Understanding the Technical and Cognitive Challenges, and Closing the Gaps in Architectural, Engineering, Construction-Facility Management Standards

Mehmet Yalcinkaya
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Aalto University
School of Engineering
Department of Civil Engineering
Aalto BIM Collaboration
Supervising professor
Prof. Vishal Singh, Aalto University, Department of Civil Engineering, Finland

Thesis advisor
Prof. Vishal Singh, Aalto University, Department of Civil Engineering, Finland

Preliminary examiners
Associate Prof. Mohamad Kassem, Northumbria University Newcastle, Mechanical and Construction Engineering Department, United Kingdom
Assist. Prof. Jakob Beetz, Eindhoven University of Technology, Dpt. of Built Environment, Netherlands

Opponent
Prof. Timo Hartmann, Technische Universität Berlin, Institut für Bauingenieurwesen, Germany
**Abstract**

The Architecture Engineering Construction-Facilities Management (AEC-FM) industry is complex, involving many actors from different domains. This brings the need for utilization of digital data coming from different digital sources. Building Information Modeling (BIM) tools can generate and process the standardized digital data format. However, the exchanged digital data may not provide all the relevant information that is required for the range of dynamic tasks. Consequently, additional data needs to be included and exchanged separately which generates resistance to full adoption and implementation of standardized solutions and frameworks. If project stakeholders do not understand the requirements of standards well enough, the corresponding data may not necessarily be useful for the project. In contrast, if the usage and usability factors are well-planned, the end-users may still be able to utilize relevant data without the need to know the extensive technical details. To achieve the balance between generic standards applicable to the wider domain and still meet the unique requirements of the industry, standards may need to be augmented by IT solutions that allow customization for extended functionalities.

The above statement raises a generic question for a conceptual and theoretical understanding of the overall standardization and digitalization efforts in the AEC-FM industry. The primary interest of this research addresses this problem with a multidisciplinary approach by focusing on human cognition, visual perception and human–computer interaction (HCI). This research investigates the conceptual and theoretical aspects of the evolution of such standards, and the challenges associated with their usability and wider adoption across expert and non-expert users. Another motivation of this research is presented with a technical contribution that addresses the needs and requirements of a generic, flexible and scalable data integration, management, and interoperability platform for the AEC-FM industry while positioning the user-centric design approach at its core. Both theoretical and technical outcomes of this research are grounded with the iterative steps of design thinking and agile development process. The usability challenges are evaluated and addressed with human cognition and visual perception principles.

The validation of this research have been performed with the Finnish industry partners with research workshops, focus group meetings, hackathons and preliminary tests. The feedback from the industry representatives indicate the validity of the theoretical and technical output of this research which was seen as a novel and innovative approach to address a long-standing issue of technical and non user-friendly applications in AEC-FM digitalization in general.

**Keywords**  building information modeling, facility management, information visualization, standards, linked building data, cognitive, visual perception
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Espoo, 7 August 2017
Mehmet Yalcinkaya
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List of Abbreviations and Symbols

AEC/FM  Architectural, Engineering, Construction and Facilities Management
API    Application Programming Interface
AR    Augmented Reality
BAS   Building Automation System
BIM   Building Information Modeling
BIMsie BIM Service Interface Exchange
CAFM  Computer Aided Facility Management
CM    Construction Management
CMMS  Computer-Aided Maintenance Management System
COBie Construction Operations Building information exchange
CRIS  Common Relational Information Schema
CRUD  Create, Read, Update, Delete
CSS   Cascading Style Sheet
DOS   Disk Operating Systems
FK    Foreign Key
FM    Facilities Management
GUID  Globally Unique Identification
HCI   Human Computer Interaction
HTML  Hyper Text Markup Language
IAI   International Alliance for Interoperability
IDM   Information Delivery Manuals
IFC   Industry Foundation Classes
ISO   International Standards Organization
IT    Information Technology
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<th>Full Form</th>
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<tr>
<td>LSA</td>
<td>Latent Semantic Analysis</td>
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<tr>
<td>MIMOSA</td>
<td>Machinery Information Management Open Systems Alliance</td>
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<td>MVD</td>
<td>Model View Definition</td>
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<td>NAVFAC</td>
<td>Naval Facilities Engineering Command</td>
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<td>nD</td>
<td>n Dimensional</td>
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<td>NIBS</td>
<td>National Institute of Building Science</td>
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<td>NLP</td>
<td>Natural Language Processing</td>
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<td>OMSI</td>
<td>Operations and Maintenance Support Information</td>
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<td>OSA-CBM</td>
<td>Open Systems Architecture for Condition Based Maintenance</td>
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<tr>
<td>PDF</td>
<td>Portable Document Format</td>
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<tr>
<td>PK</td>
<td>Primary Key</td>
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<td>RDBMS</td>
<td>Relational Database Management Systems</td>
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<td>RDF</td>
<td>Resource Description Framework</td>
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<td>RFID</td>
<td>Radio Frequency Identification</td>
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<td>RQ</td>
<td>Research Question</td>
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<td>SPARQL</td>
<td>Simple Protocol and RDF Query Language</td>
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<td>SQL</td>
<td>Standard Query Language</td>
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<td>STEP</td>
<td>Standard for the Exchange of Product model data</td>
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<td>TMS</td>
<td>Transactive Memory Systems</td>
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<td>UI</td>
<td>User Interface</td>
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<tr>
<td>UID</td>
<td>Unique Identification</td>
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<tr>
<td>URI</td>
<td>Unique Resource Identifier</td>
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<td>UX</td>
<td>User Experience</td>
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<td>WebGL</td>
<td>Web Graphic Language</td>
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<td>WoBD</td>
<td>Web of Building Data</td>
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<tr>
<td>XML</td>
<td>Extensible Markup Language</td>
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Author’s Contribution

This doctoral dissertation is a monograph. The author has himself performed the research described in this dissertation with the support and guidance of the research supervisor. In the first phase of this research, the research problem and the corresponding research questions regarding the usability and functionality problems of industry standards have been defined and validated by the author by analysing the literature, the public discussion in social media/web, and unstructured interviews conducted with industrial partners. Author developed the initial prototype software implementation as the technical contribution of this dissertation and conducted initial tests to validate the proposed usability and functionality features are error and bug-free. Based on the results of initial tests, author revised the grounded theory, and improved the theoretical, methodological and technical contributions of this dissertation. As the iterative process of the applied methodology, author conducted systematic case studies with the industry partners of this research to validate the problem statements, proposed functionality and usability enhancements with the initial prototype development. The research supervisor and a senior researcher from another research group of Aalto University also supported the author during the case studies. Author further improved the initial prototype as the technical contribution of this research and developed the additional features based on the feedbacks obtained during case studies. A new theoretical concept has been also introduced within the applied research methodology. Author collected the data during the focus group meetings with industry partners, and analyzed for discussions, conclusions and future research & development tasks of this research.

As being the supervisor of the author and advisor of this dissertation, I hereby confirm the author’s contribution is valid and as presented in this section.

Prof. Dr. Vishal Singh

19.08.2017
1. Introduction

The utilization of Building Information Modeling (BIM) in the construction industry is on the rise, and progressively more BIM-based projects are being delivered. The parties in a project are using BIM with the expectation to have a positive impact on the project lifecycle. Many features of BIM such as clash detection, better visualization, energy analysis etc. can have a positive effect on the life-cycle cost by saving time and money, and deliver better quality products to the building owners. Although the majority of BIM implementation is currently focused in the design and construction phases of the project, there is also the need to use BIM data for the activities covered during the post-construction phase, under the Facilities Management (FM) domain. However, most of the BIM data generated in design and construction phases typically remains underutilized in the FM phase. The post-construction phase is the longest of a facility’s lifecycle with a total cost that exceeds the design and construction phases. This cost increases even further when considering the business point of view, accounting for the direct/indirect cost effects (Codinhoto & Kiviniemi 2014). Although the digital and printed information for the FM phase increases incrementally, as additional data is generated in each phase of the lifecycle, the post-construction phase remains one of the most disconnected phases from the rest of the lifecycle (Goedert & Meadati 2008).

Therefore, while it is desirable that the generated BIM models are used on a continuous basis to effectively manage the post-construction phase, the adoption of BIM and BIM-based approaches for FM have not been mature enough to support such objectives. The reasons for this state of BIM and FM vary to include factors such as the fragmentation of the lifecycle information stored in different systems and formats, and incomplete data documentation for the range of tasks associated with the FM domain. Besides, different phases and processes of the life cycle often involve different teams that lack effective communication and that are often reluctant to share information with each other (Ospina-Alvarado & Castro-Lacouture 2010). The varying practices used in generating the BIM models can further reduce the efficiency of the digital information flow between the project phases. Often the teams lack knowledge of different disciplines, and the adoption of standardized approaches and techniques has been low. Facility managers often end-up producing their own dataset(s) from documents/files collected from previous phases. This can be tedious, repetitive, and time consuming. The cost of such unorganized and repetitive processes can be significant.

Consequently, the challenge for building owners is to determine and specify what information should be included and/or extracted from a BIM model such that it provides useful information for the post-construction FM phase. This lack of clarity also affects the designers and contractors preparing the BIM models to be information rich sources. Therefore, the generation, management, and transfer of the digital building information is one of the most common themes in architecture, engineering, construction and facilities management (AEC-
FM) industry; and much of that focus at the international level is on the standardization and interoperability issues (Javernick-Will & Levitt 2009).

Standardization has played a vital role in AEC-FM industry for the principles of engineering design, classification of materials and assets, quantity take off, cost estimation, configuration of databases, etc. (Björk & Laakso 2010). In the standardization related to the use of BIM in AEC-FM, one of the central issues has been how to structure digital information of a facility, to facilitate the sharing of data among different disciplines through the project lifecycle. Industry Foundation Classes (IFC) provide an open data model standard to structure and exchange the digital building information. By using IFC, the information generated in various phases of the lifecycle can be stored and exchanged through an open interoperable platform enabling the flow of design, construction and maintenance information across various project groups, and increasing the efficiency of the work process during the facility’s lifecycle (Laakso & Kiviniemi 2011).

Although IFC provides significant advantages for generating, organizing and sharing the digital building information, it can be too complex to populate all IFC data in a project, and yet the IFC data may not necessarily be adequate for all the specific phases of the facility’s lifecycle. Therefore, for successful implementation of BIM for FM and associated information technology (IT) data, specific standards are desirable that focus specifically on FM information exchange. Within this context, Construction Operations Building information exchange (COBie) standard has emerged as one of the predominant standards in BIM for FM. COBie is an open, vendor-neutral industry standard that describes the product and process of collecting and validating facility lifecycle data during design, construction and commissioning phases (U.S. General Services Administration 2011; BuildingSMART 2010a; East 2007). COBie data includes a subset of the IFC data, as well additional data specific to the FM use-case, which may not come from IFC. Although the development of COBie standard is quite new compared to the other IT and FM standards, it is a rapidly and widely accepted standardization effort for BIM implementation in FM. In addition, there is strong support for COBie from several BIM software vendors as well as open-source BIM developments. COBie specification can be considered as a common template in which the information structure and the delivery format of COBie standard is planned to reduce the inefficiencies in facility information handover.

Such standardization and development efforts that provide pre-defined and structured methods for the lifecycle of digital building information have the potential to improve upon the traditional practices of AEC-FM industry. Despite such intensive efforts that have been approved, technically verified, and tested by many organizations for years, the AEC-FM industry is still suffering from inefficient digital information management. The barriers vary with different perspectives. For example, from the AEC-FM industry point of view, the software tools, systems, information structures, etc. that are developed based on pre-defined standards do not address the diverse needs and requirements of such a highly fragmented sector, typically failing to directly address the unique tasks and processes of each organization. Instead, for most organizations, it becomes “more practical” to manage their information with custom and task-specific solutions, ignoring the standards. Therefore, the challenge is to determine how the generic standards can address the specific needs of various stakeholders, who typically have unique requirements relevant to their practice and context. Standards such as IFC and COBie need to be defined broad enough to address the “common” needs and requirements of the industry as a whole, with the possibility to support custom
and unique adjustments, configurations, etc., However, such extensions and customization for all purposes cannot be within the scope of the standards.

Therefore, this thesis investigates the conceptual, technical and methodological issues associated with standardization of digital information required to facilitate BIM for FM, especially focusing on COBie. The thesis aims to assess the key challenges and barriers associated with effective and wide-scale utilization of such standards, and explore conceptual, technical and methodological approaches that can be adopted to address these challenges and barriers.

1.1 Problem Statement

The wider adoption of a technological paradigm such as BIM and the associated standards across the different phases of a project, including the FM phase, requires a holistic approach that accounts for the dependencies between the technology, processes, people and policies. Consequently, developing the ‘standards’ is not merely a technical issue, but it is equally important to understand how the ‘standards’ correspond to the processes, how people use them, and how they are supported or inhibited by the policies. Accordingly, at the broadest level this thesis outlines the problem statement as:

**Understanding and Utilizing Industry Standards and associated IT Solutions in AEC-FM Industry.**

While defining the problem statement at a broad level, the author acknowledges that significant progress has been made in developing well-defined industry standards such as COBie and developing corresponding IT solutions. Consequently, the primarily focus of this study remains on how the people in AEC-FM perceive, understand and utilize these standards, and what can be done from the user point of view to facilitate wider utilization of these standards in practice.

A standard should address the most common needs, and it may not be possible to define the standards to address all the specific requirements for the different use cases. Furthermore, no matter how well defined a standard is, if the users do not understand it sufficiently, they cannot utilize and implement it efficiently. In such a human resource intensive industry as AEC-FM, only the structure and functionality of the standards is not enough. The standards and corresponding developments should be easy to understand and use by people with varying levels of knowledge and experience. Until now, the usage and usability factors associated with AEC-FM standards has remained largely overlooked, indicating a critical gap in the literature. This oversight could be a potentially significant factor in the adoption as well as effective utilization of such advanced solutions in the AEC-FM industry. Therefore, from a conceptual and theoretical viewpoint, this research aims to address this gap in understanding and enhancing the usability aspects of standards such as COBie.

The AEC-FM industry is complex and dynamic, involving many technologies and actors from different domains at various stages of a typical project. This brings digital data from different domains in different formats, generated from various BIM and IT solutions. With the high pressure to deliver the job on time, project actors often tend to apply unique practices for data collection and exchange that they have traditionally been using, instead of investing time in learning and applying new standards. This increases the heterogeneity in the collected information. However, since most native BIM tools can generate and process the standardized digital data format such as IFC, IFC is becoming increasingly common for exchange of building data. Yet, the exchanged IFC data may not provide all the relevant information that is required for the unique and dynamic tasks. Consequently, additional data
needs to be added and exchanged separately, and all this generates a resistance to full adoption and implementation of standardized solutions and frameworks. While the project stakeholders can be forced via regulations and mandates to generate the models compatible with standardized approaches, if they do not understand the requirements well enough, the generated data may not necessarily be useful in the later phases of the project lifecycle, further increasing the data fragmentation and inefficiency. In contrast, if the usage and usability factors are well planned, the end-users may still be able to use and generate relevant data without the need to know the technical details associated with the standardized approaches. To achieve the balance between generic standards that are applicable to the wider domain and still meet the unique requirements specific to each user, and to enable the diverse requirements of the fragmented industry, standards may need to be augmented by IT solutions that allow customization and extended functionalities on top of them. Therefore, from a technical viewpoint, the problem can also be defined in terms of the need for a digital platform that can not only process, manage and utilize standardized approaches and data structures, but it should also present a flexible and scalable layer for the specific needs of the users in terms of data integration, exchange, management, etc.

1.2 Motivation and Scope of The Research

The primary problem statement raises a generic question for a conceptual and theoretical understanding of the overall standardization and development efforts in the AEC-FM industry. The objective is not to conduct a comprehensive evaluation of all the standardization efforts and associated IT developments. Instead, by choosing a suitable and representative case example for extensive study, this research investigates the conceptual and theoretical aspects of the evolution of such standards, and the challenges associated with their usability and wider adoption across expert and non-expert users. Consequently, this research focuses on COBie as the case standard. The main motivation and reason for choosing COBie as the case standard is threefold:

First, COBie standard is specifically developed for the post-construction phase of the project lifecycle in which the data generated in previous phases are to be handed over. Therefore, COBie covers a wide range of data entities that can come from various sources. Despite this wide range of data entities, COBie is not as vast or generic as IFC, which facilitates the intended study. In addition, the cost of the post-construction phase is significantly higher than the previous phases. Although COBie data can be generated via built-in and external converters from a single source (e.g. BIM file), to fulfil all the data requirements defined in COBie, a digital data flow is needed from various sources. Thus, COBie offers a fairly complex set of technical as well as procedural factors for study and evaluation, and yet focussed enough to be manageable within the scope of a doctoral thesis.

Second, although COBie has emerged as one of the predominant and widely accepted standards in BIM for FM, there is almost no usage of COBie standard in Finland, where the research has been conducted. As detailed later in Section 5.3, the initial feedback from Finnish industry about COBie was not positive in terms of understanding and utilizing the FM data. This is despite the fact that the Finnish software vendors who develop BIM tools for international markets support COBie deliverable. Therefore, within the scope of this research, COBie provides a suitable case standard where the industry is currently grappling with issues that can be studied and analysed from technical and usability perspectives.
Introduction

Third, since the scope of COBie is defined specifically for BIM-FM use case, and technical solutions in the BIM-FM use case are still to mature to the same extent as what is available for pre-construction phases, there is greater opportunity for technical interventions and experimentations on top of COBie to facilitate usability and adoption. Furthermore, unlike other phases where dedicated domain experts from specific phases are expected to contribute to the data generation, in COBie both expert and non-expert users are expected to contribute to the COBie data drops and updates. This puts additional emphasis on usability and comprehension of the COBie standard and its usability.

Another motivation for this research is to make technical contributions that address the needs and requirements of a generic, flexible and scalable data integration, management, and interoperability platform for the AEC-FM domain. Despite the standardized data structures and varied IT solutions that have existed in the industry for years, the AEC-FM industry still has challenges with fragmented digital data. The data to be used for FM purposes typically resides in separate IT systems and databases that remain disconnected from each other. Consequently, even the BIM data either remains unused or at best connected to only part of the FM data. Such challenges force facility managers to keep out of the loop of existing BIM solutions, reducing the efficacy of COBie and similar standardization initiatives. Therefore, this research seeks to make technical contributions to address this fragmentation problem. The objective of the technical development is to implement a proof of concept for a platform that provides features for better understanding, management, integration and interoperability of data from varied sources. In practice, the technical implementation seeks to enable access to the ‘right information at the right time’ via aggregation of information from multiple sources through one platform.

COBie data can be generated from various software applications used in construction management (CM), FM and BIM via their built-in or add-on tools. Therefore, generation of COBie data is not within the scope of this research. The publically available COBie datasets with the corresponding IFC files and documents are used for the initial phases of this research. The development of a “COBie data exporter” is not in the scope of this research either, because there are both commercial and open source solutions already available for this purpose.

The development of COBie standard has been an intensive industry-wide effort with extensive support from software vendors and the IT community. COBie has been discussed across the industry and academia for almost ten years now, and it is reasonable to state that the COBie structure and templates have become stable now. Therefore, this research does not consider the development of a new standard or associated information management structure. Similarly, rather than considering any modifications or changes to the existing definition or structure of the COBie standard, this research investigates how the COBie standard, with its present data structure and templates, can be made easier to understand, use, and implement in practice.

1.3 Research Questions

Following the problem statement, the research questions primarily focus on understanding the standardization process, associated data structures, approaches and challenges towards technology integration, and the usability and implementation of the standards in practice. Though COBie is a relatively new standardization effort compared to other BIM/IT-related standards, it has been promoted as one of the predominant standards in BIM for FM. There-
fore, COBie standard is the primary case standard to identify the potential reasons why the actors in AEC-FM industry have difficulties understanding and utilizing information exchange requirements and associated IT tools.

The first set of questions in this research investigate the emergence of COBie as the most widely-discussed and promoted standard in BIM for FM, with the objective to understand the factors that have contributed to its development and growth.

**Standardization Process of COBie**

- **Research Question 1 (RQ1):** What is the background of COBie and how has it developed?
- **Research Question 2 (RQ2):** How are BIM/IFC, other IT tools, and COBie related to each other?

In terms of the standardization effort, COBie standard has remained stable for almost ten years now, and during this period it has continued to grow in terms of significance and approval from various actor groups including regulatory authorities, software vendors and academic researchers. This stability in COBie structure suggests that it is considered mature enough to address the common needs of the AEC-FM industry. However, a closer review of the history and development of COBie is needed to understand the underlying factors supporting its growing stature.

**Usability Evaluation of COBie Dataset**

- **Research Question 3 (RQ3):** What are the complexities and challenges involved in handling and interpreting COBie data?
- **Research Question 4 (RQ4):** What kind of usability and cognitive aspects are missing in the current representation of COBie data?

Furthermore, modern computing and development technologies can help to enhance the existing representation and utilization of COBie data in terms of usability and functionality based on the expectations and needs of the users. This attempt requires well researched definitions for controlling, serving and modeling the COBie data as well as the functionalities for enhanced user-interface and user-experience (UI/UX). The complex, fragmented, and dynamic nature of AEC-FM industry increases the heterogeneity of workflow and management of the digital information. In particular, the data coming from the different domains and applications cause various challenges in terms of management, integration and interoperability of this heterogeneous data. Therefore, the next set of questions focus on requirements and opportunities for technology development and improved representation of the COBie data.
**Requirements for Enhanced Development and Representation for building lifecycle data**

- **Research Question 5 (RQ5):** What new features in BIM, FM or IT systems could enhance the usability and utilization of COBie data, if any?
- **Research Question 6 (RQ6):** How can the heterogeneous and fragmented AEC-FM data be integrated and linked with each other?
- **Research Question 7 (RQ7):** What are the common mistakes that users make which render the COBie data useless?
- **Research Question 8 (RQ8):** What can be the other technical and usability requirements for further development? What can be the new theoretical and technical approaches towards such a development?

Though BIM and other IT tools are successful in supporting standardized data formats, they often require flexibility and customization to address unique and specific needs of different users. Therefore, in addition to the enhanced usability features, such requirements that establish flexibility and scalability on top of the standardized technologies and approaches need to be defined. The research questions RQ5 to RQ8 investigate the technical aspects that can potentially enhance the usability and functional use of COBie data.
Achieving the objectives, and fulfilling the aim of any research, requires suitable research methodology, accompanied by effective data collection and analysis to arrive at a meaningful research output that contributes to the existing knowledge. This chapter explains the selection of the research methods suitable to this study. As described in (Fellows 2009), research methodology is “far more than the methods adopted in a particular study and encompasses the rationale and the philosophical assumptions that underlie a particular study”. Research methodology can also be described in terms of the entire research procedure, process, strategy, approach, application, paradigm, and methods used to achieve the desired research outcomes within a systematic pattern that is widely accepted to guide the researcher(s). A research methodology is applied within a study or discipline to generate findings or constructive frameworks that can provide added knowledge that is beneficial and valuable.

From the perspective of the outcomes, a research is a systematic process of analysis that can be used for the purpose of adding new knowledge to existing studies through appropriate methods and techniques to produce factual outcomes that are binding, usable, consistent, and reliable. The process of research can be categorized as the pre-empirical stage and the empirical stage (Marshall.C & Rossman 1989). The pre-empirical stage explores questions, research areas, topics and context. The empirical research includes the design, data collection, data analysis, and the corresponding outcome and development. There are different sub-sections for the structure of a research study. For this research, the following five categories are identified to outline all the research aspects that are relevant: (1) research application, (2) research type, (3) research paradigm, (4) research methods, and (5) research approaches. Following subsections introduces these categories in detail as well as represents the abstract figures for the evaluated and selected research aspects (green coloured background - darker shade indicates greater emphasis).

### 2.1 Research Application

Understanding different research applications is important to clarify how this research study is positioned. With respect to research application, a study can be categorized as pure research or applied research, depending on the intent of the conducted research and the origin of the research problem (Anderson et al. 2001). Both these categories can add new knowledge to the literature. Pure research is usually conducted to add knowledge for the exclusive purpose of attaining knowledge. It is typical that the research question is raised in connection with the previous research’s content. It involves development, testing and authenticating theories and hypotheses that may not be situated within the contemporary practice at the time of conducting the research. In contrast, applied research is performed to solve a specific practical problem, and it is grounded in problems in practice. As specified in (Kothari
applied research is a process that involves the application of existing and established theory that deals with practical endeavours. It can also be understood as a research that deals with practical problems where outcomes are situated around existing concepts or theories that are subjected to present or future development.

In this research, both pure research and applied research methods are used to identify theoretical and practical aspects of the identified research problems (Figure 1). The pure research part focuses on the usability aspects of information exchange standards used in AEC-FM industry; and handles the COBie standard to develop, test and validate the initial research questions. Based on a systematic review of the BIM and FM literature (Yalcinkaya & Singh 2014; Yalcinkaya & Singh 2015), it is shown that the existing research studies dealing with COBie have mostly focussed on implementation strategies and software practices such as how to import and export the COBie data in and out of the IT ecosystems, based on case studies and surveys. That is, the existing literature on COBie has not gone beyond the topics about definitions and specifications, technical development, implementation, and industrial practices. There is a lack of studies on the underlying usability and cognitive perspectives of approaches such as COBie. The pure research part of this thesis deals with this gap in the literature, making relevant theoretical contributions. On the other hand, applied research is also required in this study to identify the best practices that can be used to guide AEC-FM professionals when they are utilizing and working with the standardized approaches and solutions. As an outcome of the applied research, the proposed computational development is presented based on the feedbacks collected and practices observed during the real case studies.

![Research Application](image)

**Figure 1.** Employed research application techniques [darker shade indicates greater emphasis]

### 2.2 Research Type

Research types are used to describe the basic features supporting a given study. This involves the process of specifying key features that describes the research aim in context. It also involves defining what to expect from a certain research. There are five different types of a research study that can be considered when conducting a research: (1) descriptive, (2) correlational, (3) exploratory, (4) explanatory and (5) constructive (Kothari 2004). Descriptive research is defined as “an effective way to obtain information used in devising hypotheses and proposing associations” (Monsen & Van Horn 2007). It cannot be used to test and verify any study as it only describes the existing situation as it is. It is strongly related to qualitative research which is subjective and interpretive in nature. A descriptive research explains the study in its relevant context, such as time, place and culture. As a result, different researchers can describe a similar research in many different ways of depending on the context of relevant backgrounds (Monsen & Van Horn 2007). Correlational research is described as “type of non-experimental method that describes the relationship between two measured varia-
bles" (Jackson 2015). This is a research that allows the possibility of assessing and evaluating two variables within a specified study. Correlational research is centred on two or more studies. Therefore, a single study cannot be analysed through correlational studies. A study that does not require an extensive analysis of relationships between variables is not suitable for this research tactic. **Exploratory** research is described as a study that “investigates a little phenomena for which a library search fails to reveal any significant examples of prior research” (Fitzgerald & Howcroft 1998). It can be used to find, justify and explore new findings and phenomena that are useful to audiences. Therefore, it is not limited to the application of one paradigm. In exploratory research, a richer, deeper, and greater insight is explored within a study to generate new knowledge. **Explanatory** research is described as a research that attempts “to build theories that explain and predict natural and social events” (McNabb 2002). The goal of the explanatory research is the control of natural and social events and is also the view that explanatory and descriptive research are strongly related to qualitative research which allows subjective results. Events are explained in the understandings of the researcher. Exploratory research is more detailed compared to descriptive research. **Constructive** research is to solve practical problems while producing an academically appreciated theoretical contribution. The solution and (or) proposal, that is, constructs, can be based on processes, practices, tools or technical/organizational charts/diagrams. Constructive research involves the selection of a practically relevant research problem; obtaining a comprehensive understanding of the research area; design of one or more applicable solutions to the defined problem; demonstration and tests for the solution’s feasibility and applicability; association of the results back to the problem statement, and demonstrating the practical contribution; and, examination of the feasibility of the results.

