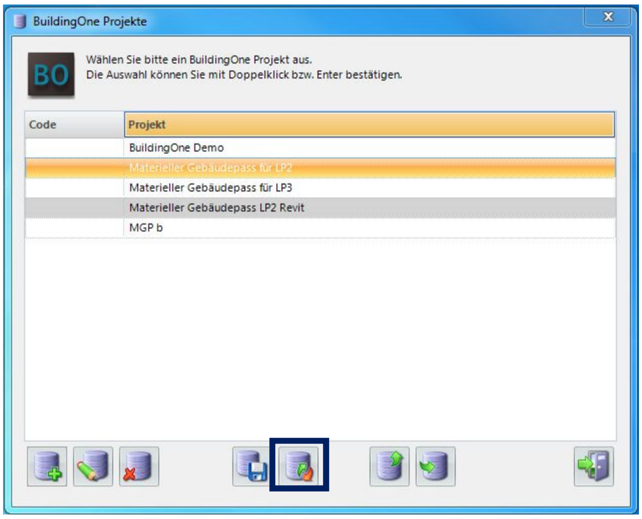
5. Select the SQL-server and establish the connection to the server. Give the project a name and create a new database.



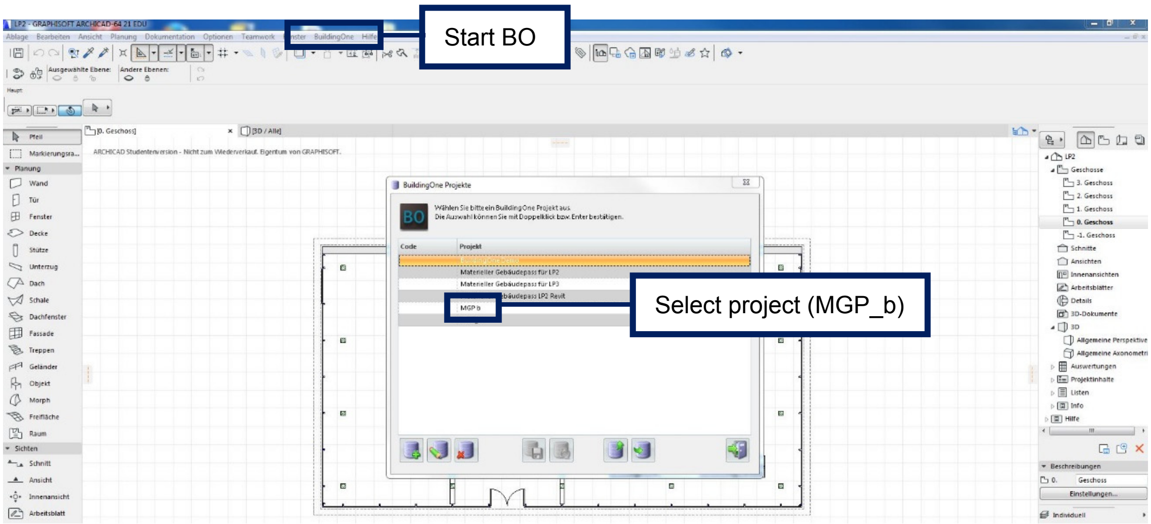




6. Select button „recover project“ and then go to the BO-template file “MPb” (in the figure: MGP_b)

