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Building Information Modeling and Virtual Reality: Editing of IFC Elements in Virtual Reality

Masterthesis

für den Master of Science Studiengang Bauingenieurwesen

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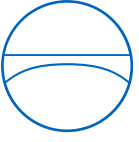
Kurzfassung

In den letzten Jahren hat sich die VR (Virtual Reality) Technologie zu einer der wichtigsten Innovationen in der Industrie entwickelt. Mit Hilfe von HMDs (Head-Mounted Displays) sind immersive Erfahrungen in einer computer generierten Umgebung möglich. Dabei können sich Nutzer in einer virtuellen Welt bewegen und mit ihr interagieren. In der Bauindustrie hat sich zudem BIM (Building Information Modeling) als neuester Standard hinsichtlich Planung, Umsetzung und des Betriebs von Gebäuden und Infrakstrukturbauwerken etabliert. Durch digitalisierte Prozesse und standardisierte Datenaustauschformate wie den IFC (Industry Foundation Classes), ist mit Hilfe von BIM ein effizientes und planungssicheres Bauen möglich. Dabei spielt die Kommunikation zwischen den Projektbeteiligten durch die Visualisierung von BIM Daten eine entscheidende Rolle. Die Visualisierung von BIM Daten in VR bietet Nutzern die Möglichkeit zukünftige Bauwerke maßstabsgetreu zu erleben und damit Planungsfehler frühzeitig zu erkennen und sie zu korrigieren. Diese Arbeit erörtert die Anwendungsmöglichkeiten von VR in BIM sowie die Bearbeitung von IFC Modellen in VR.

Kurzfassung

Abstract

In recent years VR (Virtual Reality) technology has become one of the most important innovations in the industry. With the help of HMDs (Head-Mounted Displays), immersive experiences in a computer-generated environment are possible. In this way, users can move and interact with a virtual world. In the construction industry, BIM (Building Information Modeling) has emerged as the latest standard in the planning, implementation, and operation of buildings and infrastructure. Through digitized processes and standardized data exchange formats such as the IFC (Industry Foundation Classes), efficient and reliable planning is possible with the help of BIM. There, the communication between the project participants through the visualization of BIM data plays a decisive role. The visualization of BIM data in VR offers users the opportunity to experience future buildings true to scale and thus to recognize planning errors early and to correct them. This paper discusses the application possibilities of VR in BIM as well as the editing of IFC models in VR.

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Glossary

AEC	Architecture, Engineering, and Construction
AR	Augmented Reality
BCF	BIM Collaboration Format
BIM	Building Information Modelling
BMVI	Bundesministerium für Verkehr und digitale Infrastruktur
Brep	Boundary Representation
bSI	Building Smart International
BSI	British Standard Institution
BVRS	BIM-VR Real-time Synchronization
CAD	Computer-Aided Design
CDE	Common Data Environment
COBie	Construction Operations Building Information Exchange
DUI	Diegetic User Interface
EIR	Employee's Information Requirements
FBX	Filmbox
FPS	Frames Per Second
GDP	Gross Domestic Product
HMD	Head-mounted Display
HMI	Human-machine Interface

IaaS	Infrastructure as a Service
ICT	Immersive Computing Technology
IDM	Information Delivery Model
IFC	Industry Foundation Classes
IOM	Input-Output Module
ISG	Implementation Support Group
ISO	International Organization for Standardization
MIDP	Master Information Delivery Plan
MSG	Model Support Group
MRM	Mesh Regeneration Module
MVD	Model View Definition
NBS	National Building Specification
NIBS	National Institute of Building Sciences
PaaS	Platform as a Service
R&D	Research and Development
SaaS	Software as a Service
SDK	Software Development Kit
STEP	The standard for the Exchange of Product Model data
UI	User Interface
VR	Virtual Reality
WPF	Windows Presentation Foundation

1   Introduction and motivation

Since the beginning of human existence, people have shaped their environment to ensure their survival. They had, therefore, to explore their surroundings, taking advantage of natural resources to develop new tools and techniques, which gave them protection from natural hazards. To achieve this goal all intentions have been done as a team which created the awareness of organized communal work, which is the key to success in building projects until today.

Through technical progress in the past millennials, the complexity of feasible construction projects increased which led to excellent constructions like the pyramids from ancient Egypt, temples from ancient Greek, aqueducts from the Romans or complex dome constructions in the Middle Ages. By increasing the complexity and size of construction projects, also more participants with diverse technical backgrounds were involved, which resulted in an increased coordination effort. Latest after the Industrial Revolution, with the introduction of the division of labor, proactive management and communication became the fundament of successful planning in all industry sectors. Globalization and the opening up of new markets in recent decades enabled the collaboration of international professionals, realizing outstanding building and infrastructure projects worldwide.

1.1   Introduction

Nowadays, architects, designers, and engineers have to deal with way more requirements for the creation of buildings compared to there ancestors. External influences like climate change, rural depopulation, or new ways of mobility must be considered in the design and construction of buildings and infrastructure. To meet these challenges, it requires an efficient collaboration of specialized workers. However, distributing the project in different working areas also leads to many interfaces and therefore to an increased effort to manage technical cooperation. Especially in the fragmented building sector, misplanning and lack of communication between the project stakeholders result in additional costs in big projects like "Stuttgart 21" or "Berliner Flughafen."

To avoid such scenarios as just mentioned new ways of working and new planning tools must be developed and integrated. One of the most important technology in the

architecture, engineering, and construction (AEC) industry is the digital working method Building Information Modeling (BIM). BIM offers new opportunities to improve collaborative work in the AEC industry. While BIM has been playing an important role in other European countries (especially in the UK or in Scandinavia) since a few years already, the implementation of BIM in Germany is still cautious. However, since the published "Stufenplan Digitales Planen und Bauen" by the Federal Ministry of Transport and Digital Infrastructure at least the public sector is forced to use this new digital tools in Germany (BMVI, 2015).

Another upcoming technology is Virtual Reality (VR). VR has its roots in the gaming industry and is meanwhile one of the most promising new technologies in the industry. As with the development of computer games, 3D models for instance of a building can be integrated into a game. In this game, users can navigate and explore the virtual 3D model of the building. Using so-called head mounted displays (HMD) users can even experience the 3D world immersive and scaled. Thus the user thinks that he or she is located within the virtual world – in the so-called VR.

1.2 Aim of thesis

The objective of this work is to bring the digital working method BIM and the visualization tool VR in one common context. For this purpose, it is examined to what extent VR can support BIM. This thesis arises the following questions:

- What possibilities offers VR?
- What features of VR are suitable for BIM?
- Can VR support BIM?
- Can BIM models be edited in VR?

1.3 Structure of work

Based on these questions, the structure of the work results in five main chapters.

Firstly, to identify possible use cases for VR in the BIM workflow, BIM itself has to be explained. Therefore, important terms, data types and the BIM workflow will be defined. Because the latter part of the work deals with visualization and editing of BIM -models, the underlying data type IFC will be explained in detail (especially the geometric representation of *IfcElements*).

In chapter three the VR technology is clarified. Besides, the explanation of the software and hardware components of VR, a literature review of suitable VR applications in the AEC industry will be given. Afterward, possible scenarios and use cases of VR in BIM are shown.

In chapter four a case study of the successful integration of VR and BIM from the logistics department of BMW is presented.

The last chapter concludes the work with a summary.

2   Building Information Modelling

Digitization is present in all fields of economy and society and will also lead to significant changes in the AEC industry. Therefore, the industry must face numerous challenges but also opportunities to improve productivity in the industry (Leigh, 2018). In the last decades, the AEC industry could not improve their efficiency, although modern technologies like Building Information Modelling (BIM), Virtual Reality (VR) or Cloud Technologies are available and the overall economic productivity constantly increases (Gerbert, Castagnino, Rothballer, Renz, & Filitz, 2016).

One reason for this inefficiency is the lack of digitization in the AEC industry. A published study (see Figure 1) from the consulting group McKinsey shows the level of digitization in the construction industry compared to other industry sectors (Agarwal, 2016).

It is apparent that there is no general digitalization approach which fits for every industry. Because of industry-specific characteristics, the adoption of modern technologies and processes in the AEC industry is different compared to other sectors. One of these characteristics is the uniqueness of each building. This character arises due to the demands of the individual constructors, various stakeholders, the location of the building project and the applied construction procedures (Bargstädt, 2010). Furthermore, as every building is being built only once, standardized processes are more difficult to implement compared to series production like car manufacturers (Reinheimer, 2017).

There is much potential in the digitization of communication and processes in the building sector. The exchange of information, like construction plans, is still mainly done in the paper form, which causes an enormous effort of information procurement and request. This form of collaboration and data exchange is still dominating the market which leads to loss of information and inconsistent data during the whole life cycle of a construction project for all stakeholders (Biggs, 2017).

McKinsey Global Institute industry digitization index; 2015 or latest available data

Relatively low digitization — Relatively high digitization

● Digital leaders within relatively undigitized sectors

Assets | Usage | Labor

Columns: Overall digitization[1] | Digital spending | Digital asset stock | Transactions | Interactions | Business processes | Market making | Digital spending on workers | Digital capital deepening | Digitization of work

Sector
- ICT[2]
- Media
- Professional services
- Finance and insurance
- Wholesale trade
- Advanced manufacturing
- Oil and gas
- Utilities
- Chemicals and pharmaceuticals
- Basic goods manufacturing
- Mining
- Real estate
- Transportation and warehousing
- Education
- Retail trade
- Entertainment and recreation
- Personal and local services
- Government
- Healthcare
- Hospitality
- Construction
- Agriculture and hunting

[1]Based on a set of metrics to assess digitization of assets (8 metrics), usage (11 metrics), and labor (8 metrics).
[2]Information and communications technology.

Figure 1: Digitization of the Construction Industry to other sectors (Agarwal, 2016)

Not using the high potential of automatization and digitization for planning and construction processes can also be seen using low investments in research and development (R&D). Although the construction sector has, according to (Gerbert et al., 2016) annual revenues of nearly $10 trillion, or about 6 percent of the global gross domestic product (GDP) in 2016, it invests less than one percent of its revenues in R&D, whereas the automotive or aerospace sectors invest 3.5 to 4.5 percent of their revenues into R&D.

Fact is, the AEC industry must increase their productivity and efficiency to follow up the other industry sectors and to avoid costs and schedule overruns of construction projects, like the "Elbphilharmonie" or "Stuttgart 21". Achieving this goal is only possible by using new digital tools, like VR or cloud technologies with the BIM model as the core data source for all project stakeholders.

Before explaining VR and its potential in combination with BIM, the most important BIM terms and BIM itself will be described.

2.1   What is Building Information Modeling?

Building Information Modelling (BIM) is defined as a working method, which is based on collaborative design, construction and operation of a building with all stakeholders involved in this project. The main goal is the continued use of all data of the building throughout the whole life cycle of a building (buildingSMART, 2018). Therefore a digital twin of the future building must be designed, containing all relevant semantic and geometrical data of the building, accessible for all stakeholders in a shared digital space, known as a common data environment (CDE). This digital twin is called the BIM model (Borrmann et al., 2018).

Besides additional semantic data, the particular aspect of a BIM model compared to a "classical" computer-aided design (CAD) 3D model, is the 4D (+time), 5D (+costs), 6D (+as built) or rather 7D (+life cycle) character (Aengenvoort, 2016).

By adding the time dimension to the geometric 3D model, a construction schedule and workflow simulation is feasible. With the help of the monetary data of the building, construction costs can be calculated in the tender phase already. 6D and 7D are dimensioned for "BIM in operation." 6D is thereby the connection between the construction and operation phase. As built assets are automatically transferred to the operation phase and can then be used for further facility management software (Batlle, 2017). With the help of 7D, the preliminary calculation of operation and life-cycle costs can be done in the design phase (Aengenvoort, 2016).

With the help of the BIM model, faster analysis and validation of planning alternatives are possible, and the model can be adjusted in early project stages, if necessary. Furthermore, collision checks between the different models of the disciplines are possible at certain project stages, which can spare the project stakeholders from unpleasant surprises on-site during the construction phase.

To ensure the efficient and smooth operation of BIM, all digital processes and data interfaces must be predefined.

Therefore it is mandatory to provide rules and software independent data standards. For the exchange of BIM-models, the standardized Industry Foundation Classes are used. If non-proprietary standards like IFC are used, the so-called openBIM approach is applied (buildingSMART, 2018).

2.2 Industry Foundation Classes and buildingSMART International

While the designing, construction, and operation phases much different software are used. To ensure collaborative work with consistent data and to guarantee the interoperability of these various tools, a non-proprietary data standard which contains all necessary information of a building is needed. Also, this data structure claims to access this information at any time during the whole life cycle of the building project – from planning to demolition (Borrmann et al., 2018).

For this reason, the IFC as an open data standard for digital description and exchange of BIM models was developed. It is maintained by "buildingSMART - the international home of openBIM" (BuildingSMART-Tech, 2018a). This international independent, no-profit organization is divided into two sub-committees: The Model Support Group (MSG) and the Implementation Support Group (ISG). The MSG is mainly responsible for the development and maintenance of the IFC specifications and their implementation into IFC compatible software. Furthermore, it coordinates the Model View Definitions (MVD), a subset of the IFC format which allows users to handle only the parts of IFC that they need for their project. The MVD itself and one example, the so-called Construction Operations Building Information Exchange (COBie) will be explained in detail in chapter 2.4.2.

Nowadays, according to continuing globalization, a lot of international stakeholders are involved in a construction project. Using the BIM approach only makes sense if all participants from all countries are implementing BIM in their workflows and use IFC for exchanging relevant data.

For this reason, buildingSMART International (bSI) consists of several chapter members. Every country can form a chapter, representing the vision and interests of bSI in its designated territory (for example the buidlingSMART e.V. in Germany). Using the chapters, each country can contribute to the BIM standards. Thereby country-

specific differences of the AEC industry are considered, and a suitable BIM-implementation strategy can be developed for each country, being in the framework of the bSI community (BuildingSMART-Tech, 2018a). How the technical structure of IFC looks like is explained in the following chapters.

2.2.1 Structure of IFC - STEP and EXPRESS

BIM is following the approach of integrated product modeling (Grabowski, Anderl, Polly, & Warnecke, 1993). Using this approach, it is possible to capture all data of complex engineering systems (e.g., a construction project) considering consistent and lossless model data transfer at any project phase. Therefore, it is necessary to specify and structure the relevant data for all possible task. Since 1984 product models are specified semantically and syntactically by the International Organization for Standardization (ISO) with the ISO Norm 10303-Standard of the Exchange of Product Model Data (STEP) (Haas, 1993). Based on this standard the IFC were developed and had their own official ISO-Standard (ISO 16739:2013) since the release of IFC4.

Although the IFC standard is meanwhile independent of the STEP-format, the technology of the STEP-standard was adopted. One important adopted feature is the data modeling language EXPRESS (Borrmann et al., 2018). With the help of this specification language, complex product models can be exchanged. According to the EXPRESS specification, which describes the product model on a logical level, the physical STEP – exchange file is built. Figure 2 shows an example of the representation of a polygon in EXPRESS as well as a specific exchange file in the STEP-format. The STEP file is an ASCII file in which individual data records with their attributes and references to other data records are displayed in sequential order (Zilch, Diedrichs, Katzenbach, & Beckmann, 2013).

EXPRESS-Definition	STEP-Austauschdatei

ENTITY cartesian_point
  SUBTYPE OF (point);
  Coordinates : LIST [3:3] OF length_measure;
END_ENTITY;
 	
ENTITY poly_loop;
  polygon : LIST [3:?] OF cartesian_point;
END_ENTITY;
	#77 = CARTESIAN_POINT ((0, 0, -3.4));
	#78 = CARTESIAN_POINT ((1.1, 0, -3.4));
	#79 = CARTESIAN_POINT ((0, 2.1, -3.4));
	#80 = POLY_LOOP ((#77, #78, #79));

Figure 2: Specification of a polygon in EXPRESS and exchange STEP file (Zilch et al., 2013)

Based on the concept of the specification of product models with EXPRESS and the provided exchange interfaces of STEP in the ISO 10303 the IFC were developed. The

aim is to describe the complex relations between the needed exchange information in a building project, structured in a heretical object orientated way (Zilch et al., 2013). The hierarchy of the IFC and a more detailed description of the entities and attributes of the standard will be described in the upcoming chapters.

Besides the description of IFC in a standard data modeling language like EXPRESS, it is also possible to use the extensible markup language (XML). The so-called ifcXML can be either generated directly from the sending application or the EXPRESS format. IfcXML files are usually 300-400 % larger than an IFC file in EXPRESS (bSI, 2018a).

