MASTER THESIS

Towards a Reference Architecture for BIM (Building Information Model) Integration in the Construction Industry

Developing and prototyping a reference architecture and data platform to help overcome the barriers of Building Information Modeling (BIM) adoption by the Architecture, Engineering, and Construction (AEC) industry and to support digital transformation and transition to smart industry.

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Preface and Acknowledgements

The completion of this research marks the end of my time in Enschede and at the University of Twente. All these years ago, when I graduated high school and started studying Artificial Intelligence in Amsterdam, I had no idea I would end up this far from home studying Business & IT. I am however glad that I did. I ended up studying something I love, that's highly relevant in todays' world and that will hopefully serve as a strong foundation for the challenges to come in my future.

When I started this thesis, I thought I had a lot of knowledge and that it would mostly be a matter of applying this knowledge in an innovating way. As it turns out, I did have a lot of knowledge, but there is so much more out there to learn. I knew very little about the construction industry, had never heard of BIM before and while I knew a lot about integrations, I never had to build one before. This work thus proved to be a huge learning experience.

Therefore, I am grateful to everyone who made this happen. First of all, I would like to thank CAPE Groep and especially Pieter for giving me a chance to perform this thesis research. You introduced me to a lot of interesting people, allowed me to sit in on a very interesting meeting and were always helpful in keeping me on track during these months. You were also never shy in giving your opinion on the architecture and giving helpful feedback. I also want to thank Mark and everyone else at CAPE who were patient enough to listen to all my questions, shared their expert knowledge and made this research happen. I also want to thank everyone at the construction company for being very helpful by providing the case, extensive feedback and a clear practical application for my research.

From the University, I would like to thank Maria and Marten, who were always willing to help despite their own busy schedules. I'm glad you were there to offer feedback and be critical. Spending this much time in practice makes it easy to slip a bit too much into practical applications away from scientific work, so I'm thankful you were there to guard the scientific quality of this work. Lastly, I want to thank you for providing me with the opportunity to write a paper and present in at a conference in Berlin. This was a great opportunity for me to see more of the scientific world and meet some interesting people. It almost made me apply for a PhD position. Almost!

A special mention is required for my family, without whom I'm not sure I'd have ever reached the point of graduating at all. Thank you for all your support over the years. Lastly, I want to thank all my friends for always encouraging me, while providing me with ample distractions.

Executive Summary

Traditionally, the Architecture, Engineering, and Construction (AEC) industry relies heavily on the use of paper-based communication. This is a major source of errors resulting in extra costs, delay, friction and even lawsuits in the construction process, since AEC projects typically involve complex communication-intensive processes across multiple organizations.

In the past years, Building information modelling (BIM) has been hailed as the solution to help with many of these problems. BIM is one of the most promising recent developments in the architecture, engineering, and construction (AEC) industry. Using this technology it is possible to digitally construct a virtual model of a building. BIM has proven to provide various benefits, but also faces some barriers during its adoption. The biggest barriers we've found were the high knowledge requirements, and thus training costs, and difficulties integrating different BIM platforms.

This leads to a proposed reference architecture and data platform to help overcome these barriers of Building Information Modeling (BIM) adoption by the Architecture, Engineering, and Construction (AEC) industry and to support digital transformation and transition to smart industry. The reference architecture focusses on keeping the traditional application landscape intact (therefore reducing training costs) and simplifying BIM integrations by adhering to the industry wide standard for BIM models: the Industry Foundation Classes (IFC). The architecture is prototyped using eMagiz Integration Platform as a Service (IPaaS), BIMServer and Mendix.

We provide science and practice alike with an example of a functioning, process-wide BIM integration. By reducing the two biggest barriers identified in literature, namely *Required Training and Knowledge* (by allowing users to work without BIM without having to learn everything about it) and *Software and Integration issues* (by creating an open integration based on existing standards and simplifying the integration tasks), the reference architecture will hopefully increase BIM adoption.

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1. Introduction

In this chapter, an introduction to this research project is provided. First, an overview of the (Dutch) construction industry is provided. Then, the concept of Building Information Modelling (BIM) is introduced, followed by some information about the case, the problem statement, research goals and methodology. We conclude this chapter by providing some clarity on the scope and limitations of this work, as well as an overview of the structure of this report.

The Architecture, Engineering and Construction (AEC) industry is an industry that leaves a visible mark on the world. Buildings and other constructions are a large part of the daily view of billions of people. Buildings are part of our cultural heritage; think of master pieces such as the pyramids of Egypt, the colosseum and the Forum Romanum in Rome, the Eiffel Tower in Paris. All these buildings are known around the world, and form a huge part of the culture of these cities and even countries. It is also a functional industry; people need housing, schools, offices and transportation.

The AEC industry is a diverse one; the building projects range from large hotels and stadiums to roads and aqueducts. Larger projects often require collaboration between many different parties throughout the lifecycle of a construction project.

In order to facilitate this collaboration, we have made some strides since we build the pyramids of Egypt. Building Information Modelling (BIM) has been hailed as a tool perfect for collaboration, and has been the focus of digital transformation within the AEC industry for the past ten years. Using this technology, it is possible to digitally construct a virtual model of a building (Azhar Salman, 2011). In the years since its introduction, BIM has grown to be the centrepiece of the AEC industry (Eastman, 2011).

1.1 Context

1.1.1 Dutch AEC industry

According to the central bureau of statistics, The Dutch AEC industry is responsible for roughly four to five percent of the GDP (Gross Domestic Product) of The Netherlands (Centraal Bureau voor de Statistiek 2017a). In reality, the economic value of this industry is even bigger, since the construction industry collaborates extensively with different parties, such as advisors and suppliers.

Year	2010	2011	2012	2013	2014	2015	2016	
Contribution AEC industry	30 531	30 295	27 826	26 456	27 223	28 201	29 965	Million
GDP of The Netherlands	631 512	642 929	645 164	652 748	663 008	683 457	702 641	Million
Percentage of GDP	4,83%	4,71%	4,31%	4,05%	4,11%	4,13%	4,26%	

Table 1: CBS GDP statistics for the Dutch AEC industry, in million euro
Source: CBS Statline 2017, 'Opbouw binnenlands product (bbp); nationale rekeningen'.

The Dutch AEC industry is also very fragmented. In 2008, construction companies larger than 50 employees made up less than one percent of the total amount of construction companies (see figure 1)(Centraal Bureau voor de Statistiek 2017b). Furthermore, the construction industry has historically been known for their slow innovation.

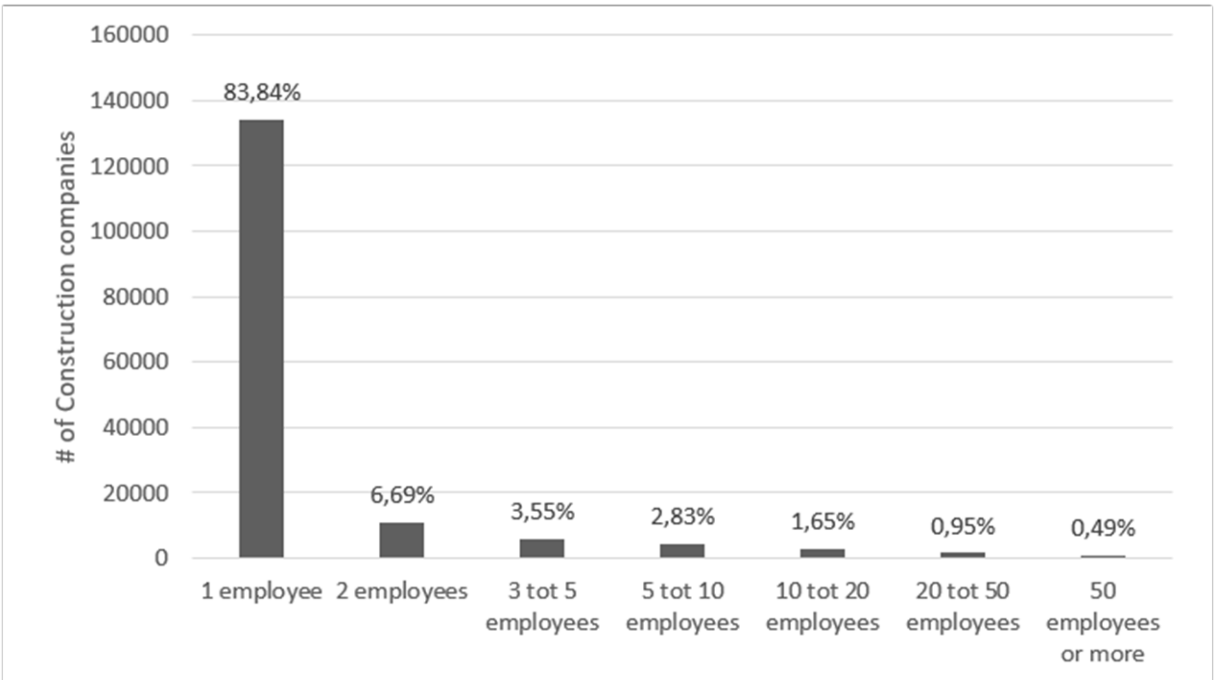


Figure 1: Number of construction firms by employee count in the third quarter of 2017.
(Sum of General Construction, Specialized Construction and Water-, Ground- and Road- Construction)
Source: CBS Statline 2017, 'Bedrijven; bedrijfstak'

The Dutch construction industry consists of two massive organizations with a yearly revenue over 5 billion euro, namely BAM and VolkerWessels. Then there are six more with a revenue ranging between 1 and 3 billion euro, seven with a revenue ranging between 300 and 800 million euro and then a rather sizeable middle of the pack ranging between 100 and 300 million euro in revenue.

1.1.2 Digital Transformation and BIM

When it comes to digitally transforming the AEC industry, we found that existing literature spans many of the common DT subjects, such as Internet of Things / Sensoring, Big Data / Data Management and AI / machine learning. Automation and Standardisation are two other key areas. However, digital transformation in the AEC industry has been slow; factors such as the heavily fragmented construction industry and unsophisticated supply chain make it harder to digitize the whole construction process.

There is however an innovation that has made great strides the past years. Traditionally, the whole design, planning and control as well as the construction process was based on 2D drawings. Building information modelling (BIM) is one of the most promising recent developments in the architecture, engineering, and construction (AEC) industry. Using this technology it is possible to digitally construct a virtual model of a building (Azhar 2011). In the years since its introduction, BIM has grown to be the centrepiece of the AEC industry (Eastman 2008).

1.2 Problem Statement

Many construction and civil engineering companies already use BIM in their building projects, making the adoption of BIM generally successful. However, BIM has various barriers barring it from being utilized to its fullest potential. An earlier exploratory literature review identified various benefits and barriers of BIM usage (Bosdriesz 2018).

The benefits of BIM have been described abundantly in existing literature. Solnosky described the current state of BIM benefits and challenges (Solnosky 2013). They found that the biggest perceived benefits of BIM are improved scheduling durations due to better error detection and elimination, a decrease in material procurement time, faster incorporation of changes suggested by various parties and rapid generation of design alternatives. These benefits closely resemble the benefits identified in the literature review performed earlier, in which we conclude that the benefits noted most often in existing literature are increased productivity, better clash detection and a reduction in conflicts / needed changes. Furthermore, it was concluded that there is a clear financial benefit to using BIM (Bosdriesz 2018).

When it comes to barriers, the barriers encountered most often were complex standards, high knowledge/training requirements and differing BIM usage between parties and integration thereof.

In practice, we identify many of the same barriers. Difficulties in integrating BIM solutions between parties, or even BIM solutions with other, traditional systems that are in use, is proving difficult and is a large barrier towards further BIM adoption. At the same time, the construction industry is growing, and the traditional 2d based methods of communication are often no longer sufficient, as BIM usage is enforced for many government projects.

While inter-organisational collaboration is the big goal of BIM, intra-organisational usage of BIM can improve drastically as well. it appears that BIM is still largely limited to usage in the planning and design stage, and less so during construction and building management stages, despite literature supporting benefits for both.

In short, there is a large gap between current scientific literature and practical implementations. BIM adoption, while increasing, is still not as high as it could be, and is often limited to certain stages of the construction process.

1.3 Case and parties involved in this Research Project

1.3.1 Cape Groep

Cape Groep is an IT company situated in Enschede. They have extensive experience in integration solutions. Cape provides expert knowledge as well as prototyping tooling and evaluation possibilities for this research. Furthermore, they initiated the project in collaboration with one of their partners, described below.

1.3.2 Case: Construction Company

In order to reduce the gap between science and practice and increase BIM adoption, interviews are performed during both the problem investigation and artefact validation/evaluation stage, with the help of experts at a medium sized Dutch construction company. The company has roughly between 300-600 employees. In a yearly top 50 ranking of 2017 by industry magazine Cobouw, they were ranked in the 20s with a revenue of over 150 million euro over 2016 ('Cobouw50 2017' 2017).

They provide expert knowledge as well as the case study for this research. Their core activities consist of real estate development, civil and utility building, management & maintenance, infrastructure & environment and residential building.

1.4 Research Goals

The goal of this research is to improve BIM integration possibilities, by providing the AEC industry with a clear reference architecture for BIM Integration. By prototyping this architecture, we hope to give a clear example of how BIM can be integrated with further processes within a construction organisation. This translates into the following research question:

Research Question: *What are the characteristics of a reference architecture for BIM integration designed to facilitate BIM adoption?*

This research question reflects the overall goal of this study; we want to implement a practical solution of BIM integration that reduces the gap between literature and practice, and helps the industry to gain the full benefits of BIM. In order to answer this question, the following sub questions have been determined:

- **Sub question 1:** *What are the current barriers to BIM integration and adoption within the AEC industry as found in existing literature as well as practice?*
  This question will be answered partly in an exploratory literature review and partly with the construction company case study.

- **Sub Question 2:** *Which standards, initiatives and tooling exist within the BIM domain and should be part of the architecture/prototype*
  This question will be answered by performing an exploratory literature review

- **Sub Question 3:** *Which frameworks for BIM integration and interoperability already exist?*
  This question will be answered by performing an exploratory literature review

  Sub Question 4: *Which levels of BIM maturity are currently identified in literature?*
  This question will be answered by performing an exploratory literature review

- **Sub Question 5:** *Which aspects should be part of a reference architecture for BIM integration?*
  This question will be answered partly in an exploratory literature review and partly with the construction company case study.

1.5 Approach and Methodology

The approach of this study is twofold. Firstly, an exploratory literature review will be performed in order to determine the current landscape of BIM tooling, architectures as well as existing standards and initiatives. Secondly, the results of this review will be compared with the practical situation at a medium sized Dutch AEC company and an architecture will be designed based on the findings of both these studies, as well as findings from an earlier exploratory literature review (Bosdriesz 2018). This design is then validated, applied to a prototype and evaluated at a medium sized Dutch construction company.