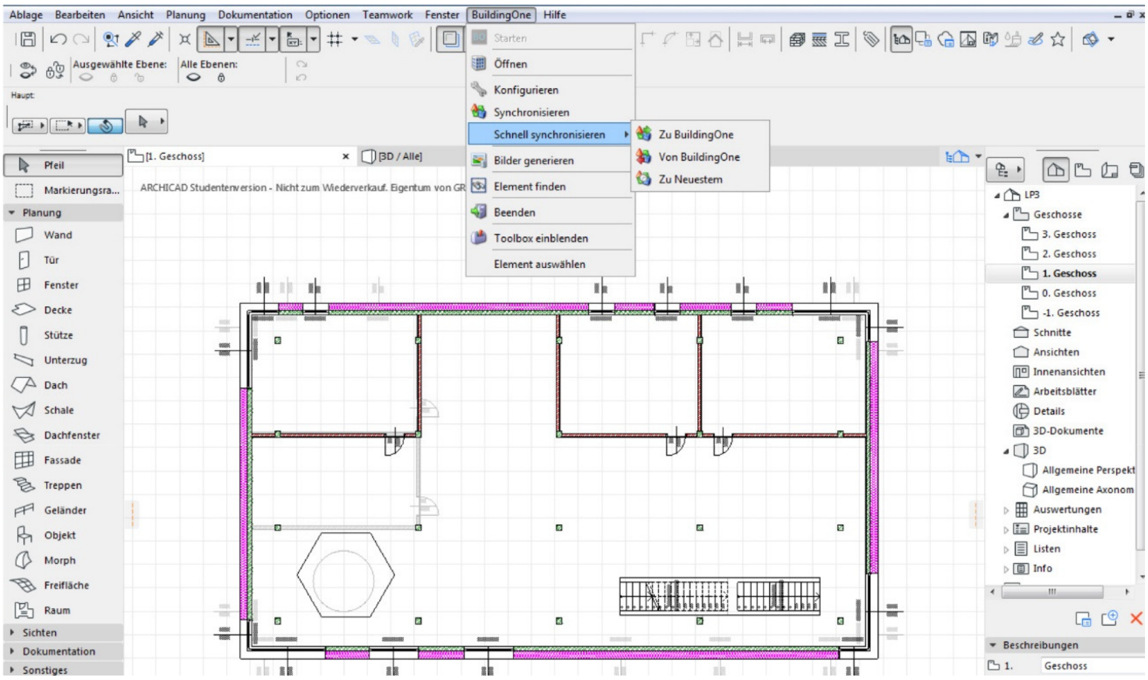


7. Start BuildingOne in Archicad and select the currently loaded project

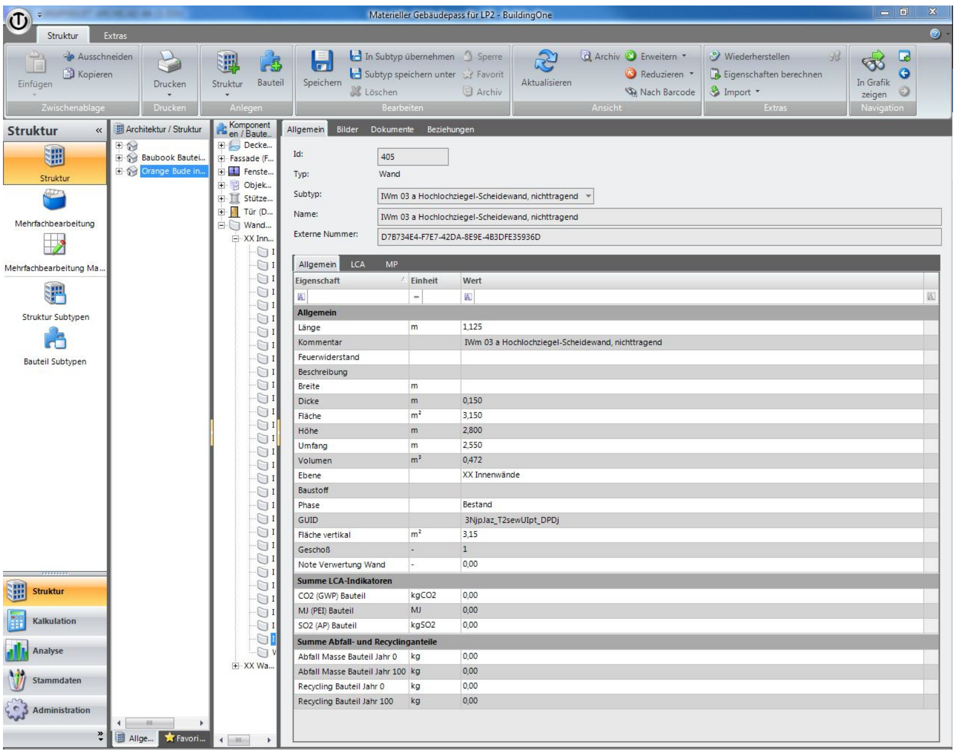


8. Create a new building

9. Select the layercombination „MP“ in Archicad. Then go to „BuildingOne“- „Schnell synchronisieren“(fast synchronization) – „Zu BuildingOne“(to BuildingOne).