This study primarily falls in the category of constructive and exploratory research (Figure 2). As it is presented in the coming chapters, the combined application of heterogeneity and standardization with BIM-FM is a new research area. The research conducted in this thesis is original. Although there is relevant literature existing in different domains and research areas, there is no literature specifically on the challenges and practices while handling standardized approaches, especially those associated with IT solutions for BIM and FM. Since the COBie standard has almost a 10 year history, there is no existing literature about the usability aspects of COBie. The relationships, possibilities, potentials, and opportunities within this study are explored and presented to develop a prototype computational implementation to enhance the usability and practicality of COBie standard. The implementation is discussed, evaluated, and improved through the iterative phases of this research.

![Research Type](image)

**Figure 2.** Employed research types

### 2.3 Research Paradigm

Research Paradigm is defined as the theoretical outline or structure that guides how the research is viewed and approached by the researcher(s). These are theories or hypothesis which
define how people view the matter differently and how it influences personal behaviour of specific individuals. However, research paradigm can also be described as a structure that is used to create theories (Fellows & Liu 2015). Research paradigms can respond to three principal questions, which are:

- Ontological questions, which determine the nature of reality, i.e. subjective, objective, pragmatic;
- Epistemological questions, which decide what is the general belief. It draws a disparity from what is viewed as consistent and trustworthy study. This can be related with positivism, realism, and interpretivism.
- Methodological questions which investigate how a researcher goes about a research, and what processes are used from inception to completion.

Ontology is a broad term that can be described as conceptions of reality. Fitzgerald and Howcroft (Fitzgerald & Howcroft 1998) classified ontological position into two different categories. These are realist and relativist. Realist perspective is external tangible structures or frameworks that are independent to the aptitude to attain knowledge which is non-subjective. While relativist perspectives are related to subjective realities constructed in the mind, and they have multiple realities depending in social issues in context such as culture or language. On the other hand, Fellows R. (Fellows 2009) states that in philosophy, ontology can be viewed as objectivist or constructivist, and that “objectivist ontology sees social phenomena and their meanings as existing independently of social actions, whereas constructivist ontology infers that social phenomena are produced through social interaction and are therefore in a constant state of revision”.

Epistemology is described as a suitable, adequate and acceptable study within any discipline of knowledge. Fellows (Fellows 2009) described epistemological perspectives as an approach that is “bounded by the positivist view that the methods of natural science should be applied to the study of social phenomena, and the alternative orthodoxy of interpretivism view that the method of natural science and people in that phenomena have different subjective meaning for the actors studies. Epistemology is a division of thinking or ideology that focuses on the nature of knowledge and its relationship with the reality, which is how certain individuals perceive the creation of knowledge.

Kothari (Kothari 2004) described empirical research to be rooted in research tasks conducted through experience or observation without the application of a system or theory. This approach is more based on data and information, in so much that assumptions can be easily verified through the application of direct or indirect experience or observations. Empirical research can begin with a hypothesis that a study can examine or experiment. Data generated from the analysis can be used to produce a cause and effect relationship between the variables involved.

The methodological position of this research is established through mixed methods, which is the combination of qualitative and quantitative research methods that are described in detail in the next section. Qualitative research method is understood to be strongly related to the process of collecting in-depth data to achieving desired research outcomes. Therefore, an interpretivist paradigm was considered as it is also strongly associated with qualitative method (Figure 3). Mixed methods were used to achieve the aim and objectives of this research as both statistical analysis and in-depth interpretation of qualitative data is required to understand the research outcomes, causes and effects that arise. Interpretivist paradigm was used for the purpose of this study as it allows the opportunities to explore realism of con-
text. In addition, the quantitative research method is also applied in this research to conduct a thorough and detailed identification of the trends and patterns in the BIM research (Chapter 3), as well as to validate the problem statements and associated research questions through the conducted focus group meetings (Chapter 5) and development hackathons (Chapter 4).

2.4 Research Methodology

Research methodology can be thought as the steps covered through the entire research process from inception to completion. It includes the need to identify possible components that can provide robust data to the research to be reviewed and analysed. The entire research sequence has to be drawn at the early research stages to guide the research systematically identifying aims, objectives, methods, tasks, etc. The identified research questions can be handled to define the methodologies applied to any research study. Based on the research questions which are presented in Section 1.3, this research adopted multiple methods. However, deductive reasoning process was applied to all stages of this research to organise the findings from different data sources such as qualitative and quantitative literature analysis, focus group meetings, hackathons, etc.

A framework can be drawn using the common sense on the problem statement and associated research questions. However, to achieve the validity and reliability, thorough reviews of the BIM and FM literature should be performed. In the beginning of research, to identify and validate the relevancy of the problem statement and research questions, a statistical quantitative analysis method has been conducted as the first step in this project. This analysis also identified the research patterns and topics of a large corpus of BIM literature by applying the text mining and natural language processing techniques. There are some advantages behind this quantitative methodology. First, the subjectivity of the analysis results are eliminated. While in qualitative analysis method, subjective opinions and interpretations of the researchers are likely, quantitative analysis method is more consistent and trustworthy with no subjective features attached. This enables objectivity of the results, hence acceptable outcomes. Second, computational assistance can be utilized for the quantitative analysis. Using computational method a large amount of data can be analysed within a short time period, unlike what can be covered in qualitative analysis. In this research, a qualitative analysis method could not be applied for the analysis of the 975 BIM-related research articles. However, in addition to the quantitative analysis of the 975 articles, a qualitative analysis of the relevant and selected FM literature has been performed, following traditional literature review approach. This analysis describes and categorizes the primary research topics in FM; as well as identify the relationships and connections between these categories with the revealed research patterns in quantitative BIM literature analysis. The qualitative analysis and quantitative analysis method confirmed and complemented each other.

The initial steps of this research study include both qualitative and quantitative research methods for the validity and reliability of problem statement and research questions. Howev-
er, when this research is reviewed from a broader perspective, the iterative steps of design thinking and agile development are harmonized to construct the main method of this research.

Design thinking is a proven and repeatable problem solving approach that any domain of business or profession can employ to achieve solution. It is an approach of solution-focused thinking which starts with a better solution goal (Dorst & Cross 2001). It uses divergence and convergence through ideation to generate and maximize ideas. Ideation is a process of generating many ideas through exploratory thinking and is based on a premise such as having a lot of ideas is better than to have one good idea. Design thinking is a human-centered and solution-centric approach to define and solve problems, which encourages innovation and creativity in the problem solving process. It is well-suited more to the situations where the problem itself is not clear and/or too generic. It advocates a strong focus on problem definition, problem shaping and requirements clarification. Design thinking generally involves five basic steps:

1. **Understand**: understand the experience and expectations of the problem;
2. **Define**: process and synthesize the findings in order to form the users point of view for the proposed solutions;
3. **Ideate**: explore the variety of solutions by generating diverse possible solutions from a range of ideas;
4. **Prototype**: transform the ideas into a tangible form to experience and interact with the proposed solutions;
5. **Test**: test the prototype, observe desired users’ experience and get feedback to refine it.

While design thinking is a human and solution-centric approach, it also places great emphasis on having a clear articulation of the problem. Likewise, agile methods embrace uncertainty and are appropriate for projects where the requirements are subject to change. For agile-based development, the backlog of the approach where the functional requirements of the system under development are captured, and the quality of those requirements is a significant factor determining the success of the approach. A pairing of design thinking with agile mindset and development can occur across the lifecycle of a research project, from initiation to finalization. However, the implementation of agile methodology is particularly more relevant to the last two steps of design thinking (prototype and test) which puts strong emphasis on an incremental and iterative development processes that is adaptive to user feedback throughout.

In this research, both methods are applied to identify and understand the needs and requirements of the AEC-FM people on the standardized approaches and associated IT solutions; and frame the main features and functionalities of the proposed development solution. Although design thinking is adopted for almost phases of this research, agile development handles and constructs the final framework of this research, and the proposed computational development. Thus, one can see the implementation of design thinking steps to answer the research questions, and also the integration of agile development process during the “testing” of the proposed initial development, and collecting the feedback which are the points of the consecutive and iterative cycle of research and development process (Figure 4).
To test the validity of the identified research questions, as well as to establish the continuation of both design thinking and agile development methods, collecting the relevant feedback and deriving meaningful outcomes from them are essential steps in this research (Figure 5). For this purpose, this research applies the focus group meetings as the main method for data collection. Focus group meetings not only enable the collection of more in-depth research data, but they also provide a forum to include a wide variety of topics as well as disciplines. This facilitates sharing and clarification of the views and opinions of the participants from various disciplines in an on-going discourse regarding various aspects of research and development. To bring rigour to the analysis of the collected data, this research applies protocol analysis, which is a qualitative, process-tracing technique whereby participants think aloud and discuss while either engaging in a task, or arriving at a decision, or making a judgement (Ericsson & Simon 1993). The thinking or discussion content is typically coded or examined in terms of the interpretative processes used. Although there is not a so-called “best way” to conduct the protocol analysis, following general principles can be applied:

(1) Collection of Data: The collection of the data should be performed in real time or whenever the participants vocalize their thoughts as they engage in the task/discussion. The data collection can rely on the hand-notes of the researcher if appropriate recording equipment is not available, or recording is not allowed by the associated authority. However, if the recording is allowed, hand-notes may not be an efficient process while there are various digital recording equipment make the recording protocols simple and cost/effort efficient. In this research, focus group meetings were performed with three companies. However, recording is allowed by only one of them. The data collection of the other meetings has been done via hand-notes.

(2) Transcription of Data: The transcription of the data is the most exertive process in protocol analysis. Although computational support is available for transcription, there can be huge amount of unnecessary data, such as daily conversations, the topic of city life, industrial
news, etc. included into the transcription. For a more precise analysis, this unnecessary content should be cleaned up from the corpus. In this research, the transcription has been done by the researcher by reviewing the video recordings and picking the relevant content in the discussions.

(3) Planning the coding categories: Having an idea about the overall purpose of the meetings and discussions, and the primary objective of the analysis, facilitates the organization of coding categories. Although there is no pre-defined or constant coding scheme that can be applied to any research, the relevant research studies can be obtained as the reference and inspiration.

Figure 5. Employed research methods

2.5 Research Approach

Research approaches are classified into deductive, inductive and abductive research. The relationship between theory and research is perceived differently in these research approaches. In addition, they can differentiate based on the theory development and testing (Blaikie 2009). For example, a research can set out with a theory in hand or a research can end with a theory as the final outcome or product is achieved. Deductive research is mostly referred to have the capability of producing hypothesis through the use of theoretical models. The process is used to achieve the hypothesis can also be achieved by testing which involves the corresponding and matching of hypothesis against data. It can be viewed as the opposite of inductive research. Deductive research starts with a more generalized approach and ends with a more focused outcome. It starts with a theory which is tested through the relevant data collection process and analysis in order to verify a hypothesis. Inductive research is described as generalizations or prepositions through a detailed representation. The generalization is also generated by induction from data through conceptual frameworks. It is highly linked to data and theory associated with qualitative research and there can be a degree of uncertainty and a conclusive outcome that is possibly centred on premises at the expense of exploring richer and more detailed data that could produce desired research outcomes (Glaser & Strauss 2009). Newell and Bunard (Newell & Burnard 2010) described deductive approach to be associated with quantitative research and have the tendency to move from generalised to more specific while inductive approach is associated with qualitative research and has tendency to move from specificity to generalised context. Theory and research are viewed contrarily in the context of deductive and inductive research, theory involves generalization for inductive research which is continuously supported throughout the research. While research on the other hand involves data collection, analysis, creating patterns which is developed into generalisations and finally leads to a theory. In the case of deductive research, which is the reverse of inductive research, a theory is not achieved as the end product of the research (Newell & Burnard 2010). On the other hand, abductive research is set to address the weakness associated with deductive and inductive approaches. Specifically, deductive approach is criticized for the lack of clarity in terms of how to select theory to be tested via formulating hypotheses.
Inductive approach is also criticized because “no amount of empirical data will necessarily enable theory-building” (Sauders et al. 2003). Abductive reasoning overcomes these weaknesses via adopting a pragmatist perspective. At the same time, it has to be clarified that abductive reasoning is similar to deductive and inductive approaches in a way that it is applied to make logical inferences and construct theories. This approach, the research process starts with the facts or puzzles, and the research process is devoted their explanation (Zikmund et al. 2010). These puzzles may emerge when the researcher encounters with empirical phenomena that cannot be explained by the existing range of theories. When following an abductive approach, researcher seeks to choose the best among many alternatives in order to explain the puzzles identified at the start of the research process. In the course of explaining these puzzles, the researcher can combine both numerical and cognitive reasoning.

The use of different research approaches such as deductive, inductive and abductive research determines the study approach; they are developed from epistemological or theory applications, and also the type of question a researcher asks. Therefore, this research takes an abductive approach which starts from more generalized problem statement. At the same time, this research also applies the deductive approach as a “sub-approach” to narrow down the generalized research problem to more specific research questions. As the process of abductive approach different topics such as standardization development, BIM, FM, industrial practices, etc. were explored at the beginning of the research with a pragmatist perspective to identify possible puzzle pieces of the theory, at a later stage these components are further narrowed down to the context of usability reviews, functional development, systems integration, data management, etc. The use of a problem statement at the early stages of this study and ends with a hypothesis developed after the use of a theory through data collection from hackathons, focus group meetings. Starting with a generic problem statement is one of the basic principles of a deductive research; this also shows evidence that the research took a deductive approach.

![Figure 6. Employed research approach](image)

### 2.6 Research Structure

This section presents the structure of this research by summarizing the associated research content under the relevant chapter numbers and names. In addition, the applied research methodology in each chapter as well as the brief description about how the conducted research answer associated research question, is presented.

This thesis consists of seven chapters:

**Chapter 1** is used to give a broad overview of the research and lays out the problem statements, and associated research questions, motivation and the scope of this research study. The main problem statement is defined as understanding and utilizing the industry standards and associated IT solutions. This generic problem statement is narrowed by focusing on the COBie standard for post-construction phase of the lifecycle in which the research questions are categorized under three main themes which are (1) Standardization process of COBie
standard; (2) Usability evaluation of COBie standard; and (3) Requirements for enhanced development on top of COBie standard. The aims and objectives of this research are also clearly described stating the importance and justification of the research. This chapter is the beginning point of research and the start point of the adopted deductive approach.

**Chapter 2** presents the design and the structure of this research by introducing ontological, epistemological and empirical features and adopted research application, type, paradigm, methods and approach with the reasoning behind it. In addition, this chapter also includes a summary of the applied methodology for each chapter of this research (Table 1).

**Chapter 3** provides the theoretical background with a thorough review of the current and relevant literature about BIM and FM, as well as that of COBie standard, especially in terms of standardization development and evaluation of usability features. In this chapter, the subsections entitled as “History and Development of COBie” and “Relationship between BIM, IFC and COBie” provide a detailed investigation to understand the position of COBie standard in FM domain as well as how BIM, IFC and COBie are associated with each other. These sections also provide detailed answers for the research questions RQ1 and RQ2. For the usability features of COBie, the relevant literature about the representation of COBie dataset, cognitive science, and human-computer interaction (HCI) are reviewed. The result of this review process contributed towards the answers for RQ3 and RQ4. In this chapter both quantitative and qualitative review has been adopted to reveal the tangible reasoning for the define and ideate phases of the design thinking methodology. This chapter presents majority of the theoretical background of this research. Nonetheless, each chapter of this thesis also contributes to the overall theoretical background of this research.

**Chapter 4** presents the key assumptions, the conceptual development, and the computational development relevant to the thesis, especially regarding the improvement of usability features for COBie data representation by applying the principles and steps of design thinking. The initially identified issues, requests, and problem statements are discussed in this section for the proposed development features of VisualCOBie. This chapter also presents the development architecture, employed technologies and libraries, and the desired improvement features for VisualCOBie to enhance the usability and functionality of COBie spreadsheet representation. The initially identified issues, requests, and problem statements are tested with a small case scenario for the validation of the initial development process. Although this chapter does not include a thorough evaluation and validation of the initial ideation and development features, it presents the integration of the agile development process where the evaluation and validation is performed in detail. This chapter provides relevant answers to the presented research questions such that, the Understand step of the applied design thinking methodology provides answers to the research questions RQ3 and RQ4; the Define step provides answers to RQ3, RQ4 and RQ5; the Ideate step provides answers to RQ5; and the Prototype step, which presents the development architecture and dependencies, provides answers for RQ6 and RQ7. In this chapter, the deductive reasoning can be seen better since the outcomes of this chapter present more detailed arguments than the initial problem statement and research questions.

**Chapter 5** describes the findings from the focus group meetings, case studies, and the outcomes of the development results during the hackathons with the case companies. The analysis of the feedbacks regarding the developed VisualCOBie prototype is presented in this chapter. The results from protocol analysis on the collected data is presented in this chapter, to evaluate and validate the initial requirements that were defined in Chapter 4. The iterative
progress from the hackathons and the development work also outline the integration and complementarity between design thinking and the agile development processes. The feedback from focus group participants reveal the challenges with the existing wrong practices, and how those are reflected in the new development and improvement requests for the VisualCOBie platform. This chapter provides answers for the research questions RQ3 through RQ9.

Section 6 presents the enhanced usability and functionality request which were presented in Chapter 5, and the corresponding implementation of these requests on to the VisualCOBie prototype. This chapter presents the other core theoretical concept and the corresponding implementations which moves the VisualCOBie prototype beyond a data visualization and navigation platform. This improvement reveals the VisuaLynk, as the improved version of VisualCOBie prototype, as a flexible and scalable data integration, management, and interoperability for facility lifecycle.

Section 7 presents the outcomes of this research as per the categorization of the research questions, limitations of this research, and potential future studies which can contribute this research’s iterative lifecycle and open new perspectives to the existing methodological, theoretical and technical contribution of this research study.

To facilitate readability and getting an overview of the thesis structure, Figure 7 shows the mapping of the research questions, research methodologies and structure, as well as the chapters of this thesis.
Figure 7. Overall research structure and applied methodologies
3. Theoretical Background

This chapter includes a review of current and relevant literature to establish the theoretical background, and to build an understanding of the emergence, development, structure, representation, and the current status of COBie standardization effort. The interaction between BIM, IFC and COBie standard and associated data structure is reviewed. In addition, to validate the problem statement an analytical and systematic review of BIM literature is conducted. The representation, format, and the underlying usability issues with COBie data are reviewed, based on the literature on human cognition, human-computer interaction (HCI), as well as information visualization in AEC-FM industry. By introducing the core concepts of this thesis, and by validating the problem statement and research questions, this section aims to outline how this research fits within the context of the relevant literature and knowledge area.

3.1 Patterns and Trends in BIM and FM Research

BIM has emerged as one of the key streams in construction and civil engineering, and received a considerable amount of attention by researchers within the last decade, with a rapid increase in the number of related publications. This rapid increase in the volume of BIM research also poses a critical challenge in terms of identifying the research direction and trends. While the qualitative reviews of the literature are insightful, it is prone to be biased and limiting in terms of the number of articles that can be reviewed. Therefore, a quantitative assessment on the BIM literature by using a text mining and natural language processing (NLP) technique, called Latent Semantic Analysis (LSA) (Deerwester et al. 1990; Han et al. 2011; Sidorova et al. 2008), allows a systematic and comprehensive analysis of a large corpus of a literature. LSA is used to facilitate retrieving and querying large corpus of text-based data. As a mathematical and statistical method, LSA is used to identify the latent concepts within the textual data at the semantic level (Sidorova et al. 2008). LSA employs a set of algorithms to convert unstructured text into structured data objects, and analyse these data objects to identify patterns for the discovery of knowledge. The main idea behind LSA is to collect all the contexts belonging to the words in the corpus, and derive associated factors that represent related concepts.

In the beginning phases of this research, to identify the research patterns and detailed research questions, the researcher applied the quantitative analysis on BIM literature published from 2004 through 2014 (Yalcinkaya & Singh 2015). Three steps were applied to collect and finalize the data. Initially the articles were identified from the academic research
databases using the search phrase “building information modeling” in the titles, and/or abstracts, and/or keywords. To enlarge the corpus size, phrases “bim” and “building”; as well as “bim” and “information modeling” were used together during as keywords of the search. The returned articles were collected and organized by their names, authors, published journal/conference, year, etc. After the duplication check of the search results, 525 Journal and 450 Conference publications were collected for analysis.

This systematic analysis revealed the twelve principal BIM research areas. In addition, ninety specific research themes associated with the twelve principal areas have been identified, clustered, and associated with each other. The principal research areas and the research themes comprise the comprehensive patterns of BIM research, which indicate the directions and trends in BIM research. According to the yearly distribution, the revealed principle research areas during 2004-2005 include architectural design process, BIM training and education, BIM-based project management, and information exchange topics. Through 2006-2008 new research themes such as adoption, energy management, urban/building space design and analysis and facilities management (FM) topics have appeared. For FM research, although there are 8 journal publications that appeared through 2006-2008, this number gradually increased during 2009-2011 period to 31, and during 2012-2014 to 48 publications.

In this analysis, the detailed research themes are identified by running the LSA technique to cluster the topics under ninety different groups. The revealed detailed research themes are then semantically linked with the twelve principal research areas with cross-loading analysis. For FM, several research themes matched up including:

- *health care facilities* (Irizarry et al. 2014; Lucas et al. 2013),
- *lessons learnt from BIM implementation for maintenance* (Kiziltas & Akinci 2010),

In addition, the research on BIM for FM is concerned with the generation, specification and management of required information, as reflected in the associated research themes of

- *model transformation among different processes* (Yong et al. 2012),
- *information retrieval and querying* (Kim et al. 2013), and
- *semantic reasoning of BIM-based information* (Kim & Grobler 2009).

Similarly the theme *implementation of BIM at pre-design phase* (Ham et al. 2008) emphasizes generation of information for facilities management from the early phases of project lifecycle.

The results of this analysis have directed the researcher’s studies on the BIM-related FM topics since the majority of the identified research themes for FM have appeared after the year 2012. This indicates the increased interest of academia in FM. In addition to this quantitative analysis, researcher collected the revealed journal and conference publishing and performed another review to identify the detailed subjects about BIM for FM. In this review, a qualitative analysis has been performed on the collected literature by assigning codes (keywords) to the reviewed documents, based on the focus and the main content of the paper. The analysis highlighted which BIM aspects come more often for FM? What are the gaps? And, what are the key concepts and potential research fields? The code analysis revealed the most common topics discussed in the BIM-FM literature, including:

- *data integration and interoperability,*
- *information exchange and sharing,*
• decision support, and
• early integration with facility design.

The data integration and information exchange mostly refers to the integration of different IT tools and associated data content used in FM practices. Computer Aided Facility Management (CAFM) systems are commonly used to integrate various facility information. However, the re-usability of the data in CAFM solutions and the fragmented nature of AEC-FM industry makes the data integration and information exchange challenging (Motawa & Almarshad 2013). To overcome this problem, such systems which can integrate 3D BIM models and FM information in a database can be developed as a knowledge-based BIM system (Wang & Xie 2002). Since existing CAFM systems have inadequate capabilities and functions for collecting the building information pushed from various stakeholders and different phases of the project lifecycle, BIM based applications are being developed to simultaneously collect data from different stakeholders and transfer this information to the facility manager in a cloud environment (Jiao et al. 2013). However, the number of applications that can be integrated as well as the representation of all the integrated data is still an open question. For such FM requirements, BIM can act as a virtual database application. However, BIM is not enough by itself to collect and transfer the facility data. For the runtime data integration, an example was given in the literature for the integration of BIM systems with communication technologies such as radio frequency identification tags (RFID). The integration through database servers or cloud services can provide access to the run-time data of the assets in a facility (Shen et al. 2012; Ko 2009).

The interoperability issues are also emphasized several times in literature. The majority of BIM and IT-based software applications are mostly implemented in isolation which cause lack of interoperability among the systems. Therefore, sharing the data in such a heterogeneous IT ecosystem becomes complicated. In addition, the lack of clarity regarding the data requirements, responsible actors and information handover contribute to this complexity (Becerik-Gerber et al. 2012). To overcome this problem, different technological and strategical approaches have been defined in literature such as using extensible markup language (XML) for exchange, transfer, archival and re-usability of facility data through different database and software systems, and web-based platforms (Teague et al. 2003). Similarly, the utilization of IFC for FM has been covered in the literature. IFC provides a framework for the digital representation of building design, engineering, construction and operation data to facilitate information exchange between BIM software applications. However, the information transferred with IFC contains lots of other information which are not needed for FM activities. Therefore, it should be filtered to make it more usable. COBie specification filters the complex IFC, and captures the life cycle information which is more relevant for FM purposes (East & Nisbet 2010). The next subsections present a detailed review of COBie. However, the summary of general BIM-FM literature defines the COBie as the simplified non-geometric subset of IFC and usually presented in spreadsheet format (Sabol 2013). Although there is an agreement on the requirement of COBie for structuring the FM-related data, it has been found to be complex and unclear to use (Anderson et al. 2012; Gnanarednam & Jayasena 2013). This review also led to the conclusion that there are various data structures and corresponding configuration of existing IT solutions for BIM and FM. Organizations need not fit their dynamic FM processes to suit a particular technology for decision making, which may otherwise result in a continuous effort of technology and end-user adaptation. Instead, they should define the dynamics of their FM strategies and adapt the related specifi-
cations/standardization for BIM and FM, which suit their individual organizational and operational strategies (Yalcinkaya & Singh 2014).

### 3.2 Background and History of COBie Standard

BIM has strong capabilities to generate, manage the building data and visually represent it by covering all the properties and quantities of building components. Despite the potential advantages of visualization and database capabilities of BIM applications, one of the most important requirements for management of a facility is the relevant, filtered, and timely access to the information among the thousands of it which usually cannot be transferred to the FM team due to the manual and/or paper-based data entry. In 1983, the National Research Council Building Research Board recognized the necessity of delivering the useful facility information by proposing an integrated database solution, which is now referred as one of the first attempts to reduce the additional cost of capturing of a facility data which is needed for FM tasks (Scarponcini 1996).

Many FM professionals have been using computerized systems such as CAFM, Computer-Aided Maintenance Management System (CMMS), Building Automation Systems (BAS), etc. to organize, manage and deliver their digital building information. However, the variety of software products and their versioning cause inefficiencies in automatic transfer of the data into these systems. In this case, the manual process of data entry becomes error-prone and capturing the enormous amount of data may become impossible. Electronic papers, such as PDF, is also a common way to exchange information. However, there is no difference in practicality unless the necessary computational configurations are available to capture the standardized data (e.g. IFC data) in PDF. In addition, paper-based information delivery is still commonly applied due to familiarity without eliminating the inefficient process (Anderson et al. 2012). COBie specification was developed to overcome such challenges and establish a non-proprietary version of exchange data by identifying the content of the required information, their exchange phase and method, as well as the responsible actor of the project (East 2007). The development process of COBie began in 2006 under National Institute of Building Science (NIBS) Facility Maintenance and Operations Committee, and with an extensive review of literature and private industrial/association efforts. The review focused on two aspects:

(1) Determination of the useful minimum in terms of specific information requirements, responsible actors and associate lifecycle phases; and

(2) Definition of the convenient data exchange standards to prevent existing inefficient way of information exchange process. From the private industry perspective, life cycle information exchange was evaluated based on the business cases, specific business requirements, information handover plan, and implementation with software applications (East 2007).