2.2.2 Hierarchy of IFC

The architecture of IFC is defined by four conceptual layers (see Figure 3), which are structured by their level of detail, increasing from bottom to top: Resource Layer, Core Layer, Interoperability Layer, and Shared Layer. Each layer consists of several components (in Figure 3 blue elements) which are assigned to an individual schema. Elements from higher layers are built on elements from lower levels, which means the higher ones can reference the lower ones, but not the other way around (Zilch et al., 2013). Through this modular hierarchy the core elements remain independent (Borrmann et al., 2018).
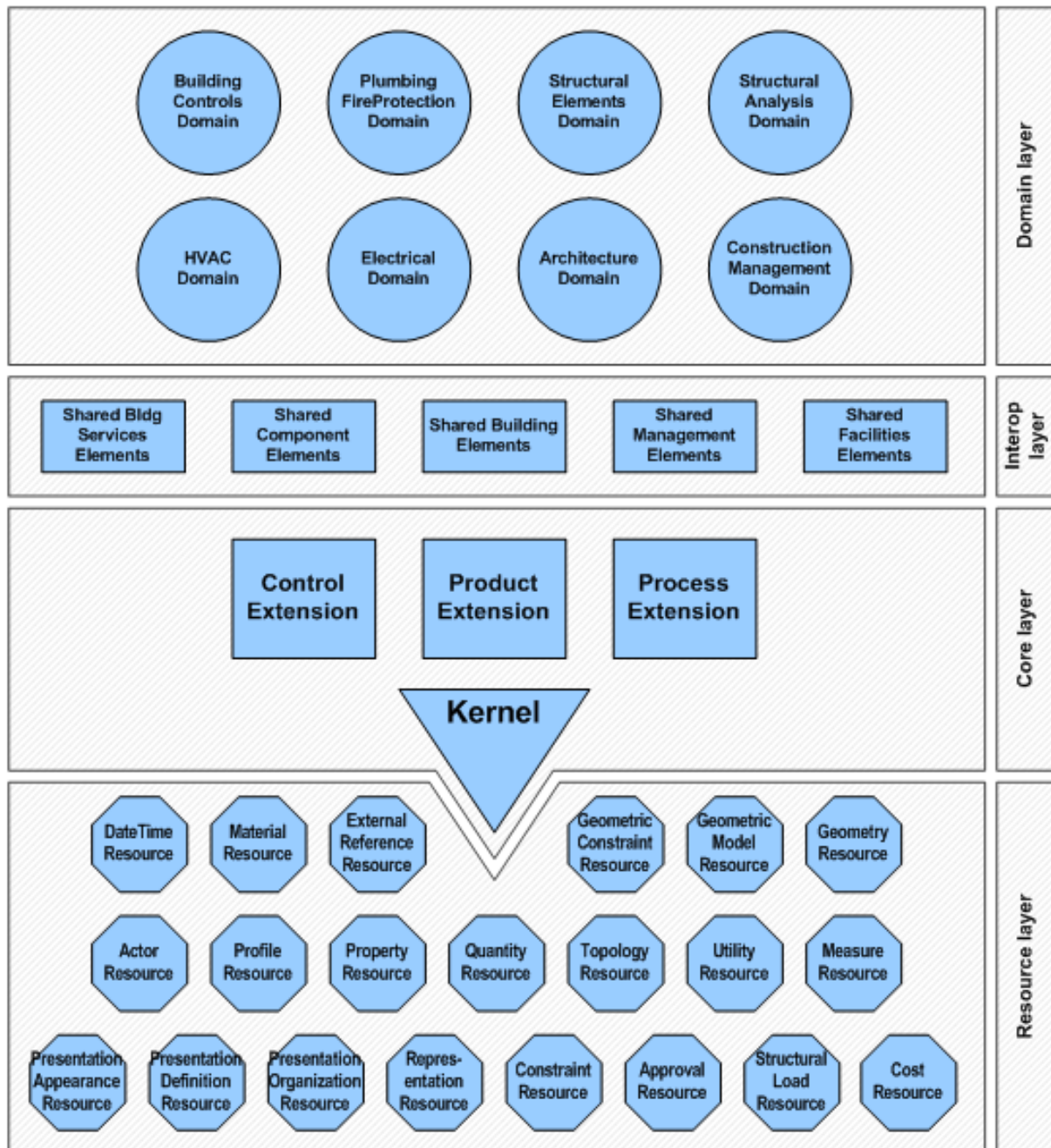
Figure 3: IFC4 Data Schema Architecture (bSI, 2018t)

The individual layers are defined by bSI in the documentation of IFC (bSI, 2018t) and will be summarised briefly.

Resource layer: The lowest layer contains schemas, which cannot exist autonomously but can be applied overall in the IFC model (Borrmann et al., 2018). This means the classes of this layer do not have entities or rather globally unique identifiers (bSI, 2018t). One important schema is the geometry resource which contains basic geometric elements like points or vectors.

Core layer: In this layer, the core elements of the IFC object model are located. "Kernel" and "Core Extensions" define the basic structure, relations and the concepts of the model, which can be specialized and referenced by following higher layers (Zilch et al., 2013). Furthermore, all entities from this layer have a globally unique id. One important schema is the "Product Extension." It contains subclasses of an IfcProduct such as IfcElement, IfcOpeningElement, IfcRelFillsElement and RelVoidsElement (Borrmann et al., 2018).

Interoperability layer: This layer provides entity definitions for concepts or objects, which are used by at least two different domains. The aim is to ensure data exchange between different disciplines (Zilch et al., 2013).

Domain layer: The highest layer includes all classes which can only be assigned to one specific discipline (e.g., architecture). These classes cannot be referenced by another layer or another domain specific schema (Borrmann et al., 2018). These classes are usually applied for information exchange within one domain (bSI, 2018t).

Note: While the description of the IFC hierarchy the focus will be on the needed classes and attributes which are responsible for the geometric representation of IfcElements. To describe the whole structure of IFC in detail would go beyond the scope of this thesis. The reason for the description of the geometric representation in detail is in chapter 4.3 the feasibility of how IfcElements in VR can be modified is presented.

As already mentioned before, IFC is based on an object orientated data model with an inheritance hierarchy. This implies the concept of generalization and specification in the structure of IFC (different layers), which defines attributes from which classes are inherited (Borrmann et al., 2018). The hierarchy is defined by the semantics of each element.

To understand how, e.g., walls or windows are represented in an IFC model and how they can be modified, the concept of the geometric representation in IFC must be explained. Hence, the corresponding classes and their location in the IFC hierarchy must be clarified. In this context, the *IfcProduct* class plays an essential role. However, before having a closer look at this class, the basic structure of IFC and the position of *IfcProduct* in the hierarchy will be explained. In Figure 4 one part of the IFC hierarchy is shown.
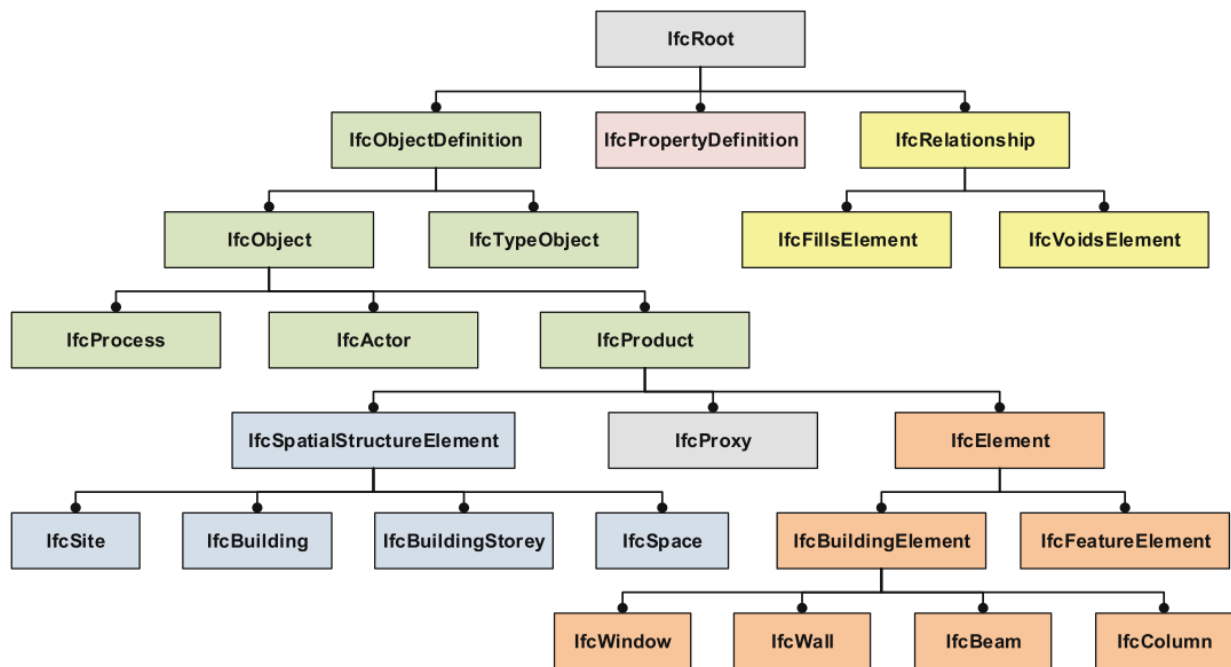
Figure 4: IFC data model with important entities of the top level hierarchy (Borrmann et al., 2018)

The basic class of the inheritance hierarchy is the *IfcRoot* class. All entities which do not belong to the Resource Layer are indirectly or directly derived from this class and can be used independently (bSI, 2018r). The next level of the hierarchy contains the classes *IfcObjectDefinition*, *IfcPropertyDefinition* and *IfcRelationship*. The *IfcObjectDefinition* is the abstract superclass of all entities which are representing either physicals (construction components), spatial (opening) or conceptual elements (costs, processes, etc.) (Borrmann et al., 2018).

To link different building elements with each other (e.g., the window is part of a wall) relations need to be defined. These objectified relationships can be set with the *IfcRelationship* and their subclasses. These relations are very important for linking different *IfcElements* which each other and will be described in detail in chapter 4.3.3.

In the next level the *IfcObject*, the parent class of the previously mentioned *IfcProduct* is located. IfcObject presents the generalization of all semantically treated processes or things in the IFC object model. This includes physically tangible elements like walls, physically existing elements like spaces as well as process related items like work tasks (bSI, 2018i).

Since for the geometric representation neither the processes (*IfcProcess*) nor the involved stakeholders of the construction project (*IfcActor*) are important, the *IfcProduct* and their subclasses will be explained in the following chapter.

2.3   Geometry Representation - IfcProduct and their subclasses

The *IfcProduct* is the abstract representation of all entities in the IFC model which are related to a geometric (*IfcElement*) or a spatial (*IfcSpatialStructureElement*) context (see Figure 4). As described before, the IFC hierarchy is structured semantically with the concept of generalization and specification. Therefore, as shown in Figure 5 the geometric representation is independent of the semantic hierarchy.
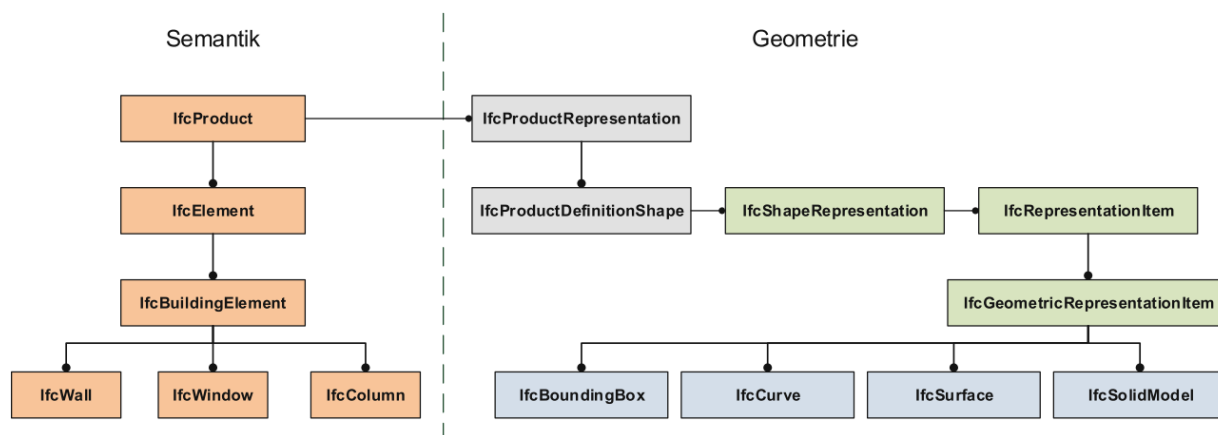
Figure 5: IFC data model: Separation of semantic & geometry of the IfcProduct (Borrmann et al., 2018)

Based on a simple example of a standard wall, the *IfcProduct* and their important subclasses for the geometric representation will be explained. The wall was designed in Revit 2018 and was exported as an IFC4 in Reference View. Figure 6 shows a screenshot of the wall opened in the Xbim Xplorer (Lockley, 2018b).

At the top left corner, the *IfcWallStandardCase* is classified in the spatial hierarchy (*IfcProject, IfcSite, IfcBuilding, IfcBuildingStorey*), while on the right side the 3D view of the IFC model can be seen. At the bottom left side, all the properties of the selected object are shown in a table with two columns. The left column defines the name of the attribute and the right one the corresponding data type or its value.

Besides the *GlobalID, Type, Name* and other properties, the focus will be on the two attributes *ObjectPlacement and Representation* which are framed red. Usually each subtype of *IfcProduct*, in this case, an *IfcWallStandardCase*, holds a shape representation and an object placement (bSI, 2018m). The *ObjectPlacement* is responsible for the correct placement (bSI, 2018j) and the *Representation* (bSI, 2018q) for the geometric representation of the *IfcProduct* in the IFC model.
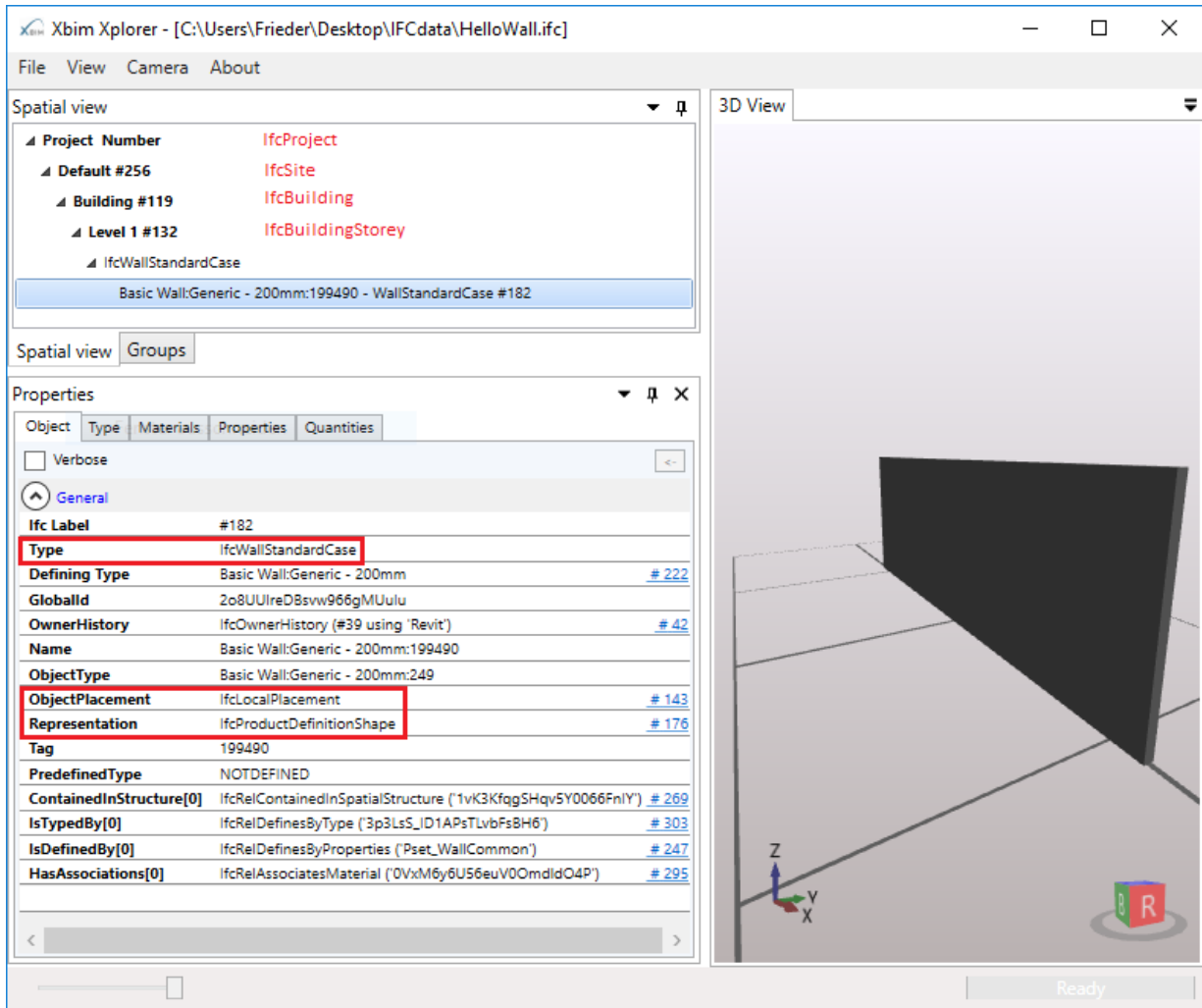
Figure 6: IfcWallStandardCase in XBim Xplorer (Lockley, 2018b)

In Figure 7 the data structure of the IfcWallStandardCase with the *Representation* and the *ObjectPlacement* and their respective data types *IfcProductDefinitonShape* and *IfcLocalPlacement* are highlighted. At the bottom level, the related attributes of the next level in the hierarchy are displayed. In the following two chapters "both sides" of the tree will be explained in detail.
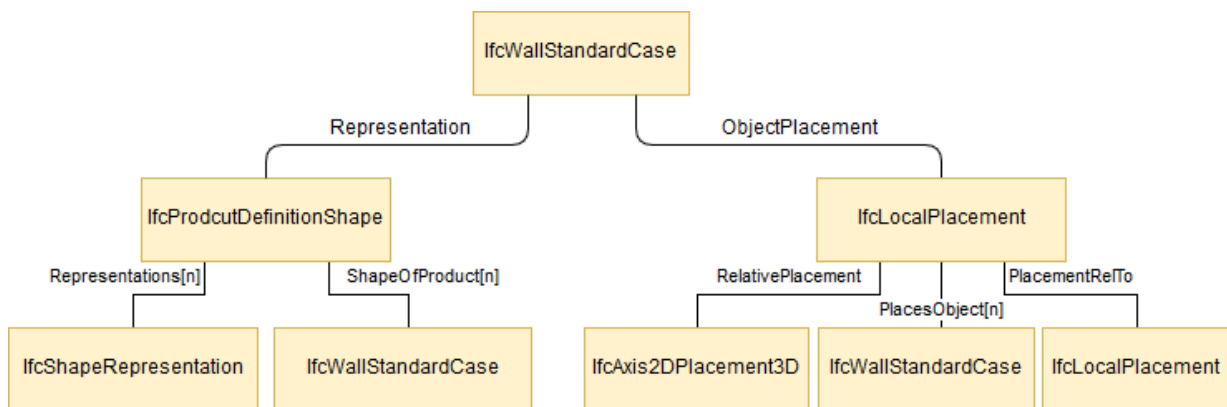
Figure 7: Data Structure of IfcWallStandardCase with the attributes Representation and ObjectPlacement

2.3.1 Geometric shapes – IfcProductDefinitionShape

With the attribute *Representation* (see Figure 7) the *IfcProductDefinitonShape* defines all shape relevant information of an *IfcProduct* (bSI, 2018n). An IfcProduct can have multiple geometric representations, which can be added to a list (*Representations*[n]). Each element (*IfcShapeRepresentation*) of this list describes various geometric representations of the *IfcProduct*. Thus, an *IfcWallStandardCase*, for instance, can be described either in 3D represented via solid geometries like an extruded face or/and in 2D with a polyline. The available representations in 3D/2D for *IfcProducts* are listed in the IFC4 documentation (bSI, 2018s). Using the various representations, the needed geometry for a use case (e.g., for a 2D floorplan) can be requested. The *ShapeOfProduct*[n] implies the inverse list and contains the *IfcProducts* which are shaped by the representation, here the *IfcWallStandardCase*.