This research follows the Design Science Methodology for Information Systems and Software Engineering as described by Wieringa (Wieringa, 2014) as an overarching methodology. This methodology uses the engineering and design cycle as a central concept for IS design research. This cycle is shown in figure 2. It describes how an artefact is designed within the context of information systems. The design cycle consists of three stages: The **Problem Investigation** is the preparation stage, in which the design is prepared by studying the problem that the artefact is meant to solve as well as the context in which it's going to operate. The **Treatment Design** is the stage in which the artefact is designed; requirements are specified and optionally already existing treatments are examined. In the **Treatment Validation** the treatment is validated within the context, and checked whether it fulfils the goals and requirements. The engineering cycle includes a fourth, the **treatment implementation**, as design projects often serve a real world need, this stage exists to actually implement the treatment in a real world application. This stage is however outside the scope of this project.

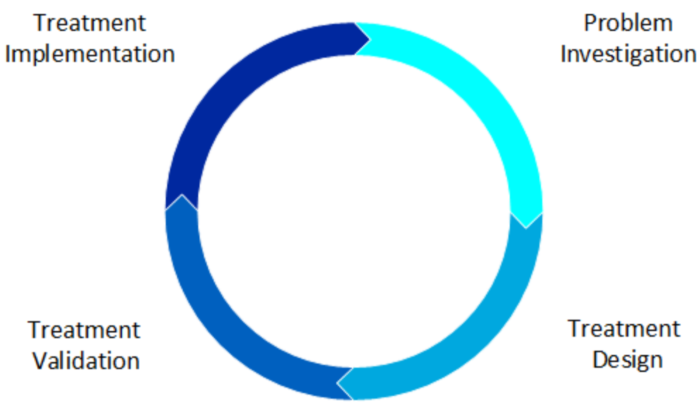


Figure 2. The Engineering/Design Cycle of the DSM Methodology

1.6 Research Motivation

1.6.1 Relevance for Science

While BIM as a concept and many of its facets have already been studied extensively, a gap still appears to exist between scientific literature and practice. By providing a solid foundation with an architecture for BIM integration, the goal is to lower the barrier of BIM integration difficulties, thereby increasing BIM adoption. For science this would lead to being able to focus more on new BIM technologies and applications, with practice not being as far behind and therefore able to implement these new findings quickly.

1.6.2 Relevance for Practice

The goal is to provide practice with a clear example of the benefits that BIM can bring to your organization. By providing a reference architecture, we hope to take away some of the complexity of integrating with BIM solutions. In the future, this might even bring BIM to its original goal of becoming a collaboration tool between the parties in a construction process.

1.7 Scope

While the research described here is not specifically aimed at the Dutch construction industry, all practice related work is done with Dutch companies and initiatives. While the goal is to deliver a broadly applicable architecture, the case study and evaluation are both performed for the Dutch construction industry, and may vary for other markets where BIM adoption might be less, or more mature.

1.8 Structure of the Report

The first chapter introduces this study. It covers information about the context, problem statement, the approach and methodology as well as the scope and limitations of this study. Furthermore, it describes the motivation for this study.

The second chapter is an overview of the current issues with BIM integration and adoption. This is partly a summary of an earlier literature review (*"An Exploratory Literature Review Into the Digital Transformation of the (Dutch) Construction Industry"* (Bosdriesz 2018)), and partly a case study of the practice of a medium sized Dutch construction firm.

Chapter two consists of an exploratory literature review, looking at the current landscape of BIM tooling, existing architectures as well as existing standards and initiatives. Chapter three further explores the problem by identifying stakeholders and describing a case study. In the fourth chapter, the architecture and platform are designed.

The fifth chapter describes prototype that is developed based on the reference architecture and in the sixth chapter the design is validated, and then evaluated based on the prototype. Lastly, chapter seven summarizes our findings and provides some recommendations for further research.

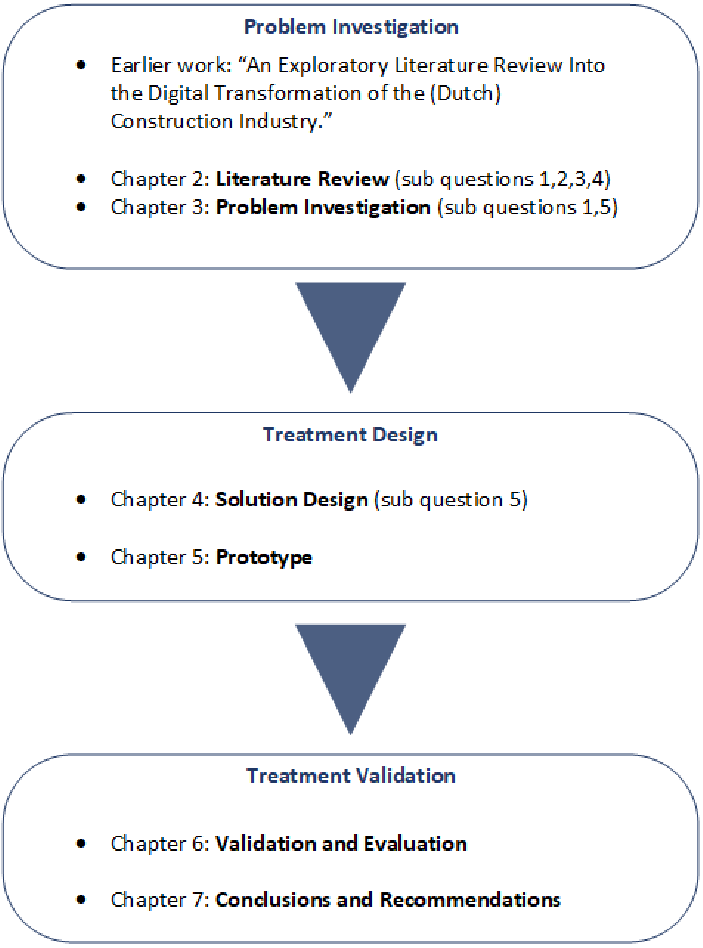


Figure 3. Structure of report within the context of the Design Science Methodology.

2. Literature

In this Chapter a literature review is performed. It discusses the current BIM literature in order to identify BIM barriers, existing standards and initiatives as well as existing BIM architectures. Furthermore, an attempt is made to define BIM maturity levels.

2.1 Barriers for BIM adoption

Yan and Demian questioned 67 AEC academics and practitioners in the UK and found that according to their beliefs, the biggest barrier to BIM adoption was the time and human resource cost of BIM training (Yan and Demian 2008). This seems in line with a more recent study of BIM adoption in the Dutch construction industry by a Dutch publisher of market research in the construction industry. In their research they found that the required training and knowledge for BIM was the number one concern regarding BIM adoption ('BIM & Ketensamenwerking in Kaart' 2015). A close second was 'difference in BIM usage between parties'. Bryde et al found that most of the negative benefits or challenges of implementing BIM focussed on software or hardware issues (Bryde, Broquetas, and Volm 2013).

In their assessment of the current state of BIM benefits and challenges, Solnosky identified the following challenge classes (Solnosky 2013):

- Legal and contractual
- Educational training
- Information modelling
- Software
- Cost

These classes largely coincide with the findings from the explorative literature performed in preparation of this thesis (Bosdriesz 2018). Solnosky also identified major possible future benefits for BIM, mainly in the domain of integration. Further integration with existing processes is the next step of BIM, but still proves to be a challenge.

In order to compare these barriers with our case study, we identify four main barriers:

- *Barrier 1*. **Required training and knowledge**
- *Barrier 2*. **Difference in BIM adoption between collaborating parties**
- *Barrier 3*. **Software and integration issues**
- *Barrier 4*. **Legal and contractual**

2.2 BIM Standards and Initiatives

The Industry Foundation Classes (IFC) standard is an open data model used in the BIM domain. It is designed for the exchange of construction models. It is maintained by buildingSMART and has since been adapted as the ISO 16739 international standard (ISO 2013). The Geometric aspects of IFC are mostly defined or derived from a different ISO standard, ISO 10303 (ISO 2014) which also specifies the STEP Physical File (SPF) encoding that is most commonly used in IFC files (.ifc)(Arroyo Ohori et al. 2017).

IFC (ISO 16739) → Object Related Information
IFD (ISO 12006-3) → Product Related Information
IDM (ISO 29481) → Process Related Information

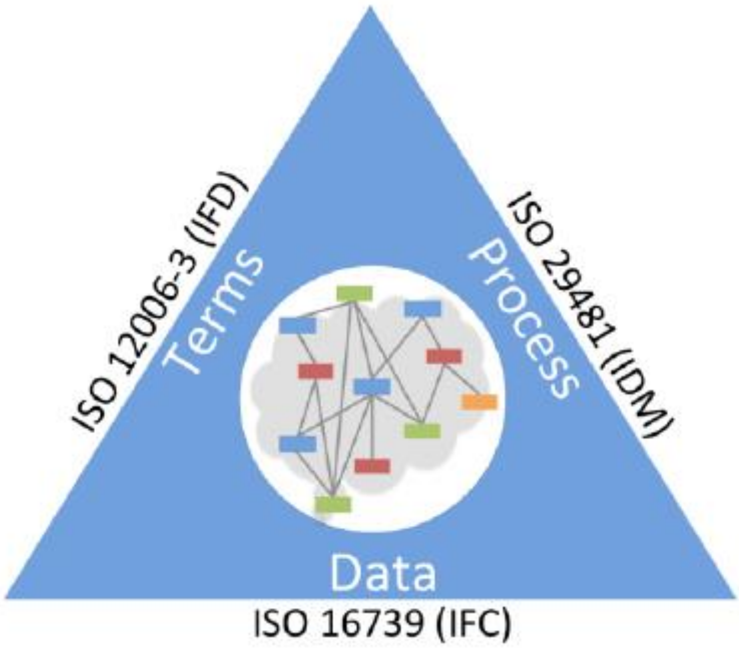


Figure 4. IFC standard.
source: The IFC standard: A review of history, development, and standardization, information technology (Laakso and Kiviniemi 2012).

IFC is both the term for the filetype and the common data model. It contains both geometric and non-geometric data about a building project. It is essentially an entity-relationship model based on the EXPRESS data modelling language (also described in ISO 10303-11 (ISO 2014)). For example a door can have both attributes and properties attached on both the type and instance level.

There are currently two relevant versions of IFC; IFC4 is the newest version currently available and contains modified and enriched existing entities and lacks some obsolete and deprecated IFC2x3 entities. IFC2x3 is the previous version. They are not automatically compatible with each other.

IFC2x3 is currently used more widely in practice, and many industry agreements still use this standard. Therefore IFC2x3 appears to be the more relevant standard for the near future.

IFC provides a common schema to exchange all data that could possibly be exchanged between BIM tools. However, not every case of data exchange needs the full data set. An IFC MVD (Model View Definition) describes a subset of the IFC schema with specific information requirements, dependent on the process that the exchange is a part of.

Within the larger standard of IFC, local initiatives usually exist to streamline the exchange of design phase model information. For the Dutch AEC industry, one of these initiatives is the ‘BIM basis ILS’ (BIM Loket 2016). It is in essence an agreement between several parties in the AEC industry on how they deliver their IFC models. It describes which fields should always be filled with information, naming conventions and other conventions for seamless IFC data exchange.

2.3 Existing BIM architectures

In order to develop a reference architecture for BIM integration, we must first look at existing architectures within the BIM domain. We will discuss some of the often cited architectures within the BIM domain.

There have been several attempts at establishing a framework for BIM interoperability and cooperation. Most focus on either on the organizational aspects or the technological aspects of interoperability and cooperation.

One of the earliest of such attempts was made by Froese et al. They describe a general reference architecture for distributed, model-based integrated system (Froese et al. 2000). They describe their architecture in terms of three tiers, namely the Applications/Presentation Tier, the *Business Objects/Middle Tier* and the *Data Tier*.

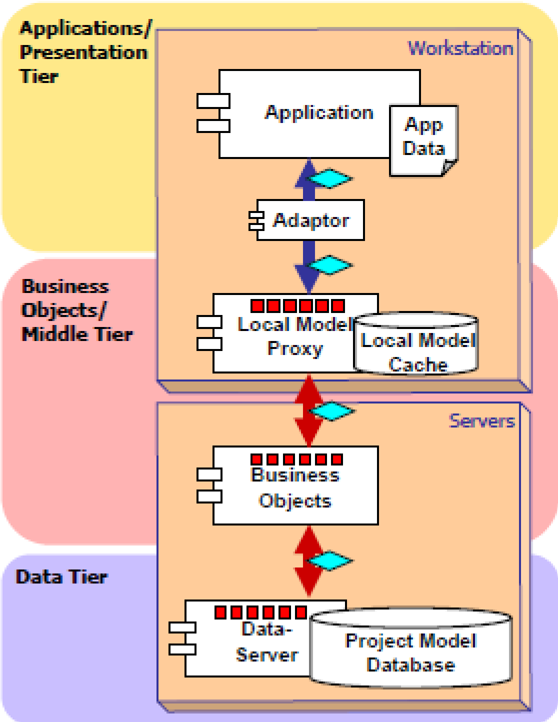


Figure 5. A reference architecture for a distributed, model-based, integrated system by Froese et al. (Froese et al. 2000).

This reference architecture seems suitable for BIM integration, however at the time of writing many of the standards, initiatives and technologies that we have now weren't available or established yet. Therefore an updated reference architecture is desirable.

Other architectures and or platforms found in literature often focus on one aspect of BIM integration or collaboration, or focus more on an organizational level.

Based on an analysis and case study, Singh et al. came up with operational technical and support technical requirements for, and developed a, theoretical framework of a BIM-based multidisciplinary collaboration platform (V. Singh, Gu, and Wang 2011). They present a "framework that categorizes and specifies features and technical requirements for a BIM-server to serve as a collaboration platform". They do however not discuss any products nor do they validate using a prototype. They note that AEC projects are multi-organizational and multi-disciplinary and adjust the requirements accordingly.

Das et al. presented a similar framework, for integrating the construction supply chain in an attempt to solve the data heterogeneity and data sharing problems in the construction industry (Das, Cheng, and Law 2015). It describes an ontology based web service framework using various ontology based tools and techniques (OWL, Sparql etc).

Sanguinetti et al. (Sanguinetti et al. 2012) proposed a system architecture in which the data requirements for various analyses are automatically generated from a comprehensive BIM model, rather than having a separate BIM model for each purpose, using MVDs.

During the review it became apparent that due to the multidisciplinary nature of BIM, various frameworks exist but each of them focus on a certain discipline, domain or aspect of BIM. Therefore, for the development of a reference architecture for BIM integration, it is useful to look at existing architectures outside of the BIM domain.