Association efforts took significant place during the development of COBie. The following developments for information standards were considered for the development of COBie standard. Machinery Information Management Open Systems Alliance (MIMOSA) is an industry sponsored non-profit organization and serving for industrial equipment information systems. The most important specifications published by MIMOSA are the Open Systems Architecture for Enterprise Application Integration (OSA-EAI) (MIMOSA 1998) and Open Systems Architecture for Condition Based Maintenance (OSA-CBM) (MIMOSA 2006). These standards describe how to integrate asset management information and how to transfer in-
formation in a condition-based maintenance system. The implementation of these specification is performed with Common Relational Information Schema (CRIS) which is used to connect different tags used in separate systems so that it is possible to find out what is the tag for an asset. CRIS provides a model that assigns every entity with a Globally Unique Identification (GUID) number. This GUID number can then be associated with system-specific tags (MIMOSA 1998). International Alliance for Interoperability (IAI) and its open-source framework for exchange of facility information IFC, also describes the majority of components, equipments, systems, spaces, zones, etc. and the associated attributes. Besides, the multi-variable way of IFC models’ representation such as EXPRESS language and XML format is an advantage for representation of COBie data. OmniClass is a International Standards Organization (ISO)-based classification system for construction industry which provides a systematic taxonomy for electronic databases (OmniClass 2017). It is also useful for many BIM application to structure their report organization, object library, etc., hence for COBie as well to classify the building components represented in COBie data. Including the specified associations’ standards, totally twelve published data exchange standards for the process industry were reviewed to identify equipment, process, systems, procurement, operations and management datasets which are convenient for the development COBie standard (East 2007).

In addition to the association efforts, the practices of the public organizations were also taken into consideration during the development of COBie. US Naval Facilities Engineering Command (NAVFAC) provides Operations and Maintenance Support Information (OMSI). OMSI is an information package which includes the key information produced during design, construction and commissioning of a facility. The information is organized in three groups which are (1) facility information, (2) primary systems information, and (3) product data (Raymond 2004). The delivery of an OMSI package can be done in three formats: paper-based/printed copies, portable document format (PDF), and in the format that compatible with CMMS applications. The convenient information type and delivery phases were evaluated during the development of COBie standard. In addition to OMSI, the electronic OMSI provides the required facility information in a structured spreadsheet file with a specified template, during the facility information handover (NAVFAC 2011).

3.3 The Relationship Between BIM, IFC and COBie

Based on the development history presented in Section 3.2, one can say that the COBie is a template which is based on the composition of existing information specifications and exchange standards which have been in use for years. The information structure and the delivery format of COBie standard was shaped based on the existing process to simplify the previous inefficient process of facility information handover. Currently COBie can be presented and delivered as Standard for the Exchange of Product model data (STEP), XML and as a Spreadsheet markup language (or spreadsheet form). By considering the end-users’ knowledge and experience with the first file-formats, spreadsheets become the most useful way of representation of COBie data. The spreadsheet format of COBie standard includes several workbooks and associated columns in which the users import the information from software and/or fill in manually. Both automatic export and manual entry can work for generating COBie data. However, the distributed sources of building information makes the implementation of COBie challenging. The need for a common building information format
which contains the information requested in COBie, is an essential point for the success of COBie.

In conjunction with the emergence of BIM in the industry, IFC has become a common way to communicate with, and exchange the building information. IFC data scheme includes variety of building components, and can be imported and exported between various software applications, represented in STEP and/or XML format. In addition, it is related to building information classification such as OmniClass via BIM authoring tools. However, the overall structure of IFC is too large and complex to exchange and/or represent a specific set of domain data which includes its own hierarchy and semantics. During the IFC standardization process, a shift occurred which changed the direction of IFC’s development strategy from interoperability for all AEC-FM industry to an improvement in communication, productivity, and quality for phases of the project lifecycle (Laakso & Kiviniemi 2011). The useful minimum of IFC provided the minimum set of information packages for specific lifecycle phases, disciplines and/or business cases. As a result of this minimalistic approach, Information Delivery Manuals (IDM) (Wix & Karlshoej 2010) and IFC Model View Definition (MVD) (BuildingSMART 2010b) formats were developed and became the official elements of IFC standardization. While IDM provides the documentation and guidelines about the technical needs for software implementation and individual end-users’ role for process workflow, MVD considers both customers (or business-related end users) and software developers’ needs to narrow down the complete scheme and develop the specific sub-sets of IFC which is implementable by software application. Laakso and Kiviniemi summarize the IDM and MVD concepts as:

“... The IFC data model is the foundation from which MVDs are defined. Software applications then implement support for specific MVDs. IDMs provide documentation and guide the workflow of IFC enabled exchanges, and are designed acknowledging the functionality of specific MVDs. These cross-referencing information exchange layers were designed to facilitate the deployment of IFC-supported interoperability” (Laakso & Kiviniemi 2011).

The minimalistic approach of IFC provided the most functional layout for automated and digital data exchange of information for COBie specification. The development and implemented strategy of COBie is presented through use of IDM and MVD, by defining the phases of specific business workflow, exchange of digital information requirements, generation of data formats for software developers and the sub-sets of IFC entities for information exchange from BIM applications. From this perspective, FM Handover MVD provided the conceptual format of the information which is the base for COBie specification; as well as the link-map between the associated IFC entities and specific information requirements such as spaces, floors, zones, components, technical systems, etc. (BuildingSMART 2013; BuildingSMART 2009a; NIBS 2012). Therefore, BIM has become an image for the generation of COBie data because an IFC file is a rich data source to feed the various information requirements in COBie specification. However, IFC is not an all-in-one and the only source for the information requested in COBie specification. Instead, some information requirements of COBie can be populated via CAFM, CMMS application and/or by manual input. At the end of the generation of COBie handover file, the distributed data can be compiled and exchanged as a single file (mostly in spreadsheet) and then separated as sub-datasets for FM activities (Anderson et al. 2012).
3.4 Representation and Publication of COBie Data

As mentioned in the previous sections, COBie data can be delivered and published in any of the three formats, IFC STEP, IfcXML or SpreadsheetML. In terms of representation of COBie data, IfcXML format can be interpreted and viewed in various parsers and/or web browsers. However, utilization of XML-based information requires some IT knowledge, which not all the end-users may have already. By considering the end-users’ inexperience and limited familiarity with the first two file formats, spreadsheet has become the most common way to represent the exchange the COBie data. The spreadsheet format of COBie deliverable provides familiar end-user implementation techniques such as sorting, querying and simple mathematical functions if needed. It is human readable, checkable and editable. A COBie spreadsheet deliverable includes up to twenty workbooks such as, Contact, Floor, Space, Zone, Type, Component, System, Job, Document, etc. and columns in which the users export the information from BIM and/or CAFM, CMMS software applications’ database mappings or export tools. In addition, the end-users can fill the COBie data manually. The data is distributed in workbooks and associated columns such that each row includes specific entities of facility data. Depending on the delivery phase and the project size, a COBie spreadsheet can include thousands of rows of facility data (Figure 8).

Despite the ease of spreadsheets and familiarity of end-users with spreadsheet logic and actions, storing and representing large amount of facility data in a tabular format with number of dependent sub-sections may have unintended effects and challenges in handling and interpreting COBie data. For example, challenges in visualizing the overall content, duplication of data entries (specially during manual input), understanding data dependencies within and between the workbooks, memory overload due to high amount of number and text-based data, etc. Similar issues are also noted in the literature about the usability and cognitive aspects of spreadsheets in general (Chen & Chan 2008; Kohlhase 2013; Hendry & Green 1994; Thorne & Ball 2008). Therefore, even though the cross dependencies between workbooks are accessible as drop-down pick lists in the COBie spreadsheet, the main difficulty that end-users have in understanding the data in the multiple workbooks of COBie spreadsheet can be summarized as the high amount of data and lack of explicit dependencies between the cells and multiple workbooks. Users need to locate the data and recognize their dependencies.
across multiple workbooks of COBie spreadsheet. This can impose a heavy memory load on the end users. Even though the schema of the COBie spreadsheet is available in COBie Responsibility Matrix as a separate file (East 2013) which end-users can refer to for checking and interpreting the dependencies, handling two separate files or adding one more workbook to the existing COBie spreadsheet may further increase the cognitive memory load. This cognitive load can limit the understanding of the semantics of COBie as specified in FM-MVD (BuildingSMART 2009a), and prevent efficient use of the data. To understand the potential limitations in the spreadsheet representation of COBie and how to enhance the existing spreadsheet representation, the relevant literature was reviewed about human-spreadsheet interactions, as well as the information visualization research applied in AEC-FM industry which are presented in the following subsections.

3.5 Human-Spreadsheet Interaction

Spreadsheet-based platforms are popular for storing, analysing, and visualizing data across all domains, ranging from business to science. In HCI community, spreadsheet is often referred-to as a task-oriented platform with high computational power. Norman states that “spreadsheets merge the computational power of the computer with a clean, useful, conceptual model, allowing the interface to drive the entire system, providing just the right tools for a surprising variety of applications” (Norman 1986). By providing a combination of an expensive high-level formula language with an easy tabular format to organize and display data, spreadsheets are easy to learn and use. In addition, spreadsheet actions can effectively guide the decision-making process without the need for complex computing actions and professional support. Therefore, the flexible and direct approach to data manipulation and management in spreadsheets has led to widespread usage (Panko 2008). Besides, almost in every business or professional domain, spreadsheets are not only used as a single-user application, but also in multi-actor environments as a collaboration tool, and as means of communication, exchange, and integration of domain knowledge (Nardi & Miller 1990).

Although spreadsheets are powerful, simple, easy to use, and facilitate the tasks of single/multi user organizations, yet crucial errors can easily occur. Several studies mention the common mistakes and challenges of spreadsheet usage in different scenarios (Chen & Chan 2000; Saariluoma & Sajaniemi 1989). Saariluoma and Sajaniemi (Saariluoma & Sajaniemi 1989) defined the two levels of a spreadsheet as concrete and visible surface level, and other more abstract and hidden level beneath the surface. The tabular layout appears at the surface level, while the connection of the cells is established in a network defined by the dependencies in the deep level. One of the basic difficulties during the handling of spreadsheets is establishing the connections between the data distributed in cells and workbooks (Kohlhase 2013). For large spreadsheets like COBie, tabular layouts for textual and numerical data do not show any direct mapping with the deep level; and in most cases, users deduce the semantic connection among the cells, columns and workbooks by visually checking them, which imposes a heavy cognitive load (Hendry & Green 1994). People process the information in the working memory, which has a limited capacity. A large spreadsheet may also impose a high cognitive load. Therefore, the process of investigating dependent data can be tedious and error-prone because many spreadsheets, including COBie, contain widely separated data. In order to help users, the visibility of the deep structure of spreadsheets must be presented to the users’ attention. This suggests that the integration of deep level structure of spreadsheets
with the surface level is desirable. The visual and interactive representation of this integration can function effectively as an evocative aid to lower the users' cognitive load.

3.6 Data Visualization and Implementation in AEC-FM

In HCI domain, the topic of visualization has been also explored and integrated with the power of computerized functions and visual environments to establish a link between the perceptual environment with the core data (Polys & Bowman 2004; Polys et al. 2004). The earliest example can be the disk operating systems (DOS). The simplest activities on a daily computer usage, such as creating or deleting a file, file transfers, etc. are performed via complex textual commands in DOS environments. However, currently these operations can be performed easily with visual aid and pre-programmed functions in the UIs. In addition to visual aids, the current state-of-the-art computerized visualization techniques provide the users real-time interactive features such as zooming and querying to navigate and browse through the data visually (Yang & Ergan 2014). Such features can partially prevent the common problems occurring with the large spreadsheets by providing a revised/queried focus via reducing the amount of data.

Visualization techniques have been in use for various domains of AEC-FM industry. The majority of literature has discussed the use of 2D, 3D, 4D, nD (dimensional) representations of the physical artefacts and the modelled facilities. For example, in 4D model developments, the most common topic includes time clashes and monitoring the construction progress by simulating the diagrammatic schedule data with the interactive 3D model. In terms of benefits of 4D visualization, Chau et al. (Chau et al. 2004) state that 4D models enhance people’s understanding of the schedule and support quick problem identification. In addition Dawood and Sikka (Dawood & Sikka 2008) quantitatively proved that 4D models can increase the efficiency of communication among construction project team. The implementations of these platforms is not limited to visualization. Currently, many 3D-based platforms also serve as a data repository. This enrichment is generally in form of BIM where the visual platform stores the digital facility information and provides a multi-user based collaboration environment. In addition to the integration of domain data with the 3D model, color-coding has often been used to cluster the semantic or dependent information using either the 3D models or domain-specific documents (Einsfeld et al. 2008; Roh et al. 2011). The visualization of the 3D data in a physical realistic environment is presented with augmented reality (AR) to facilitate the design process, site and safety management, progress monitoring, etc. (Behzadan & Kamat 2005). Similar visualization techniques are also used for FM such as color-coding to identify the maintenance status of facilities or related assets and completion status of work orders (Su et al. 2011). The integration of textual/numerical asset information with the 3D model has a potential to decrease the cognitive load of the user via the simulated navigation within the model. Similarly, dashboard-like interfaces help understand the distributed information as an abstract level and a single interface.

In the context of COBie, such visualization and data integration approaches have been applied as well. Typically, these techniques include user interfaces with an information management system at the backend; mapping the tabular COBie dataset entities with the representatives in the 3D model: or embedding a specific asset’s COBie information into the 3D model. These approaches have already been in use by some commercial products such as Solibri, 4Project and Ecodomus (Ecodomus 2016; Solibri Inc 2015; 4Projects 2013).
3.7 Data Visualization and Gestalt Principles

Data visualization is one of the core elements of this research with visual perception which can be described as the ability to perceive our surroundings through the light that enters our eyes. The visual perception of colors, patterns, and structures has been of particular interest in relation to the visualization of information and graphical user interfaces because these are perceived through vision. An understanding of visual perception therefore enables designers to design more effective and less cognitively-loaded interfaces for the humans’ working memory. Visual perception processing is facilitated by Gestalt Principles of grouping, such as connectedness, similarity, proximity, symmetry, etc. (Peterson & Berryhill 2013). Gestalt principles are the rules of the organization of perceptual scenes. Complex scenes are usually perceived as the composite of many groups of objects on some background, which the objects themselves consisting parts, which may be composed of smaller parts, etc. The principles aim to formulate the regularities according to which the perceptual input is organized into unitary forms (Ellis 1950). According to Gestalt, certain features in visual perception are universal and don’t have to be taught. Gestalt theory proposes that we see by forming light and dark objects, edges and contours into a whole image without thinking about it. The statement “the whole is different from the sum of its parts” sums up the way we recognize figures and whole forms instead of just a collection simple lines, curves and shapes. In other words, we perceive the whole without being aware of the connection of the parts, and that the essence of the whole does not change when we transpose it. Gestalt principles have been outlined as the “laws” of perceptual organization which may vary in different studies, but the following ten are generally accepted (Peterson & Berryhill 2013):

- **Similarity**, in which people give preference to simple, understandable and orderly things. Instinctively we group things that have similarity of shape, colour, or any other similar attribute. Often, coming into contact with complex forms, we try to organize them using simple components, or simple whole.

![Figure 9. Similar objects based on their shapes](image)

- **Closure** combines simple parts to create a whole. Our eyes tend to add lacking information to create a cohesive object.

![Figure 9. Similar objects based on their shapes](image)
Symmetry refers to the perception of visual things like pictures, shapes, and letters as a whole, even if they are incomplete. It gives the feeling of order that we are looking for.

Figure 10. The cohesive cube image generated in our vision

Figure 11. The order of the images with their symmetries

Figure/Ground principle explains the relationships between positive elements and the negative space. Our eyes isolate whole figures from their backgrounds in order to understand them.

Figure 12. Example figures with the corresponding ground which generates new images

Connectedness refers to the connecting elements (e.g. lines) within the visual elements which make us think that they are somehow connected.

Figure 13. Different shapes and connecting lines

Common Region demonstrates the connection between elements by separating them. Every element in the separated region will be perceived as a part of a whole.
Proximity states that in a set of distributed objects, we tend to group those things together that are visually closer to each other.

Continuity explains how we experience a group of visual elements as a continuous line. If there is any intersection between elements, we perceive them as two single uninterrupted lines.

Common Fate states that regardless of how far apart the elements are placed, or how different they appear to be, if they are seen moving together they will be perceived as related objects.

Past Experience refers to the experiences we have with a cognitive trigger such as an image, music, smell, etc. For example, the hard disk icon on a UI reminds of the “save” action for a digital file.
Depending on the case, sometimes two or more gestalt principles can be at play which reinforces our perception. The evaluation of COBie spreadsheet based on the gestalt principles, and the employed principles for the VisualCOBie approach is presented in the next chapter.

### 3.8 Summary of Chapter

This chapter introduced the theoretical background with a thorough review of the relevant literature about BIM and FM. The results of the conducted literature reviews showed the increased interest of academia to the BIM-FM related topics within the years which also provides the ground for the validity of the overall research domain and topic. Although COBie standard can be seen as a synthesis of the existing information exchange and management standards, there are strong ties between COBie and BIM, because reasonable amount of COBie data can be extracted from IFC. This chapter also showed that such domain specific standards like COBie have adopted a *minimalistic* approach and contributed to the development of IFC standard via MVDs. Therefore, BIM is considered as a media to populate the COBie data. However, BIM is not the only source to generate COBie. For the usability features of COBie, the relevant literature about the representation of COBie dataset, cognitive science and human-computer interaction (HCI) were presented to identify the common usability practices and limitations on spreadsheets in general. In addition, the aspects of visual perception with the support of gestalt principles are presented in this chapter. The reviewed literature can be associated with the representation of COBie data since spreadsheet is the most common form of representation and delivery of the COBie data.
4. Development of VisualCOBie Prototype

The theoretical background presented in Chapter 3 provided the fundamental arguments and guided the researcher to elaborate the detailed aspects for the theoretical and practical contribution of this research. In this chapter, the outcomes of Chapter 3 are used to structure the iterative design thinking and agile development methodologies applied in this research. In addition, the presented theoretical background is further elaborated with new studies in the literature to improve the theoretical contribution. With the presented and new literature, as well as the applied methodologies, this chapter presents the development process of the first prototype of VisualCOBie application which is a dynamic information visualization and navigation platform, specifically built for COBie standard. As specified in Chapter 3, since the spreadsheet representation of COBie standard has limitations for the end user in terms of usability and functionality, alternative representation, publication and functional methods have been evaluated based on the applied design thinking principles. Therefore, one of the objectives of this research is to make BIM-FM data, especially COBie data more accessible and usable by the end-users, including inexperienced and non-FM people, who would likely have difficulties in understanding and using the large COBie spreadsheet effectively.

The discussions with the Finnish FM and real estate companies further reinforced the above-mentioned need to account for both expert BIM-FM users as well as regular FM personnel and operators as potential users of COBie data. In addition, the discussions suggest that since we expect COBie handover to occur in different phases of design and construction as well, subcontractors with limited or no BIM-FM background should also be able to understand COBie requirements and deliverables. Correspondingly, the other objective of this research is to develop a flexible and scalable data integration, management and interoperability platform for lifecycle data management. The on-going problems of AEC-FM industry in understanding, managing and integrating digital data, forces the industry to shift themselves to external solutions/ecosystems which breaks the interoperability chain. This is also observed in the Finnish AEC-FM companies. For example, one of the real estate and facility management company has twelve different systems in use to manage their organizational, operational and other lifecycle data. Therefore, a question can be raised such as: “Can such a generic platform, which aggregates various data sources and presents them with an easy-to-use interface, become a necessity?”

To reach the objectives of VisualCOBie prototype, it is essential to understand the characteristics of the existing representation of COBie data, end-user needs, requirements, current challenges and expectations of the end-users, such that these can be addressed through ideation and enhanced features. This research and the proposed development employ the steps of design thinking with the iterative process of agile methodology which is commonly used in software development. Since both design thinking and agile methodology rely on co-evolution of problem and solution through an iterative process (Dorst & Cross 2001; Poon &
Maher 1997), these two approaches reinforce each other in the context of this research. While design thinking principles support both conceptual and detailed design phase, the agile methodology is particularly relevant to the implementation and detailed design phase of the project. The steps of design thinking principles, which are introduced in Chapter 2 are applied to understand the issues with COBie representation, define the problem, ideate the solution with respect to the findings of the literature review, the qualitative discussion with the Finnish industry partners, and the BIM for FM workshop that gathered 40 participants, including international speakers.

4.1 Design Thinking for COBie Spreadsheet

4.1.1 Understand

The first step of this iterative process is to understand the problem context and assess the key challenges in effective usage of the COBie spreadsheet in its current form. While it was desirable to obtain direct feedback from COBie users in practice, there is very limited use of COBie in Finland. The leading AEC-FM companies interviewed during a Finnish BIM-FM research between 2012-2014 (7 companies and 13 interviews, including 2 large real estate owners, 2 software vendors, contractors and property developers) (Holmström et al. 2015) reported that COBie is perceived by their personnel as complex and cumbersome, and they have not gone beyond internal reviews of COBie within their BIM/FM/IT teams. Most personnel consider COBie to have same challenges as the existing spreadsheet based practices at their work, and they would not make the switch to COBie until mandated by the authorities. As mentioned in Section 1.2, development and the update of a new/existing information exchange standard, such as COBie, is not in the scope of this research. Nonetheless, the COBie standard already has considerable regulatory acceptance in many countries by now. Therefore, COBie can be assumed to be mature and stable enough to be utilized in this thesis. Based on the feedback obtained from the meetings the underlying usability and navigational challenges with large spreadsheets seem to be one of the key challenges that are carried onto COBie spreadsheet by default, and this needs to be addressed. Consequently, it is important to understand how users interact with large spreadsheets, navigate through the data, and establish the semantic connections; and what are the factors that increase the cognitive load and the perceived complexity of such spreadsheet based representations.

The “understand” section of the design thinking methodology provides the core topics for the theoretical contribution as well as the fundamental basis for the technical contribution of this research. Visualization of any data improves human perception by increasing the cognitive capability and reducing the complex cognitive work. The easy recognition of sensory symbols due to the shape, colours, photographic image and its meaning in the human brain, facilitates recognition of patterns without a pre-attention (Duncan & Humphreys 1989). On the other hand, COBie spreadsheet representation lacks the visualization and above-mentioned Gestalt principles that could help a person to utilize COBie data. In contrast, all the geometric and non-geometric data of a facility is represented in numerical and textual form in the COBie spreadsheet without any visualization. Therefore, the other principles of Gestalt cannot be associated with the COBie spreadsheet directly because this form of COBie data representation increases the cognitive load of the users. Processing and deriving the semantics from COBie dataset is slower than any appropriate visualized form, because
the textual and numerical data is processed in a consecutive series of activities while the visual representation is processed in parallel with the perception (Ware 2012). Although the COBie spreadsheet representation is the main argument point in this research, this problem of representation is not only the case for COBie spreadsheet, but also for many other spreadsheet files or digital/printed documents in which vast amount of information needs to be utilized. The rich content of visual triggers such as colour, size, shape, position etc. with the support of Gestalt principles can potentially reduce the need for serial processing of the data. Instead, the large network of neurons in the eyes can rapidly capture the features of visual representations and implicitly pick the visual patterns with the image-based meaning of symbols (Ware 2012).

To understand the potential challenges that people have with large spreadsheets like COBie, the literature review presented in Section 3.5 about the human-spreadsheet interaction has been further expanded with an additional review of the relevant literature (Woods 1995; Helander et al. 1997). It was found that navigation through large spreadsheets affects the decisions and actions that contribute to a user’s ability to find and understand the relevant information. When the virtual representation of any type of data is distributed and much higher than the actual computer screen, users cannot process the data parallel in-mind with what they see on the screen. Instead, they split up the large structure and navigate the predecessor/successor sections via zoom and/or move-to actions. In literature, this issue is referred as the keyhole effect (Helander et al. 1997). The keyhole effect increases when the size of virtual information is larger than the actual visualization environment, e.g. computer screen (Woods 1995). Another issue in dealing with large spreadsheets like COBie is getting lost in which the user becomes lost in the virtual environment and fails to achieve the original task while he/she navigates and searches within the data. According to Halender (Helander et al. 1997) the users “… do not know their present location in the system relative to the display structure and find it difficult to decide where to look next within the system”. Another problem is referred to as trashing (Henderson Jr & Card 1986). As in the COBie spreadsheet, when the user tries to find dependent information –sets- from different workbooks, he/she must serially shift among different workbooks. This results in delays and cognitive memory load. The increase in the memory load can also trigger mental workload by focusing on the interface instead of the original tasks. While the user is experiencing the spreadsheet structure, he/she may need to memorize certain amount of the semantic links and path different sections to achieve their task. In many cases, AEC-FM professionals are expected to deliver tasks in a limited time and under limited sources; and using the COBie spreadsheet within these conditions can be challenging. In this case, users generally tend to adapt their existing work style to the limitations of the environment/system (Woods 1995), which decreases the quality of work and performance of the user. While one can argue that the user can simply use the search functionality of spreadsheet applications to find a specific COBie data, in case of the need for checking the dependent information of the specific entity, the user will have to perform this action repetitively because there is no explicit mapping or flow between these entities.

4.1.2 Define

The Understand phase of design thinking provides the core theoretical aspects of this research and gives the overall picture about the common challenges that a user is likely to face when they are interacting with large spreadsheets like COBie. To outline the problem defini-
Development of VisualCOBie Prototype

tions and the potential enhancements, it is essential to state the target user’s role and expertise assumed in this research. The developed prototype is intended for all potential users of FM data, including inexperienced and/or non-FM people who have limited or no experience with the COBie spreadsheet. The most critical users are the key personnel involved in data handover and data drops, including the different members of an FM team ranging from the manager to the service men who have to verify and deal with the data, the BIM and data coordinators from design teams and contracting teams, etc. As the researcher found through the interviews and workshops (Holmström et al. 2015), effective facility management require mapping data from various information sources, irrespective of a standard data structure or information exchange at the core. Consequently, different stakeholders will be required at different stages of the facility lifecycle to understand and interact with the FM data, including COBie data for the later phases of the project lifecycle. All the users may need to interact with and use the COBie data in different ways. Therefore, the researcher also focused on the inexperienced users so that the proposed development remains as inclusive as possible. At the same time, based on the discussions with the industry partners and collaborators (Aalto BIM Collaboration 2013), the research established that even seasoned FM professionals have expressed difficulties in understanding and using the COBie spreadsheet. Therefore, the researcher aimed to develop a solution that will also increase the efficiency of experienced users while they interact with the COBie data. Based on the outcomes of the literature review presented in Chapter 3 and the interviews with the Finnish industry partners, the following problem statements (requirements) were formulated the Understand process:

- Losing focus while navigating between workbooks. Need to work in a platform in which navigation is easier and interactive
- Having difficulty to process COBie data within different workbooks. Need to see all the COBie data and dependencies in an easy and abstract level
- Having difficulty to see the dependent information within workbooks. Need to see the dependencies of a specific COBie data.
- Lack of ability to search for a specific data based on its dependencies. Need to to find the specific COBie data based on its dependencies
- Having difficulty to understand the semantic links among different COBie entities. Need to see search results in a simplified format.
- Difficulty in accessing a specific data entity and its dependencies. Need for the functionality which does not force the user to navigate repetitively
- Lack of ability to select COBie data entity within the 2D/3D BIM models, and see selected entity’s dependencies. Need for a platform in which BIM model and COBie dataset are mapped with each other
- Having duplications when entering COBie data manually. Need for a platform which warns the user for duplications and prevents multiple data entries automatically.
- Having difficulty to track the new COBie data in each delivery phase of project. Need to track previous and new information sets, and perform Create, Read, Update, Delete (CRUD) actions for any COBie data entity effectively.