In Figure 8 an example of a shape representation as an extruded area (*IfcExtrudedAreaSolid*) is displayed. In this case, the shape of the body (e.g., wall) is created by extruding a cross section (*SweptArea*) to a certain direction (*ExtrudedDirection*) with the desired length (*Depth*). The initial plane is defined as a 2D primitive, here an *IfcRectangleProfileDef* (bSI, 2018e).

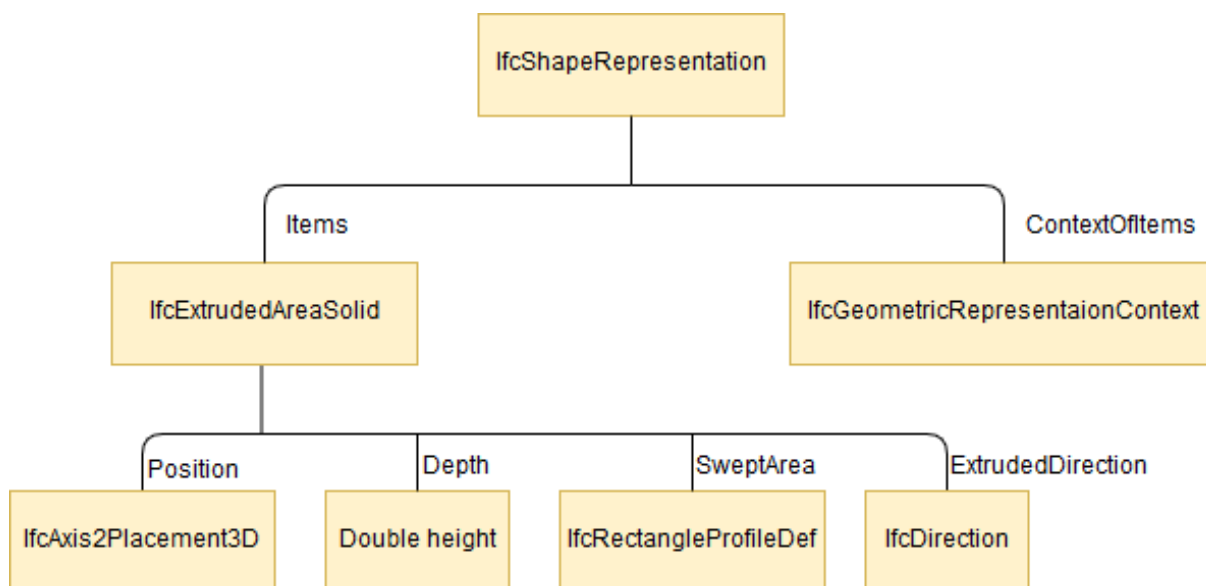*Figure 8: Creation of a 3D body with an IfcExtrudedAreaSolid*

While the *IfcExtrudedAreaSolid* is responsible for the actual shape of an element, the *IfcGeometricRepresentationSubContext* puts the shaped *IfcProduct* in the geometrical context within the whole IFC model (of the *IfcProject* see "Spatial View" in Figure 6). One *IfGeometricRepresentationSubContext* can be applied to several shape

representations of an *IfcProduct* and aligns them in the *IfcProject*. In this context the attributes *WorldCoordinateSystem, CoordinateSpaceDimension, Precision* and *TrueNorth* from the parent entity (*IfcGeometricContext*) are shared (bSI, 2018g).

An *IfcProject* can have minimum one and maximum two *IfcGeometricContexts*. One is mandatory to represent the *IfcProject* in model (3D) view and the second one can be applied if the *IfcProject* needs to be represented in plane (2D) view. Both geometric contexts can have several sub contexts (bSI, 2018f).

Since an *IfcProduct* can have several representations, each representation is assigned to a different *IfcGeometricRepresentationSubContext*. Thus, various views and scales of the IfcProduct can be defined, which enables the control of the level of detail of its shape representation (bSI, 2018g).

Note: *Although this chapter explains the geometric representation of an IfcProduct it is not possible to separate the geometry and their placement completely, so a brief introduction is necessary. The placement (IfcLocalPlacement) of the IfcProduct in detail will be explained in chapter 2.3.2.*

As seen in the data structures the *IfcExtrudedAreaSolid* (see Figure 8) and the *IfcRectangleProfileDef* (see Figure 9) have both a *Position* attribute where they define their coordinate system. However, the *Position* attributes are holding different placement types: one is in 3D and the other one in 2D.
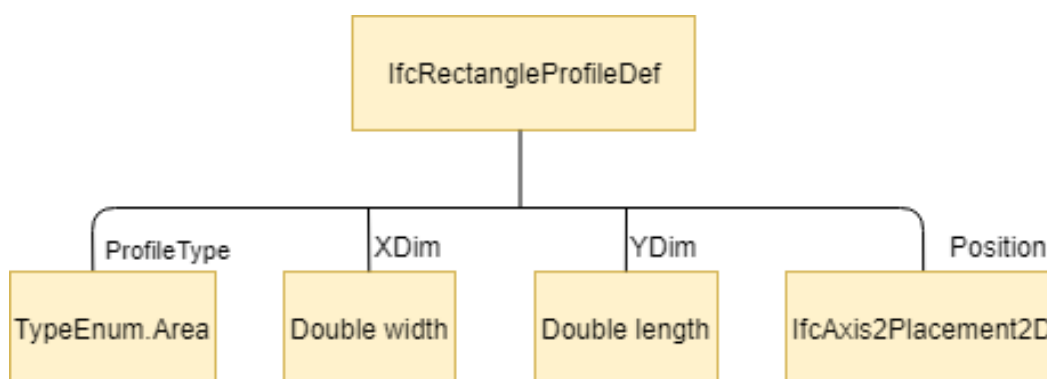
Figure 9: Data structure of profile definition for a swept solid

In the following two cases, which are depicted in Figure 10, the relation between the 3D placement (*IfcAxis2Placement3D*) of the body and the 2D placement (*IfcAxis2Placement2D*) of the swept area will be presented.

In the first case, the 2D profile definition does not provide a position coordinate system, and the profile is placed in the x/y plane of the object coordinate system (see chapter

2.3.2). Because the profile is placed centric within its coordinate system, the 2D position of the rectangle and the 3D position of the body have the same origin (bSI, 2018o).
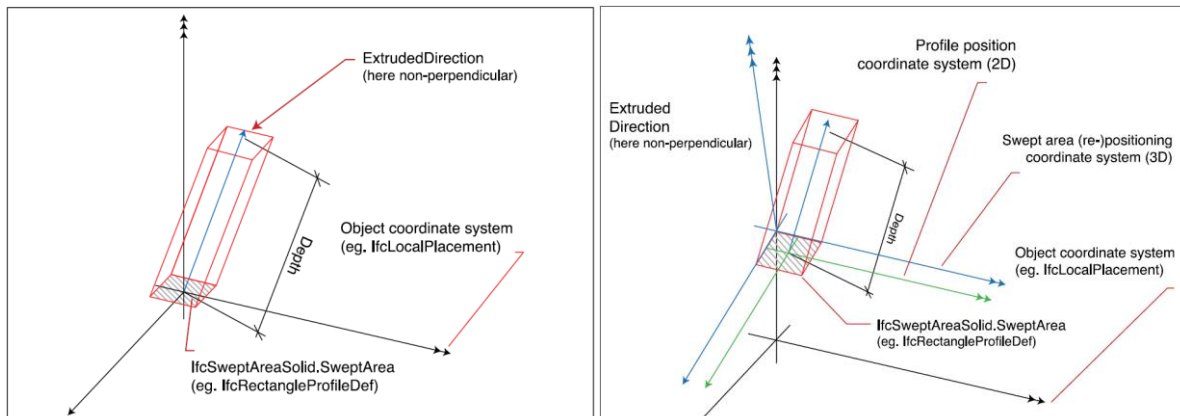
Figure 10: Extruded area solid geometry (left) and repositioned extruded area solid (right) (bSI, 2018e)

If a 2D profile has a coordinates system, the profile is provided by a parameterized profile definition (IfcParameterizedProfileDef). With the parameterized profile definition, the position of the 2D coordinate system of the swept area can be defined at any point within the x/y plane of the underlying coordinate system, here of the swept area (see the right picture the blue coordinate system). Since the origin of the 2D profile is in the center of the bounding box of the profile, it also becomes the origin of the body (bSI, 2018l). The result is a repositioned solid within the object coordinate system (bSI, 2018e).

2.3.2 Placement of geometry – IfcLocalPlacement

Besides the geometry description, the placement (*ObjectPlacement*) of the *IfcProduct* depicts the second important attribute (Figure 7). It is responsible for the definition of the *IfcProduct* coordinate system and holds an *IfcLocalPlacement* which implies three important components: *PlacementRelTo, PlacesObject[n]* and *RelativePlacement* (bSI, 2018j).

There are three different ways to place an *IfcProduct* within the IFC model. Either absolute within the geometric representation context (usually the world coordinate system), about another *IfcProduct* or a grid reference (bSI, 2018j). Since IFC models are usually exported from parametric modeling software (e.g., AutoDesk Revit) where elements are designed about each other, only the relative placement of an *IfcProduct* will be discussed.

If for example a wall is placed on one floor of the building, the coordinate system of the wall is placed about the building storey which is referenced by the attribute *PlacementRelTo*. If this relation is not given, the wall is placed within the world coordinate system (bSI, 2018h). How this relation shall be defined for the various subtypes of the *IfcProduct* is explained in the IFC4 documentation (bSI, 2018h).

While the *PlacementRelTo* defines if the IfcProduct is placed relatively or absolutely, the *RelativePlacement* is responsible for the actual placement of the object. The attribute defines the transformation of the object coordinate system to the relating one, (e.g., to another *IfcProduct* coordinate system) and holds an IfcAxis2Placement either in 2D or 3D (bSI, 2018h).

In Figure 11 the data type *IfcAxis2Placement3D* and its three attributes (*Location, RefDirection, and Axis*) are highlighted. Depending on the attribute *PlacementRelTo* the origin (*IfcCartesianPoint*) of the object coordinate system is given absolute or relative. For the description of the local coordinate system, two axes (Z and X) can be defined. The orientation of the Z (attribute *Axis*) and X (attribute *RefDirection*) axis are described with the *IfcDirection* data type (bSI, 2018d). Using the direction ratios, the data type defines only the direction of the two axes and doesn't imply the length of the vectors (Lipschutz, Spiegel, & Spellman, 2009). The Y axis is derived from the X and Z axis and is always perpendicular to the X-Z plane (bSI, 2018c).
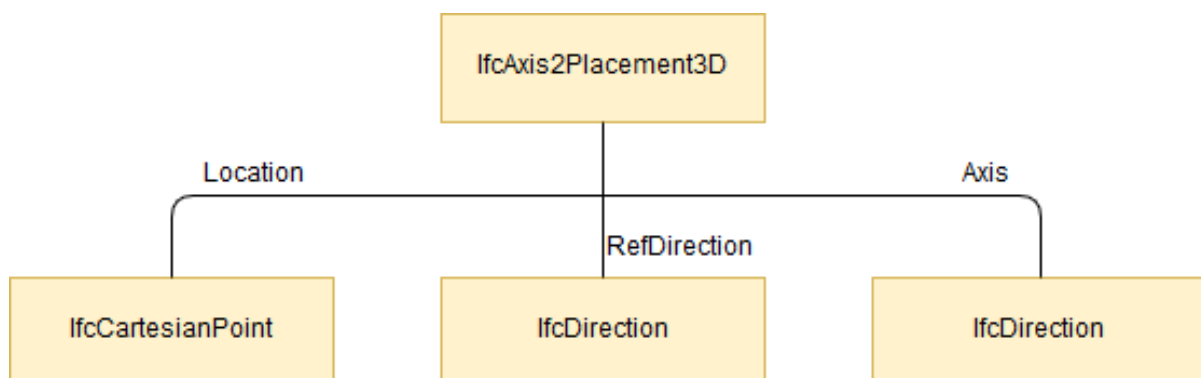
Figure 11: IfcAxis2Placement3D

Through this concept, the location of an *IfcProduct* is defined explicitly. In Figure 12 the explained structure of *IfcAxis2Placement3D* is visualized.
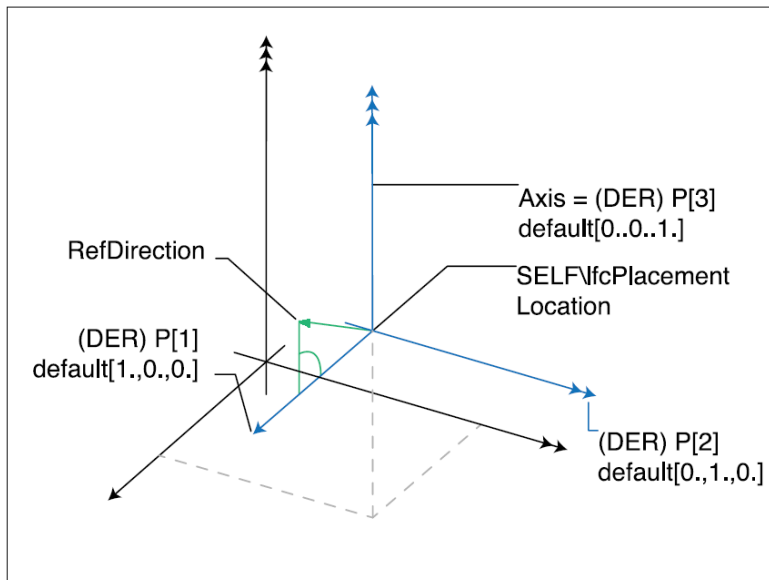
Figure 12: Placement of an IfcProduct in 3D with two axes (bSI, 2018c)

It is essential to understand the concept of the geometric representation of *IfcElements* for visualizing or editing IFC models in the desired software environment (e.g., software for VR applications). Because to access or to edit data of individual objects of an IFC file, the structure where the data is stored must be clear. In Figure 13 the whole data structure from an *IfcWallStandardCase* which was described in this chapter is highlighted.
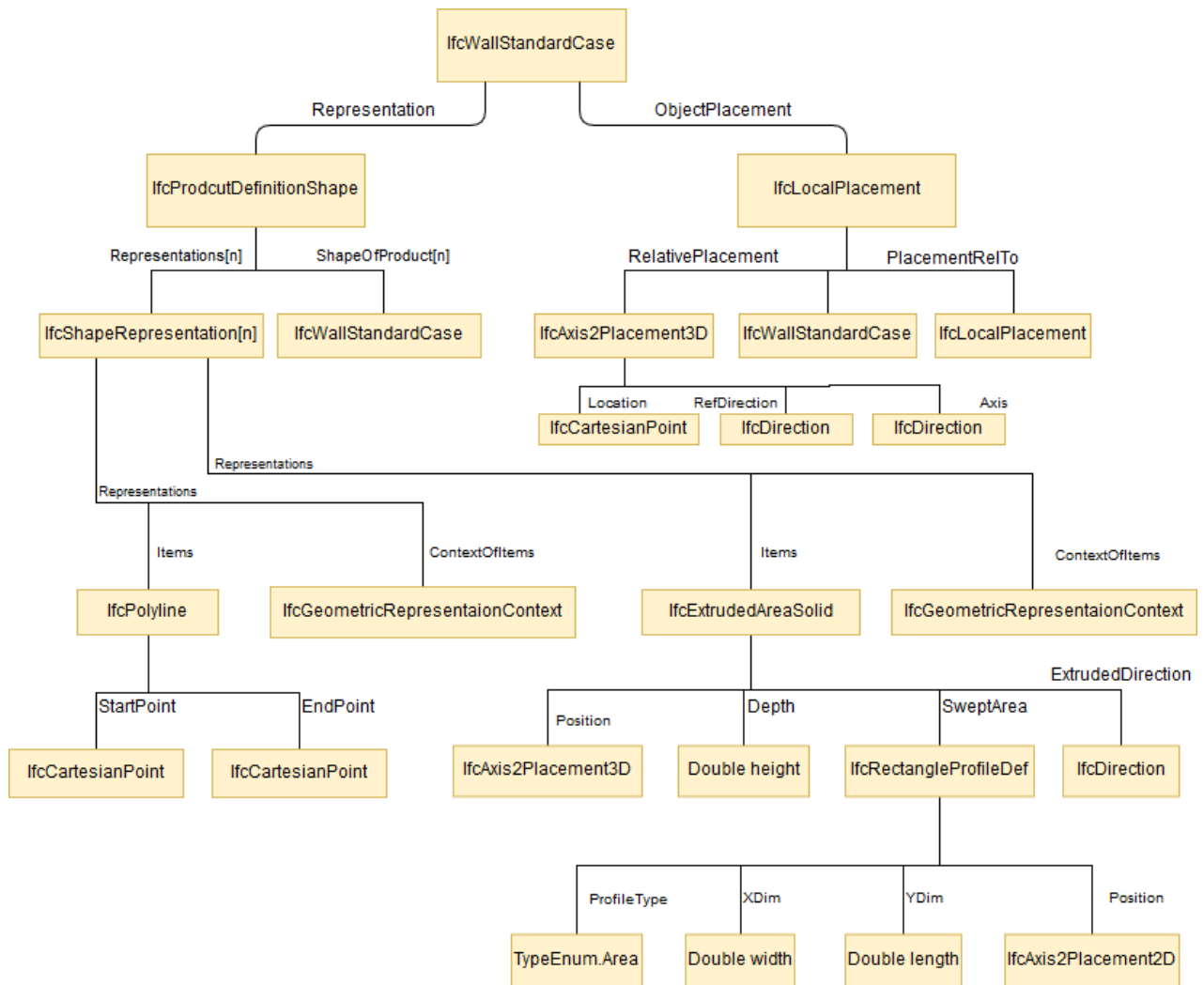
Figure 13: Data structure of an IfcWallStandardCase

2.4 BIM Collaboration

To find suitable use cases for VR applications in BIM, the BIM workflow must be explained in addition to the IFC data structure. Therefore, collaboration formats (e.g., BCF and COBie) and the information delivery circle within a BIM project will be outlined. As already explained at the beginning of this chapter, the essential characteristic of a collaborative BIM project is the exchange of geometric and semantic data during the project phases between the different disciplines. To guarantee a successful BIM project, all stakeholders need to be up to date on the current plans of the design and eventual changes in the construction project. Therefore, all planners must be informed which data must be exchanged at what time of the project. For this reason, standardized processes and data exchange formats are necessary and need to be defined at the start of every construction project.