Singh et al performed an analysis of 31 existing papers on integration platforms spread over various disciplines and developed a reference architecture for integration platforms (P. M. Singh, Van Sinderen, and Wieringa 2017). They describe various components over three layers: the Data Layer, The Application Layer and the Service Layer. This is, in the most general terms, similar to the reference architecture for a distributed, model-based, integrated system by Froese et al (Froese et al. 2000).

Figure 6 depicts the components of the reference architecture as developed by singh et al.

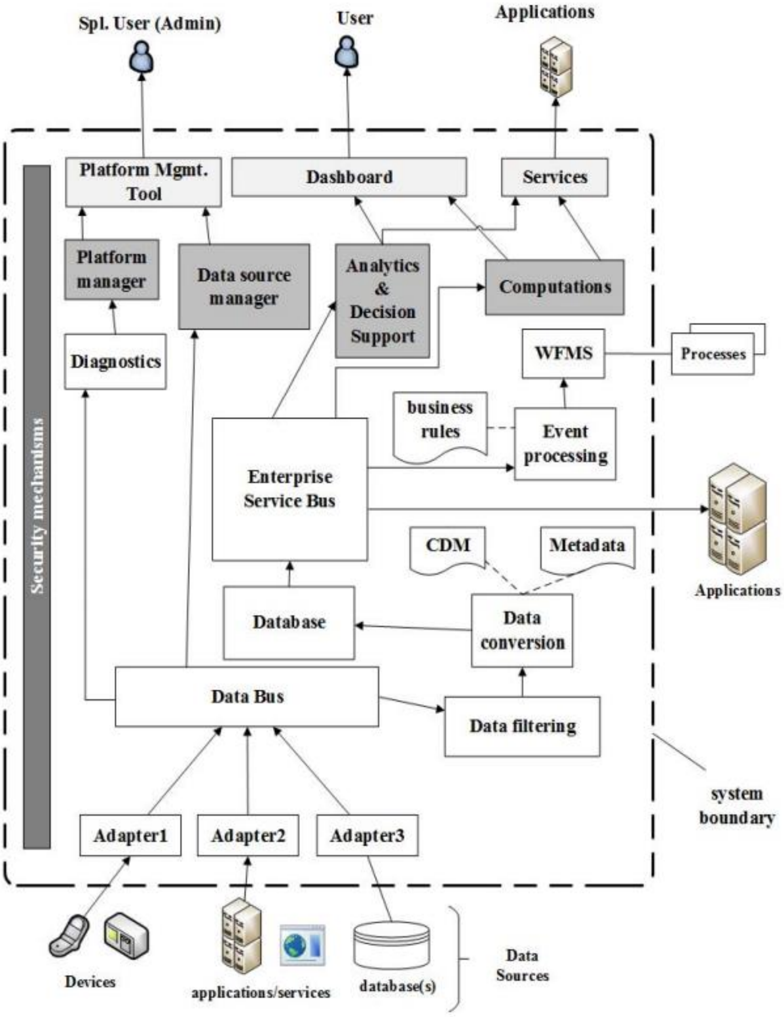


Figure 6. Reference Architecture for Integration Platforms by Singh et al. (P. M. Singh, Van Sinderen, and Wieringa 2017)

2.4 BIM Performance and Maturity

As discussed before, in the past years BIM has made huge strides to becoming industry standard, especially for complex construction projects. During this process however, it became clear that implementing BIM in practice was not always easy. The sheer amount of possibilities attributed to BIM lead to an increased need for the assessment of BIM performance within an organisation.

There have been several attempts at establishing a way of assessing this BIM performance. One of these is the TNO QuickScan. The BIM QuickScan tool aims to 'serve as a standard BIM benchmarking instrument in the Netherlands'. The scan is intended to be performed 'in a limited time of maximum one day', and focusses on 4 overarching topics: organization and management, mentality and culture, information structure and information flow, and tools and applications (Sebastian and van Berlo 2010).

'Each chapter contains a number of KPIs in the form of a multiple-choice questionnaire. . . With each KPI, there are a number of possible answers. For each answer, a score is assigned. Each KPI also carries a certain weighting factor. The sum of all the partial scores after considering the weighting factors represents the total score of BIM performance of an organization' (Sebastian and van Berlo 2010).

Another stride towards making BIM performance and maturity measurable was done by Succar et al. in a number of different publications.

Succar identifies several BIM capability stages (Succar 2010). These stages are summarized in table 2.

Pre-BIM status *Disjointed Project Delivery*	• Traditional way of working: heavy focus on 2D documentation. • No data derived from 3D modelling. • Collaborative practices between stakeholders are not prioritised and workflow is linear and asynchronous.
BIM Stage 1 *Object-based Modelling*	• BIM implementation is initiated through the deployment of an 'object-based 3D parametric software tool. • Single-disciplinary models. • Architectural design models and duct fabrication models. • Used primarily to automate generation and coordination of 2D documentation and 3D visualisation. • Other deliverables include basic data exports (e.g. door schedules, concrete volumes, FFE costs,...) and light-weight 3D models (e.g. 3D DWF, 3D PDF, NWD, etc...) Which have no modifiable parametric attributes. • No significant model-based interchanges between different disciplines.
BIM Stage 2 *Model-based Collaboration*	• Active collaboration with other disciplinary players. • The interchange (interoperable exchange) of models or part-models (either through proprietary or non-proprietary (IFC) file formats). • Model-based collaboration can occur within one or between two Project Lifecycle Phases.

	• Only one 'collaborative model' needs to hold 3D geometric data to allow for semantic BIM interchanges between two disciplines. • Although communications between BIM players continue to be asynchronous, pre-BIM demarcation lines separating roles, disciplines and lifecycle phases start to fade. • Some contractual amendments become necessary as model-based interchanges augment and start replacing document-based workflows.
BIM Stage 3 *Network-based Integration*	• Semantically-rich integrated models are created, shared and maintained collaboratively across Project Lifecycle Phases. • This integration can be achieved through 'model server' technologies (using proprietary, open or non-proprietary formats), single-integrated/distributed-federated databases, Cloud Computing or SaaS (Software as a Service) (Wilkinson 2008). • BIM Stage 3 models become interdisciplinary nD models (Lee et al. 2003) allowing complex analyses at early stages of virtual design and construction. • Model deliverables extend beyond semantic object properties to include business intelligence, lean construction principles, green policies and whole lifecycle costing. • Collaborative work now 'spirals iteratively' around an extensive, unified and sharable data model. • From a process perspective, synchronous interchange of model and document-based data cause project lifecycle phases to overlap extensively forming a phase-less process.
Integrated Project Delivery *Interdependent, real-time models*	• A long-term vision of BIM as an amalgamation of domain technologies, processes and policies. • The delivery and continuous evolution of a highly integrated multi-dimensional model connected to multiple external databases and knowledge sources in real-time. These include services' grid, building management systems, geographic information systems (GIS), cost databases, operations business logic, etc...

Table 2. BIM capability stages according to Succar (Succar 2010).

Source: Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies (Underwood and Isikdag 2010)

Based on all the earlier work, they established a framework consisting of five complementary components positioned to understand BIM performance and to enable its assessment and improvement (Succar, Sher, and Williams 2012). The components of the framework are as follows:

- BIM capability stages representing transformational milestones along the implementation continuum;

- BIM maturity levels representing the quality, predictability and variability within BIM stages;
- BIM competencies representing incremental progressions towards and improvements within BIM stages;
- Organizational Scales representing the diversity of markets, disciplines and company sizes
- Granularity Levels enabling highly targeted yet flexible performance analyses ranging from informal self-assessment to high-detail, formal organizational audits.

Summarized, they look at BIM capability, maturity and competencies in relation to organizational scales.

The term ‘BIM maturity’ refers to the quality, repeatability and degree of excellence within a BIM capability. Although a BIM ‘capability’ denotes a minimum ability, BIM ‘maturity’ denotes the extent of that ability in performing a task or delivering a BIM service/product (Succar, Sher, and Williams 2012).

For BIM maturity, they established a BIM maturity model based on various existing models for BIM maturity, as well as several maturity models established in other disciplines. They identify five levels of BIM maturity, but don’t specify the exact requirements for each level. Combined with the capability stages described above and the competency sets, these can serve as an assessment tool for BIM performance.

	Initial/ad hoc	**Defined**	**Managed**	**Integrated**	**Optimized**
Level	1 / a	2 / b	3 / c	4 / d	5 / e

3. Problem Investigation

In this chapter, the research problem is investigated further by looking at the practice of a medium sized construction company. The stakeholders are identified and a case study is performed in order to compare literature findings with practice.

3.1 Stakeholder Assessment

Stakeholders have been an important aspect of both business and IS research ever since the term emerged in the mid-1980s. A focal point in this movement was the publication of Freeman's Strategic Management- A Stakeholder Approach (Freeman 2010). Within IS research, the definition of stakeholder that's used is often the one found in **ISO/IEC/IEEE 42010**. This standard is an international standard for architecture descriptions of systems and software (ISO/IEC/IEEE 2011). The definition of a stakeholder found in this standard is: "A individual, team, organization, or classes thereof, having an interest in a system".

It is important to consider various stakeholders in a design science project, as they are the source of goals an restraints of a project; which in turn lead to the requirements of the treatment (Wieringa 2014).

3.1.1 Stakeholders in the construction industry

The construction industry is a very fragmented industry, and thus there are often many stakeholders in a construction project. This further depends on size and context of a project; building an aqueduct will have different stakeholders than a residential building.

At the most general level, any construction project will have three major groups of stakeholders, namely a **Client**, the **Construction Firm** and **Subcontractors**. The client is often the initiator of a project. They want something build and provide the requirements for a construction project. The construction firm is the coordinator of the project; they are the ones hired by the client in order to get the project built. They in turn often hire a number of different subcontractors to perform (parts of) the construction project, for example they might use the services of an architecture firm, an electrician is hired, a plumber is used to provide their services. All these stakeholders have to work together to deliver the final product.

In many construction projects there are however also indirect stakeholders, such as the general public that lives close to the construction site and local authority. They influence a construction project, for example because of local laws and or resistance to a specific project. Figure 4 provides an overview of how these stakeholders generally interact.

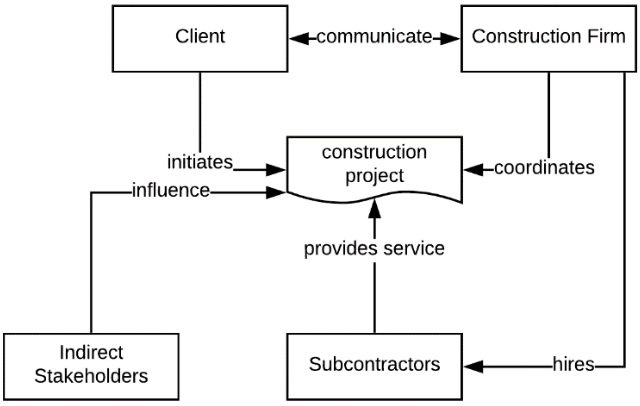


Figure 7: construction project stakeholders

3.1.2 Stakeholders for intra-organizational BIM Integration

For the artefact to be developed we are looking to identify the stakeholders for BIM integration. BIM integration can be inter-organizational or intra-organizational between departments. The stakeholders of such an integration therefore differ on a case by case basis, it could be an integration between the construction firm and the client, or the firm and its subcontractors, or the firm internally. Inter-organizational integration/collaboration comes with its own share of barriers regarding data ownership, governance and financial responsibilities (Lam 2005), which our artefact won't address; it focusses on improving BIM integration on a technological as well as intra-organizational level.

For the artefact, we identify the following intra-organizational stakeholders:

On a group level

The construction firm

The construction firm has their own role in this. They want to push further BIM usage and integration because they identified the benefits. They are responsible for overseeing the whole project.

The various departments

Each department has their own goals and requirements for the artefact. The software they use, their workflows or their demands may all influence the requirements of the artefact.

On a user level

Non-technical user

This stakeholder group describes all the users of the various departments that have no extensive BIM training. These are the users that should be able to use the data contained in the models in their own workflows, but without encountering the complexities of BIM.

Modeller

These are the BIM experts who create the models. They are responsible for both the design as well as including the initial data in the model. Depending on data requirements in other processes, they may need to include more or less object information.

3.2 Case Study

The Case study was performed at a medium sized Dutch construction company. They have roughly between 300-600 employees. In a yearly top 50 ranking of 2017 by industry magazine Cobouw, they were ranked in the 20s with a revenue of over 150 million euro over 2016 ('Cobouw50 2017' 2017). The data was gathered through semi-structured interviews as well as during the regular sprint reviews. For more information about this process, please consult chapter 6.1.1 for an overview of experts.

3.2.1 Barriers identified in practice

At the construction firm investigated for this research, some kind of BIM usage the norm for most projects, at least as far as designing 3D models capable of containing extra object information. For each of the barriers identified from literature, we discuss whether we encountered these in practice.

Barrier 1. **Required training and knowledge**

This barrier is present in our case study. The company has BIM experts as well as designers, but any pilot project that requires non BIM trained employees to participate, is expected to run into resistance.

Barrier 2. **Difference in BIM adoption between collaborating parties**

This barrier is present, but not as strongly as in the past. They often work with the same set of parties, and therefore know what to expect when it comes to their BIM usage. They have guidelines in place for how models should be delivered and what they should contain, and the design stage is very collaborative. However, if BIM usage would be pushed beyond the design stage, this barrier might re-emerge, since different parties play a part during the construction process; they might have differing BIM capabilities from the firm itself.

Barrier 3. **Software and integration issues**

This barrier is present. Wanting to increase BIM usage as well as enriching the data available in the models is highly desired, but the desire is to connect BIM to existing software solutions/workflows, so integration is required. The solutions for this have been scarce, as many products seem to focus on bringing as much functionality as possible into the model, rather than extracting and adding data from and to the model through existing solutions.

Barrier 4. **Legal and contractual**

We didn't encounter this barrier, but it was not focussed on either. It is out of the scope of this project, and shouldn't impair intra-organizational integration.

3.2.2 BIM usage in practice

While investigating a medium sized Dutch Construction Company, it became clear that a gap exists between the possibilities of BIM described in the extant literature, and the actual usage of so-called BIM models in practice.

During the BIM model is an important document during the design and planning phase. Upon the acquisition of a new project, a first BIM design is developed in Autodesk Revit. This model is then converted to the open standard IFC and shared with subcontractors, who each check the model and refine it with their own additions. Then, in a joint session between all the stakeholders / subcontractors, the design is finalized. This is also the point at which the BIM model stops being used extensively. The purchasing department sometimes uses some data from the model, but sporadically, not automated and not standardized. In rare cases, mostly large projects, the construction site has a TV in the worker room where they can check the model, but in general the model is not used for the construction process either. This situation is depicted in figure 2.