The above problem statements describe the key requirements for consideration during the ideation of new structures and functions for the targeted solution. Once these statements were formulated, qualitative feedback was obtained from members of an FM team (4 people) from one of the case companies to validate if we had captured the key issues with COBie and
Development of VisualCOBie Prototype

4.1.3  Ideate

In the ideation phase of VisualCOBie development, the aim was to generate the broadest range of possible solutions instead of coming up with the “right” solution. This was achieved by eliminating the linear decision-making process for a solution. Based on the discussions in the Understand and the Define sections, it is important to understand and apply the Gestalt principles for the development of VisualCOBie approach, as they are based of the visual design and perception. In addition, these principles should be utilized for the other core theoretical concepts of this research. Therefore, the researcher tried to look beyond the obvious solutions, and evaluated them with an unbiased perspective. The problem statements presented in Section 4.1.2 are summarized and mapped as the following (Table 1)

<table>
<thead>
<tr>
<th>Problem Statement / Challenge</th>
<th>Summary Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Losing the focus while navigating between workbooks. Need for a work in a platform in which navigation is easier and interactive</td>
<td>High cognitive load of textual and numerical data</td>
</tr>
<tr>
<td>Having difficulty to process COBie data within different workbooks. Need to see all the COBie data and dependencies at an easy and abstract level</td>
<td>Lack of visibility of semantics and data dependencies</td>
</tr>
<tr>
<td>Having difficulty to see the dependent information within workbooks. Need to see the dependencies of a specific COBie data</td>
<td>Lack of visibility of semantics and data dependencies</td>
</tr>
<tr>
<td>Lack of navigation and query capabilities</td>
<td></td>
</tr>
<tr>
<td>Lack of search for a specific data based on its dependencies. Need to find the specific COBie data based on its dependencies</td>
<td>Lack of navigation and query capabilities</td>
</tr>
<tr>
<td>Having difficulty to understand the semantic links among different COBie entities. Need to see search results in a simplified format</td>
<td>High cognitive load of textual and numerical data</td>
</tr>
<tr>
<td>Lack of visibility of semantics and data dependencies</td>
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<tr>
<td>Lack of navigation and query capabilities</td>
<td></td>
</tr>
<tr>
<td>Difficulty for accessing a specific data entity and its dependencies. Need for the functionality which does not force the user to navigate repetitively</td>
<td>Lack of visibility of semantics and data dependencies</td>
</tr>
<tr>
<td>Lack of navigation and query capabilities</td>
<td></td>
</tr>
<tr>
<td>Lack of selecting the COBie data entity with the 2D/3D BIM model and see selected entity’s dependencies. Need for a platform in which BIM model and COBie dataset are mapped with each other</td>
<td>Lack of 2D/3D BIM model integration</td>
</tr>
<tr>
<td>Lack of navigation and query capabilities</td>
<td></td>
</tr>
<tr>
<td>Having duplications when entering COBie data manually. Need for a platform which warns the user for duplications and prevents multiple data entries automatically</td>
<td>Lack of data generation, integration and control mechanism</td>
</tr>
<tr>
<td>Having difficulty to track the new COBie data in each delivery phase of project. Need to track previous and new information sets, and perform Create, Read, Update, Delete (CRUD) actions for any COBie data entity effectively</td>
<td>Lack of data generation, integration and control mechanism</td>
</tr>
</tbody>
</table>

The ideation phase revolved around the possible solutions for the above issues. Some of these issues have already been taken into account in the existing COBie spreadsheet structure. For example, colour coding is used to differentiate between the mandatory, optional and/or the system-generated information. This also helps the users to recognize and categorize data segments cognitively with visual aid of colors as associated with the “common region” principle of Gestalt.
In the early conceptual design stage, the researcher also explored solutions such as dashboards. However, while dashboard like solutions were user friendly, the amount of data presented to the user at one time was too narrow and the dependencies were not presented adequately (Figure 19). In VisualCOBie development, the researcher aimed to address these inadequacies as well. The following subsections present the key ideas applied in the proposed solutions, corresponding to the key challenges.

**Figure 19.** A prototype for the dashboard idea to represent the COBie data

### High Cognitive Load of Textual and Numerical Data

As noted earlier, the serial processing of data by human brain causes a high cognitive load while using the COBie spreadsheet. This problem can be resolved if the data is presented in some other forms, besides the pure textual and numerical data. One of the possible solutions is using charts to reduce the cognitive load and present data in an abstract form. However, this may not be an appropriate way since the data is heterogeneous and the amount of data is big. Therefore, it is difficult to represent all COBie data in a single chart and perform CRUD actions, because they can be the key parameters to establish the semantic links between different information sets. The workbooks and columns of the COBie spreadsheet provide a searched and tested structure for the proposed VisualCOBie development. COBie data is clustered within columns and workbooks in which semantically related data is located in the same workbook and/or column. Building on this existing structure of COBie, VisualCOBie proposes assigning a pre-attentive figure –a sensory symbol- (icon) to each column and workbook individually. Sensory symbols are chosen because human brain already has predefined meanings for sensory symbols. These meanings are multicultural, and can be understood without any learning/process (Hofstadter 2001; Roberts 2002). For example, a floppy disk image on a UI triggers the “save” action in human brain. Since the meaning of the sym-
bol is familiar and commonplace, the serial processing is eliminated in the human brain. When users look at the symbol, they can easily assign a meaning to symbol. This feature is associated with the Gestalt’s “past experience” principle which refers to the experiences we have with a cognitive trigger, such that the assigned figures should recall the meaning regarding what the data group is about. For example, an envelope figure can recall the email word in the end user’s mind.

Lack of Visibility of Semantics and Data Dependencies

The dependencies of the COBie data are one of the most important issues that need to be addressed. The COBie spreadsheet representation has a structure (East 2007), and users can check this structure to understand the dependencies of COBie data. In addition, with increasing experience with COBie spreadsheet, users can gradually learn and establish the semantic structure of the data entities. However, this can take much time depending on the user and the size of the data in spreadsheet, and it appears to be a bottleneck in getting new users (at least in Finland) started with COBie. As an alternative, the dependencies between the data entities can be mapped with hyperlinks within the COBie spreadsheet. However, this solution does not reduce the amount of navigation to find a specific set of entities and their dependencies. The hyperlinks only show and forward the user to exact entity that is linked. There are existing dependency tracking modules developed for spreadsheets (Kohlhase 2013). While this remains one alternative solution, since this approach continues to work within the spreadsheet platform, the high cognitive load resulting from the spreadsheet interface continues to be a limitation. Therefore, VisualCOBie proposes a node-link (force-layout) graph representation to show the dependencies of the COBie data. In a node-link diagram, there are two fundamental elements: “vertices” to represent the data entity as a node, and “edges” to represent the relationship/dependency a line or curve (Figure 20).

![Figure 20. Representation of node-link diagram (graph)](image)

The reasons for choosing a node-link representation are twofold. First, it eliminates the tabular structure of existing COBie representation and allows the user to see the exact COBie data entity with its dependencies in the same platform. In addition, the combination of many nodes and links of different data sets generates the broader semantic network of the entire COBie structure, which create a COBie graph. Second, together with the sensory symbols (images) used for nodes, node-link diagrams reduce the cognitive load on the user. In addition to the Gestalt’s “past experience” principle associated with images, the node-link representation of COBie data can also be associated with “connectedness” since visual icons are connected and associated with each other with a line; “proximity” since the COBie data entities which are listed in one of the workbook are grouped under the same visual cluster; “common fate” since when one of the nodes are moved somewhere else in the UI by the end user, the other nodes (data entities) under the same cluster also move together; and “symmetry” since the different data entities/groups can be distributed symmetrically in the UI.
Current spreadsheet form of COBie representation is not efficient because users cannot perceive the semantics efficiently.

In addition to the corresponding Gestalt principles, the proposed node-link representation of VisualCOBie approach also refers to another theoretical concept regarding the visual perception and human cognition. In our everyday life, each bit of information entering our brain, every sensation, memory or thought, which incorporates every word, number, code, line, etc. can be represented as a central shape from which radiate with millions of hooks. Each hook represents an association, and each association has its own array of links and connections. This information processing ability and learning capacity derives the concept of Concept Mapping of which the mind map is a manifestation. Human brain’s concept mapping pattern can be seen as a branching association machine with lines of thought radiating from a virtually infinite number of data nodes. Concept mapping as is traditionally understood today was first referred in the 70s (Stewart et al. 1979) and subsequently developed by Novak and Gowing (Novak & Gowing 1984).

In general terms, mind mapping is a technique that can demonstrate how people visualize relationships between various concepts (Novak & Gowing 1984). Relating to cognitive maps in psychology and above-mentioned principles of Gestalt, mind maps provide a visual representation of dynamic schemes of understanding, and associate the information entities with each other within the human mind. Although mind maps can include labelled concepts, linking words, and clear hierarchies, they might also include other sorts of visual and graphic representation of concepts and propositions that attempt to convey an understanding or relationship among different concepts within a map which is also one of the proposed enhancement with VisualCOBie approach. These might include word links, directional arrows, or just simple connectors like lines or overlapping circles (Mls 2004). In addition, Tony Buzan, who is the inventor of mind maps, also incorporated the Gestalt principles into mind map (Buzan & Buzan 1996). According to him, mind maps enable to use the natural innate tendency of the human brain to complete wholes and effect the closure “open” or unfinished parts of wholes.

Mind mapping joins various elements in our brains and meets the needs of the brain as a whole, using words, numbers, order, sequences, colors, images, etc. which reflects the natural thinking process. They can allow to extract knowledge that we are not even of possessing, because they can reach the areas of memory that cannot be easily explored using other methods (Buzan & Buzan 1996). In comparison with the mind map concept, the spreadsheet representation of COBie data does not include the associative elements visually. Although the COBie data itself includes the related information about the facility, discovering those relationships requires knowledge and experience.

On the other hand, moving the COBie data in a mind map causes lots of nodes and associated branches with other nodes which results in a huge network with high visual complexity to discover and understand the data with all visual elements and their spatial distributions in the mind map (Ghoniem et al. 2005; Huang et al. 2009). Therefore, corresponding computational requirements may be needed for such abstract visualization, query, etc. functionalities. Those requirements is more detailed in the next problem statement and Section 4.2.

Lack of Navigation and Query Capabilities

Navigation and querying the large data sets is another essential action needed to find a specific data entity. In spreadsheet representation of COBie, users can move to different columns and workbooks, and use the spreadsheet’s built-in search functionality (ctrl/cmd+F, conditional formatting). These methods have limitations as explained previously, such as getting
lost, invisible dependencies, etc. In this research, possible solutions have been evaluated such as searching with multiple keywords, highlighting the query results, etc. However, depending on the other problem statements and previously suggested improvements, the spreadsheet platform is considered as the main limitation to address. To overcome this limitation, VisualCOBie proposes the following two approaches:

- Navigate and search by-group of the data, and
- Navigate and search by-dependency of the data

These two approaches are established based on the node-link representation of COBie data structure in which the semantic links between the individual entities and data clusters are available. Therefore, while the user searches a specific entity, as it could be done in spreadsheets before, he/she is also able to navigate through and search a specific data by the dependencies.

The improvement to navigate/search by group and dependency can be performed in spreadsheets as well. However, there should be some predefined conditional statements or programmatic macros to perform these functions, which requires coding knowledge on part of the end user. Besides, depending on the complexity of the query, writing a query can be even more difficult than to understand the spreadsheet structure itself. The two approaches mentioned above also refer to the Gestalt’s “similarity” principle because all the data entities which belong to the same data group can be searched and navigated by-group of the data and considered as similar because the same visual figure is assigned to the data entities. In addition, the “connectedness” principle can also be referred. As it is presented in Section 4.3.3, different data groups can be searched and navigated by-dependency and chained up with each other continuously with a connecting line between each other.

In addition to the proposed functionality for this problem statement, the representation of the queried data is also important. Since the users are able search by dependencies, they should see the query results based on the dependencies. In other words, the query results should semantically and continuously chain up with each other. VisualCOBie proposes dynamically-updated and semantically-chained natural language-based results of the queries with the queried entity dependencies. Same as the above-mentioned functionalities, this functionality also refers to the Gestalt’s “continuity” principle. This functionality is also important to prevent the user from “getting lost” (Section 4.1.1) while they are navigating/searching a specific entity. With this functionality, users are able to check what they have queried up to the moment, and/or which path they have followed until they find the exact data entity. Detailed explanation is presented in the Section 4.3.3.

Lack of 2D/3D BIM Integration to the Visualization

As mentioned in the previous sections, COBie data can be generated from various BIM, CM and FM software applications. The performance of various software applications to generate COBie data has been reviewed (BuildingSMART 2009b). These software applications have many functionalities to facilitate the users’ work; and one of them is providing 3D virtual representation of the facility. Users can rotate, walk-through, and apply other navigation actions. In addition, these models act as the UI of the digital data repository of a facility. From BIM models, COBie data is generated by extracting specified subset of the IFC element according to the specification on FM Handover MVD. After the extraction, the COBie data is parsed to a spreadsheet file and becomes ready for use and handover. However, the default configurations of spreadsheet applications do not provide one-to-one interactive mapping between the information entities of COBie spreadsheet and the corresponding virtual objects.
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in the 3D BIM model. Although the explicit links between the COBie and IFC data is acquired and presented in COBie spreadsheet in the form of \textit{ExtIdentifier}, which contains the GUIDs, the relevant computational conditions has to be built for the one-to-one mapping.

VisualCOBie proposes direct interaction and mapping with the BIM environment. The high cognitive load associated with the spreadsheet representation can be reduced by an enhancement like this. The inspiration for this functionality comes from the already existing commercial BIM software applications (Solibri Inc 2015; 4Projects 2013; Ecodomus 2016) in which a one-to-one entity-model mapping is provided to increase the usability of COBie in which the COBie data can be also browsed either from the dynamic spreadsheet modules, 3D view via picking the objects, or the corresponding entity in the tree-view structure. However, these applications keep the tabular structure of COBie data in their UIs. To address this limitation, VisualCOBie proposes to visualize also the dependencies of the selected building component/element form 2D/3D model in its UI with a node-link diagram and replace the spreadsheet representation of COBie. Therefore, while the users are able to see the information of the selected building element, they are also able to see its dependencies.

\textbf{Lack of Data Generation, Integration and Control Mechanism}

COBie data can be generated automatically with BIM, CM, FM software applications and/or their built-in/external plugins. This method provides efficiency by enabling faster production and preventing duplications. However, not every software application has the functionality to export all the data required in each workbook of COBie spreadsheet. Besides, COBie is by design not intended to handle every specific information requirements defined in FM Handover MVD. Therefore, users may need to enter the additional or missing data manually, and this can cause duplications. Since data entities in COBie have one or more dependencies, this mistake can cause duplication and/or omission of data for specific entities. For example, while the user checks the attributes of the duplicated entity, he/she can see blank cells even though the same entity has some attributes already somewhere in the spreadsheet. As specified in (East 2007), the handover of COBie file should occur in different phases of the project. Therefore, the data in a COBie spreadsheet increases in each delivery with new data entries and/or addition of new attributes of the existing data. Users may want to see the changes in each phase of delivery or the information sets. However, many of these applications push the COBie data set out of the software ecosystem by parsing the data to a spreadsheet. Therefore, during the next COBie extraction, if the previous COBie export is not kept in the software/module and left in the spreadsheet, or if there is no control mechanism built in the COBie spreadsheet, then same data can be generated many times. Multiple COBie spreadsheets make the tasks more challenging. However, if there is a control mechanism which tracks the data entities, possible duplications can be prevented. In addition, there may be a need to modify the existing data entities or create new COBie data entities depending on the FM task scenario.

Currently with the existing spreadsheet representation of COBie, there is no control mechanism to prevent duplications of the data and their dependencies, and perform any CRUD tasks for new/existing COBie data. VisualCOBie proposes the functionality to track the data and prevent possible duplications by providing a new dependency to the existing data entity, and allows the end-users to perform CRUD tasks. Therefore, these proposed functionalities can improve the usability and control of COBie data and enhance the user experience since the end-users do not deal with duplicated data and their dependencies. On the other hand, this feature can allow the end user to manage the already generated COBie data, and inte-
egrate them with other data sources if needed. From the cognitive point of view, this functionality has the potential to enhance the applicability and scalability of VisualCOBie approach, such that the end user can define new data groups and entities, define specific properties, assign visual figures, as well as associate these data entities with a semantic link between each other, just like the similar approach of mind mapping.

4.2 Computational Approach for VisualCOBie Implementation

This section presents the results from the prototyping phase of VisualCOBie platform which is also the technical contribution of this research. The general layout and framework of VisualCOBie is based on the specified problem statements and proposed solutions/functions. The overall layout of VisualCOBie is designed to make the COBie information visually presentable to decrease the cognitive load on the user based on the presented theoretical concepts, using graph-based links to see the dependencies, and enabling interactivity to make the platform easy to use. Following subsections describe the prototyping and implementation of VisualCOBie.

4.2.1 Overall Architecture of VisualCOBie Implementation

The implementation architecture of VisualCOBie is based on three layers (Figure 21):

**User Interface** layer provides the functional and interactive environment in which the users can see the 3D model and interactive 2D floor plans, facility information structure, node-link representation of COBie data and results of potential queries in a visual way. This layer includes three information view sections. “Spatial Information View” presents the 2D/3D model of the facility. In this view, users can navigate inside the model, select the building components/elements and see the detailed information of them. The other section is named as “Hierarchical Information View” in which the information is grouped and presented within an object tree structure. The user can search the specific information entity by looking the categorized information of the facility. In addition, “Relational Information View” is where VisualCOBie is located, adjoining to two other views. In this section, users can select the data groups of COBie workbooks; reach the specific data in COBie and see the dependencies; see preattentive symbol of the information entities with their label; make queries both from a built-in search box and from the two other information views; see the results of their queries as a visual feedback; and the other proposed functionalities of VisualCOBie.

**Data Integration and Process** layer is the working engine of VisualCOBie and the other integrated platforms, which are described in the next section. In this layer, a BIM platform is integrated with VisualCOBie to import an IFC file, extract the COBie subset of it, and parse to a spreadsheet. The transformation of COBie spreadsheet to semantic graph-based data is performed with a converter script written by the researcher. This script reads the COBie data from the COBie spreadsheet and pushes it to the database. This provides access to the data, run the proposed functionalities of VisualCOBie, extract the data from database, and visualize it based on the user’s navigation and query.

**Database** layer includes both the database of BIM based platform and the graph-database of VisualCOBie platform. There is no direct integration between these two databases in this layer. They are individually configured for the proposed visualization and functionalities of VisualCOBie. However, the integration and interaction between these two databases happens in the upper layer.
4.2.2 Development Environment of VisualCOBie

During the implementation of VisualCOBie, open source BIMserver (Beetz et al. 2010) has played an important role, providing a platform which allows importing an IFC file, render it to visualize the 3D facility model; generate the component/entity structure of the facility; export the source IFC file to different formats; and more importantly, generate the COBie spreadsheet via its open source COBie plugin (Bogen 2015). Therefore, open source BIMserver is used as the base platform to implement VisualCOBie and establish the proposed functionalities. The hierarchical and spatial information view of the UI has been generated by bimvie.ws in the initial phase of the development process.

The relational information view is generated with an open source information visualization library called popoto.js (Ciminera 2014). The node-link visualization of COBie dataset is built on top of Neo4j, an open source graph database (Webber 2012), in which the COBie data is transformed and pushed into this database with the script written by the researchers. This script defines semantic relationships of the data entities in COBie data structure. The initial development has been programmed without any web development framework, the researcher typed plain hypertext markup language (HTML), cascading style sheet (CSS) and jQuery library for the initial prototype. However, in the later phases of the agile development process, a more structured web development framework is used. The relationships for VisualCOBie is derived from the structure and the organization of the existing spreadsheet schema and representation of COBie. For example, in COBie spreadsheet, while the required sections are yellow color-coded, the data sections which are referenced from other workbooks, are salmon/pink color-coded; and the data in the green color-coded section simply define the semantic relationships between different workbooks. A sample relational data structure is also presented in COBie responsibility matrix (East 2013). In this matrix, the primary key data (PK) and the foreign key data (FK) are used to define the semantics among the COBie data entities. Transformation of COBie data into the graph database and the generation of the semantic relationships are performed with a declarative graph query language called Cypher.
A floor can include many spaces” and “A space is located in a floor”
“A person creates a space and floor data”

With the Cypher syntax, person, floor, and space data with the defined semantic relationships can be expressed as the following (Figure 22):

```
CREATE CONSTRAINT ON (floor:FLOOR) ASSERT floor.name IS UNIQUE     (1)
CREATE CONSTRAINT ON (space:SPACE) ASSERT space.name IS UNIQUE      (2)
CREATE CONSTRAINT ON (person:EMAIL) ASSERT person.email IS UNIQUE   (3)
MERGE (person:EMAIL {email:{email}})                             (4)
MERGE (floor:FLOOR {name:{name}})                                (5)
MERGE (space:SPACE {name:{name}})                                (6)
MERGE (floor)-[:INCLUDES]->(space)                              (7)
MERGE (space)-[:LOCATED_IN]->(floor)                             (8)
MERGE (floor)-[:CREATED_BY]->(person)                          (9)
MERGE (space)-[:CREATED_BY]->(person)                           (10)
```

Figure 22. Cypher syntax for the specified query

In the above query snippet, the first three lines define the uniqueness of the attributes (name and email) of the person, floor and space data since they are also defined as the PK in COBie spreadsheet schema and defines an index for further queries. The fourth, fifth and sixth lines define the person, floor and space data as a node with their attributes in the VisualCOBie graph. Although in the Figure 22 only the “name” and “email” attributes are presented, there are many attributes were defined based on the data in COBie spreadsheet workbooks. Finally, the codes in the seventh to tenth lines define the semantic relationships between person, space and floor data. Similar to the above expression, the semantic relationships for all COBie dataset are defined in data integration and process layer.

The possible interactions and functionalities in the hierarchical and spatial information view have already been provided by BIMserver and bimvie.ws platforms. These platforms are used with their default functional configurations and no modification in the source code has been made. However, the layouts of these information views have been modified to integrate the relational information view. Therefore, we can say that VisualCOBie is developed on top of the open BIMserver and Neo4j. The UI layer allows direct interaction with the data and provides visual feedback to the user. However, the integration between the hierarchical and spatial information views with relational information view—in other words, the interaction between BIMserver and VisualCOBie platforms— are defined and established in the “Data Integration and Process” layer. To establish the integration and the proposed functionalities, application programming interfaces (API) are used. An API is a set of functions, protocols or tools for building software applications. The APIs specify how the software components and user interface should interact. In this research, BIM service interface exchange (BIMsie) API (Leon van Berlo 2013) has been used to access the BIM/IFC data and establish a mapping between BIMserver and data entities in VisualCOBie. To provide this integration and the proposed functionalities of VisualCOBie, the API of Neo4j graph database has been implemented in the platform. Therefore, connection between two APIs has been established to make VisualCOBie platform a BIM integrated and a graph-based implementation.
4.2.3 Initial Functionality Test with a Common BIM Model

The researcher uploaded an IFC model to test the proposed functionalities of VisualCOBie. The Clinic Model project, which is one of the common BIM files provided by NIBS (East 2009), is used for the tests. The project has been described as follows;

“The Clinic Model project is based on a medical and dental clinic building at a location in the South-West US... A representative set of redacted operations and maintenance manuals are also provided in COBie Spreadsheet Format...” (East 2009).

The COBie spreadsheet provided with the IFC model has been used as the start point of the test. Although a new COBie file can be generated via BIMServer COBie plugin (Bogen 2015), the existing COBie spreadsheet was used since it includes the construction process data such as documents, work orders, manuals, etc. As specified in the COBie specification, such documents can be defined and linked in the BIM application with relevant IFC entity and can be exported to the COBie spreadsheet. However, due to the lack of experience/knowledge of many professionals, most of the time these files are kept in separate folder/repository. In the test, it is aimed to experience how VisualCOBie can help users to explore and understand the COBie data with the support of integrated BIM platform and the proposed functionalities. Before presenting the main functionalities, it is necessary to explain the basic terms used in the following paragraphs:

**Node**: a common term used to represent data. It is represented with a visual figure in UI. This term gets the following adjectives based on the functions:

- **Root-Node**: represents the data groups. For example the “Space” workbook of COBie is the Root-Node in the VisualCOBie. A Root-Node is meta-level and defines the unique properties, but these properties are not defined in the Root-Node

- **Value-Node**: represents the unique data entity under the Root-Node. For example, “Space_A101” is the Value-Node of the “Space” Root-Node. A Value-Node has the properties which is defined for the associated Root-Node, and it each of these properties have associated values.

**Link (relationship)**: represents the semantic relationship between Nodes. It is represented with dashed-lines in the UI.

- **Root-Link**: represents the semantic relationship between two different Root-Node. This type of relationship can have properties and values

- **Value-Link**: represents the semantic relationship between a Root-Node and its associated (child) Value-Node. This type of relationship cannot have any properties and values. However, by-default it represents the relationships “Root-Node HAS Value-Node” or “Value-Node ASSOCIATED_TO Root-Node”

- **+Button** (plus-button): is a red color + icon which is located on top-right corner of each Node. It holds the onClick function in the system to expand the Links between the Nodes

- **-Button** (minus-button): is a red color – icon which is located on top-right corner of each Node. It holds the onClick function in the system to collapse the Links between Nodes. When clicked, it turns back +Button again.

- **Navigation Arrows**: are the navigation buttons which are used to see individuals Value-Nodes under the associated Root-Node. They are located on top-left and top-right corners of each Root-Node

- **Root-Node List**: is the list of all Root-Nodes in the system. For example, the COBie spreadsheet workbook are listed in the Root-Node List.
The researcher used the specified problem statements to check the functionalities in the following sub-section:

**Statement 1:** Losing the focus while navigating among workbooks. Need for a work in a platform in which navigation is easier and interactive

This requirement has been met by providing the workbook names of COBie spreadsheet in the left part of the “relational information view” section of UI with the Root-Node List. Users can simply click on the workbook names to select. The selected workbook is represented as a root node with the workbook name and the pre-attentive figure. For example, as shown in Figure 23. When the user clicks the SPACE from the Root-Node List, the corresponding SPACE Root-Node is presented. Similarly, when the user clicks the SYSTEM from the Root-Node List, the corresponding SYSTEM Root-Node is presented. As mentioned in Section 4.1.3, the assigned figures on the Root-Node refer to Gestalt’s “past experience” principle and trigger the meaning associated with the Root-Node.

![Figure 23. Selection of COBie worksheets](image)

**Statement 2:** Having difficulty to process COBie data within different workbooks. Need to see all the COBie data and dependencies at an easy and abstract level

**Statement 3:** Having difficulty to see the dependent information within workbooks. Need to see the dependencies of a specific COBie data.

These requirements have been met by allowing the user look-up the data from the Root-Nodes, which can be selected from the Root-Node List. After the selection, the user has two options:

1. Start to search the specific entity node by navigating inside the Root-Node. When the user clicks on the Root-Node, related Value-Nodes pop-up in the UI (Figure 24).
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2. Or, click the +Button to see the relationships of the Root-Node. As specified above, the relationships are represented with a dashed-line between the Root-Nodes. The value of the relationships is explicitly listed as a text on top of each relationship dashed-line (Figure 25). The following figure also represents the considered Gestalt principles which were mentioned in Section 4.1.3. Such as, the “connectedness” principle can be seen between the different Root-Nodes with a line and the corresponding relationship with each other; “proximity” principle can be associated with the individual SPACE Value-Nodes which are grouped around the SPACE Root-Node. In addition, when the end user selects the SPACE Root-Node and moves around, the associated SPACE Value-Nodes also move the same direction with the Root-Node. This interaction refers to the Gestalt’s “common fate” principle. Besides, the radial and symmetrical distribution of associated Root and Value Nodes can be associated with the Gestalt’s “symmetry” principle.
Statement 4: Lack of search for a specific data based on its dependencies. Need to to find the specific COBie data based on its dependencies

Statement 5: Having difficulty to understand the semantic links among different COBie entities. Need to see search results in a simplified format.

These requirements have been met via “Search/Navigate by-dependency” function of VisualCOBie. The user can query the database based on the dependent workbooks and the data inside. For example, we test the following scenario:

“The user wants to see all Spaces that are located in the First Floor and Circulation Zone; and include all Components which belong to asset type Door Type-F”

To perform such a query in the COBie spreadsheet the user needs to shift across couple of workbooks and columns, one after the other. In contrast, with VisualCOBie the user can easily query the COBie data by selecting the dependent nodes and the associated data entities. To do so and to see the query results dynamically, the user can apply the following steps:

1. Select the Space Root-Node from the Root-Node List and see the Space Root-Node in which 496 Space data entities are available at the beginning of the query (Figure 26).