Before explaining an idealized BIM workflow in chapter 2.4.4 the most important terms need to be clarified. At first, two exchange formats will be explained followed by which role cloud services play in the BIM workflow. At the end of this chapter, a general idealized BIM workflow proposed by the British Standard Institution (BSI) will be clarified.

2.4.1 BIM Collaboration Format

Depending on the BIM use case IFC can contain large data volumes. To avoid exchanging large IFC files after every single update of the model the BIM Collaboration Format (BCF) provides an easier communication tool between users. It is an open BIM exchange interface between different software, based on the IFC standard (buildingSMART, 2018). The BCF was introduced to share issues or to propose design changes in the BIM data model without exchanging entire IFC files (BuildingSMART-Tech, n.d.). The format enables a model-based communication between different modeling software and informs about status, perspective, location and the involved building component of the issue in the corresponding IFC data model.

Figure 14 shows a screenshot of a BCF file opened in the viewer from BCFier - an open source BCF client (Matteo Cominetti, 2018). On the left side, all issues are listed. On the right side the selected issue "Ducts are designed in elevator shaft" is displayed. The issue contains a snapshot of the clash as well as two comments by two different users. Technically a BCF file is a conventional ZIP-Container (Wikipedia, 2018c) containing three components: markup.bcf, viewpoint.bcfv and snapshot.png (Steinmann, 2017).
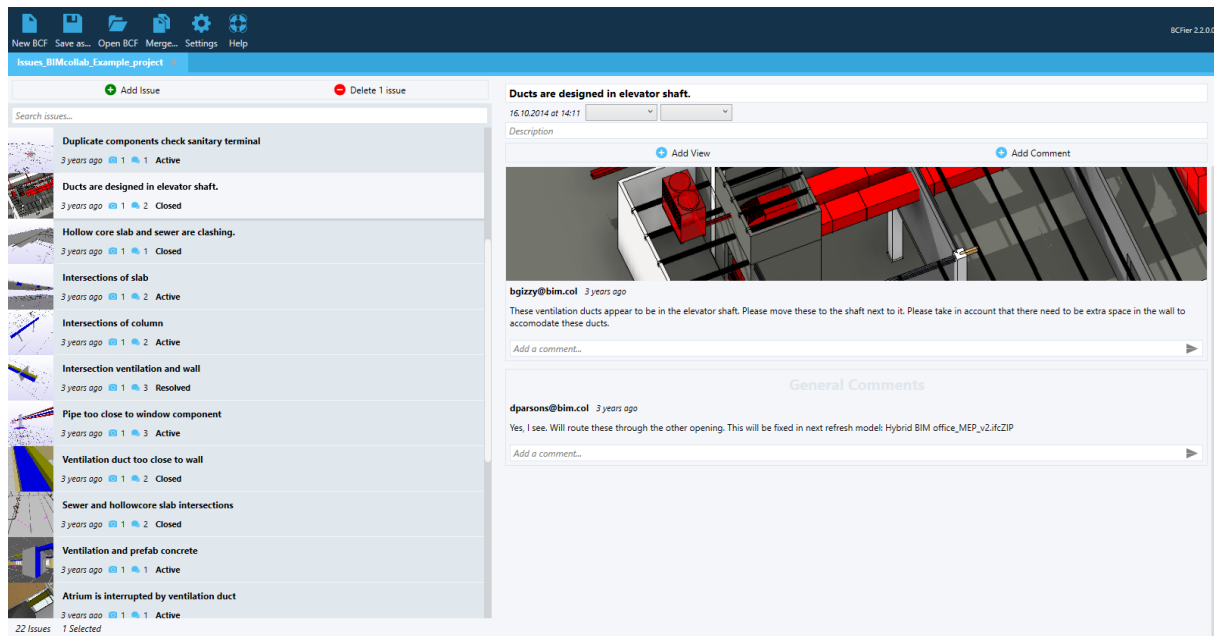
Figure 14: BCF Sample from BIMcollab in BCFier (Matteo Cominetti, 2018)

A BCF file can be created and exported by nearly every BIM authoring software. Depending on the software vendor free Add-Ins are available. The created BCF files can then be gathered and shared on a server, accessible through BCFapi web services for every stakeholder of the project (Steinmann, 2017). One provider for BCF cloud services is BIMcollab (BIMcollab, 2018).

2.4.2 Model View Definition

Another possibility to facilitate the data exchange in a BIM project is to define so-called model view definitions (MVD). On the one hand, comprehensive IFC files with all information are desirable, but on the other hand in many cases, only a small part of the IFC data is needed. For instance, for static calculations, attributes such as floor coverings are just as unimportant as the geometric model of interior design shapes for an energy analysis (Borrmann et al., 2018).

To avoid the transmission of large IFC files and thus unnecessary data, the complexity of the IFC schema can be reduced. It is, therefore, appropriate to specify the IFC format regarding project phase, application, and user. The definition of an IFC subset is called the MVD. To create an MVD one or more data exchange requirements, for instance, the employee and a supplier must be defined.

Each data exchange in a BIM project identifies exchange requirements for software interfaces between the respective project participants. These requirements must specify what information in what data format is transferred. One example of an MVD is

the Construction Operations Building Information (COBie). It is an information exchange specification for the needed data to operate a building and is hosted by the National Institute of Building Sciences (NIBS) (NIBS, 2018).

A proposed procedure how to define information requirements is the Information Delivery Manual Method which was developed by the bSI (BuildingSMART-Tech, 2018b).

2.4.3 Common Data Environment and Cloud Services

On a construction project, much information is produced, often unstructured and difficult to find. To administrate all relevant data a single source of information is needed to avoid duplicates or mistakes (Designing Buildings Wiki, 2018a). This online place is called the common data environment (CDE). Depending on the size and type of the project the CDE in a BIM project can be a project server, an extranet or a cloud-based system. The CDE provides an online place for gathering, managing and sharing data amongst the project members (Fred Mills, 2015). This includes not only data which were created in the BIM environment like IFC or BCF but also conventional digital formats (e.g., .csv) (Designing Buildings Wiki, 2018a).

Standards on how a CDE is implemented in the BIM workflow are provided by the British Standards Institution (BSI) in the specification "Collaborative production of architectural, engineering and construction information – Code of practice BS 1192-2007" and will be summarized in the next paragraph (BSI, 2016a). The BSI is the international market leader of standards, training, and certifications and provides several BIM standards which are claimed world-wide (Wikipedia, 2018a). All-important BIM – standards from the BSI can be downloaded for free (BSI, 2016b).

The CDE - standard is divided into four phases which are illustrated in Figure 15 (the process begins in the top-right corner and continues counter clockwise). In the first phase "Work in Progress," the project members can design their data in-house. This means each concerned architect or planner designs its required output using their organization's software, whereby each organization is responsible for the quality of the data.

After the task teams checked, reviewed and approved their design data, the data is suitable for coordination and can be shared ("Shared Area"). Before the data in the area "Shared" is available for the wider project members (e.g., for tender or

construction), the data must be authorized. The authorization conditions should be defined in an early stage of the project (see Standard PAS 1192-2). Are the conditions satisfying the coordinated and validated design output can be used by the whole project team ("Published Documentation")?

After the design and the construction phase, all data (e.g., models, documents, asset register, etc.) are available in the "Archive" and can be used for operation, maintenance or demolition of the building.
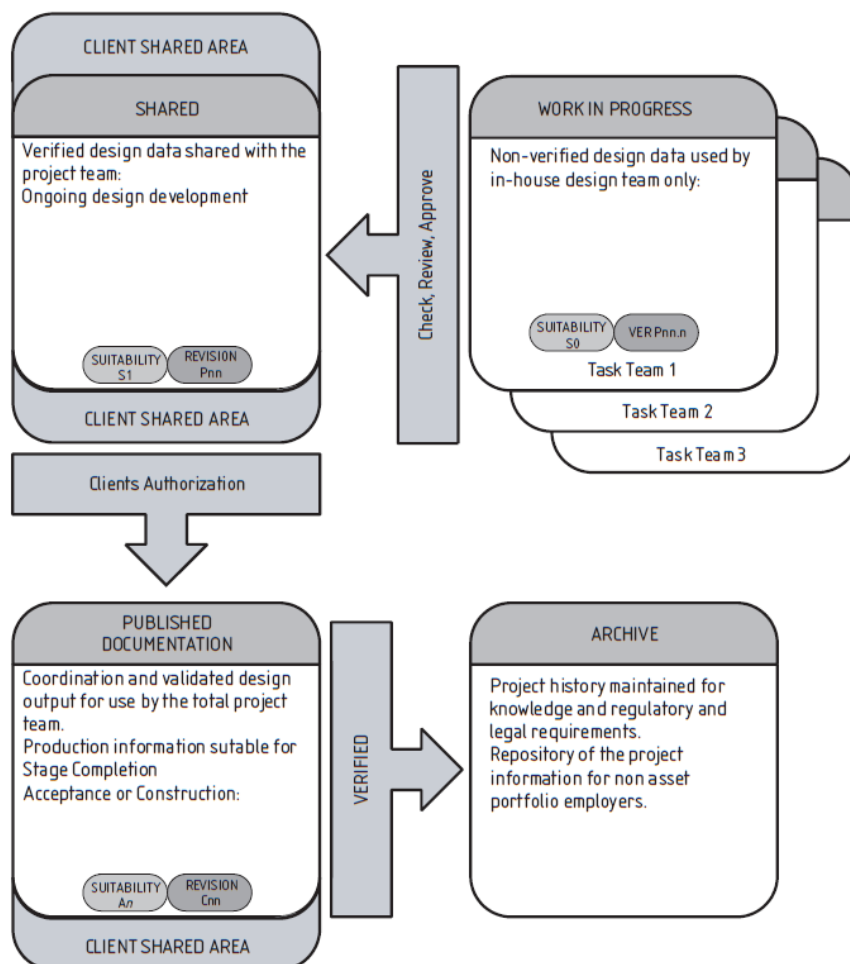
Figure 15: Document and Data Management according to BS 1192:2007 (BSI, 2016a)

Although the standard was developed on a state level, the specifications are adopted by other countries as well. The BIM Task group which is responsible for the BIM implementation in Europe has identified the CDE as a key process criterion in their "Handbook for the Introduction Building Information Modelling by European Public Sector" (EUBIM Task Group, 2016).

To upload, share and retrieve the data in the CDE a service is needed, to guarantee easy and fast access to the appropriate project stakeholders. As in many other

branches, an efficient and easy way to share and access information is using cloud computing technology (Mell & Grance, 2011). As already mentioned before a CDE must not be provided in a cloud-based system, but its use is becoming increasingly important in the AEC-industry (Afsari, Eastman, & Shelden, 2016).

The cloud architecture consists of several layers between the client, who wants to request and the server, which provides the data. Depending which layers the user wants to use or edit three major types of cloud services are possible: Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS) (Mell & Grance, 2011). The different services are highlighted in the image below.
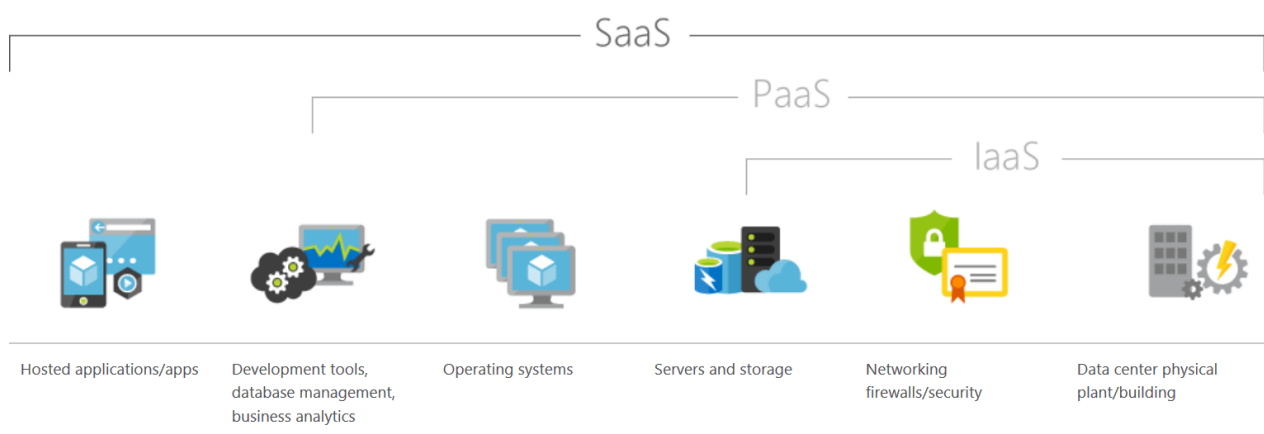
Figure 16: Framework of cloud computing (Microsoft Azure, 2018)

The IaaS is the most basic service in cloud computing and provides the consumer servers, storage, networks, hardware and other fundamental computing resources. Clients can deploy their operating system, development tools and arbitrary software. In comparison to IaaS, PaaS gives the customer the capability to only deploy his applications onto the cloud infrastructure (Mell & Grance, 2011).

In contrast to IaaS and PaaS, SaaS offers an "all inclusive" solution for customers. This includes hardware (servers, networks, etc.) as well as a complete software solution (app, middleware, etc.). The user can purchase the software from a cloud service provider on a "pay-as-you-go" basis. This means users pay rent for the SaaS to use the service over the internet (usually with a web browser). The service provider is responsible for the security and availability of data of the user (Microsoft Azure, 2018).

The SaaS is a perfect use case for the requirements of a CDE: a web-based client for uploading, retrieving and updating data no matter if users are at the office or on site. Therefore, software vendors like Oracles Aconex (Aconex, 2018) or ThinkProject (ThinkProject, 2018) are offering CDEs with an integrated SaaS. They provide so-

called virtual project rooms where all stakeholders of a construction project can access the corresponding data. Using a folder-permissions-matrix, the administrator of the virtual project room can specify which user has which rights to read, upload or edit data. The matrix is set at the beginning of the construction project and is uploaded to the project room as a CSV file (Conject, 2018). Why the CDE plays a key role in the BIM workflow, it is explained in the following chapter.

2.4.4 Common Data Environment in the BIM Workflow

As explained in the previous section, the CDE is the single source for all relevant data during a construction project. This includes all data from the design, construction and operation phase. The CDE is, therefore, a key instrument of a BIM-project. To ensure the success of a BIM project, requirements for quality, type and the time of data drops of the corresponding data needs to be specified at the beginning of each BIM-project. Guidance for that gives the BSI with several norms and standards.

In Figure 17 the standard for an ideal and conceptual BIM workflow in the capital and delivery phase with the CDE in the center is highlighted. In the following, this workflow from the BSI is explained briefly to find suitable use cases for the integration of VR applications in the BIM processes in the next chapter.

The information delivery cycle of a BIM project starts either in the top right corner at the box "Need" if it is a building from scratch, or at the right-hand arrow "Assessment" if it is a project on existing buildings (BSI, 2013). Here the processes will only be described for buildings from scratch.

Firstly, the owner or investor of the future building must specify the so-called employer's information requirements (EIR). The EIR define what information the employer requires from their internal team and suppliers for the development of the project and the operation of all built assets. This includes documents, model files (e.g., IFC, BCF) and when data should be exchanged in the project life cycle. Sections of the EIR are then included in the procurement processes with each supplier including contractors, consultants, advisors, etc.. (Designing Buildings Wiki, 2018c).

After the prospective suppliers respond with a pre-contract BIM execution plan (BEP) which implies their approach, capacity, and capability the employer evaluates the appropriate offer. If the pre-contract BEPs are suitable, suppliers integrate their proposals in the master information delivery plan (MIDP). Naturally, the definition of

the EIR and the provision of a BEP is an iterative process (Designing Buildings Wiki, 2018c).

In the MIDP all information deliverables are listed. If there is more than one supplier, an overreaching BEP and MIDP should be developed. The MIDP sets out what information is required, who is producing it in which format by whom for every project stage. It is, therefore, the basis for all data exchange of the whole project (Designing Buildings Wiki, 2017).

To guarantee a consistent data exchange between the different project teams the CDE is the key online platform. Here the project stakeholders drop and retrieve their data in corresponding project stages. Usually, seven data drops (after each project stage) are intended in the workflow: Brief, Concept, Definition, Design, Build & Commission, Handover & Closeout, Operation & Use. This includes models (e.g. IFC), data structures (e.g. COBie) and reports (e.g. PDFs) (Designing Buildings Wiki, 2018b). Furthermore, by integrating the CDE in the cloud, firms can keep track of the massive amount of data that construction projects generate on-site or from the office (CMiC, 2017).

Although software vendors have integrated the standards (PAS 1192:2 / PAS1192:3) for the CDE in their products already, they are still open questions. For example, data security, model ownership and intellectual property (Stefan Mordue, 2015). Therefore, much research is needed regarding BIM referring to cloud interoperability and its standardization (Afsari et al., 2016).

Nevertheless, in the BIM processes, a lot of potential use cases for VR applications are spotted. If stakeholders are following the BIM approach, many exchange interfaces of 3D models arise. Whenever 3D data are exchanged, people could review their design virtually. That applies for internal processes, like troubleshooting of design within a company (e.g., before the transfer of the design from the "Work in Progress Phase" to "Shared" in Figure 15) as well as for external processes like the transfer of data between to project phases in Figure 17.