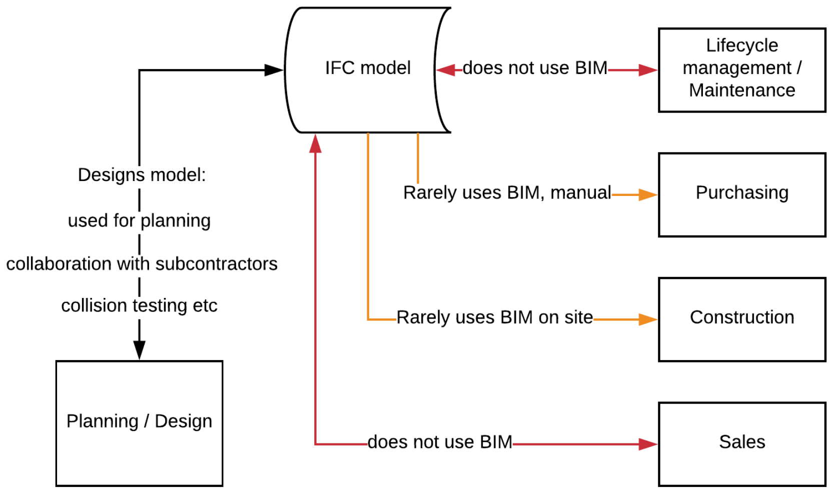


Figure 8. Current BIM usage in Case Study

The construction company is rapidly growing, and are noticing that their current way of working is leading to an exceedingly large amount of paperwork. In addition to the BIM model, they still use several separate documents which contain much of the same data as the BIM model. Their wish is to further integrate their BIM usage with their existing processes, but in their opinion existing tooling falls short.

3.2.3 BIM Vision

In the case study, experts mentioned that their vision for BIM is a less consolidated approach, but with BIM as a central data source. Currently you see that a lot of extra features get added to BIM software to add new dimensions of data, however, these experts believe that a less consolidated approach is superior. In this approach, BIM is centralized as data source, but extra processes or dimensions are handled in their own tooling, specialized for that specific task. All object information should still be related to objects in the model, but enriched with task specific data stored in separate databases.

4. Solution Design

As mentioned earlier the most notable technical reason AEC companies are not yet reaping the full benefits of adopting BIM is the lack of interoperability between BIM implementations, organizational barriers for collaboration, and different maturity levels of using BIM across but also within organizations.

In view of this, we argue that a *reference architecture* and a *data platform* are useful artefacts to help overcome these barriers.

In this chapter, the design process of the said artefacts is described. The architecture design is based on two factors: Firstly, the current situation at a medium sized Dutch construction firm, and secondly the current state of BIM literature. Requirements for the solution will therefore be based on needs both from practice (the case study) and literature. The chapter starts with a study into existing BIM tooling as well as architectures; in order to design a reference architecture, it is essential to know which resources are already out there.

4.1 BIM Tooling

Since BIM is a topic that covers various disciplines and has a rather long history of development, the BIM landscape consists of many different tools and types thereof. Furthermore, it is difficult to define when a tool is a BIM tool or not.

Generally, we can divide BIM tooling in several categories, the first and foremost of which are the design tools; these tools are used to create the actual model of a building. In general, the relation of tools is described in figure 5.

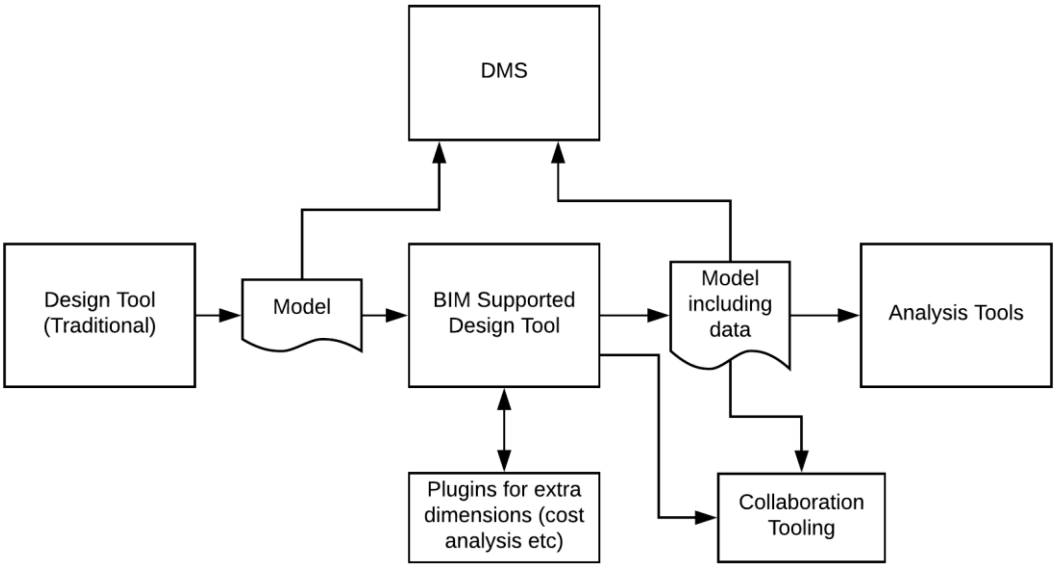


Figure 9. Relation between types of BIM tooling

Not all these tools are required, nor does every organization use them all. Sometimes, a model will be made in a traditional design tool and then imported into a BIM supported one, sometimes a design will be made in the BIM supported tool itself. There is also tooling that perform several of these tasks. It is also not comprehensive, there are other specialized tools for example lifecycle management, which is outside the scope of this study. But in general, these are the tools that can play a role in BIM workflows.

Design tools vary a lot, depending on preference, industry and tasks to be performed. They range from tools like AutoCAD that are mainly used as pure design software for 2d/3d drawings, to tools like Revit that exists specifically to enable BIM. They can be enriched by additional plugins to offer support for additional dimensions or to be able to directly connect with collaboration/cloud tooling. BIM supported design tools form the core of BIM, they enrich the models with data and provide the models used for analysis like clash detection, cost analysis and energy consumption analysis.

The table below lists some of the tools available within the BIM domain.

Name	**Publisher**	**Category**	**Proprietary/Open Source**
AutoCAD	Autodesk	Design	Proprietary
Sketchup	Trimble	Design	Proprietary
BricsCAD	Bricsys	Design	Proprietary
Vectorworks Fundamentals	Vectorworks	Design	Proprietary
Tekla Structures	Tekla	Design + BIM	Proprietary
Revit	Autodesk	Design + BIM	Proprietary
ARCHICAD	Graphisoft	Design + BIM	Proprietary
DDS-CAD	Data Design System AS	Design + BIM	Proprietary
AECOsim Building Designer	Bentley	Design + BIM	Proprietary
BricsCAD BIM	Bricsys	Design + BIM	Proprietary
Vectorworks Architect	Vectorworks	Design + BIM	Proprietary
Tekla BIMSight	Tekla	Analysis/collaboration	Proprietary
BIMServer	Supported by TNO/TUE	Collaboration/data management	Open Source
Trimble Connect	Trimble	Collaboration/data management	Proprietary
AutoDesk 360	Autodesk	Collaboration/data management	Proprietary
BIMSync	Catenda	Collaboration/data management	Proprietary
BIM+	AllPlan	Collaboration/data management	Proprietary
EDMmodelServer	Jotne EPM Technology AS	Collaboration/data management	Proprietary
IFCHub	IFChub	Collaboration/data management	Proprietary

Table 3. A selection of existing BIM tooling

4.2 Requirements

In order to conceptualize our Reference Architecture for BIM integration, several requirements were established. These will be listed and discussed here.

R0. ***The system must allow for other applications to extract object information from a BIM model.***

This is the basic premise of the architecture. For a move towards BIM models as centralized data source throughout the construction process, other applications must be able to access the object information stored within the model in order to use them for their regular workflows.

R1. ***The system must allow for other applications to modify object information in the corresponding BIM model.***

Much like R0, This is the basic premise of the architecture. Other applications must be able to enrich model object data with their own, process specific data. This keeps the central BIM model up to date, and allows for more dynamic BIM usage.

R2. ***The system must use a centralized repository for the BIM models, making the model the leading document throughout the construction process.***

This requirement is based on expert interviews. Their BIM vision was to have BIM models as a central data source, with business processes having existing data sources in use. These existing data sources can then be used to enrich BIM model data, or simply be used in parallel, with objects information linked to BIM objects. This way, not everything has to be stored in the model itself, but every information used is retraceable to a BIM model object.

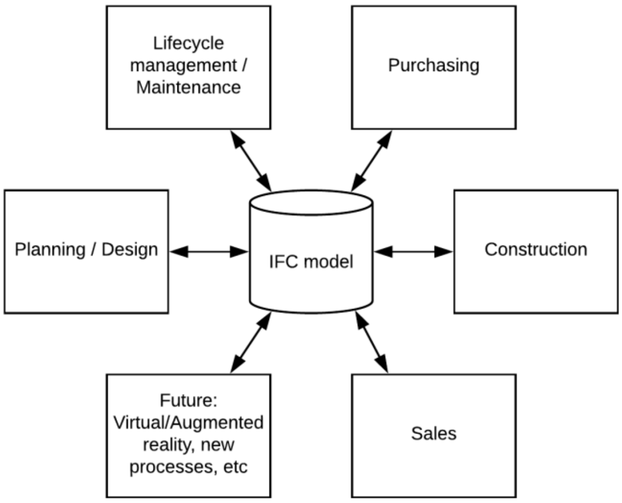


Figure 10. Requirement 2, based on the Shared Data Model

R3. ***The system must allow for seamless integration with the traditional applications used by non-technical users***

In the previous chapter we identified a group of stakeholders called **Non-technical Users.** These users have no BIM training, or experience with BIM software.

One of the biggest barriers for BIM adoption identified in both literature and practice, is the high amount of knowledge required and the resulting human resource cost for training people. It therefore seems unfeasible to have every user trained to be fully capable of using and understanding BIM software. Therefore, in order to design a system that improves BIM integration and adoption, it becomes paramount to keep the BIM complexities somewhat hidden from these users. Therefore, a requirement for the system is to allow users to use their traditional applications that are built specifically for their business process. These applications should be fed BIM model data, but this can be handled mostly on a technological level, causing the least amount of extra complexities for end users.

R4. ***The system must implement the current industry wide standard set of Industry Foundation Classes (IFC)***

IFC has mostly been accepted as the industry wide standard for BIM collaboration and model sharing (Laakso and Kiviniemi 2012). In order to keep the system application-agnostic, the system must implement these open standards for their models. This ensures both compatibility with other software vendors who support IFC, as well as a vendor agnostic system.

4.3 Architecture

Based on the aforementioned requirements, the following architecture was developed. The architecture is partly based on the architecture for a distributed, model-based, integrated system by Froese et al (Froese et al. 2000), but altered for modernized BIM needs. Furthermore, it can largely be mapped on the Reference Architecture for Integration Platforms by Singh et al. (P. M. Singh, Van Sinderen, and Wieringa 2017).

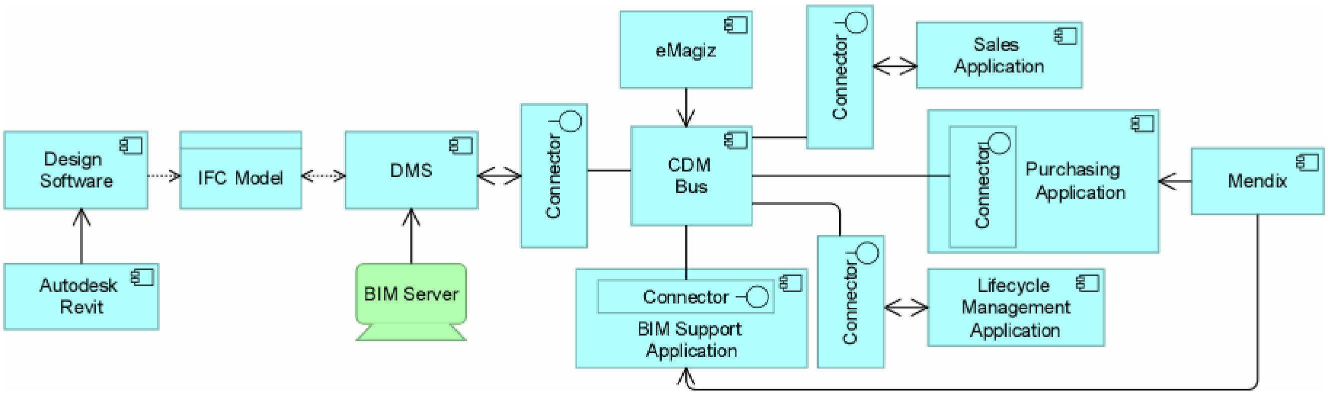


Figure 11. A Reference Architecture for BIM integration

The **Design Software** is used to develop the first edition of the model. During the design, the objects of the model are enriched with available data, and the model is exported to a IFC model. This IFC is stored on the DMS. By using IFC, it is likely that anyone wanting to implement this architecture can keep using their familiar design software, as IFC is already (rapidly becoming) the non-proprietary industry standard for BIM models, as previously discussed in 2.2. This satisfies requirement R4.

The **DMS / Model Repository** component of the architecture serves as the back bone of the architecture. It is a central repository / database for BIM models, which manages existing models for the various construction projects. Different teams and departments can connect to this data source and access the models assigned to a project, and both extract and enrich object information. For the developed prototype, the open source application BIM server was used for this component, this choice is motivated in the next chapter. It enables querying of the model data (stored as a relational database). Furthermore, it offers an API which allows for access to this data. This component serves as a large part of the data layer, provides functionality compliant to requirements R0 and R1 and is the core of requirement R2. It further satisfies R4 by being fully IFC powered. It is furthermore powered by platform agnostic technologies, making it a solid choice for a research project trying to implement a reference architecture that is to be applied to a wide variety of construction companies.

In order to integrate, some kind of **integration platform** or **Enterprise Bus** should be used. There are many options on the market for this specific task, but it is important that it can provide the communication between the BIM repository and the existing application landscape which needs to be integrated. For the prototype, the eMagiz Integration Platform as a Service (iPaaS) was used, mostly for practicality reasons as it was already the integration platform of choice at the case construction firm. The **Connector** components provide the messaging between the bus and the applications. The various messages are translated to and from a **Common Data Model (CDM)**. In our prototype, this CDM is based on the BIM Service interface exchange (BIMSie), but depending on the situation, requirements for the CDM may vary. This component is part of the data as well as the service layers, providing an easy to understand platform to monitor integrations as well as create new ones. It is an integral component to satisfy requirement R3, and provides functionality for requirements R0 and R1.