2. Click the +Button to see the other Root-Nodes related with the Space Root-Node, e.g. the Floor and Zone. Click on the Floor Root-Node and select the “First Floor” Value-Node. After this selection both the number of data entities in Space Root-Node and the other dependent workbook nodes is queried (Figure 27).
3. Click the **Zone** Root-Node and see the **Zone** Value-Nodes. Find the “Circulation” zone Value-Node and select it. After this selection, the query system reduces the number of **Space** and all other dependent Root-Nodes (Figure 28).

4. The query based on the first two dependencies are now completed. Next queries are based on the dependent data between the **Component** and asset **Type** Root-Nodes. Therefore, the end-user should click the +Button on component workbook node to see the **Component**-dependent data sets where the asset **Types** are linked with “BELONGS_TO_ASSET” dependency. The user can see the queried **Component** Value-Nodes that are related to the **Space** and asset **Types** (Figure 29).
5. As the last phase of the query, the user should click on the asset **Type** Root-Node and select the “Door Type-F” Value-Node. After the selection, the data is queried based on the dependencies. The user will see that there are 5 **Components** located in the corresponding **Spaces**. If the user wants to see the specific **Space** or **Component** Value-Nodes, he/she simply clicks the nodes and gets the detailed data (Figure 30). As it can be seen in Figure 30, consecutive queries are applied to reach the final result. Although the query steps cannot be shown dynamically in this thesis document, related Root-Nodes are visually chained up continuously after every step of the query. As mentioned in Section 4.3.1, this feature and the final visualization refers to the Gestalt’s “continuity” principle.

**Figure 29.** Query the Component Root-Node data over asset types

**Figure 30.** Selection of the Type data.
6. At the end of the query process, the results are shown below the graph representation in an easy-to-understand natural language form. All the dependencies are also listed in the natural language query to enrich the query process and also chained up with each other continuously. In addition to these, Cypher based translation of the natural language query is also automatically generated as the user performs the visual query. This Cypher query statement can be used to query the data directly in the database layer and can be shared with other users (Figure 31).

**Figure 31.** Natural language result, list of dependencies, Cypher query statement and query results

**Statement 6:** Difficulty in accessing a specific data entity and its dependencies. Need for the functionality which does not force the user to navigate repetitively.

This requirement has been met by developing a search engine for VisualCOBie in which user can type the name of the specific data entity in a search box and access the specific entity. The search box is integrated with the dynamic query system explained above. For example, the researcher tested the following scenario:

“The user wants to see the all dependent information of the **Component** entity named FireSprinkler-390”

To perform such a query in COBie spreadsheet, the user needs to go **Component** workbook, find specific component entity and check all other workbooks whether there is a related information for the **FireSprinkler-390**. And if yes, what is the dependency/relationship with the related workbook? In VisualCOBie, following steps give the result and its dependencies:

1. User enters the **Component** name into the search box and clicks the “Search” button. After that, the **Component** workbook node number is reduced to one which only the search **Components** entity is available to select (Figure 32)
2. User selects the searched **FireSprinkler-390** entity and click the +*Button* to see all its dependencies. If the user wants to see the property/value of any dependent workbook node, he/she can simply click on the node and see the information. In the following figure, user can see which **System** does the **FireSprinkler-390** belongs to (Figure 33)

3. If the user wants to see another dependent information of **FireSprinkler-390**, he/she can perform the same action of different workbook nodes. On the other hand, if user wants to see the dependent information to **Fire Protection System**, he/she
can select the **System** workbook node and click the *+ Button* again to see the dependencies (Figure 34).

![Diagram](image)

**Figure 34. Dependencies of system information**

**Statement 7**: Lack of selecting the COBie data entity with the 2D/3D BIM model and see selected entity’s dependencies. Need for a platform in which BIM model and COBie dataset are mapped with each other.

This requirement has been met by mapping the BIMserver platform with VisualCOBie via the integration of BIMsie and Neo4j graph database APIs in the data integration and process layer. The established communication allowed integration three information views in the UI layer as well. Overall process for this statement follows this procedure (Figure 35)

1. The user can visualize and navigate through the 3D BIM model and the hierarchical information structure
2. User selects a specific entity from either hierarchical or spatial information views
3. After the selection, user clicks the “Search” button
4. The “COBieGraph” tab of the workbook list shows selected element
5. User select the element and click the +Button to see the dependencies of selected element
6. User applies the previous actions explained for other statements, and
7. See the query results in natural language form with the list of other dependencies
Statement 8: Having duplications when entering COBie data manually. Need for a platform which warns the user for duplications and prevents multiple data entries automatically.

Statement 9: Having difficulty to track the new COBie data in each delivery phase of project. Need to track previous and new information sets, and perform Create, Read, Update, Delete (CRUD) actions for any COBie data entity effectively.

The solution proposal for the Statement 8 and 9 were not included to the scope of initial prototyping phase in this research. There are two main functionalities have been planned for these statements. The first solution is intended for manual data input layer to VisualCOBie. This layer checks the existing COBie data with the new input of the user, and warns the user for any potential duplication. This functionality uses the Primary Keys (PK) and Foreign Key (FK) as specified in COBie responsibility matrix (East 2013) for duplication check. In addition, the developed platform for CRUD actions performs this check as well. The CRUD actions are also connected to access rights for the end users who have different user profiles, that is who has what access rights to which part of the data. This is a complex matrix of types of data, and roles of actors such that BIM coordinators may have full CRUD rights for most of the data, while the regular end-users might have only Read rights to only some part of the data. The data control and access right mechanism were not included into the initial prototyping phase. Although, there have been feedbacks obtained during the public demonstrations from the Finnish companies, the main objective in this prototype was to establish the usability and query functionalities.

4.2.4 Initial Validation of VisualCOBie Prototype Development

The development of VisualCOBie prototype followed the design process of iterative development. Accordingly, at each stage of the development the implementation has been analysed and evaluated for refinement and further development. At the time of the initial prototype, VisualCOBie has been tested by the researchers using publically available data-set. The objectives of these validation studies were twofold:

First, to test the internal validity of the prototype implementation, that is:
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- whether the VisualCOBie implementation meets the technical tests in terms of error-free and bug-free data transfer from the spreadsheet format and other information sources; and
- whether all the mentioned usability and functionality features are reliably accurate and consistent in the implementation with identified theoretical aspects.

The mentioned theoretical aspects are satisfied in the initial prototype development. As mentioned in above paragraphs, the visualized node-link representation of COBie data refers to many principles of visual perception. In addition, the overall representation of different data groups and entities reflects the representation of mind maps with Root-Nodes, radial branches, descriptive label and figures. However, one can create a mind map digitally with the relevant software and can define the nodes, branches, labels, text, etc. dynamically on the UI of that application. This feature was not considered in the initial prototype development. Instead, the predefined COBie data structure and the corresponding conversion is used.

Second, to conduct preliminary test with industry partners and potential users if the implemented system and its features could address the challenges they had reported with COBie and other spreadsheet based systems in their FM practice. These tests and feedback were planned in form of demonstrations and focus group interviews with selected industry partners where the researcher was invited to present VisualCOBie to various stakeholders from the Finnish AEC-FM industry (Figure 36 and 37).

![Figure 36. Presentation of VisualCOBie Prototype to Finnish industry stakeholders](image)

Both the internal validation studies and qualitative studies with potential users were positive while revealing opportunities for further development and refinements. Qualitative feedback from potential users indicated high positive sentiments towards VisualCOBie approach and initial prototype, which was seen as a novel and innovative approach to address a long-standing issue of technical and non-friendly interfaces in AEC-FM solutions in general, and not only limited to COBie. The positive feedback from these demonstrations and focus group interviews was further reinforced with commitment and offers from some company representatives to conduct preliminary pilot studies using VisualCOBie in their existing projects.
The details of these projects and the detailed analysis for the validation of VisualCOBie approach will be presented in the next chapter. In addition, as the continuation of design thinking and agile methodology, the new and improved requests from the case companies is introduced with the continuous implementation.

Figure 37. Presentation of VisualCOBie Prototype

4.3 Summary of the Chapter

After the broad review of the literature presented in Chapter 3, this chapter contributed new knowledge with new studies in the literature and provided the theoretical background for the initial reasoning and prototyping. Compared to the HCI literature presented Chapter 3, this chapter specifically focuses on the human-spreadsheet interaction to reveal the initial problem statements/challenges in handling the COBie spreadsheet; as well as evaluate them based on the Gestalt principles and conceptual mapping concepts. The prototype development phases are also introduced with the implemented enhancements by considering the relevant principles of visual perception and mind maps. In addition to the presented literature review, the feedbacks obtained during industrial meetings conducted in Finland, supported these challenges. Based on these statements, the initial UI layout, computational configuration, user interactions and functionalities of the VisualCOBie prototype is presented and tested with a public COBie model and datasets. These methodologies are applied in the rest of this thesis iteratively. However, the preliminary feedback collected from the initial prototype can be seen as the first step of this iterative progress.
5. Validation Studies for VisualCOBie Approach and Prototype

The preliminary requirements for VisualCOBie prototype were identified during interviews with the industry participants in Finland (Holmström et al. 2015), and during the BIM for FM workshops with international participants from academia and industry (Aalto BIM Collaboration 2013), and from feedback of national/international research groups. Besides that, a detailed scan of discussion about COBie on the social media and online discussion forums helped the researcher to define the problem statements and initially developed functionalities of VisualCOBie. As the continuation of Chapter 4, this chapter presents the results of the conducted use-case studies and development hackathons with one of the case company to validate the initial problem statements; as well as identify the new usability features and functional requirements. After completing the first initial prototype presented in Chapter 4, the researcher conducted three industrial case studies to test and evaluate the existing functionalities of VisualCOBie. The obtained feedback and additional requirements at the end of these case studies guided the researcher for continuation of the agile development process. In addition, the feedbacks and additional requirements provided new directions for VisualCOBie to extend its applicability beyond a visualization and navigation tool for a specific information exchange standard (i.e. COBie); and to become a platform for a flexible and scalable data integration, management and interoperability platform for facility lifecycle data (detailed in Chapter 6).

Both design thinking and agile methodology rely on co-evolution of problem and solution through an iterative process (Dorst & Cross 2001; Poon & Maher 1997). These two approaches reinforced each other in the context of VisualCOBie research especially for the last steps, which puts strong emphasis on an incremental and iterative development process that is adaptive to user feedback throughout. Conducted pilot studies for the external validity revealed positive and negative feedbacks, existing challenges with data management for the companies, as well as the new functional requirements for the further versions of VisualCOBie. Therefore, each outcome of the pilot studies acted as a trigger which orients the researcher to review the initial problem statement, requirements and developed functionalities iteratively. Three pilot case studies have been in progress with three different Finnish industry partners. Although COBie standard, as the core start point of VisualCOBie, is for post-construction phase and FM business domain, there is variety in the profile of case companies, such that the case companies include (1) an FM software development company, (2) a property development company, as well as (3) a real-estate owner, who have all offered to conduct pilot tests with their real project data. The reasons for this variety are twofold. First, all these three companies have either internal or outsourced FM teams/service providers in their projects. Although they reviewed COBie standard but did not use actively in their projects, the initial meetings with these companies revealed similarity of their existing and/or intended
Validation Studies for VisualCOBie Approach and Prototype

facility data structures with COBie. Second, during the public demonstration of VisualCOBie in research and industry workshops, such feedbacks were obtained from these companies that VisualCOBie was seen as a novel and innovative approach not only for COBie standard, but also other IT standards and solutions which these companies develop/use for their projects to enhance their data management, navigation and visualization functionalities.

5.1 Data Collection

The data for the validation of this research and prototype development have been collected via video recordings of focus group meetings. By the time of the submission of this thesis, there are two completed and one on-going pilot case studies. However, only the FM software development company allowed the researcher to record the meetings due to privacy concerns associated with the function of the building, involvement of government, etc. A non-disclosure agreement has been signed to keep the data out of public domain. Hence, the thorough analysis presented in this research is only for the data obtained from the meetings with the FM software development company. With other companies, such feedbacks have been collected through notes from the discussions. This can be assumed as a limitation for the validation of VisualCOBie approach in this research. However, the industrial relationship of the three case companies alleviates this limitation, because the FM software company’s products are actively being used by the other two companies in the remaining two projects. Hence, similar feedbacks, requirements and development strategies have been obtained by the other companies as well. There have been six focus group meetings in seven months with the FM software developer company which covered a total duration of 16.8 hours (Figure 38). In addition to the feedbacks, discussions, improvement requests obtained in these meetings, a considerable amount of time has been spent with hackathons to apply the improvement requests programmatically to the initial VisualCOBie prototype. Collected video streams from the FM software company have been transcribed into text and reviewed individually by the researcher to identify the relevant sentiments regarding the VisualCOBie approach. In these reviews, the discussions such as detailed programming issues, code compatibility, debugging, API connections, research studies, industry matters, etc. were eliminated. After elimination, a total of 623 sentiments have been analysed.

![Figure 38. One of the case study meetings with the FM software developer company](image)
The validation studies with the FM software company have been performed over the integration of VisualCOBie platform with the company’s proprietary solutions as well as the COBie dataset created from a sample project IFC file. The hackathons conducted with the company and validation results are detailed in Section 5.3. The results of the development and validation studies have also been considered during the case studies with the property development company because they also use the FM software developer company’s products in the case project. In the initial phases, the COBie data set of the case project, FM software data (from software development company solutions) and their own data structure have been implemented into the VisualCOBie platform and relevant feedback was collected regarding the usability, functionality and further improvement of this approach. However, the lack of acceptance of COBie standard and associated data structure in the property development company revealed the need for the implementation of Talo 2000 classification system in VisualCOBie prototype. The Talo 2000 classification system is developed in Finland with the collaboration between various construction industry players. It forms the foundation for the exchange of construction information for all parties (Rakennustieto 2006). Although it is not an international standard like COBie, the acceptance and usage of Talo 2000 is dominant in Finland where this research is conducted. The request for the implementation of Talo 2000 was found relevant for the employed agile development methodology of this research for further improvements. However, due to international contribution of this research, lack of time to understand the classification, and lack of knowledge of the researcher in the local language of Finland, this request was not taken into consideration within the scope of this thesis. The third pilot case study is an on-going work with a real estate owner company which manages more than 10000 public and private buildings in Finland. In this project, the building data in IFC file as well as the different IT tools which are used for project management, portfolio management, space management, etc. are being integrated and visualized in VisualCOBie.

The collected sentiments were segmented for protocol analysis based on the roles of the participants in the company. Protocol analysis is a research method used for behavioural analysis of the research participants and their thinking (Austin & Delaney 1998; Crutcher 1994). Detailed introduction about protocol analysis is presented in Section 2.4. The segmented data were then clustered firstly using an open-ended approach to identify the main themes. Based on these themes a coding scheme has been developed and applied to the data for detailed inspection of the focus group meetings as also suggested in (Singh et al. 2011). The design of the coding scheme reflects the importance of various factors, such as cultural and work practices, technical and computational integration, data management and organization, etc., affecting features of VisualCOBie approach. In the initial steps of the validation, four different coding schemes have been identified: (1) Roles/Disciplines, (2) Type, (3) Context, (4) Content. These categories are used to cluster the data to reveal aspects which summarize the meetings, such that the researchers can identify the patterns of different aspects for the validation of VisualCOBie approach across different roles such that:

**Roles/Discipline Category:** is used to classify the data based on the disciplinary and functional background, and/or role of the participant in the company and research group. Categorizing each sentiment based on the disciplinary/role of the participant gives useful information about the importance of the different aspects to different user groups.

**Type Category:** is used to classify the data based on the perceived purpose of each sentiment (Figure 39). The codes for the *Type* category were defined as:
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**Suggestion/Idea**, to capture any relevant suggestion regarding the current status of the VisualCOBie approach and further phases of the research and development;

**Concern/Doubt**, to capture statements that may raise direct or indirect concerns or doubts associated with different features of VisualCOBie such as usability, functionality, applicability, scalability, etc.;

**Opinion/Viewpoint**, to capture statements that can be equated as opinions or viewpoints either about the features of VisualCOBie or the industry. These include the complementary sentiments that support or weaken the topics discussed in the focus group meetings;

**Observation/Analysis**, to capture statements that identify root-causes, observations and reasoning behind the discussion topics;

**Query**, to capture the questions that are directly or indirectly related to the theoretical and technical aspects of VisualCOBie as well as the developed functionalities;

**Strategy**, to capture statements associated with strategy relevant to VisualCOBie, industry, the case study, the conducted hackathons, as well as that for further development phases;

**Request**, to capture to-do list which the case company wants to see both as the results of case study and in the next version of the VisualCOBie prototype (presented in Chapter 6).

**Context Category**: is used to mark the circumstances under which a given statement has been discussed (Figure 40). Classification with Context category includes:

- **Initiated**, if the statement was for starting a new subject of discussion;
- **Question**, if the statement is a question directed to any of the participant in the meetings;
- **Follow-up**, if the statement was continuing an on-going subject initiated earlier in the discussion; and
- **Reply**, if the statement was a reply to a question asked earlier

**Content Category**: classifies the statement based on the subject of discussion and identifies dominant topics (Figure 41). Accordingly, there are five codes within this category:

- **Technical/Computational**, to capture the statements regarding the development plan for the conducted hackathons, for further improvements, for compatibility and integration of VisualCOBie prototype with the case company’s proprietary solutions and other BIM platforms;
- **Cultural/Work Practice**, to capture statements associated with the validity of problem statements based on the existing work practices and the culture of AEC-FM industry;
- **Data Organization**, to capture statements associated with how the case company’s data structure should be modified to enrich the existing COBie dataset as well as to be modified for the integration; and to capture the issues associated with the utilization the IFC data within the existing IT solutions, etc.;
- **Use Case**, to capture statements that detail and plan the steps associated with the use case project and development based on the Strategic points captured under the Type Category;
- **Business Case**, to capture the statements regarding the business value of VisualCOBie approach and the development prototype (later for final development) for the AEC-FM industry, and identify the expectations of the industry from the customer point of view.

The classification of some of the sentiments with the above categories is presented in Appendix A.
5.2 Initial Analysis to Introduce Focus Group Meetings

The analysis of the collected sentiment data was performed under two main steps. In the first step, such comparisons of the collected data was done by clustering them under different coding schemes to allow classification and summary of the collected data from different perspectives. For example, *Role vs. Content* mapping indicates which content has the dominant issues to specific disciplines; *Type vs. Content* mapping indicates awareness, interest and knowledge about the content; and *Roles vs. Types* mapping indicates awareness, interest and knowledge across specific roles/disciplines.
In the second step, the sentiments were reviewed and analysed to see whether they validate the initially identified problem statements of VisualCOBie approach, employed theoretical principles, as well as the developed functionalities of VisualCOBie prototype. In addition, the classification which is revealed in the first step is mapped with the results of the analysis of the second step. The analysis results of this step draw a picture for the applicability of VisualCOBie approach for the whole project lifecycle as a scalable and flexible data management platform with the discussions and requests during the meetings.

5.2.1 Classification of Discussions based on Participants’ Background/Role

The focus group meetings included participants clustered as (1) researcher team and (2) company team; and the role of each participant has been identified based on their expertise and current positions in the company. The identification of backgrounds/roles of each participant allowed to identify who was more active and which background/discipline is interested and contributing more on which categories during discussions. From the research team, there have been three participants who are:

- Research Tool Developer (Researcher) and,
- Research Expert (Researcher’s advisor)
- Research Expert (Web of Building Data Research Group)

From the case company, there have been:

- CEO of the company,
- Operations & Facility Management Head,
- Research & Innovation Head,
- Software Developer and,
- Software Development Head

Contribution of different roles is equated in terms of the frequency of the sentiments coming from the corresponding participants. These mappings provide some useful information about the importance of different aspects discussed for VisualCOBie approach within each participant and their role in the company. According to Figure 42, it can be seen that %38 of the overall sentiments have been shared by participants based on their **Observation and Analysis**. Besides, they shared their **Opinions and Viewpoints** as well as the **Strategical discussions** share almost equal amount of sentiments (~20%) in these meetings. Based on the analysis and presented chart in Figure 42, it can be seen that:
The **Research Tool Developer** is the most active participant by contributing more than one-third (31%) of the overall discussion clustered under the *Type* category. However, his contribution is concentrated on the *Observation and Analysis* (150 sentiments) about different aspects of VisualCOBie approach. Furthermore, there is a relatively minor contribution to raise Strategy discussions (38 sentiments).

The **Operations & Facility Management Head** presented his *Opinions and Viewpoints* (63 sentiments), *Observations and Analysis* (54 sentiments) of different aspects of the discussion content. In addition, he contributed to the *Strategy* discussions (48 sentiments).

Similarly, the **Research & Innovation Head** presented his *Opinions and Viewpoints* (42 sentiments), as well as *Observations and Analysis* (53 sentiments) of different aspects of the discussion content. In addition, he contributed to *Strategy* discussions (31 sentiments), nearly as much as the **Research Expert** (27 sentiments).

Mapping the participants' *Roles* with the *Context* of the discussion draws the overall picture for the participants of the focus group meetings. In this research, the majority of the sentiments are either *Replies* or *Follow Ups* of on-going discussions. In a group meeting environment this result is not surprising because many people can express their suggestions, concerns, observations, etc. consecutively. Therefore, researchers concentrate on the *Initiated* and *Questioned* segments because the segments under this code either started a new topic and/or changed on-going flow of the discussion. Figure 43 shows that the **Operation & Facility Management Head** and **Research & Innovation Head** have more often initiated discussed topics and raise questions.

![Mapping the Roles vs Context for the Collected Sentiments](image)

**Figure 43.** Contribution of different participants for the Context of the discussion

The distribution of the sentiments under each of the Content category is mapped according the *Role* of the participant. This *Role* vs. *Content* mapping of the focus group meetings allows the identification of issues that specific participants actively discuss, showing interest in specific aspects of the VisualCOBie approach. According to the results represented in Figure 44, Technical and Computational aspects are the most common topics discussed with 280 sentiments (30%) of the overall discussion. Similarly, a considerable amount of discussion has focused on the Data Organization topic with 256 sentiments (28%). The close values between these two categories can raise the question whether there is a correlation among the topics discussed under these categories. A similar question can also be raised for the Cultural/Work Practice and Use Case categories since the number of sentiments are 181 (20%) and 192
(21%) respectively. This question will be discussed in the next sections of this chapter. Based on the analysis, Figure 44, it can be seen that:

1. The Research Tool Developer mainly contributed to the Technical and Computational aspects with 123 sentiments as well as the Data Organization aspects of the discussion content with 99 sentiments. There is also a relatively minor contribution of the tool developer to the topics about Cultural and Work Practices as well as definition of Use Case.

2. There is a balance of contribution of the Operations & Management Head to each category of the discussion except to the Business Case with a total of 243 sentiments. His main focus is Data Organization and Cultural and Work Practices with 66 and 65 sentiments respectively. He contributed to the Technical and Computational (54 sentiments) and Use Case aspects (55 sentiments) of the discussion almost equally. Similarly, the Research & Innovation Head’s contribution shows an equal pattern for each of the categories of discussion, except the Business Case with a total of 195 sentiments.

3. In this mapping, the contribution of Software Development Head can be seen as well, especially on the Technical and Computational aspects of the discussion. The CEO of the case company attended only one of the meetings, and that too far a part of the meeting, to provide his feedback. As it can be seen from, the CEO’s Figure 44 feedbacks are equally distributed on the Business Case, Cultural and Work Practice, as well as Use Case aspects of the discussion content.

Figure 44. Contribution of different participants for the Content of the discussion

5.2.2 Classification of Discussions based on Type vs. Content

The distribution of the sentiments under the Content category is mapped according to the Type of data. This mapping allows (1) identification of aspects that participants need information about VisualCOBie approach (Query, Concert/Doubt) or (2) observation of participants who have knowledge and experience to share (Suggestion/Viewpoint, Observa-
tion/Analysis) or (3) examination of expressed interest and desire from the participants in features they would like in VisualCOBie approach (Strategy, Request). According to the results presented in Figure 45:

1. Technical and Computational aspects is the most common group discussed in the meetings with 367 sentiments. They are mostly shared as an experience based on Observation and Analysis (126 sentiments) more than as a Opinion/Viewpoint (55 sentiments) and Suggestion/Idea (38 sentiments). However, it can be seen that, a reasonable amount of Technical and Computational discussion (95 sentiments) referred to the Strategic points/decisions during the discussions.

2. Data Organization is the second most common group discussed in the meetings with 316 sentiments. Similar with Technical and Computational category, the discussions show a similar pattern in terms of distribution between Observation and Analysis (129 sentiments) and Opinion/Viewpoint (47 sentiments). The majority of discussion about Data Organization also has a considerable amount of effect for the Strategic points/decisions.

3. The topics about Cultural and Work Practices and Use Case shows an almost equal amount of discussion with 232 and 237 sentiments respectively. The majority of discussions clustered in these categories were shared as Observations and Analysis with 83 and 90 sentiments; and Opinion/Viewpoint with 63 and 54 sentiments.

4. The topics about the Business Case covers the minority of the discussions. While there is not any Suggestion/Idea and Request raised up for VisualCOBie approach, there are a few feedbacks given as Opinion/Viewpoint and Concern/Doubt about the current state of VisualCOBie approach. In addition, a few Strategic point have been raised for further evaluation of VisualCOBie.

![Figure 45. Mapping the sentiments based on their Type and Content](image)

The collected sentiments during the meetings with the case company provided a rich data source to see the patterns among participants, type, content, and context of the discussions. In addition, this discussion pattern has also provided the evidence to validate the problem statements/challenges identified for the representation of COBie data; as well as the initial requirements of VisualCOBie approach (Section 5.3). Therefore, in the next section, the ap-
plied protocol analysis is extended and the identified patterns are mapped with the summary of initial VisualCOBie requirements. Besides that, during the meetings, the existing functionalities of VisualCOBie prototype have been improved and further functional requirements have been identified. The next section also presents the analysis results regarding the validation of the defined usability and functionality requirements of VisualCOBie approach.

5.3 Implementation Practices and Usability Validation of VisualCOBie

The discussions in the focus group meetings provided valuable feedbacks for the evolution of VisualCOBie approach. Although the initial idea behind these meetings was to get feedbacks to validate the arguments of VisualCOBie approach, the conducted hackathons with the software development team of the case company contributed to the existing usability and functionality of the initial VisualCOBie prototype. In addition, by understanding and experiencing the needs and practices of Finnish industry with facility management practices and software solutions, the future set of features have been evaluated and identified which shifted the VisualCOBie approach to be more than a data visualization and navigation tool. The implementation of new set of features is presented in Chapter 6. Therefore in this section, the discussion results are presented under three main questions, which are:

1. What kind of observations and feedbacks have been conducted for the initial VisualCOBie approach and prototype; and how these feedbacks validate the initial problem statements?
2. How VisualCOBie approach is enhanced and integrated with case company’s software applications and what are the common mistakes?
3. What are the defined set of future needs and requirements for the agile development process?

5.3.1 Validation of the Usability Requirements

As mentioned in the previous sections, VisualCOBie research and initial prototype adopt the steps of design thinking with the iterative process of agile methodology which includes the collection of feedbacks regarding the prototype development. Therefore, this section presents the outcomes and the feedbacks collected from the case companies during the focus group meetings. In the Ideation phase (Section 4.1.3), the initial problem statements have been summarized (below to recall the statements) which are presented in Table 1.

- High cognitive load of textual and numerical data
- Lack of visibility of semantics and data dependencies
- Lack of navigation and query capabilities
- Lack of 2D/3D BIM model integration
- Lack of data generation, integration and control mechanism;

Section 5.2 presents the results of protocol analysis to summarize the discussions in the focus group meetings within the categories of (1) participants role, (2) discussions type, (3) context and (4) content. Although that analysis provides valuable insights about the awareness, dominant subjects, interests and knowledge about the content across specific roles, the connection with the initial problem statements is still missing. The above summarized needs/requirements have been validated during the meetings by expanding the initial protocol analysis via categorising the statements of participants with the summary of the initial problem statements. For validation, the researcher aimed to get related feedback from the
participants based on their unbiased ideas and perspectives. Therefore, initial problem statements, corresponding needs/requirements, and underlying theoretical aspects have not been introduced to the participants of the case company. Although COBie is not used actively by the case company and their customers, there is enough knowledge about COBie’s structure, data generation and handover practices. In addition, the case company’s internal solutions and related data structures have similarities with the COBie schema; and spreadsheets are the common platform for data manipulation and delivery in many cases.