However, from which features of the VR technology can BIM benefit? To find the answer, the VR technology, and its features will be explained in the next chapter. At the end of the "VR-Chapter" suitable use cases for VR in BIM will be presented.
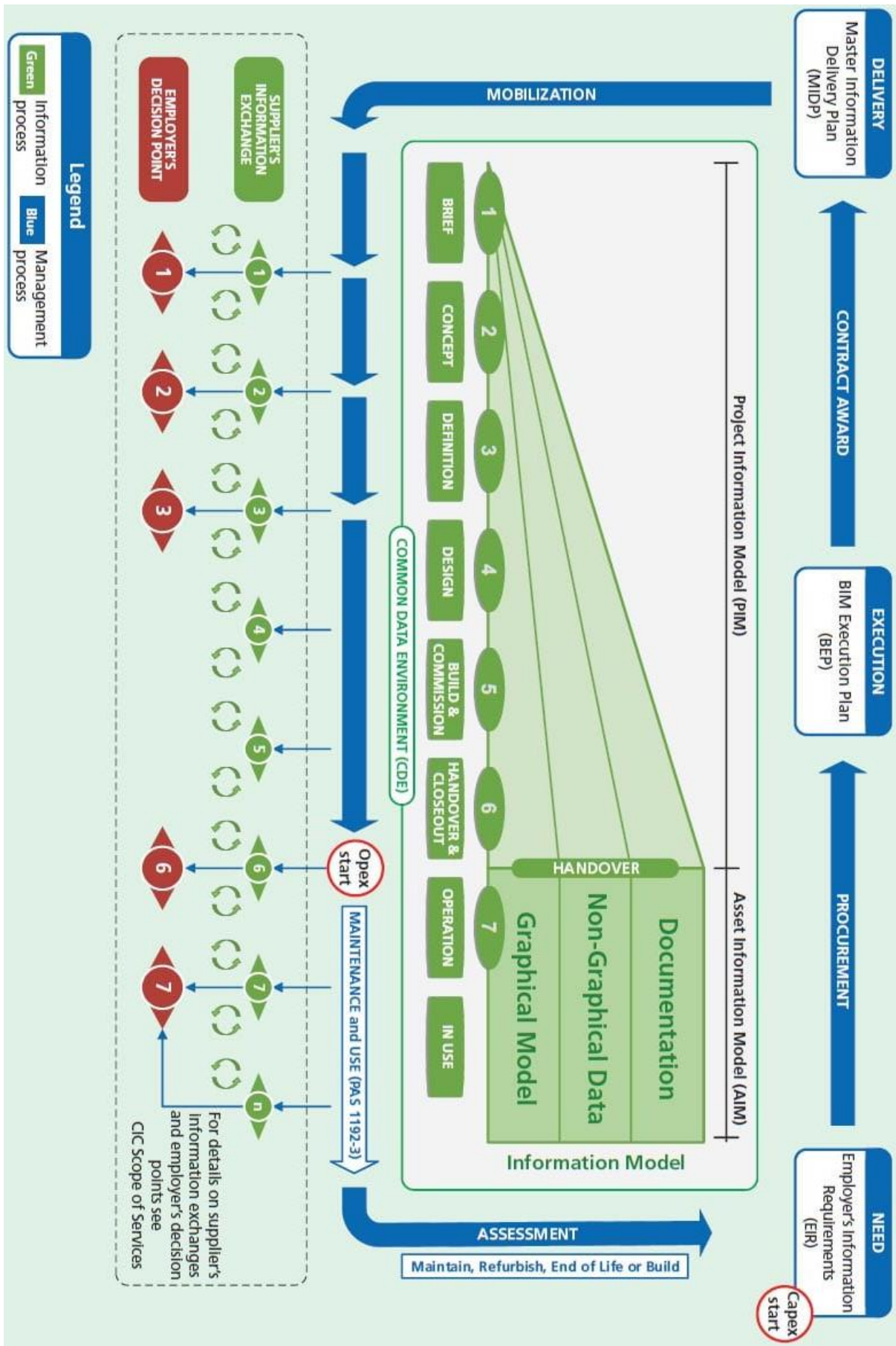
Figure 17: Information Delivery Cycle from the BSI (BSI, 2013)

3   Virtual Reality

Besides new digital methods like BIM, also new hardware technologies are disrupting the industries. One of these is head-mounted displays (HMD). An HMD is a head-worn visual output device which presents images on display. Using an HMD give users the opportunity for an immersive experience in a virtual environment – the so-called virtual reality (VR). In an immersive environment, the users accept virtual elements created by a modeling software and "forget" the physical reality. Thus, users think a computer-generated 3D world is real, and he or she is moving within this world (Rouse, 2018).

Thereby, buildings, rooms, workplaces, machines, and technical-scientifically complexes can be experienced before they exist in reality (Warnecke & Bullinger, 1993). Thus, concepts and drafts of 3D objects can be tested, changed and optimized virtually in early planning phases.

Although the technology is well-known since the 80s, it took a while for its breakthrough. However, due to improved computer performance and appropriate graphics cards, market researchers believe that VR is going to influence different industries in the next years significantly (Ballhaus, 2017). This trend can also be seen by increased investments into R&D companies. In 2017 until the first quarter of 2018 over $3.6 billion were invested from venture capitalists and corporates into augmented reality (AR) and VR start-ups (Tim, 2018). This trend is also noticeable in the AEC industry. A survey of the Chaos Group, a worldwide leader in computer graphics technology, shows that over two-thirds of architects or architectural visualization professionals are planning to use VR in 2018 (Chaos Group, 2017). With the help of the immersive experience of future planned buildings, troubleshooting can be done faster in the initial stages of the design process. Shifting troubleshooting to initial stages of the construction project is the same aim that BIM targets. Therefore, VR and BIM can have a symbiotic relationship.

However, before bringing VR and BIM in the same context, the VR technology in general and what is needed to achieve an immersive experience will be explained. In the second half of this chapter, an overview of the state of the art of BIM-VR applications is given, concluded with useful application possibilities of VR and BIM.

3.1   How to create an immersion?

One of the most important requirements for an immersive experience is that the user must perceive his or her virtual environment in 3D. This effect is achieved by the principle of stereoscopy. The principle is based on the fact that every human and every mammal perceives its environment through two eyes and thus two slightly different perspectives. With the help of the brain, the two images are then joined together, creating a spatial vision (see Figure 18). The understanding of the stereoscopy enables the rendering of 2D images with a spatial sense of depth that does not exist physically (N.E. Thing Enterprises., 1993). Therefore two photos with the same motif but from slightly different angles are put in a stereogram like in Figure 19 on the left side. If the users look through the stereogram, each eye can only see one picture, the brain combines the images into one and thus the picture(s) seem(s) to be in 3D. Thus spatial views can be created "artificial" (MindScaper, 2018).
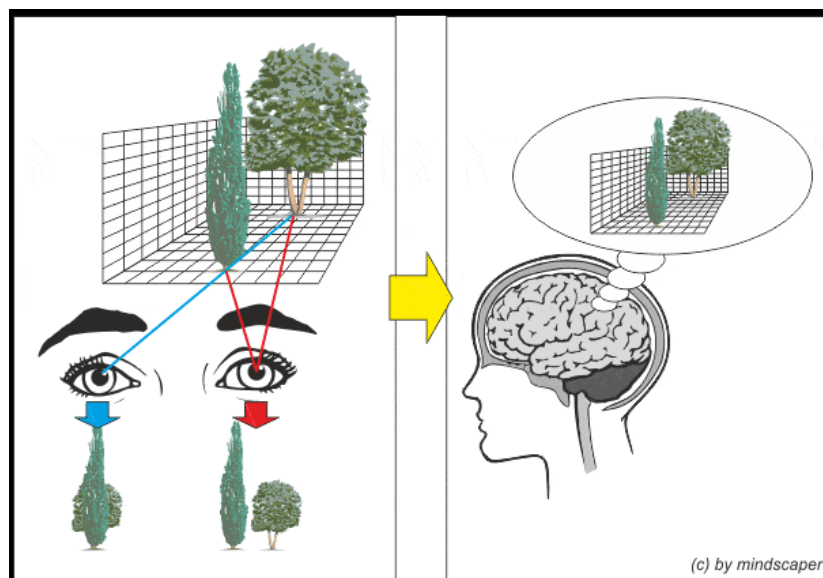

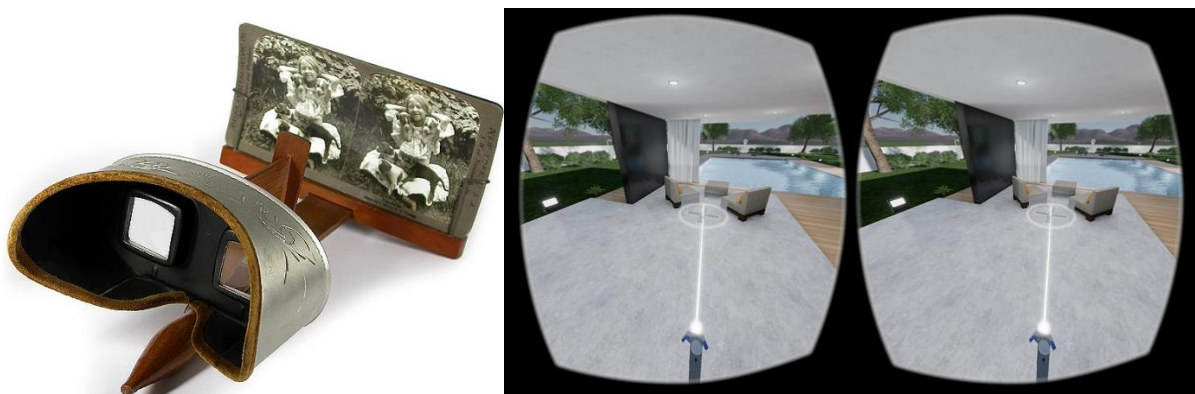*Figure 18: Principle of stereoscopy* (MindScaper, 2018)

Figure 19: Immersion effect through a stereogram from the beginning of the 20th century (Tauber, 2013) *and through a head-mounted display nowadays* (AEC Mag, 2016)

The immersive 3D effect on HMD works the same way as with stereograms. However, the eyes are not shown an analog 2D image, but an image or video of a computer-generated 3D world on a digital display. The process of how a computer creates these digital 2D images of a computer-generated 3D world, and thus later a video, is known as 3D rendering. Thereby the input 3D data is converted to pixels and shown on a 2D image based on the position of a "virtual" camera (see Figure 20). The resulting image is then displayed on a screen (e.g., smartphone display, PC monitor or HMD) (Mikael Johansson, Roupe, & Tallgren, 2014).

A real-time rendering software creates and renders these 2D images so fast that for the user an illusion of motion is produced (a video) - in real time. The faster 2D images are rendered (frame rate), the smoother and more real the video looks (Möller, Haines, & Hoffman, 2008). In the case of HMDs, two "virtual" cameras are rendering two images from a slightly different angle on two separate screens for the respective eye (see Figure 19 right). Thus, the user of the HMD thinks he or she is located within a virtual 3D model.
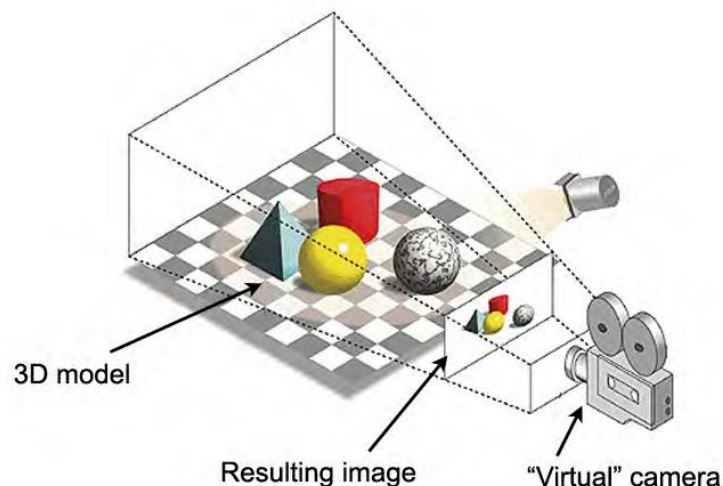
Figure 20: Rendering of a 3D model by a "virtual" camera on an image (Mikael Johansson et al., 2014)

However, the immersive effect is the greater, the more detailed the virtual environment was made and how good this virtual environment is rendered, depending on the hardware and software that is used (see next chapters 3.1.1 and 3.1.2). Besides the visual sense, also the audio sense, through additional earphones or the haptic sense through electric plastic pads on top of the fingertips (GoTouchVR, 2018) can also be triggered which increases the immersive experience additionally. However, the immersive effect through other human senses then the visual sense are not discussed in this thesis.

3.1.1 Hardware

Independent of the provider of the VR system, the hardware consists of an HMD, a computer, smartphone or console on which the software runs that creates and renders the virtual 3D-world (see chapter 3.1.2) and some form of input devices like controllers to interact with the virtual world. Furthermore, sensors are necessary to track motions and location of the user (O'Boyle, 2018). In general VR hardware can be classified into two main segments which are highlighted in Figure 21.

Figure 21: Virtual Reality Hardware Sets: Gear VR (Samsung, 2018) *and HTC Vive* (HTC, 2018)

The segmentation of these two types is based on the source of the video input. VR glasses like the HTC Vive have an integrated display which is connected to a computer (usually via an HDMI cable) to transfer the video to the screen(s) in front of each eye (O'Boyle, 2018). More affordable VR systems are smartphone-based devices. Users can clip a smartphone to a headset, for instance, Gear VR by Oculus (Samsung, 2018). That means that the smartphone is the HMD and the source of the video input at the same time. Depending on the operating system of the phone, apps can be downloaded, which create the stereoscopic vision of the VR content on the smartphone screen (Samsung, 2018). Of course the resolution and quality of the rendered video on a smartphone is limited. Using smartphones for VR purposes is therefore not suitable for every use case.

However, for both device types, the video is shown on two offset screens in front of each eye which creates the stereoscopic effect, and the user gets a "3-D impression" of the video (Rheingold, 1994). In the following, the HMDs with an integrated display and an external PC are presented.

To create a satisfyingly immersive experience HMDs and computers must have the appropriate performance: Computers which can produce high-definition images (input-device) and capable HMDs to display them (output-device).

To deliver a seamless VR experience PCs must have a strong performance especially regarding CPU (Central Processing Unit) and GPU (Graphics Processing Unit). The GPU should be able to maintain at least a framerate of 90 frames per second (FPS) (e.g., NVIDIA GTX 970 or AMD R9 390). The slowest recommended processor is an Intel i5-4590. Beside GPU and CPU also other PC hardware components like RAM (Random Access Memory), storage type (SSD) and cooling systems must be considered as well (Andrews, 2018).

Depending on the VR headset, the requirements for the VR-PC may differ slightly. VR headset vendors like HTC Vive (HTC, 2018) or Oculus Rift (Oculus, 2018) are also providing recommendations for appropriate VR-PCs. These recommendations should be considered. Otherwise, motion sickness can appear which makes the VR experience inedible (Sharpton, 2018).

Two significant challenges making the transition from a 2D display graphics to an immersive display must be faced. A high resolution reframed in the context of the human visual system and the display of this resolution at lower latencies to preserve the continuous illusion of reality (Kanter, 2015). Regarding the requirements for VR headsets, among others, the following characteristics are important (360camera, 2018):

Field of view: How much of the human eyesight will be covered, wearing the VR-headset. The human eye has a field of view around 180 degrees.

Tracking: Technology that is used to track the movement of objects (like the head or the hands) in real life to represent them in VR.

Resolution: Number of pixels in vertical and horizontal. An image with a high resolution appears realistic (Kanter, 2015).

Pixel Density: How many pixels are essentially visible in a square inch. The higher the density the clearer the image.

Frame Rate: Frequency at which consecutive images appear on display (frames per seconds). A minimum frame rate of 90 fps (or Hz) is necessary to ensure a realistic and comfortable VR experience (Read, Meyer, & Gamma Group., 2000)

Figure 22 shows a comparison of a selection of VR sets available on the market regarding their specifications. Depending on the financial budget and the use case

different VR sets are suitable. The cheapest VR sets like "PSVR" and "Lenovo Explorer" start around 200$ (source: Amazon).

Specs	HTC Vive	Oculus Rift	PSVR	Samsung Odyssey	Oculus Go	HTC Vive Pro	Lenovo Explorer
Image							
Max Field of View	110°	110°	110°	110°	100°	110°	110°
Max Resolution	2160×1200 (1080×1200 per eye)	2160×1200 (1080×1200 per eye)	1920×1080 (960 × 1080 per eye)	2880 x 1600 (1440 x 1600 per eye)	2560 x 1440	2880 x 1600 (1440 x 1600 per eye)	2880 x 1440 (1440 x 1600 per eye)
Screen Type	Duel AMOLED	Duel AMOLED	AMOLED	AMOLED	Fast-Switch WQHD LCD	Duel AMOLED	LCD
Pixel Density	461ppi	456ppi	386ppi	615ppi	Unknown	615ppi	706ppi
Sensors	Accelerometer, gyroscope	Accelerometer, gyroscope, magnetometer	Accelerometer, gyroscope	6-Axis ACC & Gyro, 3-Axis Compass, Proximity sensor, IPD Sensor	Gyroscope	SteamVR Tracking, G-sensor, gyroscope, proximity, IPD sensor	Proximity, Gyroscope, Accelerometer, Magnetometer
Max Refresh Rate	90Hz	90Hz	90Hz, 120Hz	90Hz	Unknown	90Hz	90 Hz
Tracking	6 DOF IR Laser-based 360-degree tracking using "Lighthouse" Base Stations	6 DOF Constellation camera optical 360- degree IR LED tracking	6 DOF PlayStation Camera optical 360-degree LED tracking	2 x 6 DOF camera	Orientational Tracking	–	2 x Inside-out motion tracking cameras

Figure 22: Comparison of VR headsets with integrated displays (360camera, 2018)

Of course, all these hardware components for the VR-PC and the HMD need much space and are therefore very unhandy. VR-PCs with powerful hardware are big and heavy and are therefore usually provided as a desktop – PCs (see Figure 23 left).

Additionally, for the power of the tracking sensors and the connection between the headset and the PC, many cables are needed. Also, most VR sets can only be used in a calibrated area (e.g., blue square in Figure 23 left). This stationary hardware set-up can lead to restrictions for some uses cases, where the needed space is not provided.

However, meanwhile, some VR hardware providers offer backpack PCs to get rid of the cables and to increase the mobility (see Figure 23 right). Also, wireless headsets are on the market already (Newhouse, 2018). Nevertheless, setting up a stationary basic VR hardware system with sensors on tripods, and a strong gaming notebook costs only 15 minutes time including calibration (referring to own experience).

Figure 23: Stationary (HTC, 2018) *and mobile* (HP, 2018) *VR scenario*

3.1.2 Software – Game Engine

Besides the hardware components, also software is needed which creates and renders realistic virtual 3D worlds. In general, developing VR applications is much like developing video games, as they are both 3D interactive experiences. Suitable software for creating 3D worlds in VR are so-called game engines. Game engines are software-suites that provide developers with a framework for developing games. They have a construction kit which helps developers to create and develop their own game and are capable of managing 3D environments, importing custom assets such as 3D models, images, sounds and videos (Blow, 2004). This includes APIs for lightning, physics, animations or interactions in the gameplay. Through the implementation of a physic engine, 3D objects can be given gravity. As a result, for example, collisions between game objects are possible (Unity, 2018a).