An extra application called **BIM Support** is tasked with handling any BIM related messaging. A supporting application is required if data were to be sent back, as the bus itself has no memory, and in order to work with the IFC model, some data about IFC objects (such as type, objectID, projectID, revisionID) has to be retained. It is however not feasible to have this data available in every application that wants to use BIM data, which concluded in the addition of a support application.

Therefore, BIMSupport functions as an extra layer of translation and memory between the model repository and the traditional application landscape.

If a purchasing application is in need of object information about a 'Door' object, BIMSupport knows that it should ask the model repository for IFCDoor objects. Furthermore, it can link purchasing object ids with IFC object IDs, and essentially masks the existence of IFC objects from the traditional applications. The functionality of this application could possibly be implemented in the data repository instead.

5. Prototype

In order to validate the architecture, a prototype was developed and implemented, based on the reference architecture described in chapter 3. This chapter describes the development process as well as each of the prototype components. The prototype was developed within the context of a medium sized Dutch construction firm. The first subchapter describes the business process simulated with the prototype; afterwards, the actual prototype is described.

5.1 Use Case

In order to develop the prototype, we took a very specific use case for one business process to simulate. A non-technical user from the purchasing department wants to know which articles he or she has to order. The BIM model contains information about objects, and therefore is an ideal source of data for this purpose. The user opens the project in his or her usual application environment, and gets a list of all the objects that are relevant for his or her purchasing operation. The user also wants to add an article number to one of the objects (enrich the model data). This use case is illustrated in figure 11.

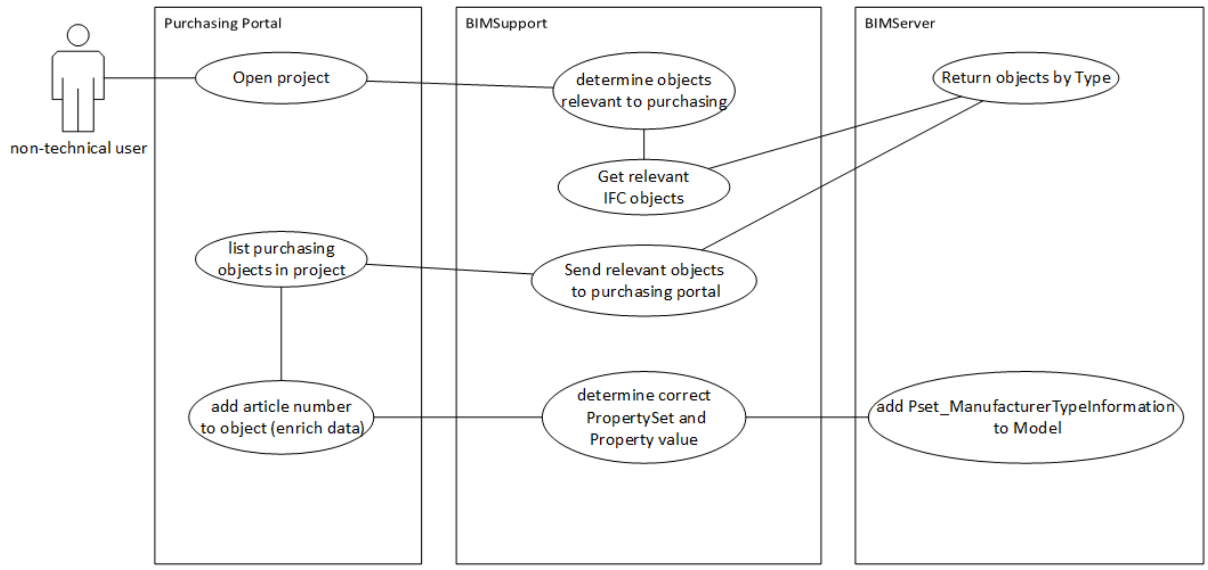


Figure 12. Prototype use case

5.2 DMS / Model Repository

For the DMS / Model Repository, a database is needed that can contain BIM model data. Since development time is limited for this research project, a ready to use product is preferred. Looking at the available tooling from chapter 3.1, there are several products that provide some kind of IFC model repository. Many of them provide a whole portal/cloud environment, which is more than needed, and a lot of them are closed source with a proprietary data format.

Since Requirement 4 states that the industry standard IFC should be used, we limit our choice to platforms that have IFC support. As such, we chose to use the BIMServer application. BIMServer is an open and stable software core to easily build reliable BIM software tools, with a rich API used to interact with the models. The software core of BIMServer is based on the open standard IFC and therefore knows how to handle IFC data, and the models are loaded into a database, allowing for querying, merging and filtering of the BIM data. Furthermore, it comes with core server features like revisions, authorization, compare, query, model checking, merging, etc.

Out of the box, it comes with several plugins to show its possibilities. In order to set up a test environment for the prototype, a plugin called bimvie.ws was used. This plugin provides a portal over the core BIMServer functionality, so that it can be used and managed from a web browser. This plugin is shown in figure 12.

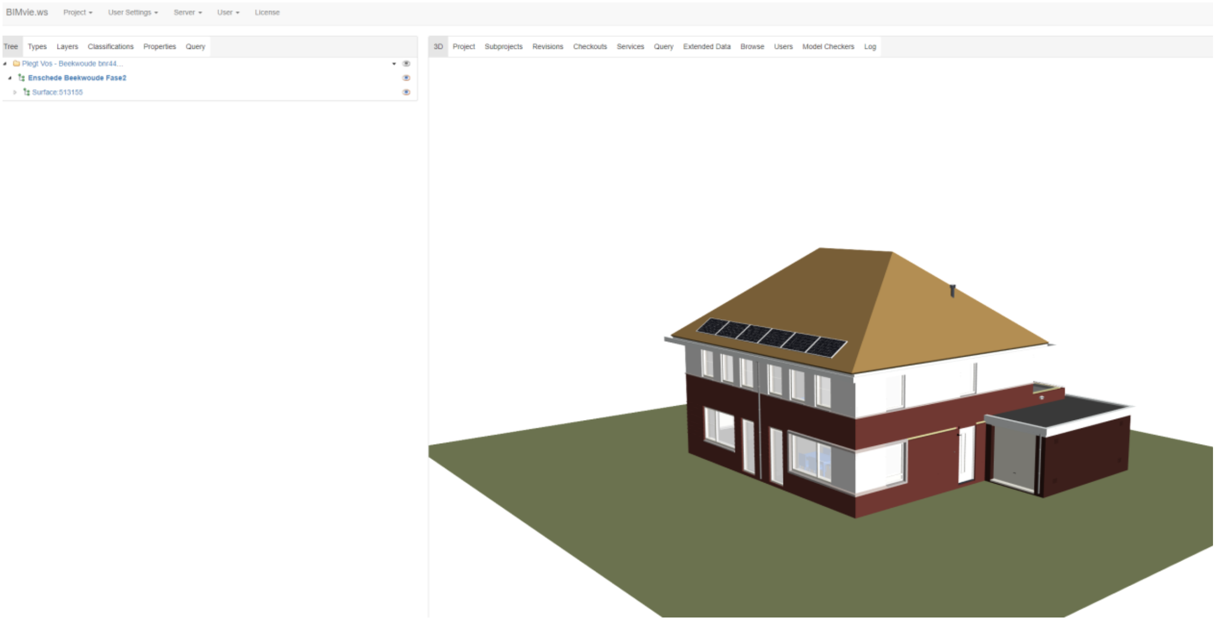


Figure 13. bimvie.ws, a plugin which adds a web portal to BIMServer

In order to further develop and test the prototype, two projects were added to BIMserver. One small residential building (as shown in figure 12), which represents a large number of the projects done by the company. The second project was a bigger project for an apartment complex. This project had more stakeholders than the usual projects and was designed by an architecture firm rather than inhouse.

5.3 Integration

5.3.1 Integration Platform

In order to integrate with the model repository, a tool was needed to fulfil the integration platform / bus role. While many tools exist on the market to provide integration, many of which are supplied by some of the giants in the technology world. SAP, Microsoft, Oracle and others all offer a wide variety of integration products. For the prototype, the eMagiz Model Driven Integration Platform as a Service (iPaaS) was used for integration purposes. It was chosen for three main reasons:

- It was already used in the application landscape used to test and validate the prototype, therefore more expert knowledge was available and the focus could be on the benefits of the integration architecture, rather than the technological complexities.
- It is a user friendly, model driven way of designing integrations; this means there's nearly no coding required, making it quicker to pick up for a limited duration research project.
- The eMagiz platform has often been used with Mendix, the tool used to develop the prototype Purchasing Portal and BIMSupport applications. This combination of tools is therefore thoroughly tested and well supported.

eMagiz consists of several components. Central to the communication is the Java Message Service (JMS). In addition to this central component, a connector runs for each of the external servers that are part of the integration; these components handle the communication to that specific endpoint. Lastly, a component, in the figure below denoted as container, contains the functionalities for transforming messages to and from the CDM, and contains essentially all the eMagiz logic.

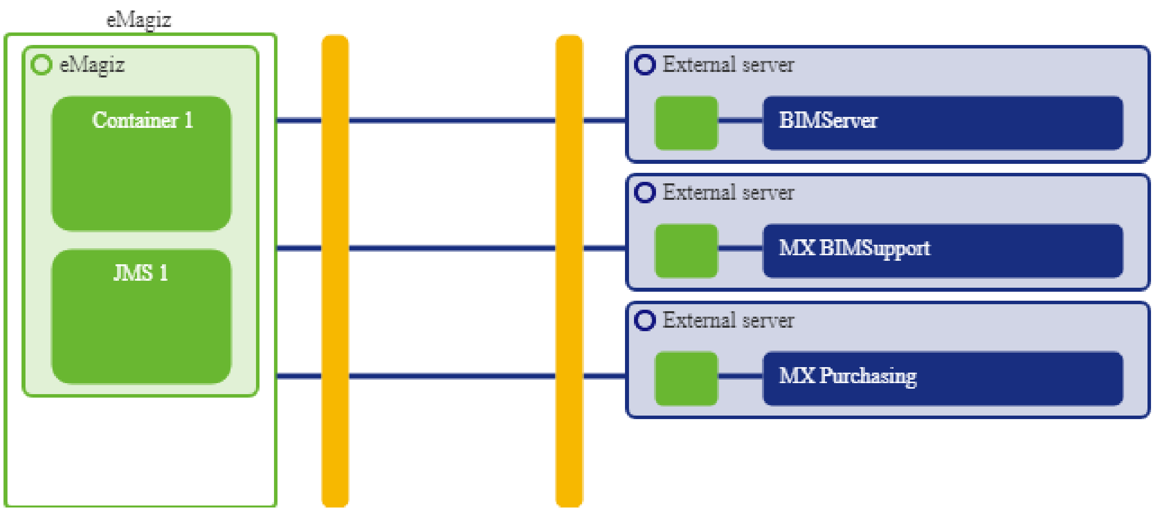


Figure 14. The eMagiz architecture of the prototype

5.3.2 CDM

In order to facilitate messaging between the various components of the architecture, a common data model has been developed. It has initially been based on the BIM Service interface exchange (BIMSie), a standard API for BIM cloud integration. Since the DMS / Model Repository makes use of this API, the messages were based of that. Later, some extra terms were added to the CDM in order to facilitate messages in the traditional application landscape. The CDM can be seen in figure 14.

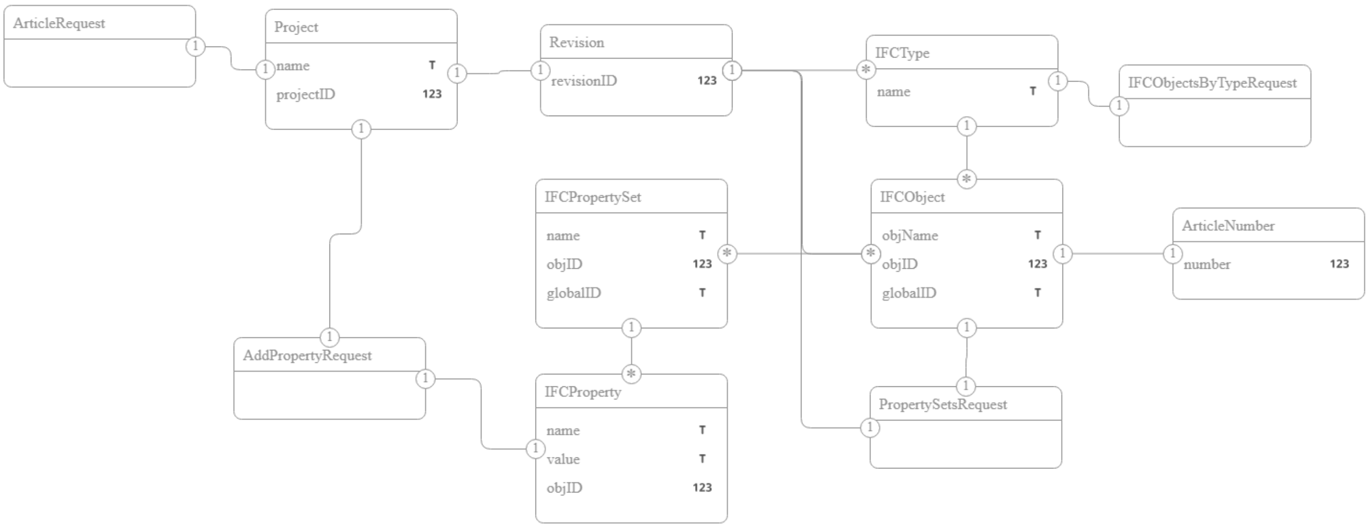


Figure 15. The Common Data Model used in the Prototype

A ***Project*** has a *name* and *projectID* field, and is used in both ***Article*** and ***AddProperty*** requests. An ***IFCPropertySet*** has fields for *name, objID (object ID) and globalID*. It contains any number of ***IFCProperties*** which have *name, value and objID* fields and are also used in ***AddProperty*** requests. Furthermore, an ***IFCObject*** has any number of ***IFCPropertySets*** and a certain ***IFCType.***

5.3.3 Messaging

In order to perform each of the tasks described in the use case, there are various messages that can be sent in the prototype. Figure 16 shows the general message overview of the prototype. All