The problem statement of **high cognitive load of textual and numerical data** has been discussed and validated during the meetings by extending the initially applied protocol analysis (presented in Section 5.2) with an additional classification of the sentiments based on the relevancy of the problem statement. Table 2 presents the distribution of the sentiments based on the role of the participant and the type of the discussion for the problem statement “**high cognitive load of textual and numerical data**”. The results of this analysis show that this problem statement is mostly referred based on “Opinions/Viewpoints” and “Observations” (18 sentiments for each category) of the participants in which the “Operations Manager” accentuated at most. Besides, the “Research & Innovation Head” and “Research Tool Developer” referred to the same problem statement in the same classifications.

Table 2. The Type of discussion for the problem statement “high cognitive load due to textual and numerical data”

<table>
<thead>
<tr>
<th>Type</th>
<th>High Cognitive Load due to textual and numerical data</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suggestion /Idea</td>
</tr>
<tr>
<td>Operations Manager</td>
<td>2</td>
</tr>
<tr>
<td>Research &amp; Innovation</td>
<td>0</td>
</tr>
<tr>
<td>Research Expert</td>
<td>0</td>
</tr>
<tr>
<td>Software Development</td>
<td>0</td>
</tr>
<tr>
<td>Research Tool Developer</td>
<td>1</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>3</strong></td>
</tr>
</tbody>
</table>

Both the nature of problem statement, and the classification of the sentiments based on "Role vs. Type” classification hint towards the **Content** of the discussions. The **Type** of the discussions for this problem statement, are mapped with the **Content** classification to show the participants’ perspective as well as the dominant concepts to handle this problem. The results of this mapping guided the research to identify the relevant validation points. According to the results presented in Table 3, this problem statement is mentioned more when the discussion topic is about existing “Cultural/Work Practices” (37 sentiments) of the case company which mostly refers about how they try to handle and manage the data, what kind of challenges they have with high amount of printed and even digital documentation in which the textual and numerical data is big. Besides, this problem statement is also discussed from “Data Organization” (21 sentiments) perspective mostly about scalability and effective utilization of large amount of text based data; as well as how they associate this data with other information systems/software. Based on the analysis results, this problem statement is seen as a valid issue to be handled and improved during the hackathons. The problem statement is
also discussed for “Technical/Computational” configuration (15 sentiments) of VisualCOBie approach with the case company’s software applications; and taken into consideration for the “Use Case” scenario (17 sentiments) modeling.

Table 3. The Content of discussion for the problem statement “high cognitive load due to textual and numerical data”

<table>
<thead>
<tr>
<th>High Cognitive Load due to textual and numerical data</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Technical/Computational</td>
</tr>
<tr>
<td>Suggestion/Idea</td>
<td>2</td>
</tr>
<tr>
<td>Concern/Doubt</td>
<td>0</td>
</tr>
<tr>
<td>Opinion/Viewpoint</td>
<td>5</td>
</tr>
<tr>
<td>Observation/Analysis</td>
<td>3</td>
</tr>
<tr>
<td>Strategy</td>
<td>5</td>
</tr>
<tr>
<td>Request</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>15</td>
</tr>
</tbody>
</table>

For the case company, a spreadsheet can be a relevant tool to manage facility information as far as the amount of data and semantic relationships between the data entities are small. If a spreadsheet is accepted as the collaborative platform to enter all equipment, component, system, space, zone, etc., understanding the data with full of texts and numbers will be one of the bottlenecks. Therefore, for the case company, the textual and numerical data represented in COBie spreadsheet and the scale of it overpasses the benefits of COBie spreadsheet in understanding the data. The proposed pre-attentive figures for each data entity in VisualCOBie was found quite interesting and facilitating. Even though the participants were not informed about the theoretical concepts of this research, they referred to the Gestalt’s “past experience” principle by stating that “We can have a guess about what the data entity is about from the assigned figure and the text under it, or which data group it belongs to...”. However, besides the positive feedback from the case company, a question was raised about a limitation of this feature during the initial prototype development “what if the end user cannot capture the meaning of the assigned figure?”. This question was considered as an additional improvement request which is discussed and presented in the Chapter 6 more detail.
During the focus group meetings, the generation of COBie data through a commercial application and open-source BIMserver COBie plugin (Bogen 2015) have been discussed and practiced. Although COBie data can be generated with exporter tools, still understanding the COBie full of text and number and bunch of columns is time consuming. In addition, some fields remained empty in the exported spreadsheet and some have obscure text such as “NaN”, “N/A” or “unknown”. During the meetings, this problem raised questions whether the functionality of existing converters is good enough or the IFC was modelled well enough. A detailed discussion for that question will be presented in section 5.3.3. In addition, this issue was reflected as a major limitation in terms of the usability of VisualCOBie since only the figure which is assigned to the node entity did not make any sense without a descriptive label under it.

The lack of visibility in semantics and data dependencies is one of the most common topics discussed in each of the focus group meetings as a problem with the on-going information management practices and one of the main limitation in COBie spreadsheet. The “Role vs. Type” classification (Table 4) reveals out the “Research Tool Developer” (researcher) (94 sentiments) and Operations Manager (92 sentiments) as the most active participants for this problem statement especially during the introduction of VisualCOBie concept to the case company. In this meeting, the ideas and the reasoning behind the VisualCOBie is mostly explained and discussed based on the “Observation/Analysis” of different topics (130 sentiments). During the case meetings, many “Opinions/Viewpoints” were shared (58 sentiments) regarding the problem statement and the proposed solution in VisualCOBie approach. As a result of these discussions, various aspects have been found strategically important (61 sentiments) especially by the “Operations Manager” (22 sentiments) and “Research & Innovation Head” (15 sentiments).

Table 4. The Type of the discussion for the problem statement “lack of visibility of dependencies”
The computational approach of VisualCOBie, presented in Section 4.2 presents the development layers and the architecture of VisualCOBie. The relational information view is planned to address the problem statement “lack of visibility of dependencies” which are related with both the UI and the backend configuration (data modeling and database). The “Type vs. Content” mapping reveals the corresponding topics that have been discussed by the focus group meeting participants. As it can be seen in Table 5, the most discussed topics are based on “Data Organization” (174 sentiments) and “Technical/Computational” configuration (127 sentiments) of the intended VisualCOBie integration with case company’s applications. The discussions are mostly based on the “Observation/Analysis” of existing applications data structure, their existing integrations and available APIs. This pattern also shows itself in “Strategy” discussions in which there are almost equal amount of sentiments are identified for “Technical/Computational” and “Data Organization” (36 and 38 sentiments) related topics. This problem statement is also the one which is discussed the most for planning the “Use Case” scenario (88 sentiments). This results also indicates the validity of the presented problem statement for the case company and the intended development progress.

Table 5. The Content of discussion for the problem statement “lack of visibility of dependencies”

<table>
<thead>
<tr>
<th>Lack of Visibility of Dependencies</th>
<th>Technical/Computational</th>
<th>Cultural/Work Practice</th>
<th>Data Organization</th>
<th>Use Case</th>
<th>Business Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suggestion/Idea</td>
<td>11</td>
<td>6</td>
<td>9</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Concern/Doubt</td>
<td>3</td>
<td>6</td>
<td>7</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Opinion/Viewpoint</td>
<td>21</td>
<td>29</td>
<td>31</td>
<td>16</td>
<td>0</td>
</tr>
<tr>
<td>Observation/Analysis</td>
<td>44</td>
<td>38</td>
<td>76</td>
<td>41</td>
<td>0</td>
</tr>
<tr>
<td>Query</td>
<td>5</td>
<td>1</td>
<td>7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Strategy</td>
<td>36</td>
<td>11</td>
<td>38</td>
<td>21</td>
<td>1</td>
</tr>
<tr>
<td>Request</td>
<td>7</td>
<td>3</td>
<td>6</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>TOTAL</td>
<td>127</td>
<td>94</td>
<td>174</td>
<td>88</td>
<td>2</td>
</tr>
</tbody>
</table>

From COBie data representation point of view, there is a steep learning curve for the case company, especially for the non-technical people to effectively understand and use the COBie data, its presentation with workbooks, rows, columns, cells, pick lists, naming conventions, formatting requirements, color coding, etc. There are similar problems with the case-
company's own software applications and corresponding data structures. The case company has four different platforms to collect, organize and manage the MEP design requirements, internet of things (IoT) sensor readings, user requests/feedbacks and operational activities. Although the integration of these systems can be established via APIs, it does not solve the problem for the lack of explicit representation of semantic relationships, hence the high cognitive load remains unless (1) data is linked semantically with each other at object-entity level, and (2) relevant computational efforts are taken to show the relationships explicitly. To understand how the data is formatted, organized, and categorized in COBie spreadsheet, both the researcher and the case-company are aware of the public documents such as guidelines, reports, sample COBie spreadsheet and spreadsheet schema. The public COBie Responsibility Matrix (East 2013) has been reviewed in detail with the case company to introduce the dependencies of data groups in COBie spreadsheet. However, during the meetings one of the most common, but usually ignored reality of AEC-FM industry has been revealed many times: “No one likes to read tens of pages to learn these details for COBie”. This specific need has been satisfied by VisualCOBie with its graph database at the backend and the implemented visualization functions in the front end. With VisualCOBie, the data entities can be associated with each other semantically. In the initial prototype, the relationships are defined and hardcoded in the VisualCOBie data converter that is written by the researcher; and then the frontend visualization functions capture the relationships by traversing the COBie graph data and visualize explicitly on the UI. This functionality of VisualCOBie was found quite innovative by the case companies such that the direct feedback such as “... now data is also grouped and connected in the user interface” and “This is quite facilitating not only for COBie but also for our data structures” from the focus group meeting participants. The first mentioned feedback can be associated with the Gestalt principles presented in Section 4.1.3 such as “connectedness” and “proximity”. In addition, the second mentioned feedback is more related with the mind mapping concept since the participants experience the computationally and visually connected COBie data and felt the need to connect different data sets and assign meaningful relationships for the connections visually, which are connected in their computational systems. This need refers to the mind mapping concept although it was not literally mentioned as a “mind mapping” functionality; and brings an extra need for a dynamic and scalable configuration of VisualCOBie prototype for the further agile development. As a new requirement in the further development, the case company also suggested to have a flexibility to define the explicit relationships between data groups by themselves. Detailed explanation for this requirement is presented in Chapter 6.

The discussed problem statements in the above paragraphs naturally bring the issue of lack of navigation and query capabilities both for COBie and other spreadsheet based data structures. The participants of the focus group meetings mentioned various types of issues for different tasks during the project lifecycle. The “Role vs. Type” classification (Table 6) reveals the Operations Manager (69 sentiments) and Research Tool Developer (53 sentiments) as the most active participants for this problem statement. Besides, the Research and Innovation Head (42 sentiments) also contributed for the discussion. The ideas and reasoning behind this problem statement are mostly expressed based on the “Observations/Analysis” (85 sentiments) and “Opinions and Viewpoints” (40 sentiments) of the participants. As the result of these discussions, this problem statement has been found strategically important (33 sentiments) especially by the “Operations Manager” (15 sentiments).

Table 6. The Type of discussion for the problem statement “lack of navigation and query”
Based on the computational approach of VisualCOBie, presented in Section 4.2, the solution proposal for “Lack of data navigation and query” problem is more related with the data integration and process layer which is connected with the relational information view where the end-user utilizes the data with the node-link diagram. The “Type vs. Content” mapping reveals the corresponding topics that have been discussed by the participants. As it can be seen in Table 7, the discussion is almost equally distributed for each topic, but the most common topic is about how to handle the “Data Organization” (80 sentiments) so all the relevant data sources are integrated and visualized in the relational information view. In the meetings, this topic was usually focused on identifying which data groups should be integrated, what are the dependencies among different data sources, and what should be the common identifiers (GUIDs or system IDs?) to link those data sources. This discussion also moved to the “Technical/Computational” (69 sentiments) aspects to define the API configurations of the case company’s proprietary solutions and VisualCOBie implementation to transfer and link the data within different systems. Besides the data organization and technical details, majority of the discussion also focused on how the VisualCOBie approach can affect the existing “Cultural/Work Practices” of the case company, what can be the resistance by the end user, and how the node-link diagram should be modified and presented so the end user can reach the desired data set/entity with less effort. This and similar questions also affected the planning of the “Use Case” scenario which includes 71 sentiments. This also indicates the validity of the presented problem statements for the case company and the intended development process.

Table 7. The Content of discussion for the problem statement “lack of navigation and query”

<table>
<thead>
<tr>
<th>Lack Data Navigation and Query</th>
<th>Technical/Computational</th>
<th>Cultural/Work Practice</th>
<th>Data Organization</th>
<th>Use Case</th>
<th>Business Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suggestion / Idea</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Concern / Doubt</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Opinion / Viewpoint</td>
<td>11</td>
<td>22</td>
<td>16</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>Observation / Analysis</td>
<td>22</td>
<td>31</td>
<td>35</td>
<td>34</td>
<td>0</td>
</tr>
<tr>
<td>Query</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Strategy</td>
<td>19</td>
<td>8</td>
<td>20</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>Request</td>
<td>5</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
The common practices and challenges to find relevant information were generally mentioned by the case-company as the distribution, storage and representation of the facility data in an intermediary spreadsheet like in COBie is not an efficient practice. In such complex spreadsheet with various data, the scale of involved data inquiry, navigation and validation overshadows the benefits of COBie since the end-user has to serially shift within many columns and workbooks. The direct feedback of one of the participants also supports this issue regarding the time limitation of the personnel to solve the consecutive problems. For example, while the personnel is serially shifting among different sources, any interruption during a session may result in a gap, breaking the cognitive process such that he/she either forgets what he is looking for, what are the results of his search up to now, or what is the search path until the moment. Especially for bigger projects, the huge amount of managed assets and properties will result in very large spreadsheets, making it difficult to locate a specific piece of information. During the meetings, the node-link interface of VisualCOBie was found quite helpful for the end user since all the queries and results are connected and these connections are presented visually. This discussion refers to the Gestalt’s "connectedness" principle as one of the aids for visual perception.

COBie data can be easily stored in traditional Relational Database Management Systems (RDBMS) in which the data groups and entities are defined with the tables and the associated rows. However, the relationships between the tables are defined with such generic definitions such as one-to-one, one-to-many or many-to-one without specifying any custom meaningful/semantic “label” and/or “property” on the relationships. Therefore performing a semantic query with standard query language (SQL) for such complex FM tasks, which may have many dependencies, requires merging many tables and their rows sequentially. This process can demand very long query strings and make the query performance quite poor. On the other hand, the proposed VisualCOBie approach with the visual and dependency-based search and query was tested during the meetings and found as a successful solution by bringing both the searched and all the dependent data groups in the same user interface with the semantic relationships. In comparison with RDBMS, the data query process is not performed by sequential process or querying the tables with long SQL-based queries. Instead, the graph database of VisualCOBie traverse the graph data with a declarative and short Cypher query. In addition, for tracking such a long chain of queries, VisualCOBie provide the natural language query tracker (Figure 31) which capture the end-user’s selections on Root-Nodes, Value-Nodes and the corresponding Links between each other and chains the query process in natural language results. This feature was found useful by the participants of the focus group meetings especially when they consider their work practices which are interrupted with all sorts of extra things.

As presented in Section 4.1.3, the ideation for this requirement proposes navigate and search by-group of the data, and navigate and search by-dependency of the data. In other words the data groups and the relationships between them are the main parameters. As a complementary request for the previous requirement, the case company proposed the need for defining the Root-Nodes and Value Nodes with their individual parameters by themselves on the user interface of the prototype. That would enable them to structure their data navigation and query functionalities. Detailed explanation about this request is presented in Chapter 6.
The integration of 2D/3D building models with the COBie dataset is not in the scope of COBie standard and representation originally. However, all the focus group meeting participants agreed that it is a “facilitating need” not only for COBie, but also any BIM related digital solutions. Research Tool Developer (58 sentiments in total) and Research & Innovation Head (50 sentiments in total) were the most active participant during the focus group meetings by sharing their “Observation/Analysis”. In addition, the Operations Manager (47 sentiments in total) also contributed to the discussion by sharing his “Opinion/Viewpoints” (Table 8). Besides, during the discussions, this problem statement has been considered as “Strategically” important for the VisualCOBie approach and the proposed development hackathons with the case company.

Table 8. The Type of discussion for the problem statement “integration of 2D/3D model”

<table>
<thead>
<tr>
<th>Integration of 2D/3D model</th>
<th>Type</th>
<th>Suggestion/Idea</th>
<th>Concern/Doubt</th>
<th>Opinion/Viewpoint</th>
<th>Observation/Analysis</th>
<th>Query</th>
<th>Strategy</th>
<th>Request</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operations Manager</td>
<td></td>
<td>4</td>
<td>1</td>
<td>13</td>
<td>11</td>
<td>4</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Research &amp; Innovation</td>
<td></td>
<td>5</td>
<td>4</td>
<td>9</td>
<td>14</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Research Expert</td>
<td></td>
<td>2</td>
<td>0</td>
<td>3</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Software Development</td>
<td></td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>6</td>
<td>2</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Research Tool Developer</td>
<td></td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>43</td>
<td>1</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td></td>
<td><strong>14</strong></td>
<td><strong>9</strong></td>
<td><strong>27</strong></td>
<td><strong>79</strong></td>
<td><strong>13</strong></td>
<td><strong>31</strong></td>
<td><strong>8</strong></td>
</tr>
</tbody>
</table>

The problem statement of integration of 2D/3D model is related with the technical and computational configuration of any BIM related digital solution. As can be seen in Table 9, the discussions regarding this problem statement is mostly categorized under “Technical/Computational” aspects (103 sentiments) in which many of the sentiments are stated as Observation/Analysis. In addition, there is also considerable amount of discussion regarding the “Data Organization” topic (57 sentiments) in which the participants focused on identifying the data structure and its key parameters for the integration with 2D/3D models.

Table 9. The Content of discussion for the problem statement “integration of 2D/3D model”

<table>
<thead>
<tr>
<th>Integration of 2D/3D model</th>
<th>Content</th>
<th>Technical/Computational</th>
<th>Cultural/Work Practice</th>
<th>Data Organization</th>
<th>Use Case</th>
<th>Business Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suggestion/Idea</td>
<td></td>
<td>11</td>
<td>5</td>
<td>3</td>
<td>5</td>
<td>0</td>
</tr>
<tr>
<td>Concern/Doubt</td>
<td></td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Opinion/Viewpoint</td>
<td></td>
<td>12</td>
<td>12</td>
<td>8</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Observation/Analysis</td>
<td></td>
<td>42</td>
<td>16</td>
<td>24</td>
<td>28</td>
<td>0</td>
</tr>
<tr>
<td>Query</td>
<td></td>
<td>8</td>
<td>2</td>
<td>5</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Strategy</td>
<td></td>
<td>19</td>
<td>8</td>
<td>11</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>Request</td>
<td></td>
<td>6</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>
This need requires the integration of the open source BIMserver and its plugins by mapping the objects with their GUID numbers which are presented in COBie spreadsheet as ExtIdentifier. Although this “mapping” functionality in VisualCOBie is found as a novel approach to enhance the usability, it is far from being an innovative solution by itself. The discussions during the focus group meetings revealed two reasons for this: (1) There are already existing solutions in the industry (4Projects 2013; Ecodomus 2016; Solibri Inc 2015) which do the same mapping with the COBie dataset by using the GUID and system-generated unique identification (UID) numbers with the associated 3D model. Those solutions also provide the bi-directional interactions like the one VisualCOBie provides. (2) There is a remaining challenge and big limitation both with VisualCOBie approach and the available commercial/open-source solutions for the bi-directional update both in COBie data and the 3D model. The common question of participants are, “what happens when there is an update in the model?” and “how is the model updated when we change a property in COBie dataset?”. Although 2D/3D model integration is partially related with these questions, the main discussion is related with the next problem statement. The initial VisualCOBie prototype was embedded in the existing BIMvie.ws UI by changing the HTML and CSS properties of the frontend code. BIMvie.ws provided a ready and working platform for the initial VisualCOBie. However, it also encapsulates the VisualCOBie in the BIMvie.ws framework. During the hackathons, the improved version is moved out of the BIMvie.ws framework.

For the implementation of 3D model viewer platform, various solutions have been tested to identify the possible alternative platform for moving out from BIMvie.ws framework. These iterations also revealed the existing practices and expectations of the case company from the 3D viewer. The first implementation has been performed with Three.js (Dirksen 2013), an open source Web Graphic Language (WebGL) library. In this implementation, 3D projected view, additional functionalities such as walk-in the model, fly-around the model, have been implemented. Although these functionalities provided extra views and alternative ways to access the building data, the hackathons and focus-group meeting discussions revealed the acceptance of this functionalities might not be as expected. It was found that the walking in the digital model from one point to another is time-consuming, and it is difficult to find a specific component information. Instead, the case company participants referred that the use of 2D model is more easy and still more common in the industry. Therefore, this option has been avoided in VisualCOBie approach. Similar to this development, an alternative development has also been tested with the a game engine to benchmark the performance of the 3D model rendering. In both tests, the IFC file has been converted and tested as .dae and .obj formats. However, although both the game engine and the open source WebGL libraries performed well enough for small/medium IFC files, the performance was quite poor to render the large IFC files since all the rendering process is done in the browser. Therefore, the production with those alternatives was found quite challenging. In addition, the conversion of IFC files to .dae and .obj formats was an external process and not in the overall development chain.
In addition to the above alternatives, the open source Web Graphic Language (WebGL) viewer BIMSurfer (BIMSurfer 2011) has been used in VisualCOBie. With the new configuration, the bi-directional integration of the 2D floor plan and the 3D model with the node-link diagram has been successfully done. Since the rendering has been processed on the BIMserver, the performance for rendering large IFC files was well enough. During the hackathons and focus group meetings, a new improvement request also has been identified for 3D viewer. Although the relationships between the data are represented explicitly in the node-link diagram, the related building components should be also shown directly on the 3D model. The detailed explanation for this request is presented in Chapter 6.

Like any other spreadsheet-based data, the lack of data generation and control mechanism for COBie dataset is not available directly with its spreadsheet form unless necessary programmatic functions are developed. The COBie data can be generated via external or built-in exporters of relevant tools or populated manually to the spreadsheet. It is an easy practice to update the COBie spreadsheet with exporters and their predefined settings. However, after the export process, the data is usually updated and maintained in the spreadsheet and users can easily lose track of changes with the associated model and/or duplicate the existing data by mistake. The feedbacks obtained during the meetings approved this problem for the case-company’s existing practices with spreadsheets. As it can be seen in Table 10, this problem statement has been discussed and approved mostly based on the “Observation/Analysis” (101 sentiments). In addition, this problem statement was also mentioned “Strategically” important (68 sentiments) not only for COBie dataset, but also a common issue for tracking the changes in BIM files. The “Research Tool Developer” (45 sentiments)
and “Operations Manager” (25 sentiments) were the most active participants who contribute the discussions.

Table 10. The Type of discussion for the problem statement “lack of data generation and control”

<table>
<thead>
<tr>
<th>Data Generation and Control</th>
<th>Suggestion /Idea</th>
<th>Concern /Doubt</th>
<th>Opinion /Viewpoint</th>
<th>Observation /Analysis</th>
<th>Query</th>
<th>Strategy</th>
<th>Request</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operations Manager</td>
<td>5</td>
<td>4</td>
<td>19</td>
<td>25</td>
<td>5</td>
<td>25</td>
<td>4</td>
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<tr>
<td>Research &amp; Innovation</td>
<td>4</td>
<td>5</td>
<td>12</td>
<td>17</td>
<td>10</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Research Expert</td>
<td>6</td>
<td>1</td>
<td>8</td>
<td>8</td>
<td>3</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Software Development</td>
<td>5</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Research Tool Developer</td>
<td>6</td>
<td>6</td>
<td>8</td>
<td>45</td>
<td>6</td>
<td>16</td>
<td>1</td>
</tr>
<tr>
<td>TOTAL</td>
<td>26</td>
<td>19</td>
<td>49</td>
<td>101</td>
<td>31</td>
<td>68</td>
<td>7</td>
</tr>
</tbody>
</table>

Although COBie standard explains the data handover phases clearly, due to lack of knowledge of the end-user, this problem can be even worse if the COBie delivery is regenerated after every update in the model. The data generation and update functionalities are developed and enhanced during the hackathons, such that, after the COBie data is transferred to VisualCOBie prototype, each data entity can be updated and/or deleted. To track the historical changes in each data entity, there is a separate “HISTORY” data group (Root-Node) defined in the backend of VisualCOBie prototype and linked with the associated COBie data entity. When the data is updated in the VisualCOBie interface, this Root-Data keeps the historical changes on the COBie data entity which describes the change, responsible person, and the date/time. If the COBie data entity is deleted by the user, the visual representation of this data entity becomes invisible on the UI while it still exists in the database. This enhancement also reflects the content of the discussions in the focus group meetings regarding the problem statement. As it can be seen in Table 11, “Technical/Computational” (182 sentiments) and “Data Organization” are the dominant contents that have been discussed for this problem statement. On the other hand, this topic was also found strategically important to be considered for the “Use Case” in which the VisualCOBie development has been improved with hackathons which is presented in Section 5.3.2.

Table 11. The Content of discussion for the problem statement “lack of data generation and control”

<table>
<thead>
<tr>
<th>Data Generation and Control</th>
<th>Technical Computational</th>
<th>Cultural/Work Practice</th>
<th>Data Organization</th>
<th>Use Case</th>
<th>Business Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suggestion /Idea</td>
<td>19</td>
<td>2</td>
<td>7</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Concern /Doubt</td>
<td>9</td>
<td>7</td>
<td>12</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Opinion /Viewpoint</td>
<td>28</td>
<td>15</td>
<td>24</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Observation /Analysis</td>
<td>53</td>
<td>24</td>
<td>51</td>
<td>21</td>
<td>0</td>
</tr>
<tr>
<td>Query</td>
<td>16</td>
<td>9</td>
<td>19</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>
Although it is not in the scope of this research, this problem statement has also been discussed with the case company especially for the control and tracking of the BIM-related information which is retrieved directly from the IFC file. As one of the main components of the VisualCOBie prototype, open source BIMServer handles the changes in the IFC file by generating a new revision of the same model. This feature was found inefficient due to high amount of space covered in the database. However, during the case studies this issue was ignored and the existing configuration of BIMserver was accepted as it is. On the other hand, the case company has considered this problem statement for the integration of external data content coming from their proprietary tools. The implemented functionalities for data generation and control during the hackathons were found useful but not comprehensive enough. Therefore, there is a further development request for a control and approval mechanism for the generated/updated data groups and entities based on the hierarchical organization of the company. The details of this implementation will be presented in Chapter 6.

5.3.2 Hackathons for VisualCOBie

The initial problem statements were discussed with the case company and corresponding functionalities were implemented to the VisualCOBie prototype in the hackathons. However, during the meetings, there was another frequent request regarding the extensibility of COBie spreadsheet. The COBie data in the spreadsheet can be extended by adding extra columns to each worksheet as its customized fields. This practice was considered more efficient instead of creating an additional data structure from scratch. However, expanding a complex spreadsheet with additional columns does not solve the overall usability problems mentioned above. The documents and guidelines of COBie standard clearly specify and draw the purposes, practices, advantages and limitations of COBie. Therefore, any change in the data structure and related data handover practices of COBie should not be associated with COBie standard itself directly. However, the direct feedback of the case company such as “COBie is not able to provide all data needed for some tasks during FM phase” shifted the outcomes of the hackathons. COBie data is extended within the VisualCOBie prototype by integrating the existing COBie data with the case-company’s proprietary solutions in VisualCOBie. Such that VisualCOBie is configured as a data-hub which aggregates the COBie data and case-company’s data coming from different software individually. Therefore, the original COBie data structure was kept as its origin.