Furthermore using game engines gives developers more time to focus on the actual design of the game environment, textures and the gameplay in a stable software environment. Depending on the technical requirements of the future game various game engines exist. Every game engine has, therefore, its strengths and weaknesses regarding programming language, physics, interoperability, etc.. To link VR devices with game engines, software development toolkits (SDK) are usually provided for free by the appropriate game engine (e.g., SteamVR (Steam, 2018)). But not every game

engine is compatible with every VR-headset. The commonly used game engines are Unity 3D (Unity, 2018b) and Unreal (Unreal, 2018).

The game development for the entertainment industry is widespread for years already. However, also for classical industries like car manufacturers or construction companies, the importance of VR technology is constantly increasing. Through the "gamification," design, training or production processes can be simulated realistic, offering new possibilities in VR. This also applies for the AEC industry and in particular for BIM. In the next chapter, the state of the art of VR applications for BIM will be presented.

3.2   State of the art VR and BIM interoperability

Working with BIM gives users from different disciplines much 3D data that can be used in different ways, for instance for visualizations in VR. As already mentioned in the introduction of this chapter the key benefit of visualizing 3D models in VR is to experience true scaled buildings before they exist. Thus, users can experience a virtual impression of their future architecture and facilities, which helps to identify design errors or to test different design options. Meanwhile, many plug-ins, add-ons, and software are available, offering VR solutions to support design and planning processes in construction projects. However, these applications vary from their features and thereby their suitability for different use cases.

As explained in chapter 2.1, using BIM models in design processes enables not only to visualize models but also to retrieve semantic data of building elements. That applies for 2D as well as for 3D views of the BIM model. So why not keep the available meta information also in VR and combine the strengths of both technologies – metadata from BIM and the visualization in VR (Sampaio, 2018)?

So far, many applications according to the visualization of BIM models in VR were developed. However, often they are only for one BIM authoring software. However, at large building projects, many stakeholders are involved – using different software. If one stakeholder wants to see a 3D model from somebody else in VR, but his software does not support a certain file format, they cannot use VR. For this reason, VR applications should be independent of the BIM authoring software or at least available for most of the design software.

As BIM is a collaborative design approach, it would also be useful if the VR application could be used by multiple people in real-time. Like in reality, design issues or possible changes are often discussed together on site. However, traveling cost time and money. So why not have virtual building site visits where stakeholders can discuss design errors and check possible changes of the design virtually?

About the just mentioned requirements, the following criteria for investigating VR application for BIM arises:

a. **Compatibility**: is the application available for different software providers or only a specific solution
b. **Multiplayer:** is it possible to have several users in one virtual environment
c. **Editable**: can the model in VR be edited (rotated, moved, change of color)
d. **Request of metadata**: is it possible to retrieve data of selected building elements in VR (name, material, type, etc.)

The investigation is done for commercial software solutions and research approaches and is therefore split into two chapters: commercial software research in chapter 3.2.1 and a review of published scientific papers in chapter 3.2.2.

For the commercial software review, each app is presented briefly and then rated explicitly according to criteria a. – d. For the approaches from research institutions the criteria a. -d. were also considered in the search. However, the scientific papers are not rated explicitly but summarized.

3.2.1 Commercial BIM-VR applications

Due to the decreased soft and hardware costs for VR solutions and the increased usage of BIM, new business models were developed (PWC, 2018). For this reason, many companies are now offering VR solutions customized for BIM authoring software. Due to a large amount of commercial software in this field, the most widely used and according to the criteria a. – d. most relevant products are presented here.

One commercial software which integrates VR in architectural design software is **Enscape** (Enscape, 2018). The real-time rendering plugin is compatible with several software vendors and offers virtual walkthroughs in a rendered model. After installing the plugin for the corresponding software, the user can virtually walk through its rendered design in VR. By editing the native model in the design software (e.g., Revit), the rendered model in Enscape is updated in real-time (Figure 24). Virtual meetings

and the request of metadata of building elements in the rendered model are not possible. Similar applications like Enscape but only compatible with Revit are AutoDesk Fuzor, Autodesk Live, and Stingray.

    a. **Compatibility**: available for Revit, Rhinoceros, SketchUp, and Archicad

    b. **Multiplayer:** no multiplayer mode provided

    c. **Editable**: changing objects is only possible in the authoring software

    d. **Request for metadata**: not possible
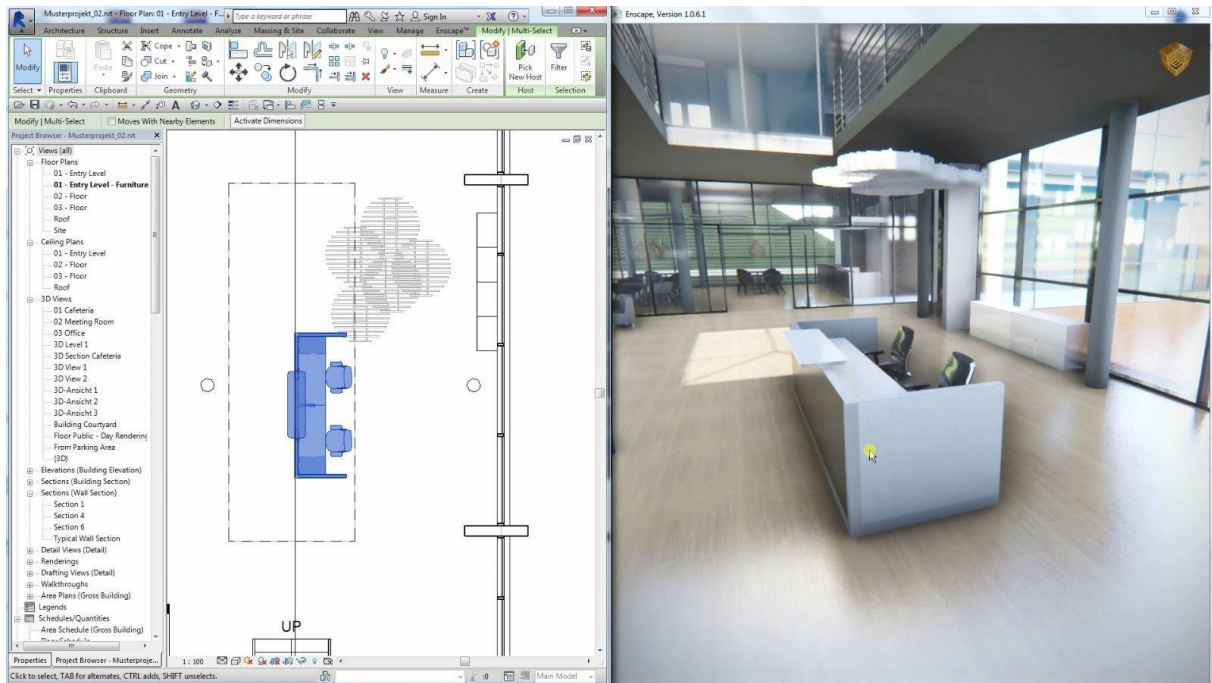
Figure 24: Real-time rendering tool by Enscape (Enscape, 2018)

Another VR visualization tool is offered by **Revizto** (Revizto, 2018). The cloud-based collaboration platform is offered as standalone software, as a plugin and as a viewer application for hand-held devices. Models of different file types can be uploaded to the cloud and then be visualized in VR. Neither editing or multiplayer functionality in VR is integrated. Only sharing of the VR camera view with other devices is possible.

    a. **Compatibility**: compatible with several BIM authoring software (SketchUp, Rhinoceros, Revit, ArchiCAD) and model checkers (Tekla, Solibri)

    b. **Multiplayer:** Multiuser real-time collaboration possible (sharing of VR camera view with other devices)

    c. **Editable**: not possible

    d. **Request for metadata**: issues (BCF) are visualized and can be opened in VR, but individual objects cannot be selected

Similar to Enscape, the company **Formitas** also offers virtual walkthroughs in rendered models in high resolution (Formitas, 2018). Editing or retrieving data from the model in VR during runtime is not possible. A multiplayer mode is also not implemented.

    a. **Compatibility**: not clear (model must be sent to Formitas to provide VR app)
    b. **Multiplayer:** no multiplayer mode provided
    c. **Editable mode**: not possible
    d. **Request for metadata**: not possible

A very promising product is offered by the start-up **IrisVR** (IrisVR, 2018). Besides the visualization of 3D models for single players, the startup also offers collaborative meetings in virtual environments. Users can have virtual discussions about the design remotely.

Furthermore, the product offers a fully automatic conversion from SketchUp, Revit, Rhino and other 3D formats to their VR application. This also includes the transfer of metadata, which enables the user in VR to retrieve attributes like material or name of a selected building element. Actual changes of the architectural model in VR are not possible.

    a. **Compatibility**: available for SketchUp, Revit, Rhinoceros, NavisWorks
    b. **Multiplayer:** yes
    c. **Editable mode**: not possible
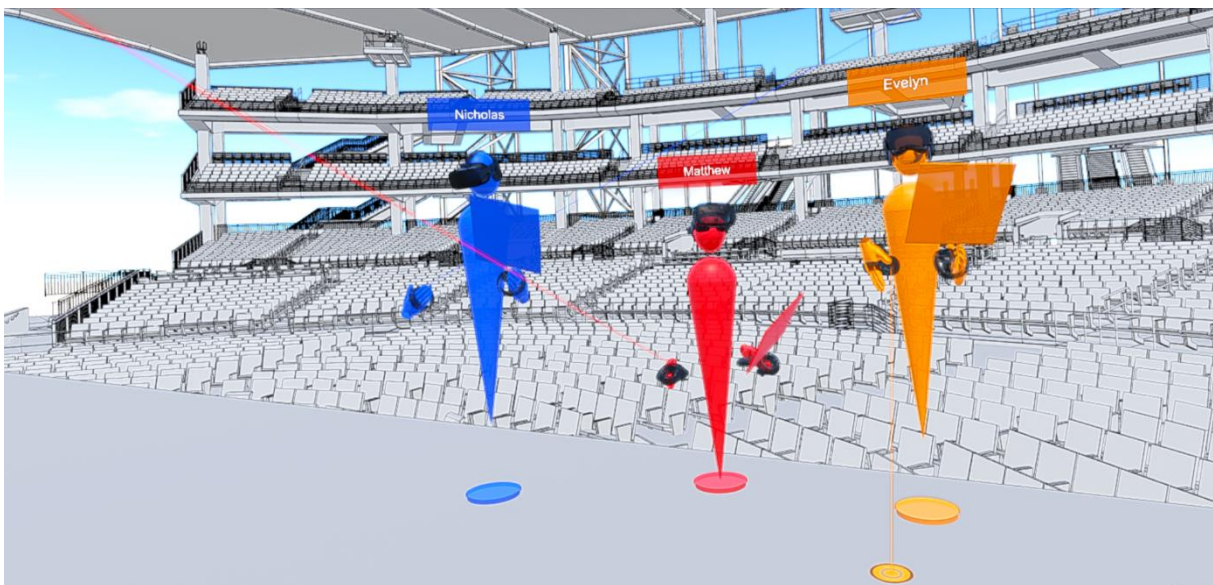   d. **Request for metadata**: yes

Figure 25: Virtual meeting with avatars in IrisVR (IrisVR, 2018)

Another start-up which advertises a VR application for BIM is **AllVR** (AllVR, 2018). The company also provides a solution for distributed meetings where several project members can communicate about the current state of the planning tasks in real time. It also provides all metadata of the building components in VR, but additionally to IrisVR, users can change the model in real-time. Move, hide and change of color and textures of objects can be conducted via a UI in VR. Compared to the other software solutions it is the only programme which offers a direct IFC import to VR.

a. **Compatibility**: is the application available for different software providers or only a specific solution
b. **Multiplayer:** possible
c. **Editable**: possible
d. **Request for metadata**: possible

3.2.2 A literature review of BIM-VR applications

Compared to commercial software providers, also research institutions engage in the field of BIM and VR interoperability.

A lot of published papers are based on the approach of visualizing models created in a BIM authoring software (e.g., Revit) in VR. One provided solution for the integration of VR in a BIM authoring software was developed by (Kieferle & Woessner, 2014). The goal of this research project was to create a bidirectional link between Revit and VR. For the visualization in VR the in-house rendering software COVISE was used (HLRS, 2018). To facilitate the bidirectional data exchange between both systems a plugin was developed, using the APIs of Revit and COVISE. Using this interface, updates of the model in Revit are directly reflected in VR and vice versa. Depending on the complexity of the geometry of the modified element this can take several minutes. After further research co-located meetings in distributed virtual environments were also implemented (Woessner & Kieferle, 2018). Retrieving information from selected building elements in VR is not possible.

Another similar approach based on a plug-in concept is developed by (M Johansson, Roupé, & Tallgren, 2016). The approach was also tested with Revit and enables virtual walkthroughs in a standalone VR viewer.

An outstanding research was developed by (Shi, Du, Lavy, & Zhao, 2016). The researches developed a BIM-based VR environment tool where remotely located

stakeholders can experience a 3D model together in real-time. The model was designed in Autodesk Revit and then pre-processed in Autodesk 3DS Max to enable virtual walkthroughs in VR. The research was further improved by implementing a BIM-VR Real-time Synchronisation system called BVRS (Du, Zou, Shi, & Zhao, 2018). With the help of this application, it is possible to update BIM-Models during runtime and showing it in VR. Using the API of Revit a plugin was developed which transfers all geometric and semantic data to databases and cloud servers, to provide real-time communication. After finishing the data upload to the servers, the data is then transferred and rebuild in a game engine (Unity). Unfortunately, changes are not possible in VR directly and can only be made by one player in Revit. After the changes are done, the model gets updated, and the other participants who are playing the role of the end-user can see the changes in VR.

Another interesting research was done by (Hilfert et al., 2016). Compared to the other approaches they did not use a BIM authoring software as the source of the BIM data for VR, but the OpenSource BIM server (BIMserver, 2018). Linking the server with a game engine (Unreal Engine) through APIs, users can upload their IFC files to the server and then experience in VR. Through this approach, the VR application is independent of the BIM authoring software. Editing the model in VR is not possible, but IFC files can be updated in different revisions to the server and then reimported to the game engine.

3.2.3 Summary of state of the art

As shown above, there are many approaches with different features for integrating VR in BIM. It is noticeable that many VR applications are developed for Autodesk products (e.g., Revit). On the one hand this is understandable because of the market dominance of BIM products from Autodesk, but on the other hand, it is not following the open BIM approach (Waterhouse & Philp, 2016). Because, if VR applications are developed for only one software provider it is obvious, that they only work within one software ecosystem. Other parties would then be excluded, which should be prevented in the area of BIM (see introduction BIM in chapter 2.1).

Furthermore, often models are just visualized without the appropriate metadata like textures, names, etc.. Without transferring the metadata of BIM models into VR, the actual BIM-character of the model gets lost.

Additionally, in a lot of papers and applications, the features in VR are limited. So far they are not many applications which combine the criteria defined in chapter 3.2 in one single software.

3.3 Scenarios of VR applications – where can VR be integrated into BIM?

Nevertheless, there are a lot of possible applications for VR in BIM and depending on the use case, different features of VR are necessary. For instance for marketing purposes, a realistic rendering of the model is important, whereas, for troubleshooting of design, a conceptual model with much metadata is desired. In the following several applications in different fields are presented.

An already widely used application for VR is in **marketing**. Through a good rendered model in VR, a customer can get a realistic impression of the future building. Therefore architects can easier convince customers who are not familiar with 2D drafts with their design. Furthermore, also the interior design can be visualized already. Several manufacturers for furniture or sanitary facilities are offering them products as an IFC file which can then be imported into the BIM model and then experienced in VR. For instance, the National Building Specification in the UK provides a BIM library where generic and manufacturer BIM objects can be downloaded (NBS, 2018). Through the availability of 3D models in VR architects and planners can communicate their design drafts easy and fast to laypersons, which is very important in early project stages in BIM.

Another promising field of VR in the early stages of a BIM project is for the communication of building projects with the affected civil society. A problem, especially for big infrastructure projects is the lack of support and approval of citizens. Usually, plans for big infrastructure projects are either communicated in containers on site or at public institutions like town halls. Citizens are often not aware of the published designs and are not aware that their neighborhood is going to change soon. Through this miss communication citizens are then surprised when the construction work begins, and for instance, trees are cut, or parks disappeared. Political resistance and demonstrations are the consequence which can lead to -in worst-case- scenario building stops. To make it easier for citizens to participate, it would be useful if the planners provide a BIM model and the users can download it on their smartphone. As described in chapter 3.1.1 they can then experience the planned building in VR with their smartphone. One exemplary approach for **mass participation** is provided by a European funded project

called Urban U_CODE, which stands for Urban Collective Design Environment (see Figure 26). Here, citizens can co-design their neighborhood with planners and investors in VR. Through the feedback and ideas of citizens, planners can react and change the design in early projects stages if necessary and increase therefore the acceptance of building projects.
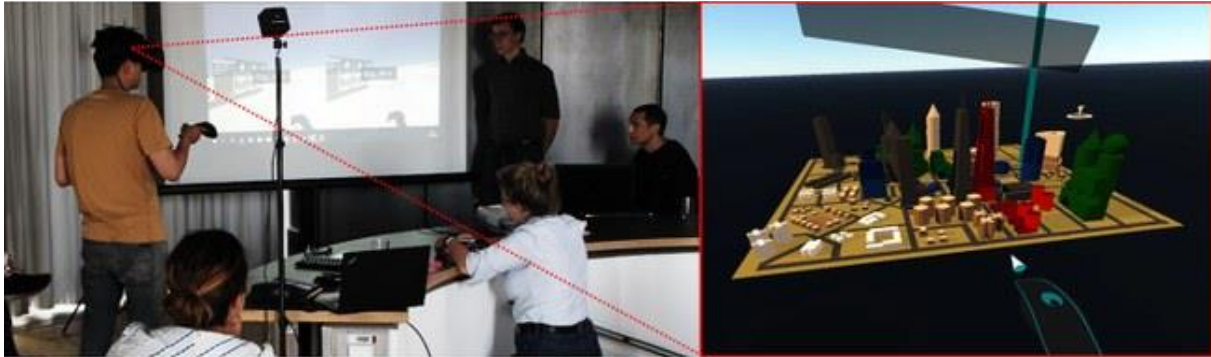

Figure 26: Mass participation for urban planning in VR (U_CODE, 2018)

However, use cases for VR can be found not only at the beginning of building projects, but also in more advanced project stages, namely between design experts. Sometimes it is very hard to communicate design errors in 2D on a plan. Using VR with a multiplayer feature two planners from different disciplines can enter the VR environment and **visit the site virtually**. In the VR application which is presented in chapter 4 users can upload several IFC models. Thus, planners from different disciplines, for example, an MEP (Mechanical, Electrical, and Plumbing) - engineer and an architect can upload their appropriate IFC model and approve their design in one scene. In the case of design errors, the planners can export a BCF file (see 2.4.1) or even change the IFC file in VR directly (proof of concept shown in chapter 4.3). This scenario is also applicable at any handovers of IFC data between different project stakeholders.