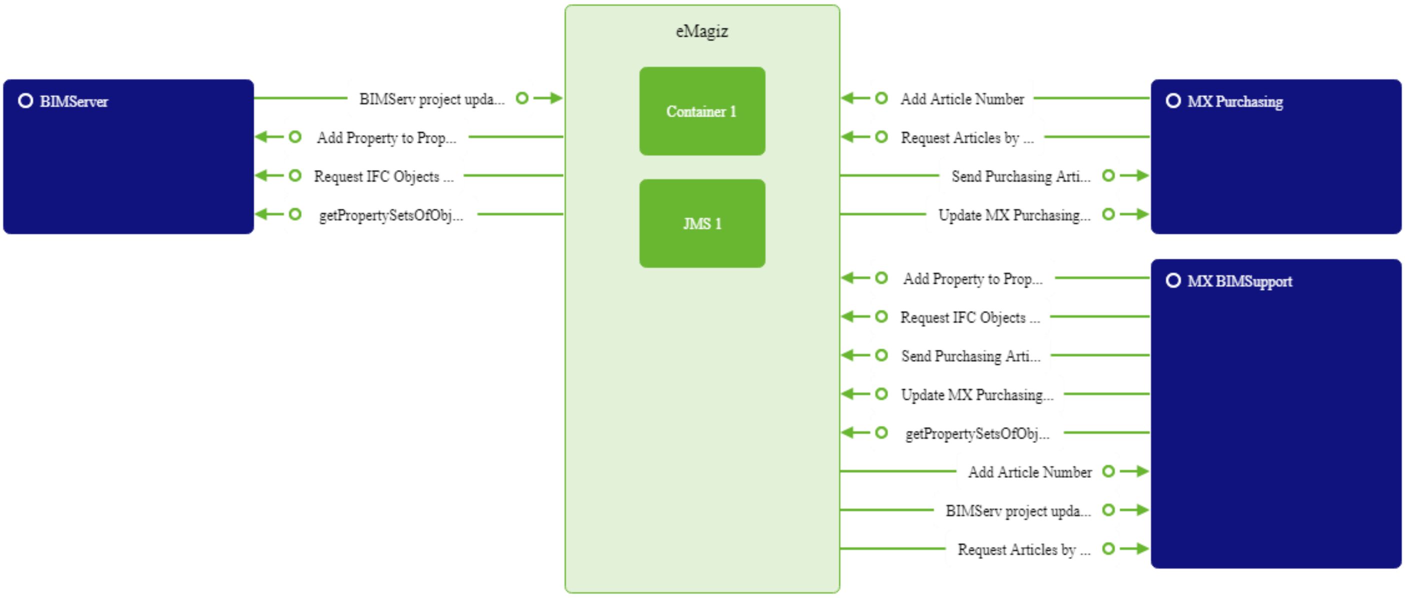


Figure 16. The message flow of the bus component

messages are sent and received in XML format, using the SOAP protocol for both the BIMServer API as well as the connection with both Mendix applications.

Between the **DMS / Model Repository** BIMServer and the bus there are four defined message types. For a project update, a full description of the flow is given as an example. Other flows are summarized and depicted in appendix A.

For flow illustrations of all message types, see Appendix A: eMagiz Flows

BIMServ project update

This is a message which contains the following:

- General project information for all projects on the repository
- All IFCTypes contained in each of the models, so that BIMsupport knows what to ask for in follow up requests.

In the prototype, this message is sent on a basic CRON timer, so that every x minutes BIMserver updates the other applications with up to date project data. A better implementation would be to send updates on change, e.g. when a new project is added or an existing project is changed, but due to time constraints the simpler solution was used. In order to create this message, several steps are taken in the eMagiz entry connector flow (shown in figure 17). It is an asynchronous connection, no response is expected.

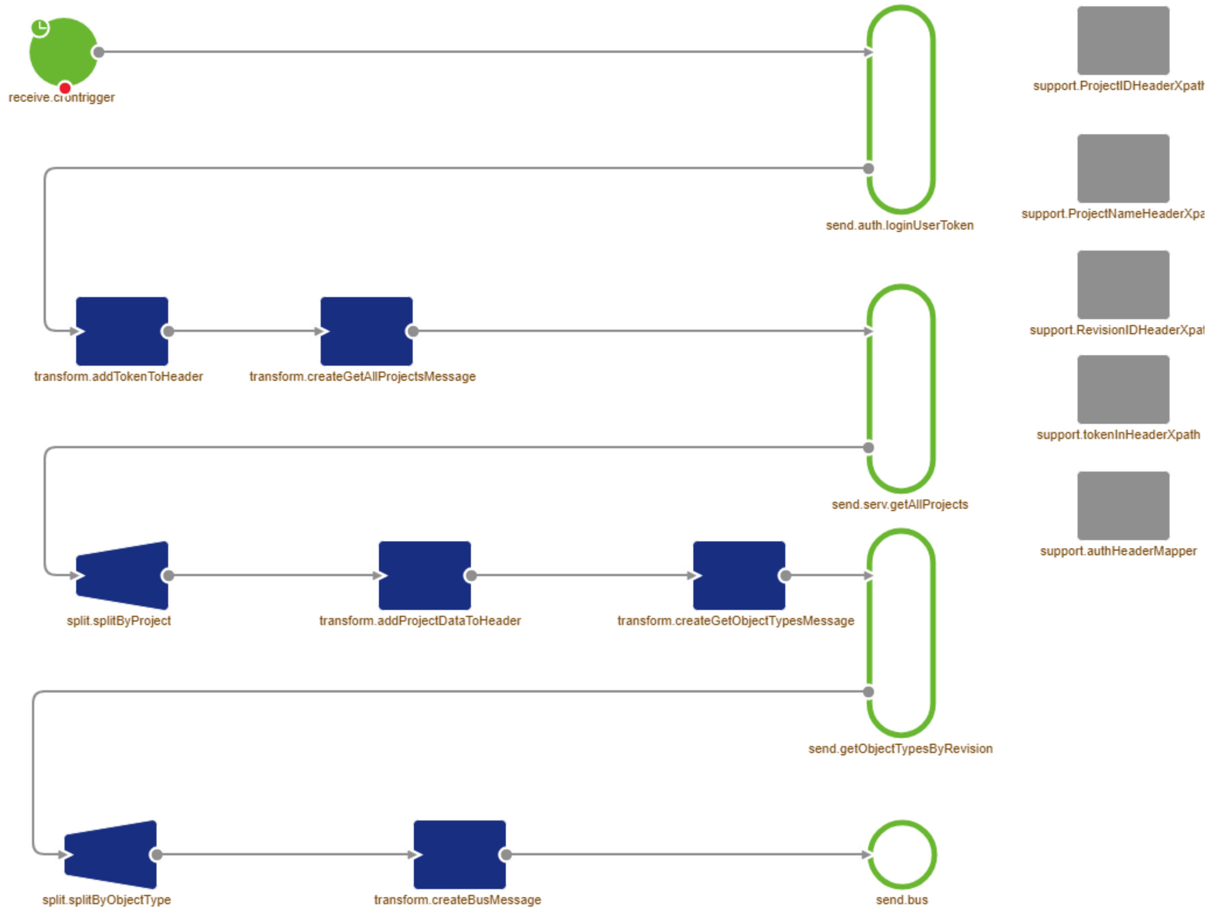


Figure 17. eMagiz entry connector flow for message 'bims-upd' from system bimserv.

When a *receive.crontrigger* is called (upon receiving the cron trigger), eMagiz sends a auth.loginUserToken SOAP API call to BIMServer, in order to log in with the user token stored in the eMagiz properties. This call returns an authorization key needed for further API calls to bimserver. In *transform.addTokenToHeader,* an xpath query retrieves this token and stores it in the eMagiz message header. *Transform.createGetAllProjectsMessage* transforms the message using xslt to a new 'getAllProjects' message. This message is then send to the SOAP endpoint of BIMServer, returning a list of all existing projects. In *split.splitByProject*, this message is split into a separate message for each project. Using another xslt transformation in *transform.createGetObjectTypesMessage,* a message is constructed per project in order to retrieve all available IFCTypes used in that model. Per IFCType, a last message is constructed in *transform.createBusMessage* and sent to the bus.

Add Property to PropertySet

This message type is used to add a property to a specific propertyset. It should contain a property, a propertyset to add it to, and the object the propertyset should be a part of. The flow for this message uses the following BIMServer API calls:

- AuthInterface.loginUserToken
- LowLevelInterface.startTransaction
- LowLevelInterface.createObject
- LowLevelInterface.addStringAttribute
- LowLevelInterface.commitTransaction

Request IFC objects by IFCtype

This message sends a request to return all simple object data for all objects of a specific IFCType (e.g. all IFCDoors). This is a synchronous call, where BIMServer immediately responds with object information. The message requires a revisionID and an IFCType. The flow for this message uses the following BIMServer API calls:

- AuthInterface.loginUserToken
- LowLevelInterface.getObjectsByType

Get PropertySets by IFCObject

This request retrieves the PropertySet(s) associated with a specific IFC object.). This is a synchronous call, where BIMServer immediately responds with the property set object information. The flow for this message uses the following BIMServer API calls:

- AuthInterface.loginUserToken
- LowLevelInterface.getDataObjectsByOID (multiple calls)

Between the Bus and the BIMSupport Application, there are several types of messages. BIMSupport handles all of the communication with BIMServer, so like BIMServer, it handles the message types ***Add Property to PropertySet, Request IFC objects by IFCtype*** and ***Get PropertySets by IFCObject*** described above it also receives the ***BIMServ project update***. Furthermore, it handles the communication with the purchasing portal. For this purpose, the following messages exist:

Update MX purchasing

This message is used to provide the purchasing portal with updated project information. It is called when BIMSupport receives new project data from BIMServer. It is a asynchronous call and consists of a **Project (name, id)** and a **Revision (id)**.

Send Purchasing Articles

This message is used to send article information to the purchasing portal. It is an asynchronous call, and consists of an associated **Revision(id), IFCType(name)** and any number of **IFCObjects(objName, objID, globalID).**

Request Articles by Project

This message is used to request article information for a specific Project. It is sent by the purchasing portal and contains a **Project(id)** and **Revision(id)**. It is used to trigger a **Send Purchasing Articles** response.

Add Article Number

This message is used to add an article number to a article. This article number is sent to BIMSupport, which is supposed to add the number to an objects propertySet called:

'Pset_ManufacturerTypeInformation'

BIMServer converts this to the correct ***Add Property to PropertySet*** message, after which it should then be reflected in the origin IFC model in BIMServer.

5.4 BIMSupport

The BIMSupport application is a Mendix application, used to store the IFC data required to enrich IFC data in the external applications. It enables the purchasing application to use its own terminology rather than having to store IFC terminology in all connected applications. Furthermore it serves as a sort of memory for when the applications in the traditional application landscape want to send object data back to BIMServer.

5.4.1 Mendix

In order to develop the BIMSupport, the tool Mendix was used. Mendix is a Low Code Application Development Platform. The choice of Mendix was made due to several reasons:

- It offers the ability to rapidly deploy fully functioning applications, allowing for the development of the whole architecture within the time constraints of a Master thesis.
- It was already used extensively in the application landscape of the construction company where the architecture is tested, as well as being the tool of choice of Cape Groep. This meant that a significant amount of expert knowledge was available, leading to quicker development.
- Its low code functionality made it easier to convey the ideas and theory behind the prototype to non-technical users.

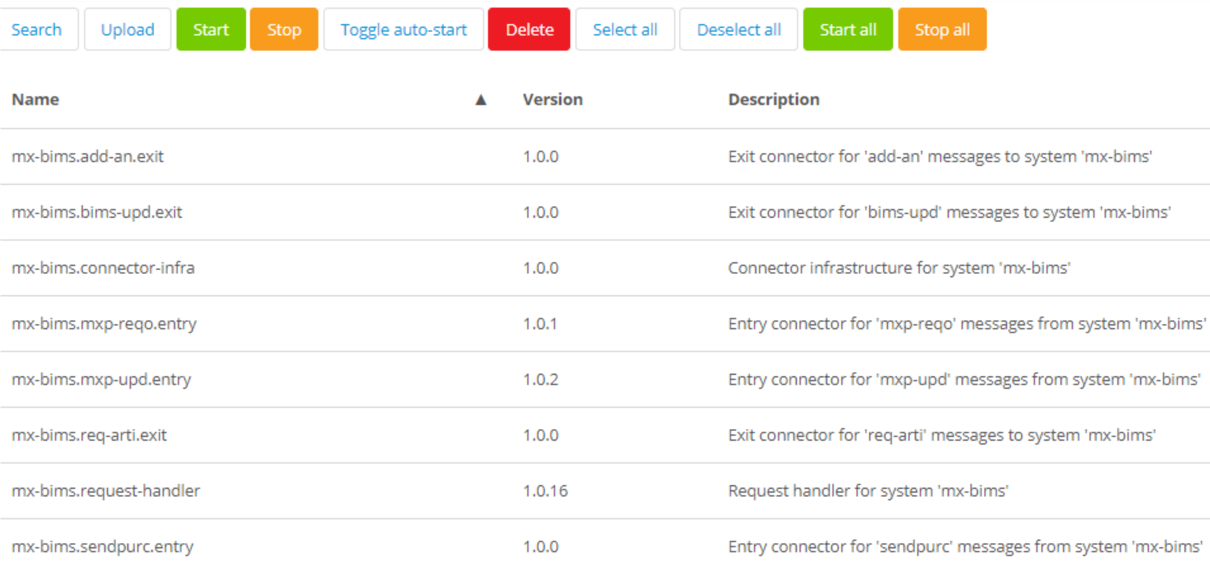
5.4.2 Functionality

Project Overview

The main page of the BIMSupport application consists of an overview of all the projects as they exist on BIMServer, including their available revisions. In the prototype, there is also a button available to send project data to the purchasing portal, triggering an **Update MX purchasing** message.

eMagiz-MX Connector

The BIMSupport application contains a eMagiz-MX connector. This is a module developed and maintained by the eMagiz team, containing all the functionality to connect with the eMagiz bus, as well as the eMagiz portal. It has an overview of all the components running, and provides basic functionality for each of them.



Name ▲	Version	Description
mx-bims.add-an.exit	1.0.0	Exit connector for 'add-an' messages to system 'mx-bims'
mx-bims.bims-upd.exit	1.0.0	Exit connector for 'bims-upd' messages to system 'mx-bims'
mx-bims.connector-infra	1.0.0	Connector infrastructure for system 'mx-bims'
mx-bims.mxp-reqo.entry	1.0.1	Entry connector for 'mxp-reqo' messages from system 'mx-bims'
mx-bims.mxp-upd.entry	1.0.2	Entry connector for 'mxp-upd' messages from system 'mx-bims'
mx-bims.req-arti.exit	1.0.0	Exit connector for 'req-arti' messages to system 'mx-bims'
mx-bims.request-handler	1.0.16	Request handler for system 'mx-bims'
mx-bims.sendpurc.entry	1.0.0	Entry connector for 'sendpurc' messages from system 'mx-bims'

Figure 18. eMagiz-MX Connector of the BIMSupport application

Purchasing Mapping

One of the main features of the BIMSupport application is the mapping functionality. This functionality allows the user to change the internal IFC object names to more appropriate naming schemes for traditional applications. For example, a user might want to order doors for a construction project. Door objects in IFC are classified as IFCDoors, but the purchasing portal may know them as just Doors. Therefore, a mapping is made between IFCDoor and Door, from which point BIMSupport always sends IFCDoor objects as Door to the purchasing portal, and as IFCDoor to BIMServer (which only knows IFCDoor objects, and not Door objects).