This step can be considered as a landmark for the VisualCOBie’s agile development process. As mentioned above, VisualCOBie research is conducted to improve the addressed needs and requirements for the usability aspects of COBie spreadsheet. However, the request for integrating the COBie data with other data sets also extended the scalability and applicability of VisualCOBie development beyond a visualization and navigation tool for a specific information exchange standard which enables the users to interact, manage and generate the data visually. The details of this development will be presented in Chapter 6.

To perform the above-mentioned extension a use-case scenario was developed with the case company. In the scenario, there is (1) an office space user, (2) a facility, (3) a tech-
nical operator as actor, and (4) VisualCOBie tool, (5) App1 to collect user feedbacks, (6) App2 to collect sensor data, (7) App3 to collect MEP design data, (8) App4 to manage work orders. To make the scenario easier to understand, the captured screenshots from the demo implementation are presented. Due to the case company’s privacy concerns, any part in the images which includes company logo, name, etc. is blurred intentionally. According to the scenario, the integration of data with the 2D and 3D buildings models should have been established. The integration of 2D model has been done successfully. However, in the following images, although the 3D model was included to the UI successfully, the integration of the 3D model with the 2D floor plan and the node-link diagram could not be established properly.

One of the aims of this use-case was also to explore how generic can the VisualCOBie be and used for different types of buildings with relevant IFC files. Therefore, instead of utilizing entire building, this use-case has been planned and presented with case company’s office building, lobby floor only. This can be seen as a limitation for this research. However, this approach helped the researcher to identify problems and update the development quickly within a short time. Corrected development has also been tested with other companies, with larger scale buildings. According to the scenario following actions happen between applications and actors.

1. The **office space user** feels the room is too cold and gives the **feedback** via **App1** (Figure 48),

   ![Office Space User gives the “Tool Cold” feedback](image)

   **Figure 48.** Office Space User gives the “Tool Cold” feedback

2. **App1** recognizes authenticated **user**, **space name** and **space id** where the **office space user** located in via bluetooth beacons,

3. **App1** delivers the **user info**, **feedback**, **space name** and **space id** to **VisualCOBie**,

4. **VisualCOBie** creates a new **service request** data with given feedback, date and time, and the user profile (Figure 49).
5. **VisualCOBie** queries the space data with the transferred *space name* from COBie dataset and retrieves the dependencies of the space based on the COBie spreadsheet schema,

6. **VisualCOBie** semantically links *service request* and *space* with a “BELONGS_TO” dependency such as (Service_Request)-[:BELONGS_TO]->(Space),

7. **Facility manager** receives notification for the *service request* and sees that (Service_Request)-[:BELONGS_TO]->(Space) in **VisualCOBie** platform. The space is highlighted on 2D floor plan (Figure 50)

8. Facility manager clicks the space node, **VisualCOBie** sends request to **App2** to retrieve sensor readings of that space,
9. **App2** returns the last 30 day sensor readings as a response to **VisualCOBie** to be rendered with a simple chart in UI (Figure 51),

![Figure 51. Rendered sensor reading charts. Data comes from App2](image)

10. **Facility Manager** opens the dependencies of space to see the dependent datasets **space** (of Step 5) such as: (Space)-[:LOCATED_IN]->(Zone), (Space)-[:INCLUDE_SYSTEM]->(System), etc. (Figure 52)

![Figure 52. Other data sets related with Space data](image)

11. **Facility Manager** clicks the system node to see the dependent system data entity in that space.
12. After clicking the **system** node **VisualCOBie** queries the COBie data and retrieves other **spaces** (defined as service zone in **App3**) which include the same **system**. These spaces are highlighted both on the 2D floor plan so the **systems** in these spaces can be
checked to prevent any potential failures (Figure 53). Spaces are retrieved from the Components which belong to the selected System. There is a two-step query in the API

Figure 53. Highlighted spaces from the sub-system data

13. After clicking the **system** node, the dependent information sets are retrieved from COBie dataset with explicit relationships including **components**,

14. **Facility Manager** checks the **components** which are belong to the system,

15. **VisualCOBie** sends the queried components which are located in that space to **App3**

16. **App3** returns the detailed MEP design data of the components to **VisualCOBie** as response to be rendered in the UI (Figure 54),

Figure 54. Detailed MEP design data retrieved from Components linked to System data

17. **Facility Manager** clicks **work order** button to create a work order for the **technical operator** and inputs the title and brief problem description in **VisualCOBie**, 
18. **VisualCOBie** generates the *work order* with required, data queried in above steps such as components, space, system, date and time, authenticated user etc.

19. **VisualCOBie** sends the *work order* to be saved *App4* (Figure 55).

---

![Figure 55. Description of the scenario problem in the work order form](image)

20. **Technical operator** receives the work order in *App4*. The built-in indoor navigation system guides the technical operator to the problematic space with a dynamic map (via space name and id) (Figure 56).

---

![Figure 56. Guiding the technical operator with App4 including indoor navigation system](image)
The above use-case scenario has been successfully implemented for the office building of the case-company by aggregating the data from four different systems under VisualCOBie prototype. In this use-case, all the data is transmitted, received and linked via the REST API of VisualCOBie and company's software applications; and saved both in VisualCOBie's and company's corresponding application database. From this perspective VisualCOBie was used as a semantic data store. However, it can also be used as a data aggregator and all data can be represented to the end-user without saving the data. The details of this feature will be described in Chapter 6. The use-case and implementations with hackathons ended in the fifth meeting with the case company.

5.3.3 Common Mistakes that Make COBie Data Generation and Usage Impractical

At the end of the use-case project implementation and hackathons with VisualCOBie, valuable feedbacks and hands-on experience were obtained to understand the common practices for FM as well as insights about why COBie standard is not used in Finland. Although the detailed use-case presentation in this thesis is for only one company, these common practices were observed with the other two case companies as well. The researcher classifies the common mistakes which make COBie impractical under two categories: (1) practices for defining the names, and (2) practices for grouping the data entities (for zones and systems).

During the hackathons, two different IFC files for mechanical design were exported both with the open-source BIMserver COBie Plugin (Bogen 2015) and another commercial converter which provided different results for each file. For example, while the commercial exporter presents the names of the components in the corresponding workbook/column of the COBie spreadsheet, the open-source converter provided "NaN" or "N/A". This result raised questions about the quality/configuration of converters regarding their validity; and correspondingly the usefulness of COBie. In the focus group meetings one participant asked the question: “If I can see the names of the components in the BIM application, why I don't see the same name in COBie export?” However, after a thorough investigation, it was understood that the naming of the elements has not been done as it is specified in the COBie standard. While COBie specifies that the names should be defined with the "name" attribute of corresponding IFC entity, for example IfcProduct.name, all the names of the components have been defined in the specific PropertySets of the corresponding design software. Therefore, the exporter cannot read the “non-existing” name value and returns “NaN” or “N/A”. This triggers problems in the integration of other data sets in COBie and VisualCOBie because in the COBie standard, the “Name” column of many workbooks are defined as the PK to map them with other data entities in other workbooks. In addition, since these data is defined in the PropertySets, some of them appear in the “Attributes” workbook in the COBie spreadsheet without any meaning to the end-user. In the meetings, due to this reason researcher got the question that “This name should be in the Component workbook. Why is it in the Attribute workbook without any supplementary data? That does not make sense to me…” This issue was reminded to the case company and validated by testing an updated file including the correct naming of a few components. As expected, the names of these components were transferred correctly and the “Attributes” of the associated data entity made sense for the end-user. However, this also leads to the discussion regarding the convenience with the existing practices of the case company. The case company was reminded to correct the naming of each elements with the correct configuration. However, as a response to this request, the researcher received a reply stating “In reality, there is no sense to enter name for all
component instances. That's why name attribute is optional, and PropertySets are better because we see all the related data in one entity. That also helps to reduce the file size” (Figure 57). During the discussion, a second question has also come up: “If open-source convert-er gave the NaN for the names, how can the data exported from commercial tool provide the names correctly?” This question was not investigated deeply either during the meetings and hackathons due to the closed system of the commercial tool. But the initial brainstorming was focused on two possibilities (1) the conversion of names from the PropertySet to the correct Ifc__name entity within the software and then transferred to COBie; (2) retrieving the corresponding Root of the IFC entity and append a unique string which is generated by an algorithm to compile the name of component. However, this still remains as an open question.

![Inheritance Graph](image)

**Figure 57.** The inheritance graph of IfcProduct based on IFC4 standard

Spaces and zones are identified as the main data entities which all other datasets are linked to. In other words, to get the detailed information about any component/element, the first question asked in practice is “Where is it located in?”. The answer to this question changes either as “Space”, usually for individual components/elements; or “Zone” for the systems and/or central units, especially to define the service areas which are served by the MEP systems, zones become an essential data entity. However, the wrong practices while defining the zones, resulted a totally empty “Zone” workbook in the COBie spreadsheet and VisualCOBie. The researcher identified two wrong practices with identifying zones. The first practice includes the definition of zone data (only the name) as an attribute of the dependent IfcSpace or IfcProduct entity. Thus, both in VisualCOBie prototype and other open-source/commercial tools, the zone name appears as a PropertySet of the space or component. It is obvious that with this approach it is not possible to get other zone data attributes as specified in the COBie standard. The second practice is about merging a group of spaces together to represent the zone, but defining these space groups again with another IfcSpace element in the design tool. This practice causes two problems: (1) by default, the zone information cannot be exported to COBie spreadsheet with IfcSpace since converter is looking for the IfcZone entity; (2) It generates another visual layer in the interactive 2D/3D model, and when the end-user clicks one of the space element, the entire space group (so-called Zone) is selected. Although this was not the case in a commercial tool, the 2D/3D model viewer of VisualCOBie prototype (based on BIMview.ws) revealed this problem.

Integration of COBie data set and case company’s proprietary system data inside VisualCOBie prototype was the biggest effort spent during the hackathons due to the above-mentioned reasons. In any other object-oriented data integration practice, a unique identification for each data entity is needed as the PK to map with other entities by using that PK and the FK of the associated data entity. In COBie standard, the PKs are clearly defined as the “name” attribute of the corresponding IFC data entity as well as where they are used as FK in other workbooks. However, due to above-mentioned reasons, the integration could not be
Validation Studies for Visual COBie Approach and Prototype

possible in the beginning since different sources were not using the same PK (entity names). Additionally, the researcher found some building elements having the exact same names which breaks the “uniqueness” requirement to be a PK as defined in COBie standard. It should also be reminded that the majority of building element/component names were defined under PropertySets. As another option to solve this problem, the GUID numbers in the IFC file were considered for use as the PK. However, two major issues emerged in the usage of GUIDs in IFC file: (1) the special characters inside the GUID strings such as “$”, “%”, “&” fails to capture GUID string completely during the API requests between the systems; and (2) generation of new GUID numbers in the design tools is possible when there is a revision in the model. For example, an already modelled mechanical component, which already has a GUID number, can be removed from the model during a revision; and if the same components (with the exact same properties) is decided to be installed and defined again in the model, the design tool generates a new GUID number for the same component. This can cause losing track of the data coming from the COBie export. The first issue regarding the special characters has been solved by converting the GUID numbers in the IFC file (so-called short GUID) and generating another GUID number (so-called long GUID) without the special characters to eliminate the problem. This newly generated GUID numbers have been transferred as the unique identification. However, the second issue could not be solved efficiently during the hackathons. The regeneration of GUID numbers for such scenarios in the design tools has been referred as a common problem for almost all BIM-based modeling, design management, and data management practices which requires a deep investigation and a separate intensive research and development effort with the core of the BIM applications. Therefore, this problem was not taken into the scope of this research.

5.4 Summary of the Chapter

The discussions to validate initial problem statements. The needs and requirements for the Visual COBie approach summarized that the extra work to discover, understand, manipulate and manage data, push some users away from adopting a COBie-based process even if it provides considerable benefits for the FM information delivery and the associated tasks. Therefore, it can be argued that the information management issues and process view of data integration and handover were the key factors so far in COBie standard, while the usage and usability factors have so far been overlooked. However, it is a separate question and maybe a research topic whether usage and usability issues should be included in an information exchange standard such as COBie.

During the discussions, the explicit presentation of the semantic links was found to be innovative, facilitating the navigation between different data sources. Since the data is linked with each other, these semantic relationships provide an extra layer for the queries as well. 2D/3D models are expressed as the most important layer for the end-user such that the end-user not only wants to access the data, but also wants to query the data over this layer. The case company has already experienced the utilization of 3D models in their practice. Therefore, 2D/3D model integration was not found to be that effective. Nonetheless, the collected feedbacks and requests of the focus group meeting participants provided valuable direction for the enhancement of 2D/3D models.

As discussed and validated during the meetings, the problem of ignoring the usability and end-user perspective is not limited with COBie, but it is a typical trend in construction tech-
technology related developments. Not surprisingly, many of these technological developments fail to reach the desired rate and desired level of adoption, because users find them difficult to use, despite their operational and technical capabilities. Therefore, the employed theoretical concepts such as Gestalt principles and concept mapping were found as valid concepts for this research and the development. Although the case company representatives were not introduced to the theoretical background of this research initially, their feedbacks and requests indirectly referred to those concepts on several occasions. This also shows the lack of consideration for the usability and end-user perspective for the developments in AEC-FM industry.

In addition to the theoretical background, the implemented technical system was also found to be effective. In particular, organising the data in a graph database proved the potential enhancements to the case company’s existing systems in terms of information query with an additional semantic layer. Besides, the interactive UI of the VisualCOBie platform and the backend functionalities convinced the participants that the integration of variable sources is not only hidden in the backend of the systems, but also available visually on the UI. During the meetings, it was also observed that when users start to see the data visually connected, they also start to think what else can be integrated, or what else do they want to see on the VisualCOBie UI for their specific tasks.
6. Agile Development Cycle: from VisualCOBie to VisuaLynk

Design Thinking and Agile Methodology can be considered as two different concepts, with the two being viewed as separate and independent of each other. Agile is primarily about the “how” of a project, in which planning is done in chunks rather than as a whole; and, the scope of work is usually variable with Agile. Design Thinking on the other hand, is about exploring and generating ideas, understanding users, and innovating to meet customer needs. In other words, it is about the why. But while there are differences in these approaches, they are also complementary in many ways. Both these approaches amplify the innovation process, and facilitate iteration cycles whereby the understanding of the problems and solutions co-evolve, providing deeper understanding of the problem context. From this perspective, both these approaches collectively contributed to both the flow of research as well as the corresponding development of the proof of concept. The focus group meetings with the case companies and the hackathons compose the last step “Test” of the applied methodology. However, each “last” step is the beginning of the continuous iterative process loop to revise, implement, and update the proposed solution. Accordingly, the initial plans and the framework of this research have been revised, based on the outcomes of the research steps; and, the validation studies and the corresponding implementations enhance the perspective, opening new research questions for investigation. While all initial research questions are presented in Chapter 1 to contextualize the objectives and the flow of this research, the following research questions were added later to the research framework after the validation studies.

Research Question 8 (RQ8): What can be the other system and usability requirements for further development? What could be the new theoretical approach for such a development?

The iterative process of design thinking and agile development improve the initial VisualCOBie approach with the revised set of needs and requirements. In this chapter, the revised version of VisualCOBie, called “VisuaLynk” is presented with the relevant reasoning, applied technical improvements, and the employed theoretical background.

6.1 Fragmentation in “One Size Fits All” Solutions

During the validation studies and hackathons, fragmentation has been identified as one of the major problems in AEC-FM industry. Fragmentation refers to the number of distinct and loosely connected companies/actors involved in construction projects, and consequently, the multiple, loosely and poorly connected, processes and tools in construction projects. In the context of AEC-FM industry, fragmentation is defined as the division resulting from the increasing number of professions, organizations and technologies involved in all processes of a building project (Abadi 2005). Fragmentation in AEC-FM industry was not the core focus of this research, and it requires a separate and thorough study in itself. Nonetheless, during the
validation studies and hackathons, fragmentation emerged as a major factor associated with the usability features and functionalities of the applications and the data structures used in the AEC-FM sector. Therefore, fragmentation was also taken into consideration from the technological and usability contexts in this research by adding them as supplementary questions to the main research problem.

The monolithic and centralized configurations of the majority of IT solutions in AEC-FM industry is often designed and expected to meet varied needs of the end-users. However, as is the case with any standardization practices and corresponding IT developments/solutions, this expectation usually fails because the industry, project, and organization level fragmentation bring unique needs, requirements, and practices. Therefore, it is unreasonable to expect that such standardizations and associated IT solutions should meet all sorts of unique needs, requirements, or problems. Consequently, despite of the numerous established IT solutions, including BIM solutions with predefined, structured/standardized datasets such as IFC or COBie, hundreds of customized IT applications/platforms are developed on top of, or in parallel with, the standardized IT solutions with their unique information structures, functionalities, and formats. This customization requirements and practices raise some unanswered questions about the scalability and flexibility of these standards and corresponding solutions.

Based on the outcomes of the focus group meetings, hackathons, as well as the feedbacks from the pilot cases, these questions can also be associated with usability problems. After the data sets are generated from the “one size fits all” platforms, processing, understanding, and utilizing the information is primarily based on the end-users’ perceptions and comprehension of the dataset. If the end-user finds the dataset difficult to use, or cannot find exactly what he/she is looking for (even if it is there), then the typical solution is either to create another custom-micro-data structure on top of the standard output or to completely ignore the problem and never use the standard output data, often leading to the situation where end-users continue using their own traditional approach to doing things. This problem escalates if the end-user has to deal with multiple data sources. In the initial phases of this research, VisualCOBie approach only handled the COBie standard, to examine and investigate the answers for the problem statement and associated research questions. In addition, the applied case studies and the hackathons went beyond the COBie standard with integration of the case company’s proprietary solutions’ data with the COBie dataset. The validation analysis showed that VisualCOBie approach has been successful to enhance the usability of COBie and other datasets coming from different sources; as well as eliminate gaps in visual cognition with its interactive node-link diagram, and the associated visual perception principles. However, new needs and requirements emerged during these hackathons.

As described in Chapter 5, the hackathons were focused on the integration of one of the case company’s proprietary solution and VisualCOBie prototype, to send and receive digital data between each other. In this implementation, many updates were needed in the source-code of the VisualCOBie prototype to meet the requirements and needs of the case company. During such implementations for the other case companies, which are not reported in detail in this thesis due to confidentiality restrictions, the researcher had to update the source code based on the company’s unique data structure adopted in another proprietary software they use. In addition, the data transfer between the different sources also needed different configurations in the API modeling. All these means that for the implementation of VisualCOBie platform with different companies and projects, majority of the source code has to be modified again, taking into account their unique data structures and requirements. Although Vis-
ualCOBie approach and platform is validated for the usability and functionality in terms of cognition, as specified in the initial problem statements; the scalability and flexibility of the implementation was limited due to the technological and digital fragmentation of the systems. This also adds limitations for the new usability requirements.

### 6.2 Revision of VisualCOBie for New Requests and Requirements

The “ideate” phase of the design thinking methodology (Section 4.3.1) presented the Gestalt Principles and Concept Mapping as the main theoretical concepts in this research. These concepts also shaped the essential requirements for the defined problem statements, as well as the corresponding computational prototype. As presented in Section 5.3.2, the research and development work with the case company focused on the integration of different systems, which require reconfiguration of the backend and the frontend of VisualCOBie prototype. During the focus group meetings, there were specific requests associated with the interaction of end user with the UI to generate, manage, and visualize the data. Table 12 presents the summarized problem statements, already implemented solution proposals, and the new usability and functionality requests for the VisualCOBie prototype (Figure 58).

![Figure 58. Discussions on the use case evaluation and new requirements](image)

To reflect the case company’s needs and present the corresponding requests in a simple way, they are presented in simple natural language form. Although these requests were initially handled as usability improvements in this research, associated technological improvements have been considered.

<table>
<thead>
<tr>
<th>Problem Statement</th>
<th>Solution Proposal</th>
<th>New Request/Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Cognitive Load of Textual and Numerical Data</td>
<td>A representative figure with a descriptive label for data entities</td>
<td>“What if the figure does not make any sense?”</td>
</tr>
<tr>
<td>Lack of Visibility of Semantics and Data Dependencies</td>
<td>Node-Link representation with explicit relationships</td>
<td>“Can we dynamically define relationships that we want?”</td>
</tr>
<tr>
<td>Lack of Navigation and Query Capabilities</td>
<td>Navigate-Search by data group</td>
<td>“Similarly, can we define the data groups, entities and properties to build customized search?”</td>
</tr>
<tr>
<td>Lack of 2D/3D BIM Integration to the Visualization</td>
<td>Integration of interactive 2D/3D model</td>
<td>“We want to see the linked data on the 3D model”</td>
</tr>
</tbody>
</table>
Lack of Data Generation, Integration and Control Mechanism

| Initial control functionality to keep the data history |
| "There should be data generation and control mechanism based on user’s role" |

From the theoretical point of view, the first three requests (blue color-coded) were considered important for this research, because the participants representing the case company recounted similar experience that mind mapping tools provide, and requested building further on that analogy. Similarly, the requests regarding improvement in links to 2D/3D models (orange color-coded) both validated the initial problem statement regarding the lack of 2D/3D model integration to COBie dataset and the corresponding solution proposal with BIMServer and BIMSurfer for the prototype development. This request was important for this research, because the end users wanted visual experience that correspond to the Gestalt’s visual perception principles, without explicitly knowing about these principles. This request also formulated a new role for the VisualCOBie approach as an additional layer on top of BIM platforms to link and enrich the IFC models. As it is detailed in coming sections, the computational functionality of this request is associated with the first three requests (blue color-coded) to include the 2D/3D models as the part of mind mapping concept. Similarly, the last improvement request (green color-coded) was taken into consideration. In this request, the prototype development is reconfigured with different user roles, associated CRUD and approval rights. Although this request is not directly related with the applied theoretical principles of this research, it validated the initial problem statement associated with the lack of data generation and control for COBie spreadsheet representation as well as provided functionalities for the use of VisualCOBie approach in industry. The new functionalities allowed the end user to define and limit the access rights of an individual project member.

6.3 Implementation of Requests

As explained in Section 6.1, the new improvement requests led the researcher to expand the scope and functionality of the VisualCOBie prototype. As part of the iterative steps of the applied design thinking and agile development methodologies, the “revision” of the existing prototype moved VisualCOBie prototype beyond a visualization and navigation tool for COBie standard to a platform for flexible and scalable data integration, management, and interoperability for facility lifecycle. This step also represents how the applied theoretical concepts of this research fit into the evolution of the research and prototype development. The initial development primarily focused on the application of Gestalt’s principles to enhance the usability of COBie spreadsheet. In addition, the mind mapping concept inspired the researcher to enhance the visualization features. Nonetheless, the initial prototype was limited to actions that can easily be handled with a mind mapping software for creating nodes, visualizing node-link with figures, and associating them with other branches etc. directly from the UI. Therefore, majority of the new requests referred to implementation of these actions.

As a recap of the relevant literature, mind mapping is defined as a technique which can demonstrate how people visualize relationships between various data groups (concepts). From visual perception perspective, mind mapping provides a visual representation of dynamic schemes of understanding, and associate the data groups and entities with each other within the human mind (Tolman 1948). Mind maps can include descriptive labels, links, hierarchies with all sorts of visual and graphic representation of concepts and propositions that attempt to convey an understanding or relationships among different data groups and enti-
ties within a map which is also one of the proposed enhancement with VisualCOBie approach (Section 4.3.1). Although the VisualCOBie approach presented the basic features to “visualize” the data in a node-link diagram which is similar to visualization of concepts in a mind map, there is still the need for functionalities to generate and control the data within the mind mapping concept. This has become one of the main features of the revised development, VisuaLynk. Further, the following sections review the questions relevant to the VisualCOBie/VisuaLynk concept representation.

6.3.1 “What if the figure does not make any sense?”

For the problem statement “High Cognitive Load of Textual and Numerical Data”, VisualCOBie prototype proposed the representation of the data with a sensory symbol (a figure) that recalls the meaning the of the data group or entity as well as a descriptive label to show its data group or entity name. The “past experience” principle of Gestalt has provided the reasoning for this solution proposal. However, during the focus group meetings and hackathons, some of the figures assigned to data entities/groups did not make any sense for the end user. Therefore, they wanted to have the choice to define these figures and labels by themselves, with potentially stronger recall value and greater familiarity or connection with their past experiences. This request supports Gestalt’s principles for visual perception and the mind mapping as the core theoretical aspects of this research. With a custom defined figure and label, the end user facilitates his/her visual perception with the “past experience” he/she has, as well as can visualize the data entity/group just like in a mind mapping software allows. This requirement is satisfied by configuring the backend and frontend code of the VisualCOBie prototype, allowing the user to select and assign the figure via drag and drop on the UI and define the descriptive label for the data group (Figure 59).

Figure 59. Assigning the custom figure and descriptive label to Root-Node

This interaction captures the link (imageURL) of the selected figure in the folder directory, and dynamically injects this link to the relevant components and services of the application. It injects itself to the query chain with the parameters defined by the end user on the UI (e.g.
node label, figure URL) and dynamically updates the data ontology in the graph database with the generated query.

Assigning the figure dynamically has only been applied for the Root-Nodes. As it can be seen in the example (Figure 60), the end user defines a new Root-Node, provides the Node Label as “CUSTOM_NODE”, defines the individual properties of the Root-Node, and uploads the associated figure on the Node Icon section of the UI. After that, the user can connect another data source via relevant API to populate the Node Entities; or define node entities manually on the UI with the values of defined properties. Either way, all node entities will have the same Root-Node figure, but different descriptive labels (e.g. names of data entities) on the node-link diagram.

**Figure 60.** Dynamically generated Root-Node on node-link diagram

### 6.3.2 “Can we dynamically define relationships that we want?”

For the problem statement “Lack of visibility of semantics and data dependencies”, VisualCOBie prototype proposed the interactive node-link diagram which includes multiple Root-Nodes, associated Node Entities and the assigned relationships between each other. The underlying theoretical concepts behind the node-link diagram (Section 4.1.3) have been validated in the focus group feedback. However, in the initial VisualCOBie prototype, the labels and properties of data entities and relationships were hard coded within the converter written by the researcher. With such a standardized/predefined approach, the dynamic and custom definition of node entities and relationships were not possible. The revised prototype, VisualLynk, eliminates this limitation as requested by the pilot end users. While the initial VisualCOBie prototype provided relevant visual perception principles, this functionality provides flexibility and functionality of the mind mapping concept, making a technical contribution (Figure 61).
Figure 61. Assigning relationships dynamically

Similar to the first requirement, this functionality is implemented by configuring the backend and frontend codes. In VisuaLynk, the end user can select the associated Node Entities as the start and end nodes, define the direction of the relationship between selected nodes to establish from or to relationship logic, and assign a label of relationship dynamically. In addition, the already created relationships can be updated from the UI as well. This interaction;

- Traverses the graph data and matches the selected the start and end nodes in the database,
- Dynamically assigns the direction and the label of the relationship,
- Builds the relevant queries with the parameters defined by the end user on the UI (e.g. direction, label) and dynamically generates the relationship in the graph database.

The configuration for the dynamic definition of relationships in VisuaLynk has only been applied for the individual Node Entities. However, when the Node Entities become related with each other, the associated Root Nodes are automatically updated with the these relationships and can be discovered in the node-link diagram (Figure 62).
6.3.3 “Can we dynamically define relationships that we want?”

For the problem statement “Lack of navigation and query capabilities”, VisualCOBie prototype proposed the navigate-search by data group and navigate-search by dependency functionalities, presented in Section 4.1.3. During the focus group meetings and the hackathons, these functionalities facilitated the navigation and search of associated data entities in the abstract node-link diagram with the minimum amount of interactions. However, the initial VisualCOBie prototype provides this solution for only the nodes and the relationships that are hard coded in the written converter. The theoretical aspects for visual perception (Section 3.7) of this functionality have been validated and found useful for the case company. Besides, performing the navigation and search on the node-link diagram provided the mind map-like interface to the end user. However, there is still a limit for the flexibility and the scalability for the initial prototype. In VisuaLynk, this functionality is enhanced with the concept of mind mapping which includes the generation of individual data entities and their property values dynamically by the end user. The previous functionalities for the dynamic definition of the Root-Nodes, Node Entities and relationships (Sections 6.3.1 and 6.3.2) are expanded by integrating them with the previously developed navigate-search by data group and navigate-search by dependency functionalities. In other words, when the user defines a new Root Node, Node Entity or relationship, the generated data is chained up in the existing query system without any extra configuration (Figure 63).