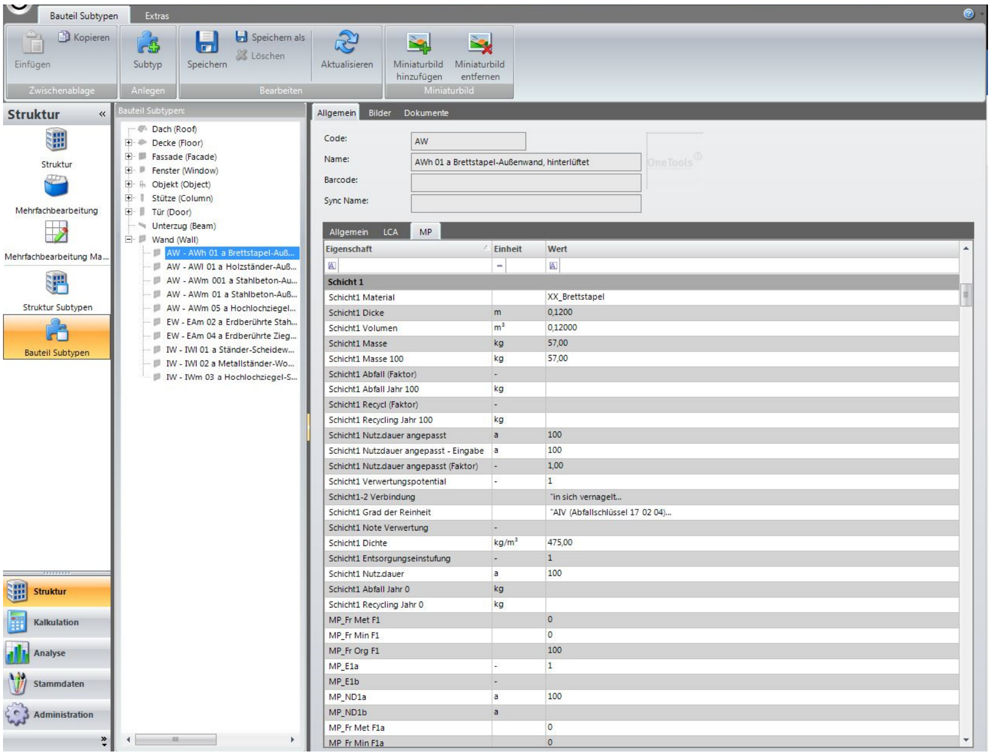


10. Assign the subtypes with the same designation to all elements from the model. Save changes after each assignment.



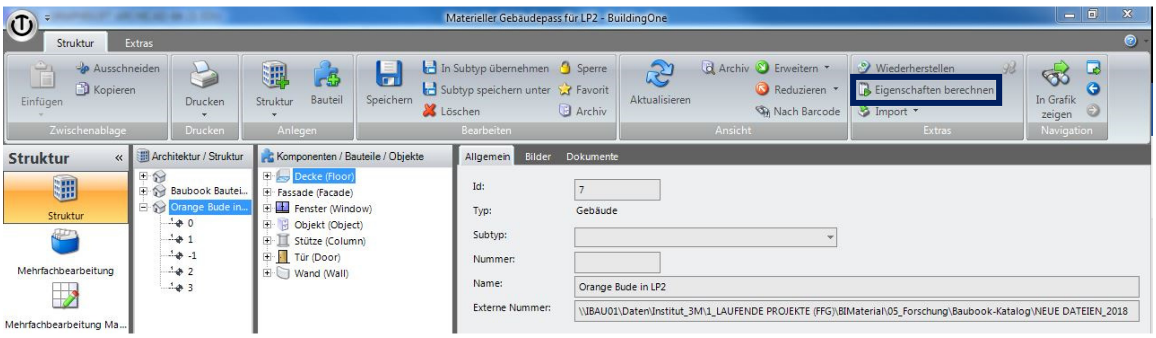
11. Check the results and change layer-thicknesses in order to optimize the model in Archicad, if desired.

12. To change specific materials of an existing element, create a new subtype by copying a similar existing one in BuildingOne and adjust the properties „recycling potential“ (Verwertungspotential), “life durance adjusted“ (Nutzungsdauer angepasst), „connection type“ (Verbindungsart) and „level of purity“ (Grad der Reinheit).



13. Assign the currently created subtypes to the elements (same as in 10.)

14. Generate the results by selecting “Eigenschaften berechnen” (calculate the properties)



15. Optimize the results by changing thicknesses or specific materials.