	BIMServer/ BIMsupport Object	Related Purchasing Object
Type	IfcDoor	Door
GUID	22erBPISX01uqcwczID30V	
ObjectID	600492430	
ArticleNr		9543230
Name	svedex_draaideur_SL01	svedex_draaideur_SL01

Figure 19. BIMSupport Object in relation to Purchasing Object

The page used to create this mappings first allows the user to select a project. After making a selection, a list of IFC objects that exist in the BIM model of said object. Per IFCobject a choice can then be made to include objects of said class in the purchasing process, and what name they should be mapped to.

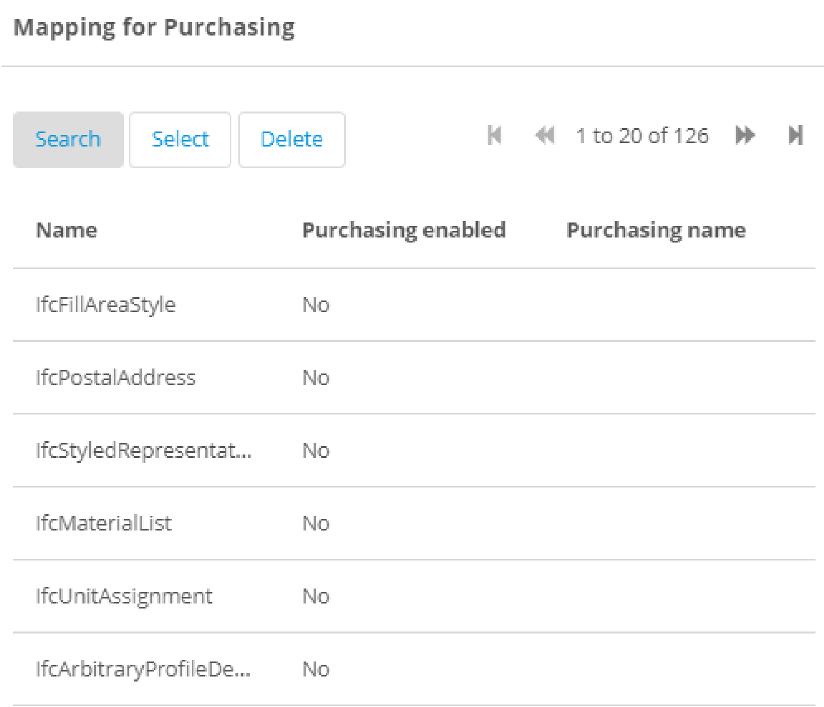


Figure 20. The mapping screen of BIMSupport

Article and article number requests

The article requests screen shows an overview of received requests for articles by the purchasing portal, showing a button which allows the user to request the correct objects from BIMServer, and send them back to the purchasing portal. The article number request screen shows all article numbers sent by the purchasing portal, which have to be delivered to the BIMServer application.

Web Services

In addition to the aforementioned functionality, BIMSupport contains various web services for handling the messaging to and from the eMagiz bus.

5.5 Purchasing Portal

The Purchasing Portal is prototyped in order to provide a basic implementation of a purchasing application. Like BIMSupport, Mendix is used for the prototyping; the reasons for this choice are the same as during the BIMSupport development. The Portal enables the end user to obtain a list of relevant objects per project from the origin IFC model on BIMServer as well enrich the data with additional article numbers. The purchasing portal does not contain IFC data, but rather article information.

5.5.1 Functionality

Project Overview

The Purchasing Portal provides the end user with an overview of the available projects from which articles can be retrieved. It shows the projects as they exist on BIMServer, as well as the existing revisions. The data is stored locally, but updated whenever BIMServer pushes a project update.

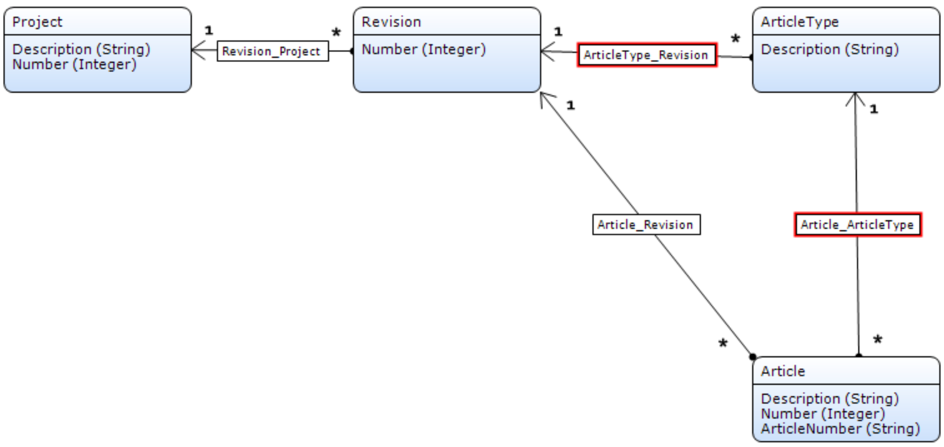


Figure 21. The purchasing portal domain model

From the project overview, a request for articles can be sent using the 'request articles by project' button. This triggers a message to BIMSupport, which then handles the article request further. Once the articles for a specific project are in the system, an article number can be added to an object. This once again triggers a message to BIMSupport, which handles the rest of the add article number functionality.

Web Services

The purchasing portal also consists of a number of web services in order to handle the integration with the eMagiz bus. Figure 22 shows an example microflow of the webservice functionality. The built in Mendix webservice functionality is used to expose a ReceiveArticles webservice. This webservice expects a message containing a ***Revision, ArticleType*** and ***Article***. The microflow then checks whether the articletype already exists in the local DB, and if not, creates a new one (in the FetchOrCreate Microflow), then does the same for the articles.

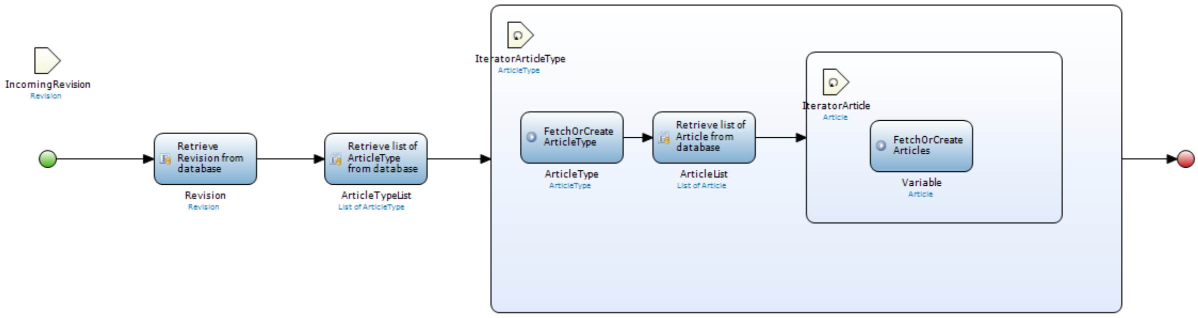


Figure 22. ReceiveArticles Microflow

In total, there are two exposed webservice operations (UpdateModel and ReceiveArticles), and another two consumed webservices: these are web services provided by the eMagiz bus, and used to send messages to the bus. The two consumed webservices are SendArticleNumber (used to add a article number to an object) and SendReqArt (used to send the request for the articles belonging to a project).

5.6 Example of Message Flow

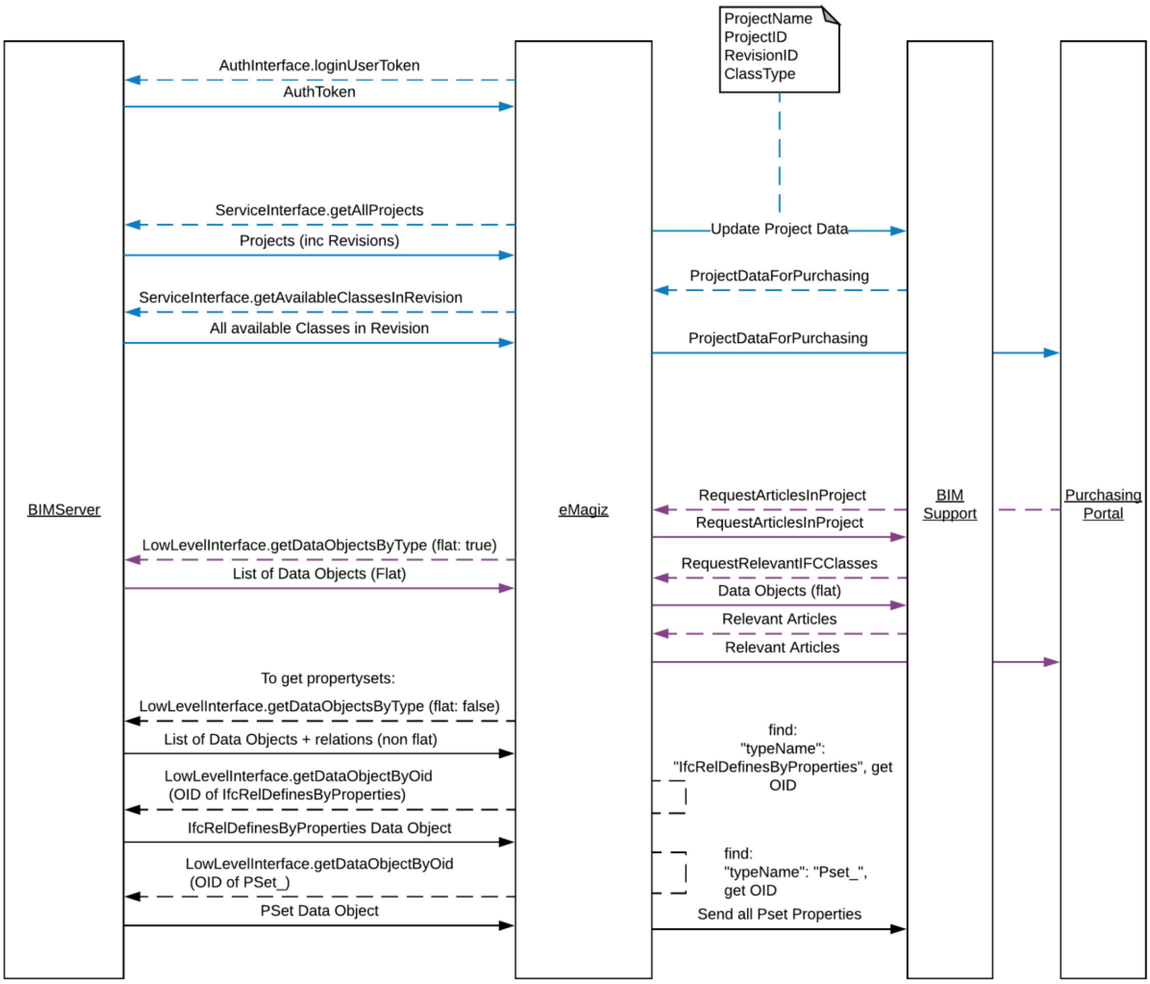


Figure 23. Message flow for retrieving BIM data

Figure 23 depicts the overall message flow of the architecture while retrieving the data required for the specified use case. At the start of every interaction between the bus and BIMServer, an auth message is sent and an auth token retrieved (logging in). In general, the message order, for each of the sections, is as follows:

- At a certain time, a CRON trigger is triggered within the **bus** that starts the project update process.
- The **bus** connects with **BIMServer**, logs in, retrieves a list of projects (getAllProjects), including revisions. Afterwards, it retrieves all of the IFCTypes which exist in said project.
- The **bus** sends all this data to **BIMSupport**, which saves it internally, and sends a version of this data that's relevant for the purchasing process back on to the **bus.**
- The **bus** delivers the relevant project data to the **purchasing portal**.

This process keeps all applications up to date on existing project data, allowing users to retrieve additional BIM data from the origin models on BIMServer.

If an end user requests project data from the purchasing portal, the following message order occurs:

- A request is made by a user in the **purchasing portal** for article information for a specific project. This request is sent to the **bus**.

- The **bus** delivers the request to **BIMSupport**, where a selection has been made which IFCObjects are relevant for purchasing, and how they should be named within the purchasing portal. (e.g., an IFCDoor is selected with the purchasing name of ‘Door’, this sends all IFCDoor objects to the purchasing portal, as Article objects, with the ArticleType ‘Door’.

6. Validation and Evaluation

In this chapter, the architecture and prototype are validated. Using the requirements set earlier, the aim is to determine whether the architecture is valid for the given goal (reduce integration difficulties without requiring much extra training for non-technical users).

6.1 Validation

The design science methodology describes the need for constant validation and evaluation while doing design science research (Wieringa 2014). Therefore, the prototype and architecture were constantly re-validated and evaluated during development.

Validation was done two-fold: firstly, a use case was established based on some of the data requirements of a user in the purchasing department. This use case serves as a scenario in which BIM integration would be highly beneficial for the overall workflow. For every step of this use case, it was determined if said action was possible with the current implementation of the architecture and prototype. This way it is determined whether the prototype actually implements the architecture correctly.

Secondly, regularly scheduled meetings were held with experts of both the Construction Company and CAPE in order to discuss progress and usability of the prototype. This validation step is used to determine whether the architecture and prototype fulfil the intended goal of reducing integration challenges while keeping training costs low for non-technical users.

6.1.1 Validation and evaluation meetings

During development, a combination of both informal regular contact and formally scheduled sprint meetings were used to validate the prototype and architecture. Informal contact was mostly used for day to day questions regarding development or small design questions, while the scheduled sprint meetings were used to validate work done thus far and to evaluate the design and development process.

The meetings always had roughly the same structure:

1. Introduction
2. Architecture review
3. Demonstration of the prototype
4. Explanation of design choices
5. Validation questions regarding the prototype and architecture
6. Wrap up and feedback for next sprint

Table 4 provides an overview of all the experts consulted throughout this research process, their roles and the manner of contact.

Company	Role	Contact
CAPE	Supervisor, Manager	informally as well as present at formal meetings
CAPE	Supervisor, Consultant	Informally, mostly technical and design help
Construction	CFO/CIO	Present at formal meetings
Construction	BIM Innovation Specialist	Informally as well as present at formal meetings
Construction	Administrator	Informally as well as present at formal meetings

Table 4. Experts consulted throughout validation process.