Another suitable use case for VR is **Training**. In the training simulation depicted in the screenshot in Figure 27, the user needs to identify safety risks in a realistic construction environment. This is pretty helpful for the training programme for construction workers. Utilizing VR, allows the user to be trained for any purposes and enables real-time responses to each action of his training. If 3D models from BIM are available in the early project stages, workers can even be trained within the future building environment.

Figure 27: Safety training in VR (Raafat, 2018)

Besides the support of the design by VR, there are also use cases to verify the final design. This is very useful regarding **escape routes**. In case of an emergency, caused for instance by an earthquake or a fire, it is essential for survival to find escape routes through the appropriate labeling (Lovreglio et al., 2018). Testing an earthquake or a fire (Figure 28) scenario under realistic conditions in VR can disclose security holes and the model has to be adjusted.

Figure 28: Testing of escape routes in VR (Hilfert et al., 2016)

As can be seen, there are many use cases, with different features of VR in the construction industry. Whether at the beginning or the end of a project, VR can be used as a supporting planning tool. However, often the VR applications are developed for very specific use cases. Either because they are only compatible with one BIM authoring software or the features of the VR application are limited.

As already mentioned in the criteria a. – d. At the beginning of the literature review, it would be useful if the VR application would not only support the work of one designer or architect but if VR would support the BIM workflow in general. Therefore the VR application must be implementable in the BIM processes, which were described in 2.4 in the BIM delivery circle. The BIM workflow provides a lot of data interfaces, where VR can be applied. Thus as the main exchange data format in BIM are the IFC, it would be useful if the VR application has a direct interface for IFC.

Using VR with IFC as the input data all project stakeholders, implied they are working with IFC, could take benefit. One application that does so is presented in the next chapter.

4 Case Study: BIM & VR at BMW logistics

To show how VR and BIM can be integrated into practical and independent of a BIM authoring software, an application from the logistics department of BMW will be explained. Objectives of this application were to import IFC files semantically and geometrically into the game engine Unity and to enable the interaction of the user with the imported model in VR. As an HMD the HTC Vive set with two controllers were used (HTC, 2018). To read the data from the IFC files the eXtensible Building Information Modelling (xBIM) toolkit was used (Lockley, 2007).

The application is based on the research from (Schubert, 2018). Additionally, to the rendering of the IFC model and other features, the feature of manipulating *IfcElements* in VR was implemented. At the beginning of this chapter, the workflow of the application will be explained in successive steps (see Figure 29). Afterward, the different features of the application are presented. In the end, the implementation of how individual IFC elements can be modified is explained in detail.

4.1 Concept and Workflow

Firstly, the application starts not in VR, but on a Desktop-PC or a Notebook. After starting the developed game in Unity (1) an open file dialog pops up (2), and the user can select one or several IFC files (3) which should be imported into the game scene. Because Unity has .Net compatibility issues with one library (xbim.geometry) of the xBIM toolkit for extracting the geometry data from the IFC model, another programme is needed to serialize this data and to build the geometry in unity. This programme which transfers the data between Unity and the IFC files is called the IFC translator (4). Within this programme, developed in C# the xBIM libraries were used to extract all relevant data from the IFC file. The extracted data is then processed and stored in a JSON file (5). The JSON file contains the needed geometrical and semantical data for each read *IfcElement* of the IFC file.

For each loaded IFC file a corresponding JSON file is created and saved in a folder (named "Streaming Assets) in the Unity project on the target machine. Any files saved in this folder with the name "Streaming Assets" in a Unity project can be retrieved during run time (Unity, 2018c). This means that, if an IFC file which was imported into the Unity scene already once and the appropriate JSON file was created, the JSON

file could be reused by Unity. This has the advantage that, if the user starts another VR session with similar IFC files, the programme must no repeat the import process (4 & 5) from scratch, but can reload the "old" JSON files from "Streaming Assets." This procedure increases the performance significantly. After the import procedure is done, the objects from the JSON files are rebuilt in Unity, and the user can start the VR session (7). Because for each *IfcElement* a game object in Unity is created the user can interact which each element individually.
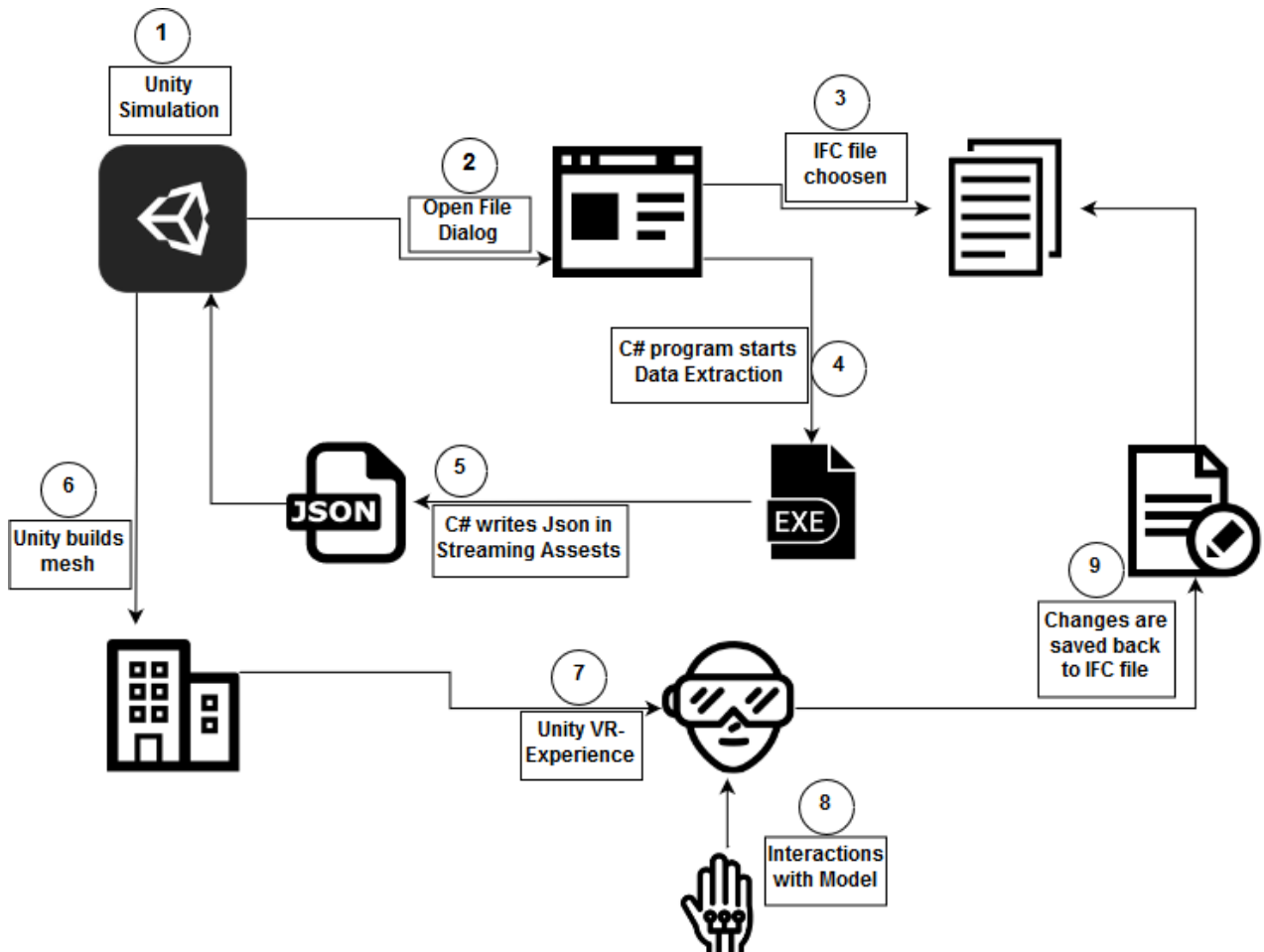
Figure 29: Workflow IFC to Unity application

In the game scene in VR, the user can switch between different play modes via the controllers (see next chapter) and interact with the model (8). If the user edits the model (e.g., rotates or moves) the changes are sent back to the original IFC file, and the BIM model gets updated. Here the changes can be sent directly to the IFC file without an additional programme like in step (4), because of the xbim.geometry library is not needed.

4.2 Playmodes

After explaining the main concept of the application briefly, the implemented features in VR are presented. As explained in the concept above, the VR session begins, after the desired IFC files are selected and loaded into the scene (see Figure 30). As a basic feature, the user can **move** freely in the virtual environment. Therefore two options for getting around in the model are provided. Either the user can "beam" himself, with a form of a laser (see Figure 30) or move in a realistic speed as you would walk in reality.
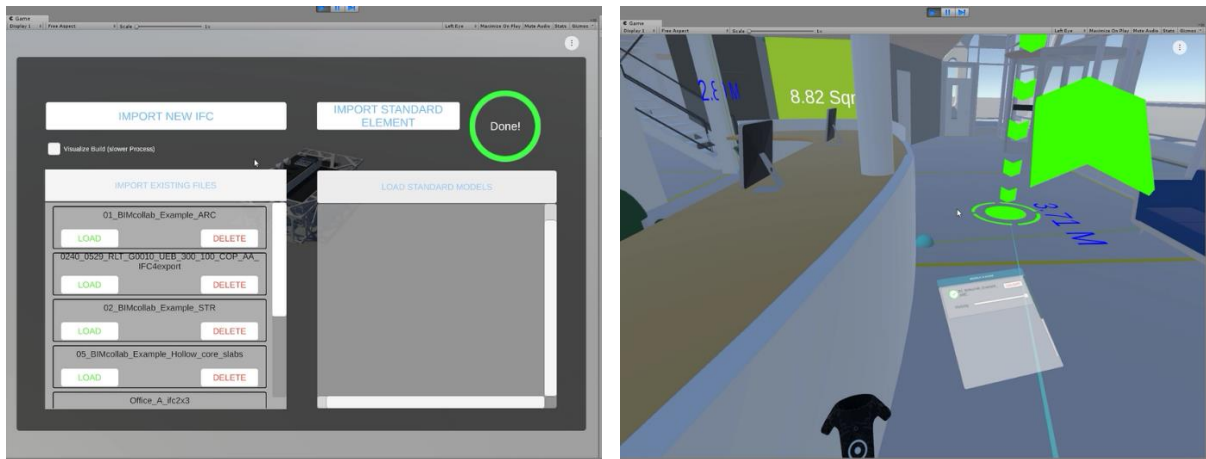
Figure 30: a User interface to import IFC files and "to beam" in Unity

Furthermore, in VR the users are enabled to measure in true scaled using an implemented **measurement tool**. Using a raycast in VR, the user can place an unlimited amount of measurement points in the form of 3D spheres. The center of each sphere is thereby snapped to the surface of the target plane to measure. If the users set two measurement points, the distance between these two points is calculated and highlighted in the scene. If more than two points are placed, the respective area of the polygon is measured and highlighted (see Figure 31 left).

Another feature of the application is the ability to select an object and **retrieve** its **meta-data**. Similar as in the measurement tool, using a kind of laser, the user can select an object in the scene. The selected object is then highlighted, and the appropriate meta-data is shown on a panel on the UI (see Figure 31 right).
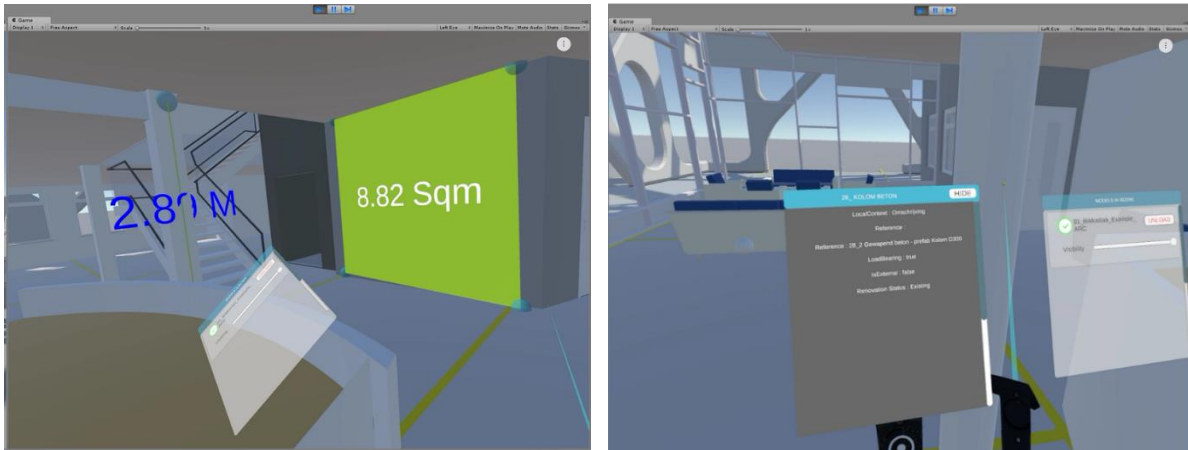
Figure 31: Measuring feature and "Retrieve Meta-Data" feature in VR in Unity

Another useful feature is the ability to **activate or inactivate** imported IFC files. As can be seen on the panel at the UI above the controller in Figure 32, there are two IFC files loaded in the scene: one architectural and one statical IFC file of the same building. Once the files are loaded in the scene, the user can activate or inactivate each file individually in the UI in VR (Figure 32). As a result, all game objects created by a file are displayed or not displayed. In addition to the ability to turn off / on all game objects from a file, only the visibility can be changed with a bar in the UI.
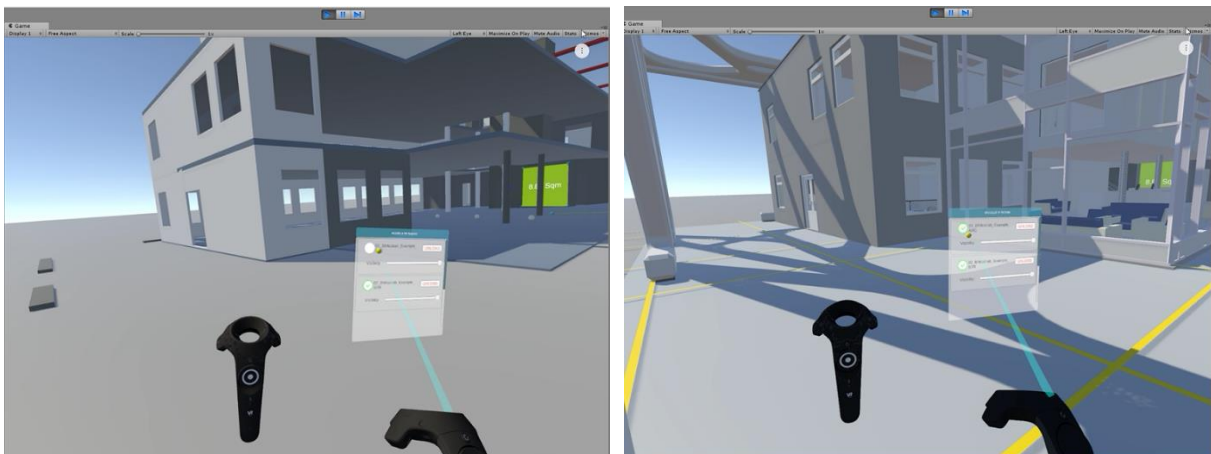
Figure 32: Activate/Inactivate loaded IFC models in Unity

Beside the mentioned features, an editing feature was implemented in the application. The objective was to enable modifications of the IFC file (e.g., rotating, moving or adding new *IfcElements* like windows) in VR.

Furthermore, adding new objects like windows or doors should be possible. After the changes were done in Unity, the modifications of the model should be transferred to the corresponding IFC file and update it. Since an immediate update would result in long loading times in VR, all changes were saved and transferred to the IFC files at the

end of the VR session. During the VR session, the modifications were only visualized in Unity without changing the underlying IFC file.

To achieve this goal, a proof of concept application was developed to show the feasibility of the desired features. The proof of concept application and the implementation in Unity are presented in the next chapter.

4.3   Editing of IFC files with xBIM Toolkit

Before the implementation of editing IFC components in VR the principle of how this can be done had to be understood at a lower scale. As explained in chapter 2.2 the IFC data standard is very complex, and it is therefore not a trivial task to retrieve or edit the data of IFC files. However, first, as with any other software or file schema a software development kit (SDK) is necessary to access the data. Using an SDK, developers can enrich applications and implement new features (Wikipedia, 2017). Regarding the IFC standard, several SDKs are available, which are listed on the BuildingSmart website (bSI, 2018b).

For the proof of concept application, the SDK xBIM was used, which enables .Net developers to create, retrieve and update BIM Models in the IFC format (Lockley, 2007). The open source toolkit fully supports geometric, topological operations and visualization of IFC. It can be download on GitHub, a web-based hosting service for version control ("About · GitHub," 2018) and is available as a NuGet package for Microsoft Visual Studio.

The toolkit is chosen because it covers agnostic solutions for IFC2x3 and IFC4 and is programmed in C#.

By the xBIM libraries, a WPF application was developed to understand the schema of IFC and the geometric and semantic relations between different IFC elements. Based on the data structure and the geometric representation of *IfcElements* which were explained in chapter 2.3, the application was developed.

To keep the application stable and fully usable it was developed with the approach of an IFC agnostic software solution (Lockley, 2018a). This means the application works for IFC2x3, IFC4 and according to the xBIM development team for all upcoming IFC data formats.

To ensure the compatibility of the tool with different IFC versions several "self-made" simplified BIM-models (e.g., Wall, Wall with Window, etc.) have been tested. The

models were designed in the Autodesk Revit 2018 and then exported as an IFC in the desired schema version (IFC2x3 or IFC4).

The app consists of a simple user interface (UI) with one list box, text fields and some buttons to interact (see Figure 33).
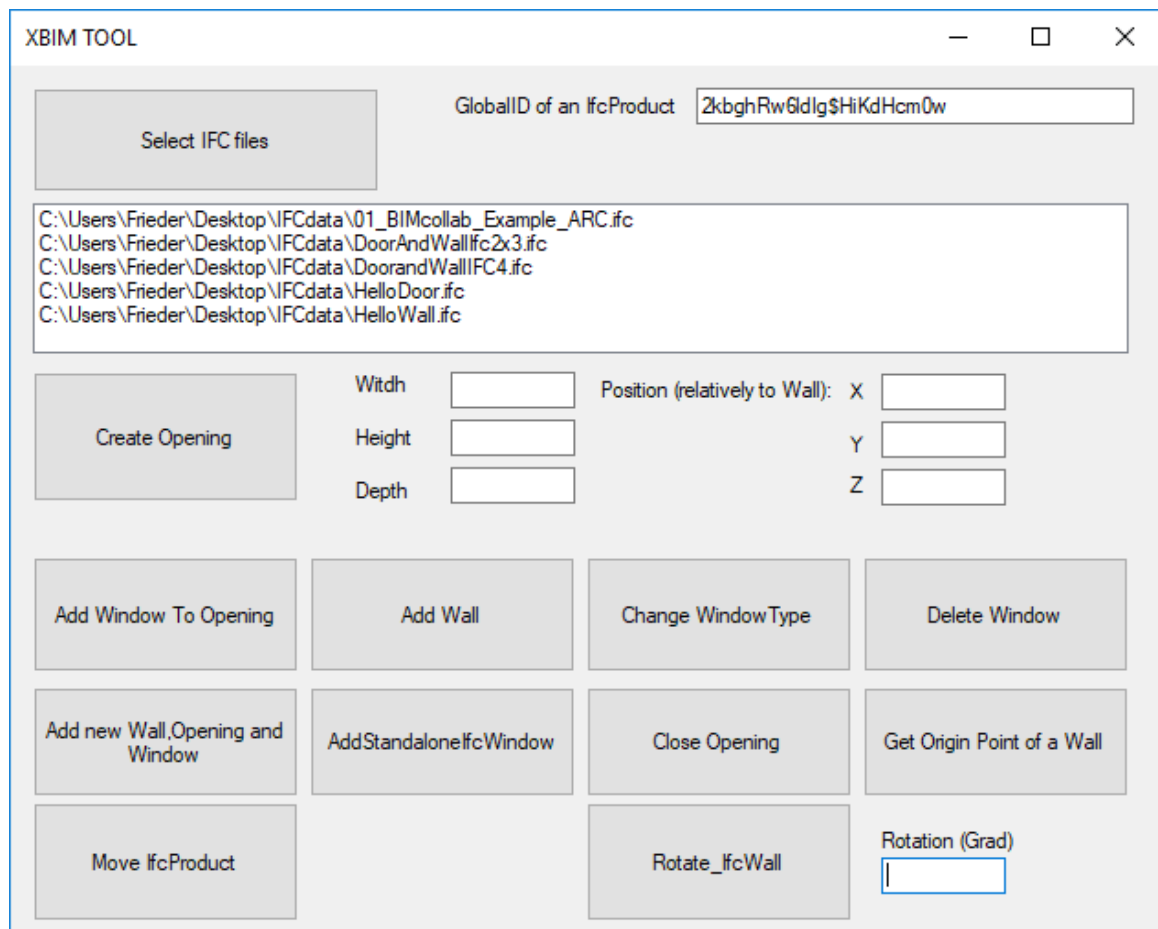
Figure 33: xBIM Editing Tool

After starting the application, the user can click on the "Select IFC files" button, which opens a file dialog to select one or several IFC files. The selected files are added to a list box and visualized in the corresponding window. All further editing is then done for each element in the list box. To edit one specific element of an IFC file, the user can indicate the *GlobalID* of an *IfcElement* in a text box. Several editing options (see buttons) were considered, and the relevant ones for the VR implementation will be explained in the following.

4.3.1 Add Wall

To understand how *IfcElements* can be created by code a functionality was developed to create and add a simple wall in 3D to an existing IFC file. Thereby the example "Proper Wall in 3D" from the xBIM website was taken into consideration (Lockley, 2007). The example provides a script which shows and explains all relevant entities and relations to create an IFC file with a wall from scratch. The provided script only works for IFC4, so it had to be rewritten as agnostic.

Compared to other file schemas creating a new *IfcProduct* like an *IfcWall* is not a simple command which can be done with one line of code. To create a proper wall in 3D, all needed entities which were described in chapter 2.3 must be created. This includes apart from the description of the geometry and its placement (see chapter 2.3.1 and 2.3.2), also the semantical integration.

All entities in xBIM must be created within transactions, which are implemented with a "using" statement in case of errors. After editing the IFC file is done, the transactions need to be committed to keeping the modifications. Within this transaction, all semantical and geometrical entities must be implemented. In the code snippet below an example of the creation of a wall within a transaction is shown (Lockley, 2007).

```
1.  using (var txn = model.BeginTransaction("Add Wall to BuildingStorey"))
2.  {
3.      //Helper function to create IfcEntities
4.      var create = new Create(model);
5.
6.      //Creation of wall in a model with height, lenght and depth
7.      var wall = CreateWallAgnostic(model, 4000, 300, 2400);
8.
9.      //Creation of relation which puts wall into the semantic hierarchy of the model
10.     var relContainedInStructure = create.RelContainedInSpatialStructure(rel =>
11.     {
12.         rel.RelatingStructure = buildingStrorey;
13.         rel.RelatedElements.Add(wall);
14.     });
15.
16.     //Commit changes
17.     txn.Commit();
18. }
```

4.3.2 Create Opening in Wall

Before a window can be inserted into an existing wall, an opening must be created. The opening is the connecting element between the window and the wall (see Figure 34 in the next chapter) but can also be standalone as a void. The creation of an *IfcOpening* is following the same principle as how an *IfcWallStandardCase* is created (see chapter 2.3). The body geometry is formed by extruding a 2D profile which is then placed with the attribute *ObjectPlacement* relatively to another *IfcElement* (e.g., a Wall) (bSI, 2018k).

Besides the geometric representation and the placement, the opening must be connected semantically with the corresponding *IfcElement* with the relation *IfcRelVoidsElement*. This relation provides a boolean subtraction operation between the bodies of the voided element and the opening (bSI, 2018p). The created void can then be filled by doors, walls or other filling elements.

4.3.3 Add Window to an Opening

One common filling element is an *IfcWindow*. Besides the creation of a simple window from scratch (see example in IFC4 Documentation (bSI, 2018u)), predefined windows can also be used. The National Building Specification (NBS), a UK-based institution for describing materials, standards, and quality of construction projects, offers a National BIM Library, where generic and proprietary building elements can be downloaded as an IFC file (NBS, 2018).

Using the "Insert Copy Function" of the xBIM Toolkit, the window from the IFC file of the BIM library can be read and then imported to the initial IFC file with the whole model (Lockley, 2007). Nevertheless, how the window was created three entities (*IfcWall*, *IfcOpening*, and *IfcWindow*) and two relations (*IfcRelVoidsElement* and *IfcRelFillsElement*) are necessary, to insert a window in a wall.
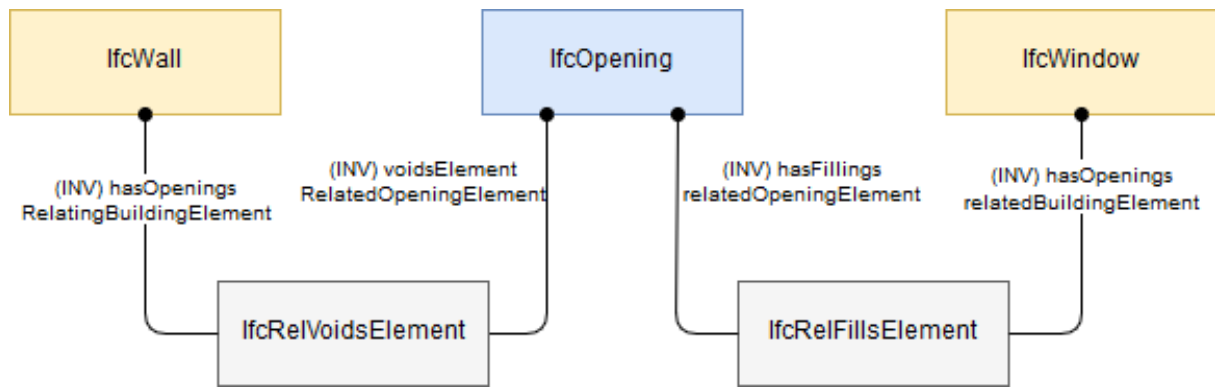
Figure 34: Relations between wall, opening, and window (Borrmann et al., 2018)

The three entities must be connected in two different ways: via a relative placement and via a topological connection. In Figure 34 the topological connections between wall-opening and opening-window are highlighted. The objectified relations *IfcRelVoidsElement* and *IfcRelFillsElement* are connecting the entities with the relationships *relatingOpeningElement* and *relatingBuildingElement* (bSI, 2018u).

Beside the topological connection, the opening and the window must be placed properly at the desired position. Therefore, the *IfcLocalPlacements* of each entity must be placed about the corresponding *IfcElement*, which means the *IfcLocalPlacement* of the window is defined relative to the *IfcLocalPlacement* of the opening and the *IfcLocalPlacement* of the opening is defined relative to the *IfcLocalPlacement* of the of the Wall (bSI, 2018u).

The definition of a relative placement is done with the attribute *PlacementRelTo* of the *IfcLocalPlacement* (see chapter 2.3.2). Because the window is placed at the same position as the opening the attribute *Location* (*IfcCartesianPoint*) of the *IfcAxis2Placement3D* from the window usually has the value (0,0,0).

In Figure 35 the procedure was tested with a sample file (No 1). Firstly, an opening with the dimensions of the future window was created in the wall (No. 2) Afterwards the opening was filled with a window (No. 3).
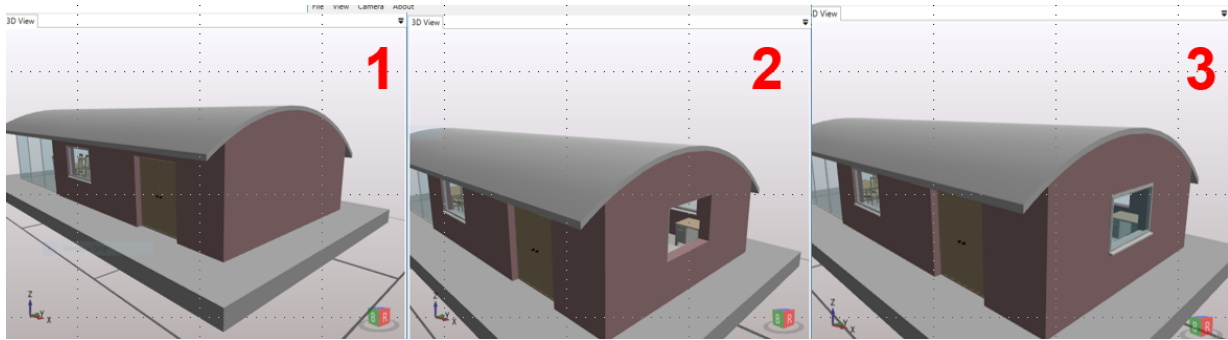
Figure 35: (1) Wall without opening (2) Wall with opening (3) Window inserted in the opening

The adding window feature is still under development and couldn't bee imported in Unity yet. Nevertheless, the proof of concept that it is possible was achieved.

4.3.4 Move and Rotate an IfcProduct

Another developed feature is the ability to rearrange *IfcProducts*. In this regard, not all *IfcProducts* should be able to rearrange. The user has to be aware of that moving or rotating bearing walls or columns can lead to substantial structural changes, which are not desired. Nevertheless, rotating or moving elements within the IFC model can be useful for some use cases.

To rearrange *IfcProducts* within the IFC model directly, the *ObjectPlacement* of the object needs to be accessed. As explained in chapter 2.3.2 the position and orientation of an *IfcProduct* is dependent on its local coordinate system. Thus, the components of the *IfcAxis2Placement3D* (*RelativePlacement*) must be changed to move or rotate the *IfcProduct*. Thereby, the *Location* and the two axes of the object coordinate system (*Axis* and *RefDirection*) need to be redefined (bSI, 2018c).

For relocating an *IfcProduct*, only the *Location* needs to be reset. Therefore, a new *IfcCartesianPoint* hast to be initialized and committed to the *Location* attribute of the object. To rotate an *IfcProduct* the two axes (Z- and X-axis) must be redefined. Depending on which axes how many degrees the user wants to rotate the object, the direction rations of the two axes must be recalculated.

Besides changing the axes, the origin of the object coordinate system can also be changed. If the origin is not changed the object will rotate around this point. By redefining the origin during a rotation, the pivot of the axis changes, which enables different rotation forms (e.g., rotating around the center or corner of the object).

Figure 36 shows the relocation and rotation of an *IfcElement* in VR. The new location and rotation are captured in Unity and then sent back to the original IFC file after the

VR session. The result is an updated IFC file with a new position and rotation of the couch as it was previously done VR.
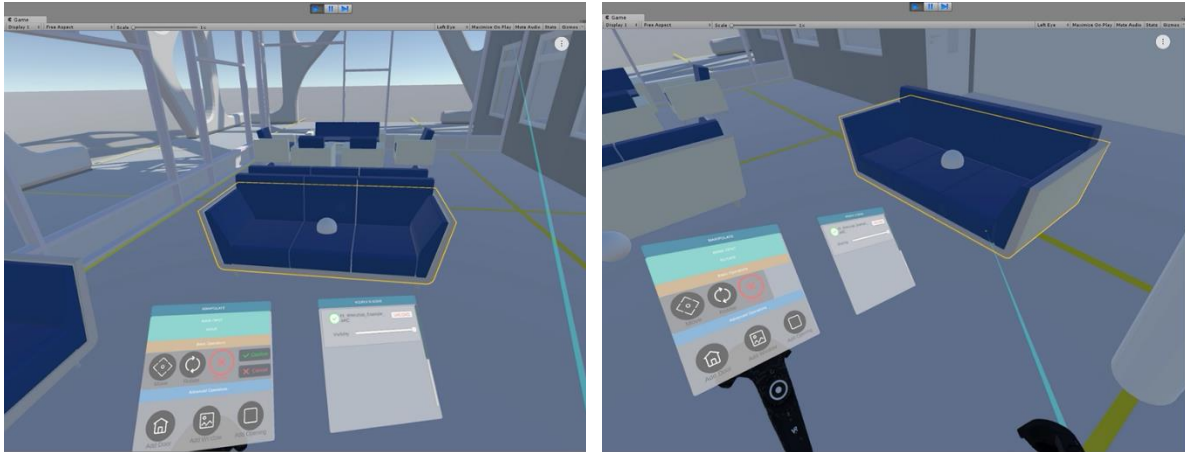

Figure 36: Moving and rotating objects in VR

Developing the WPF application lead to a deep understanding of the IFC standard and enabled editing IFC models in VR. Nevertheless, they are still many features which can be added.

4.4   Outlook

Using a game engine like Unity provides many features which can be implemented. Once the data is imported into Unity, a lot of useful features from the game ecosystem can be used. One feature is a multiplayer mode. In many games, the key feature is the ability that users can play together in a multiplayer mode via the internet. Therefore, most of the game engines offer in-house multiplayer solutions which can be implemented quite easily compared to do it from scratch. In the case of Unity, the multiplayer mode is provided by Photon Unity Networking (Photon, 2018). By implementing these multiplayer features, virtual site visits in an IFC model could be done remotely by the corresponding stakeholders.

Another feature that could be implemented is the possibility of exporting BCF files. As described in chapter 2.4.1 the BCF can help by communicating design errors or issues without exchanging the whole IFC file. By adding a virtual camera to the game scene, the user could do individual snapshots of the 3D model in VR and export them as BCF. The export function of BCF was already implemented by some commercial software providers like Enscape (Enscape, 2018).

As in any other software, an easy and intuitive UI is one of the most important aspects of successful software. If the user cannot use the application, he or she does not use

it. No matter how many features were implemented and how good an application is. Especially for such a new technology like VR, there is still much research needed how an easy and intuitive UI can be achieved. In this application, UIs were designed by asking new users in VR how they get along with the implemented UI. Depending on this feedback the UI was adjusted.

5 Conclusion

In this work, it was shown that VR and BIM complement each other very well. VR with varying features can be used in different fields of BIM wherever BIM data is exchanged and reviewed. Using HMDs architects, engineers and planners can experience their design immersive and true to scale. Virtual walkthroughs enable a realistic impression of the structure and design of future buildings. Thus, troubleshooting can be carried out long before the start of construction.

However, to use VR not only as a gimmick but as an additional planning tool for BIM, VR applications must be integrable into the BIM processes. Therefore it is important that VR applications are following the open BIM approach and provide an interface for BIM formats like IFC. With the use case from BMW, it was shown that IFC models can be imported geometrically and semantically into a game engine (Unity) and users can interact with the model in VR. In addition to the visualization, it is also possible to edit IFC models in VR without a BIM authoring software.

At the same time, the basic prerequisite for the use of VR is the availability of 3D data. In BIM projects the exchange of data is defined from the beginning. This results in many interfaces for VR applications. Whether virtual site visits between stakeholders from different backgrounds or design reviews within one team, VR can thus be implemented into processes of different project phases.

Nevertheless, the adoption of new technologies in the AEC industry in Germany like BIM or VR is still restrained. Due to the fragmented market and therefore many small companies, investments in new technologies are restrained. VR can be a new supplementary tool for BIM, but like any other new technology, it must be used and tested to find suitable use cases. Otherwise, the adoption of new digital processes and technical progress is not possible.

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Erklärung

Hiermit erkläre ich, dass ich die vorliegende Masterthesis selbstständig angefertigt habe. Es wurden nur die in der Arbeit ausdrücklich benannten Quellen und Hilfsmittel benutzt. Wörtlich oder sinngemäß übernommenes Gedankengut habe ich als solches kenntlich gemacht.

Ich versichere außerdem, dass die vorliegende Arbeit noch nicht einem anderen Prüfungsverfahren zugrunde gelegen hat.

München, 31. Oktober 2018

Frieder Kirn

Erklärung