6.1.2 Requirements

In chapter 3, requirements for the architecture were established. Let us review the original requirements and how they are addressed in the prototype:

R0. The system must allow for other applications to extract object information from a BIM model.

This requirement describes the need for other systems to be able to retrieve the object information stored in the BIM model. This is a large part of the premise of this research project; in order to centralize BIM as data source, it must be accessible by different systems.

The architecture and prototype fulfil this requirement by utilizing the BIMServer tooling, which stores the models and enables querying of the model data (stored as a relational database). Furthermore, it offers an API which allows for access to this data. This requirement is then further realized by using the eMagiz bus to create integrations with this data platform.

R1. The system must allow for other applications to modify object information in the corresponding BIM model.

This requirement describes how applications need to be able to send data back to the data platform in order to change the model.

This requirement has been challenging throughout the development and validation of the architecture and prototype.

Firstly, this requirement has brought the need for the BIMSupport application. During development, it became clear that a supporting application was required if data were to be sent back, as the bus itself has no memory, and in order to work with the IFC model, some data about IFC objects (such as type, objectID, projectID, revisionID) has to be retained. It is however not feasible to have this data available in every application that wants to use BIM data, which concluded in the addition of a support application.

Secondly, while BIMServer offers the basic functionality to create objects, there are no high level API calls for the creation of IFC Objects in BIMServer. There is no 'create PropertySet Pset_ManufacturerTypeInformation for object 94830', but only a general 'create object' call. This means that utilizing these calls requires a high degree of knowledge about the inner workings of the IFC standard and data format.

R2. The system must use a centralized repository for the BIM models, making the model the leading document throughout the construction process.

This requirement focusses on centralizing BIM as a data source. This goal is derived from the fact that we found so much data that's already available in BIM models completely unused in follow up processes, or stored in separate documents.

It is fulfilled by the inclusion of BIMServer, which is designed for exactly this purpose. It includes many of the functions required for having a model be the leading document throughout the construction process, such as: locking the document, revision management, full user control and a full API to access all these functions.

R3. The system must allow for seamless integration with the traditional applications used by non-technical users

This requirement focusses on keeping BIM training costs (which is one of the major barriers identified from both literature and practice) low, by allowing users to retain their existing software environments, while still integrating seamlessly with the BIM model data.

It is fulfilled by using an integration platform (eMagiz), which allows for custom integrations with BIMServer. This way, any application doesn't have to be designed to use BIM models specifically, but can still use the available data.

6.1.3 Use Case

In chapter 4, a use case was envisioned based on the requirements specified in chapter 3. This use case provides one clear case for a user in the purchasing department, testable in a real life environment (a medium sized Dutch construction company). The use case consists of the following actions:

Purchasing Portal

Open Project

The purchasing portal correctly shows a list of all projects to select from.

List Purchasing Objects

The purchasing portal correctly shows a list of objects marked as applicable for the purchasing process, with the correct purchasing related object names.

Add Article Number to Object (Enrich Data)

The purchasing portal contains functionality to add new article numbers to an object, intended to added to the PropertySets of the IFC model.

BIMSupport

Determine Objects Relevant to Purchasing

In BIMsupport, users can select IFCObjects and mark them as relevant to purchasing, as well as add a purchasing object name to the objects. These objects are the ones sent to the purchasing portal when an article request is handled.

Get Relevant IFC Objects and Send Relevant Objects to Purchasing Portal.

BIMsupport has the capability to ask BIMServer for the correct IFCobjects, translate them to Purchasing Objects and send them to the portal.

Determine Correct PropertySet and Property Value

In the demo, we only used a single propertySet and expected value. This has no influence on the validity of the prototype, but saved a lot of development time.

BIMServer

Return Objects by Type

This is built in functionality which the bus correctly calls for.

6.1.4 Validity of Use Case

The current use case describes a scenario in which a purchasing employee wants to order materials. An IFC model often already contains the material information, as well as manufacturer information for many objects. It would therefore be ideal if said user can simply select a project, and obtain a list of materials which can then be used in the purchasing process.

We tested this use case together with the experts, where each step was demonstrated and continuously evaluated. Each evaluation step consisted of several questions:

1) Is this functionality needed from a technical standpoint?
2) Is this functionality valuable for the purchasing process used as example?
3) Can a non-technical user benefit from this and can the functionality be simplified?

Based on the feedback to these questions, functionality was often re-adjusted. Finally we ended up with an architecture and prototype that can assist in BIM integration projects, without taxing users with non-essential BIM knowledge. It also offers a high level of customizability, the model stays intact so if visualization is needed for a process, it is always renderable. If visualization is not needed, like in the purchasing process, data can simply be transactional and adjusted for already existing systems and workflows.

6.2 Evaluation

For the evaluation, we look at the usability of the prototype, the challenges we faced and the problems that still remain / what can be improved. Furthermore, we go into the experiences of the construction company where this research was performed.

The first observation that can be made is that while querying objects on BIMServer is relatively straightforward, creating IFC Objects within the model is a complex task. It requires intimate IFC knowledge and is time consuming to develop. This has considerably slowed down development, and has led to some of the functionality to store data back in the model missing from the end prototype.

Furthermore, the prototype is limited to one use case at the moment. For a fully functional implementation that can actually support the whole construction process, more development is required.

The construction company has seen the usefulness of the architecture and prototype, but at the same time was still daunted by the complexities of IFC. In general however, the architecture has given them a much clearer view of what's needed and what's possible, and has definitely inspired them to continue their BIM innovation efforts and investments.

7. Conclusions and Recommendations

In this chapter, the research questions as determined in 1.3 will be answered. After all the sub questions have been answered, we look at the main research question of this research. Furthermore, the limitations and contributions of this research will be assessed.

7.1 Research Results

What are the current barriers to BIM integration and adoption within the AEC industry as found in existing literature as well as practice?

In chapter 2.1 we looked at the barriers as found in literature. In chapter 3.2.1 we attempted to compare these barriers with practice. While a variety of different barriers exist, we found that the biggest barriers found both in literature and in practice were *Required Training and Knowledge* and *Software and Integration issues*.

The former is about the high complexity of BIM models, and the costs of training personnel to make use of everything BIM has to offer. This also means that centralizing BIM as a data source becomes more difficult, as more users will come into contact with BIM and might need training. The latter considers all the issues with BIM software and Integration; the difficulties with software interoperability are often caused by varying implementations of the IFC standard, which makes integration a challenge too. Furthermore,

Which standards, initiatives and tooling exist within the BIM domain and should be part of the architecture/prototype?

The biggest standard that the architecture should unquestionably adhere to are the Industry Foundation Classes (IFC). While some inconsistencies still exist between different vendors implementing this standard, the IFC standard and file format have been accepted as the industry standard. This standard is also often enforced for government projects.

In extension of this standard, there are various (regional) initiatives in which participants decide amongst each other which data should be included when delivering a project as .IFC file.

Which frameworks for BIM integration and interoperability already exist?

Existing BIM frameworks largely focus on very specific parts of BIM interoperability, within specific domains. An architecture for a distributed, model-based, integrated system exists, but was published relatively long ago and doesn't take all of the modern BIM needs in account. Letting go of the specific BIM domain, there are various papers on integration platform architectures in various domains. Singh et al. attempted to consolidate all these platforms into a single reference architecture for integration platforms (P. M. Singh, Van Sinderen, and Wieringa 2017).

Which levels of BIM maturity can be identified in existing literature?

There is a wide assortment of research attempting to measure BIM performance. From this research, three concepts of measuring BIM performance emerged that are discussed often: ***BIM Capability Stages, BIM Maturity Levels, BIM competencies.*** Capability stages denote in which stage of BIM implementation an organization is, ***Pre-BIM, BIM stage 1, BIM stage 2, BIM stage 3*** or ***Integrated Project Delivery****.* The five levels of BIM maturity identified are Initial*/ad hoc, Defined, Managed, Integrated* and *Optimized*.

Which aspects should be part of a reference architecture for BIM integration?

The reference architecture should contain a integration platform or bus of some kind (the prototype used eMagiz), a data platform which handles the model data (the prototype used BIMServer) and some kind of support application that can translate to and from IFC terms and traditional construction terms in existing applications (the prototype used Mendix to develop this).

These aspects, in cohesion with each other, form the basis of the reference architecture for BIM integration.

After answering the questions above, and validating the architecture as well as the prototype, we can answer the following research question:

What are the characteristics of a reference architecture for BIM integration designed to facilitate BIM adoption?

There are three main components of the reference architecture: the data platform, the bus/integration platform and the support application. The data platform should be able to store and expose BIM models while adhering to the IFC standard. The bus is used to both be able to connect between the support application and the data platform, and between the support application and the existing application landscape.

The main characteristics are the open nature of the architecture developed, meaning any traditional tool should be able to connect and use BIM data within the existing environment. This is meant to alleviate the biggest barrier of BIM adoption, namely the high knowledge requirement. By allowing users to keep using their familiar work environments, less training is needed to adopt to the new way of working. While there will surely be changes to the work flow when moving towards a BIM centric way of working, technical knowledge requirements are lower than when users actually have to learn BIM tooling.

The architecture also serves as a starting point for businesses and researchers alike. By building upon this foundation, integration should become less convoluted and more understood.

By reducing the two biggest barriers identified in literature, namely *Required Training and Knowledge* (by allowing users to work without BIM without having to learn everything about it) and *Software and Integration issues* (by creating an open integration based on existing standards and simplifying the integration tasks), the reference architecture will hopefully increase BIM adoption.

By delivering this architecture, the hope is to provide science with a reference on which further attempts to integrate construction processes using BIM as source data. For practice, the hope is that we've shown the possibilities of BIM integration, as well as which steps to take to get there.

7.2 Limitations

The research presented in this thesis has several limitations. First of all, context of all the gathered data is one medium sized Dutch construction firm, which, while representative for de Dutch construction industry, is still just one firm. The architecture should be validated in a wider array of organizations. Furthermore, all data is focused on the Dutch AEC industry. Other markets may or may not be organized entirely differently, so results are not automatically applicable everywhere else.

Lastly, only one business process was prototyped. For further validation, a higher level of integration should be prototyped spanning several processes. This was not feasible within the time frame of this work.

7.3 Future Work

For Science

If this architecture proves to be successful, there are several additional tasks to be done. Firstly, the scope of the research could be widened much further. Currently, the prototype is limited to one use case. It could be expanded to include multiple business processes and validated as such. The prototyping was also limited to a medium sized construction company with a certain BIM maturity. Further research could determine whether the size of the firm, the country it is located or the BIM maturity levels have an effect on the usefulness of this architecture. Other country might have differently organized construction industries, with different stakeholders.

Furthermore, the CDM could be expanded upon by truly analyzing the data requirements of every single construction business process in order to create more standardized messages for additional tasks. The construction industry is heavily fragmented, and even with IFC as a standard, there are still various initiatives needed to truly make proper use of IFC, and if this can be further standardized that will reduce the entry barrier for BIM usage even further.

The big next step though, is to take the architecture further into the inter-organizational collaboration field. The construction industry is heavily fragmented, so full integration between chain partners could possibly lead to huge benefits concerning the efficiency of the construction process.

For Practice

The prototype has shown that it satisfies its requirements and that one use case could be completed successfully, but much wider tests are needed for full scale deployment. We hope that this work encourages practice to think bigger when it comes to BIM, with proper integration the possibilities are immense. Furthermore, more feedback on the usefulness in practice is always welcome.

7.4 Recommendations

The benefits of further integrating BIM data are there. We are at the point in the Netherlands where BIM is already widely used, so the models are usually already made. Using them to further strengthen your business processes with extra and more up to date object data will lessen the need for extra documents as well as reduce data duplicity. When the BIM model is leading for object related data, any change during any part of the process will always be reflected in the model. This leads to benefits for lifecycle management as well. In order to make use of this architecture and prototype, the prototype should be developed much further. A thorough analysis of data requirements within the different business processes is needed to fully understand what BIM data should be contained within the CDM.

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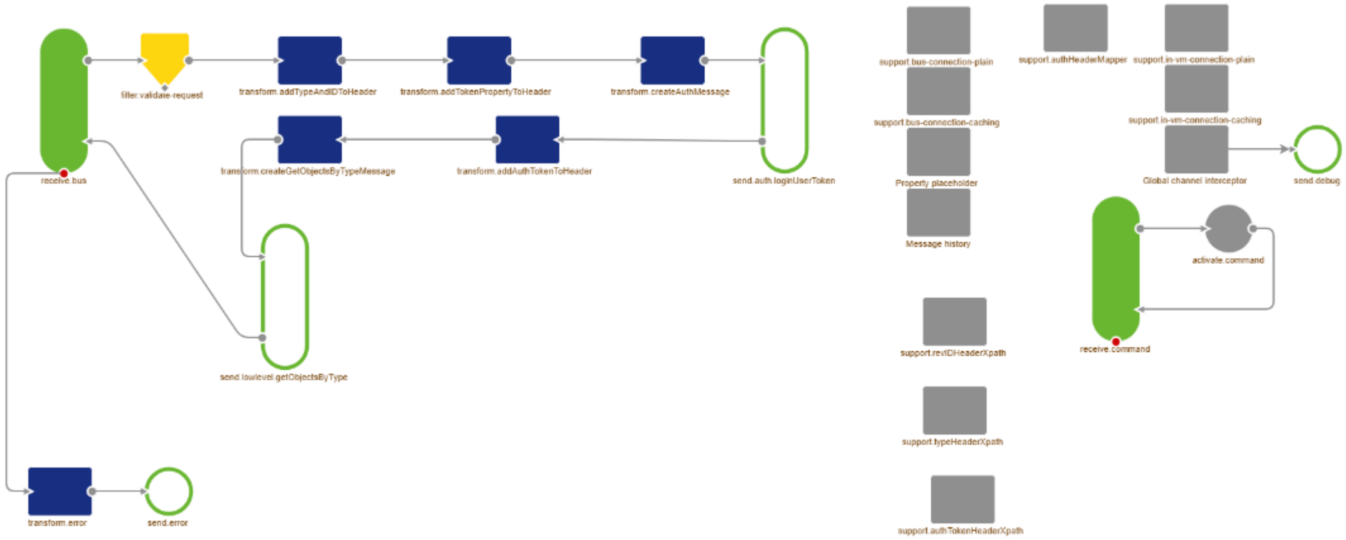
Appendices

Appendix A. eMagiz Flows

This appendix shows the remaining flows of the eMagiz bus components. These depict the interactions between the eMagiz bus and the BIMServer application.

Request IFC objects by IFCtype



Get PropertySet(s) by IFCObject