![Figure 63. Dynamic generation of Node Entities from UI](image)

Similar to the requirement presented in Section 6.3.1, this requirement is satisfied by configuring the backend and frontend code of VisualCOBie prototype which allows the user to define individual node entities of a Root Node by defining the label, GUID number (for BIM integration), as well as the values of the defined properties of the associated Root Node. This interaction:

- Captures parameters of the Node Entity with the default parameters and property values,
- Connects the GUID number with the BIM data,
• Builds the relevant queries with the parameters defined by the end user on the UI and dynamically generates the data entity in the graph database with the generated query.

After defining the node entity, the application transfers the relevant parameters to the associated components and services of the application chain the new data to the search and navigation functionalities (Figure 64).

![Figure 64. Generated Node Entity integrated with search and navigation functions](image)

### 6.3.4 “We want to see the linked data on the 2D/3D model”

In the initial prototype development of VisualCOBie approach, the integration of dynamic 2D/3D model has been established by integrating the BIMServer and BIMSurfer; as well as using IfcOpenShell library to generate 2D floor plans in the application framework. In addition, the revision of prototype has been tested with the relevant WebGL libraries and game development engines for the 3D models generated from IfcOpenShell conversions. During this process, there has not been an intense development on 2D/3D model integration for the employed theoretical aspects of this research, and the corresponding libraries have been used as default. However, during the focus group meetings and hackathons, there was high demand for the configuration of 2D/3D models of the buildings to represent the component groups, systems, zones, etc. In addition, representation of IoT data on the 2D/3D models directly have been implemented and tested during the hackathons, based on the user requests.

These development attempts have been considered novel and reinforced the need of 2D/3D models for generating and managing data in the VisualCOBie approach. Besides, it was observed that the case company was eager to experience the proposed usability features and functionalities of VisualCOBie approach directly on the 2D/3D model as well, such that:

- The linked building data should be able to visualize directly on the 2D/3D model,
- The end user should explore the relationships of building data by selecting multiple elements from the 2D/3D model directly, while they are able to define the degree of dependency among those elements.
• The end user should enrich the BIM data with dynamically generated new Root-Nodes, Node Entities as well as define custom relationships by interacting 2D/3D model directly,

While the initial VisualCOBie prototype did not provide these features, the revised development, VisuaLynk, handled these requests in its development since they contribute the theoretical and technical outcomes of this research. The BIMSurfer library, as the core 3D model viewer, and the generated 2D floor plan in .svg (scalable vector graphics) format has been modified and integrated with the core development framework of VisuaLynk application. This development addresses

**Visualization of linked building data directly on the 2D/3D model**, (1) the bi-directional parameter transfer between the graph database of VisuaLynk and the 2D/3D model, pass the corresponding variables of the linked building elements to the BIMSurfer; (2) BIMSurfer fades out the visibility of all the elements except the linked building elements; (3) at the same time, the location data of the elements are retrieved from VisuaLynk and highlighted on the 2D floor plan.

*Figure 65. Generated Node Entity integrated with search and navigation functions*

**Exploring the relationships of building data from the 3D model**, (1) The BIMSurfer library allows the end user to select multiple building elements from the 3D model. For example, like in Figure 65, two window elements were selected (transparent green color). Upon selection, the relevant parameters of the selected elements are passed to VisuaLynk to query the elements and their relationships; (2) the node-link diagram pops-up and shows the selected elements and all the relationships between each other (under development); (3) if the user wants to add new data with individual properties, he/she can apply the functionalities presented in Section 6.3.1-3 to generate new Root Nodes, Node Entities and define relationships;

**Defining the degree of dependency to visualize related building elements**, (1) As the continuation of the previous improvements, the end user can define the degree of dependency to show, for example first three or four relationships which have a high connection density with other nodes (under development); (2) and applies the necessary functionalities described above based on the use case.

The implementation of the requested functionalities based on the feedback expands the initial VisualCOBie prototype as scalable and flexible data generation platform with the employed mind mapping concept. However, the importance of the improvement request for the integration of 2D/3D model is twofold: (1) the integration of the proposed functionalities provides a new layer on top of the BIM platform to link and enrich the BIM/IFC model with external data sources from the UI directly; (2) although some of the functionalities are still under development by the time this research reported in this thesis, the theoretical perspec-
tive behind these requirements validates the problem statements, theoretical and technical contribution of this doctoral study.

6.3.5 “There should be data generation and control mechanism based on users’ role”

For the problem statement “Lack of data generation, integration and control mechanism”, initial VisualCOBie prototype proposed the history tracking of the generated data entities with a “HISTORY” Root Node associated with the corresponding Node Entity. In addition, the elimination of potential data duplications in the COBie spreadsheet has been targeted in the developed prototype. As mentioned in Section 4.1.3 and in this chapter, dynamic definition of the Root Nodes, Node Entities and the associated relationships from the UI have been presented as part of the data generation mechanism. The management and control mechanism has not been handled in the initial phases of this research. However, during the focus group meetings and hackathons, these set of functionalities are referred as an essential requirement for the industrial use of VisualLynk application by the case company. The practical implementation of mind mapping concept for the implementation of VisualLynk empowers the user to generate their own data groups and entities, and assign meaningful relationships between each other. These features also support the theoretical contribution of this research and provides the user the flexibility to create their own data structure. However, due to organizational hierarchy of a company and assigned responsibilities to the staff, this flexibility may not always be suitable for the use of VisualLynk application in industry. Therefore, role-based constraints are defined in the VisualLynk application to allow or limit the end user for data generation based on their roles and positions in the organizational hierarchy.

The new functionalities of this request are categorized under two groups:

1. Control and management of the visibility of the data and
2. Control and management of the generation of the data.

The visibility of the Root Nodes, Node Entities and the relationships between them are associated with both the company of the end user works for, and the “Portfolio Owner’s decision. In other words, the imported and manually created data is separated for each company which is registered in VisualLynk application, so the each company is able to see the data which is generated by themselves; and the portfolio owner of an individual company is able define which Root Nodes should be visible for the end users of the same company by selecting them from the UI (Figure 66).
For the control and the generation of the data, two major functionalities are implemented in the VisuaLynk application. The “permissions” function defines the CRUD rights for the each user logged in VisuaLynk application for Root Nodes and Node Entities. The portfolio owner can assign and limit the rights of individual users based on the requirement. In addition, by considering the organizational hierarchy of the company, specific approval conditions can be assigned for different user groups. In this functionality for example, the portfolio owner can rule project manager for the Root Nodes and Node entities which he/she generated, deleted or updated within the application to be approved before the data is utilized in VisuaLynk database (Figure 67).

Compared to the other improved functionalities in the revised development, this functionality does not directly contribute to the visual perception principles of this research study. However, it is supporting the usability, flexibility, and scalability of the visual perception and mind mapping concepts based on the rules of organizational hierarchy of the corresponding user company.

6.4 Initial Tests of VisuaLynk with Web of Building Data

The representation of digital information in AEC-FM domain can be assumed as the core starting point of this doctoral research in which the main focus has been to examine the usability and visualization of data based on relevant theoretical concepts. The revised version, VisuaLynk, expanded the initial technical scope of VisualCOBie with its dynamic data generation and control mechanism while keeping the visual perception and mind mapping in its roots. The implementation of this expansion has been tested with the case company to link the proprietary solutions data with the COBie dataset. In addition, the integration of open BIMserver to VisuaLynk’s application framework, provided new opportunities for the end user to link and enrich IFC data entities with external data sources from the UI directly.

However, this integration needs the Neo4j graph database as another layer and the data is linked locally with the representative IFC Node Entities in the Neo4j, but not in any global manner between IFC entities. Although this is not a major limitation for this research or for the development of VisuaLynk system, for large scale implementation this framework can become computationally expensive. Consequently, even though it was not in the scope of this
research, the research team has investigated alternative approaches for this issue both to improve the technical contribution of the iterative agile development, and also to maintain the continuous theoretical contribution for the academic studies that is conducted in the AEC-FM domain. From this perspective, the usability of VisuaLynk application has been tested with Web of Building Data (WoBD) approach.

WoBD is an approach to publish the structured data to be interlinked with each other and become more useful through semantic queries. Data is represented with the Resource Description Framework (RDF), a graph-oriented data model in which the nodes are identified with Web addresses, that is, Uniform Resource Identifiers (URI). The Web Ontology Language (OWL) is used to define the shared vocabularies used in RDF graphs to specify node types and property names (McGuinness & Van Harmelen 2004). Simple Protocol and RDF Query Language (SPARQL) enables advanced querying and updating of RDF graphs. The WoBD approach allows to connect various resources from different domains on a global scale and makes the query of data through the different sources straightforward. With these possibilities, the Linked Data approach can be considered a useful set of technologies to address and recall the theoretical and technical contributions of this research. For AEC-FM context, the linked data approach is being researched and developed by the buildingSMART Linked Data Working Group which is responsible for the development and maintenance of the ifcOWL ontology as an OWL equivalent of IFC schema originally specified in the EXPRESS data definition language. The ifcOWL ontology is aimed to be used in the Linked Data and Semantic Web based applications that consume the IFC data. Within the scope of on-going and completed developments, several IFC-to-RDF conversion tools are available with the capability to translate the building information exported as an IFC file to an RDF graph representation. In addition, different mechanisms are available to combine URIs of RDF resources with relevant HTTP methods to create REST APIs for resource management of Linked Building Data (Pauwels & Van Deursen 2012; Beetz et al. 2009; Törmä et al. 2012; Hoang & Törmä 2017).

Both VisuaLynk and WoBD use graph databases as a main storage mechanism. The current version of VisuaLynk uses the Neo4j database based on a property graph model while WoBD can use any of the standard-compliant RDF databases, a number of which are available both freely and commercially. Neo4j has its own query language called Cypher while RDF stores all support the SPARQL language. Although there are more detailed differences between property graph databases and RDF databases, one can say that VisuaLynk handles the data in a similar form and logic but with a different syntax for semantic reasoning. On the other hand, the flexible and scalable configuration of VisuaLynk is able to handle different data sources stored in different formats. To validate the applicability of VisuaLynk for Web of Building Data (WoBD), the integration of VisuaLynk with DRUMBEAT platform (Hoang & Törmä 2017) has been tested during the research process.

DRUMBEAT platform is an open-source, proof-of-concept implementation of WoBD framework produced in the DRUMBEAT research project (Hoang & Törmä 2017). While DRUMBEAT stores all RDF data in a RDF database which saves every dataset in a separate RDF graph, it also stores the non-RDF data as files in the file system. However, depending on the file type, DRUMBEAT can convert it to RDF format and then store both RDF data and the compressed original file as a reserve copy. Besides, RDF databases have one specific RDF graph called the default graph that is used to store metadata description about different datasets. As mentioned before, in IFC models, all significant objects have a GUID as an identifi-
DRUMBEAT uses these GUIDs to derive the URIs for these objects that can be used as unique handle to access the detailed data about the object. The following is an example of a URI of one building object:

https://ex.com:1234/objects/site1/architectural/F414F4F2-4D02-4B2A-8CCF-4D02F414F4F2. (this is a dummy link to represent a sample URI)

In addition, with the DRUMBEAT REST API configuration, various queries can be run based on use case scenarios. The full-scale integration of VisuaLynk with DRUMBEAT platform is yet to be fully developed and is not in the scope of this doctoral study. However, from the usability and visualization perspective, VisuaLynk platform can handle the RDF data via the URIs of individual data entities. In the initial tests:

- URIs of the RDF have been defined as “URI” property of the corresponding Node Entity in the graph database,
- This URI is passed as a hypertext reference (href) of the associated label of the node entity on the frontend configuration,
- The label of each node entity is bound to an onClick event that makes a HTTP request to the host specified in the URI. The host performs a URI lookup function and returns the description of the identified object back to VisuaLynk to be presented in the user interface.

With this configuration, the WoBD graph has been successfully visualized in VisuaLynk application. However, this does not make VisuaLynk yet a full-fledged WoBD application or compatible with other Linked Data solutions since there are major differences in the data format, storage mechanism, query language, and semantic reasoning. Nevertheless, this experiment has opened new dimensions for the future development and continuation of this research study.

### 6.5 Summary of the Chapter

The discussions to validate initial problem statements, needs and requirements for the VisualCOBie approach continued with the focus group meetings and hackathons with the case companies to receive their direct feedback and further needs/requirements refinement and requests within the framework of design thinking and agile development. The validated usability and functionality solution proposals for the VisualCOBie prototype has been found successful for the visualization of both COBie and the case company’s data coming from different sources. Although the visual perception and concept mapping as the employed theoretical concepts of the research have not been introduced directly to the participants, relevant feedbacks referred to the similar aspects of these concepts. In addition to the improved visual features, there was a need and interest in generation and control of the data. Therefore, the new requests for iterative development focused around these needs.

During the hackathons both the case company and the research group experienced the need to update the source code of VisualCOBie approach for data generation and control. This issue was critical because different companies have different data structures. As noted previously, conceptual mapping is the main theoretical aspect behind the revision of the initial prototype, because the case company referred many needs that can be addressed in a mind mapping application. Therefore, in the revised implementation named VisuaLynk, the researcher focused on the dynamic update of both the backend and frontend code from the UI directly, and the application is re-configured for this flexibility. In this step, relevant func-
tionalities are implemented which allow the end user to generate Root Nodes, Node Entities with the corresponding labels, figures, and properties; as well as to link them to each other with meaningful relationships. These features provided a mind mapping like platform for the end user who can define and organize their own data structure in the application directly from the UI. In addition, the existing node link diagram with the new functions are integrated to the BIMServer to establish the connection with IFC data which makes VisuaLynk an application that is able to handle and process the standardized building data such as COBie and IFC, and also present the flexibility to the end user to build-up on top the existing standardized data sources and IT solutions with its scalable and flexible data generation and management functionalities. In other words, VisuaLynk becomes another layer on top of the standardized IT solutions which can link and enrich the building lifecycle data coming from various standardized or plug-in IT solutions. Based on the new features, VisuaLynk can be referred as a mind mapping tool which can process standard digital building data formats.

Additionally, this chapter presented the initial test of VisuaLynk development for the utilization of WoBD. Although the technical configuration of VisuaLynk is based on different technologies than the ones used in WoBD-based solutions, the visualization of WoBD has been established in the VisuaLynk application which also opened new dimensions for the continuity of this research for future studies.

The employed theoretical aspect with the implemented functionalities answer the RQ9 “What can be the other system and usability requirements for the further development? What can be the new theoretical approach for this?”, within the context of this research. However, it should be noted that the theoretical and technical contribution of the improvements presented in this research cannot be considered as the complete answer for this question. Instead, it is one alternative solution proposal among many other solutions which can be associated with various theoretical and technical aspects.
The standards for AEC-FM industry and data specifications are increasingly being prescribed in several countries by large clients and mandated by governments. Such standards specify the information sources, structure, and exchange formats that have the potential to improve upon the traditional practices of information handling throughout the different phases of a building lifecycle. Despite such standardization efforts and associated IT developments, which have been approved, technically verified, and tested by many organizations for years, the AEC-FM industry is still suffering from inefficient information management. To date, most initiatives have focused on utilization of the outputs of different software applications in terms of accuracy and completeness of the data defined in the standards. However, there is lack of investigations that endeavour to benchmark such outputs against the representation and usability of the outputs. This research is built on the premise that developing standards and corresponding IT solutions is not merely a technical issue, but it is equally important to understand how they correspond to the processes, how people use them, and how they are supported or inhibited by the technical implementation. In particular, this research focused on how the users interact with and understand these standards and IT solutions, and what can be done from the user point of view to facilitate wider utilization of these standards in practice. Until now, the usage and usability factors associated with AEC-FM standards has remained largely overlooked, indicating a gap in the literature. This gap was considered as a potentially significant factor in the adoption as well as effective utilization of such standards and advanced solutions in the AEC-FM industry. Therefore, from a conceptual and theoretical viewpoint, this research aimed to address this gap in understanding and enhancing the usability aspects of standards.

The investigation and results of this research were presented around COBie as the case standard. The main motivation and reason for choosing COBie as the case was threefold: (1) it is specifically developed for the post-construction phase of the project in which the data generated in previous phases are to be handed over. Therefore, COBie covers a wide range of facility data that can come from various sources; (2) although COBie has emerged as one of the predominant and widely accepted standards in BIM for FM, there is almost no usage of COBie standard in Finland, where the research has been conducted; (3) since COBie is defined specifically for BIM-FM use case, and technical solutions in the BIM-FM use case are still to mature to the same extent as what is available for pre-construction phases, there is greater opportunity for technical interventions and experimentations on top of COBie to facilitate usability and adoption. Another motivation to conduct this research was to make technical contributions that address the needs and requirements of a generic, flexible, and scalable data integration, management, and interoperability platform for the AEC-FM domain. The objective of the technical development was to implement a proof of concept for a platform that provide features for better understanding, management, integration and in-
teroperability of data from varied sources while reducing the amount of effort in core configuration of the development for the various needs of the AEC-FM industry.

### 7.1 Findings from Research Questions

The wider adoption of BIM and the associated standards require a holistic approach including technology, processes, people and policies. Consequently, in this research, the development of standards was not only considered a technical issue, but understanding people’s perception of the standards and how they use them, was considered equally important. At the broadest level, the research problem focused on understanding and utilizing industry standards and associated IT solutions in AEC-FM industry. Following this problem statement, detailed research questions have been planned under three categories with the utilization of COBie as the case standard:

- Standardization process of COBie,
- Usability evaluation of COBie dataset,
- Requirements for enhanced development and representation of building lifecycle data

As presented throughout this thesis, utilization of COBie as the case standard in this research has been a valuable start point while the research questions were then evaluated for the building lifecycle data. This section summarizes the findings of the research questions.

#### 7.1.1 Standardization process of COBie

The research questions set for this topic aimed to explore and understand the underlying factors supporting the growing acceptance of COBie standard, and were mostly answered with the review of the relevant literature. In terms of standardization, COBie has remained stable for almost ten years now, and during this period it has continued to grow in terms of significance and approval from various industry groups. Based on the review presented in Section 3.2, the primary objective for the development of COBie standard is to overcome such challenges and limitations to deliver facility information which is prepared and stored in printed papers or in various IT tools that have their own data structure and format. The development process began in 2006 under NIBS FM and Operations Committee with the review of literature and private industrial/association efforts. The review focused on two aspects. First to determine the useful minimum in terms of specific information requirements, responsible actors and associated life cycle phases. Second, to define the exchange standards to eliminate existing inefficiencies in information exchange. The building lifecycle and the content of information in each data handover were evaluated based on business cases, specific business requirement, information handover plan, and implementation with software applications. Both association efforts and the practices of public industry and organizations played a vital role in the development of COBie standard, building on their existing standards and classifications in practice. As an output of this RQ, it can be summarized that, COBie standard provides an information structure template based on the composition of existing information specifications and exchange standard that have been in use for years. The main purpose of COBie standard is to provide an information structure and non-proprietary delivery format of COBie specification. COB was shaped to simplify the previous inefficient process of facility information handover.
The definition “information structure and non-proprietary delivery format” is an important aspect to understand the relationship of COBie with BIM/IFC and other IT tools, because technically, any information structure can be populated with data by hand, or with IT tools with the relevant technological infrastructure. At this point, the distributed source of various facility information makes the generation of COBie data challenging, which requires a common information format that contains the information requested in COBie. With the emergence of BIM in AEC-FM industry, IFC has become a valuable source to generate COBie data. In addition, many BIM applications provide different serialization of an IFC file together with the relevant international building data classification systems such as OmniClass. However, the digital building data stored in IFC is too large and complex to present the specific information requirements that COBie is asking. The minimalistic approach in the IFC’s development timeline provided the minimum set of information packages for specific lifecycle phases. As a result of this approach IDMs and MVDs were developed and became the official elements of IFC standardization. That approach also suited COBie, because FM-Handover MVD provided the exchange of digital information requirements, generation of data formats, and relevant IFC entities to generate the COBie data. This has made BIM as a complementary image for COBie. On the other hand, as stated earlier in the results of this research question, BIM/IFC is not an all-in-one or the only source for the information requested in COBie. Instead, IT solutions such as CAFM, CMMS are able to generate the COBie outputs when the relevant data export structure has been set.

### 7.1.2 Usability Evaluation of COBie Dataset

The research questions grouped under this topic point towards the existing limitations in the actual use of COBie despite the internationally growing stature of COBie standard. This limitation was also observed in Finland where this research was conducted. While almost all AEC-FM actors have heard of COBie, there is no practical use of COBie in Finland, and various actors continue to use their own data structures and custom ways of organizing their data. Therefore, this research based on the assessment that, among other regional factors, the challenge also lies in understanding and utilizing the COBie standard. The research questions started by introducing the existing spreadsheet representation of COBie data to briefly summarize the challenges hidden in the spreadsheet representation based on the review of literature about human-spreadsheet interaction. The most fundamental outcome of this review, as represented in the literature as well, was that the hidden dependencies of the data in a spreadsheet is a common problem in any spreadsheet structured data. Therefore, users can have difficulties to establish the semantic connections of the data within a spreadsheet. The tabular layout full of textual and numerical data increases this limitation since it does not show any direct mapping with the deep level. Besides that, the expanded literature revealed the problems regarding the size of data. The large size of data in COBie spreadsheet may result in the end user getting lost in the virtual environment, and in the process failing to achieve their original tasks while they are navigating among workbooks. Especially, in the tasks that require repetitive search, problems such as ‘getting lost’ can cause delays and high cognitive load on the end users, because they need to serially shift among different workbooks. The high cognitive load can also trigger mental workload by focusing and demanding attention on the interface instead of the original tasks. This situation can aggravate the problem when the user has to deal with multiple COBie spreadsheet files throughout the project timeline. In such a situation, the typical solution the end users adopt is to create another cus-
tom -micro- data structure to solve the problem quickly or totally ignore the problem and not use the existing data in their hand.

In addition to the issues above, the research questions under this group revealed that the default configuration of spreadsheet platforms, with lack of facilitating computational functions, limits the usability of COBie spreadsheet for the end users. For example, if the end user wants to check the dependent information sets of a specific data entity within the spreadsheet, he/she prefers a mechanism to see the dependent information on the UI instead of serially shifting among the workbooks. Besides, there is no direct integration between the COBie spreadsheet and the 2D/3D model (BIM model); or based on the project requirements, a control mechanism to populate and manage the COBie data may be required, which needs extra development. Similar problem statements have been presented in Section 3.5 and Section 4.1. The research questions under this group also referred to one of the theoretical aspects of this research, focussing on principles of visual perception. This theoretical aspect has been used to formulate detailed needs, requirements, as well as the validation of the contributions of this research.

7.1.3 Requirements for Enhanced Development and Representation for Building Lifecycle Data

The research questions grouped under this topic (RQ5-RQ9) are the ones that contribute to most of the outcomes of this research study in which various techniques and approaches were applied. Design thinking and agile development provide the main methodologies of this research by providing an iterative loop of investigation and development cycle to reveal and improve both theoretical and technical outcomes of this research. Design thinking was well-suited for this research in which the problem statement was too generic in the beginning; and facilitated the researcher with its focus on problem definition, problem shaping, and requirements classification. As the results of initial steps of design thinking methodology, this research grouped the common usability problems and solutions proposals in handling the COBie spreadsheet for:

- Reducing the usability issues due to high amount of textual and numerical data,
- Revealing the hidden semantics and dependencies of COBie data and visually presenting them,
- Providing a new way of navigation and query functionalities,
- Integration of 2D/3D BIM models and mapping COBie data entities with virtual objects
- Providing a data generation, integration and control mechanism

Each of the solution proposals for the above objectives were evaluated with different alternative approaches by considering the relevant principles of visual perception, and mind mapping as the other theoretical contribution of this research. Besides, these evaluations shaped the initial usability and functionality requirements of the corresponding solution proposals, which revealed the need for integration and linking various heterogeneous and fragmented data sources as one of the core technical aspects of this research. The initial prototype VisualCOBie, handled this integration requirement with its property-graph database which allows to define the missing semantic relationships between data groups and entities of COBie dataset.

This initial prototype has a three-tier configuration, which includes (1) user interface layer which provides the functionality in which the users can see and interact with the 2D/3D
models, facility information structure, and the node-link diagram of COBie data and the results of queries; (2) data integration and process layer that integrates the COBie dataset and the corresponding IFC file with the virtual models. During the research progress, this layer also handled the case company’s proprietary data structures; and (3) database layer which includes a property-graph database and the database of open source BIMserver. Although the prototype configuration could also be established with traditional SQL databases, establishing the many-to-many relationship structure (semantic relationships) would be very difficult. In addition, the data structure would be modelled in tables again. Therefore, the property-graph database was selected in this research for to define and manage the semantic relationships between data entities and provide a network model of the COBie data.

In the initial prototype, the proposed functionalities have been reasoned with the Gestalt’s visual perception principles as the facilitating concept for the corresponding problem statements. For example, the past experience principle has been taken into consideration for the high amount of textual and numerical data to allow the end user recall the overall meaning of the root-node or node-entity cognitively with a pre-attentive figure. Similarly, the explicit representation of semantic dependencies among the root-nodes and node-entities has been reasoned with connectedness principle. In addition to the visual perception principles, for the visual layout of interactive node-link diagram to represent the COBie data, conceptual mapping (mind map) has been considered as another theoretical background and a facilitating feature which provides a visual representation of dynamic schemes of understanding, and associate information entities with each other within the human mind.

The initial tests of the developed prototype were conducted with a common BIM model including the corresponding COBie spreadsheet data and documents to check whether the prototype development meets the technical requirements in terms of error-free and bug-free data transfer from the COBie spreadsheet to other information sources. In addition, these tests checked whether all mentioned usability and functionality feature are reliably accurate and consistent. In addition, the prototype development has been presented to the research-industry partners during workshop demos and meetings. The initial feedback indicated high positive sentiments towards the theoretical and technical development of VisualCOBie approach, which was seen as a novel and innovative approach to address a long-standing issue of technical and non-friendly interfaces in AEC-FM solutions in general, and not only limited to COBie standard and corresponding dataset representation. These positive feedbacks were further reinforced with commitment from industry partners to conduct preliminary pilot studies.

The pilot studies provided valuable inputs and opened new perspectives for the theoretical and technical contribution of this research with such new improvement requests. In this phase of the research, several focus group meetings and hackathons were conducted. In these hackathons, the VisualCOBie prototype has been integrated with the case company’s proprietary solutions to understand the potential challenges and requirement as well as to validate the usability and functionality of VisualCOBie prototype. The conducted pilot projects also revealed the common mistakes that industry actors make during their projects. The COBie output which is generated from a BIM file, looks for specific IFC entities which are defined in FM Handover MVD. The missing parameters in the BIM file are not reflected in the COBie output. For example, definition of entity names in the property sets resulted in unknown names for each entity in the COBie output. Similarly, zones have been defined by merging
Conclusion, Limitation and Future Research

spaces together and assigning them to a new IfcSpace. This resulted in an empty Zone spreadsheet in the COBie output.

During the hackathons, both the case company and the research group experienced the need to update the source code of VisualCOBie approach for data generation and control. This issue was critical because different companies have different data structures. This issue was taken into consideration for the further development and established fundamental theoretical and technical approaches. As mentioned in Chapter 6, conceptual mapping is the main theoretical aspect behind the revision of the initial prototype, because the case company referred many needs that can be addressed in a mind mapping application. Therefore, in the revised implementation, named VisuaLynk, the researcher focused on the dynamic update of both the backend and frontend code from the UI directly, and the application is re-configure for this flexibility. These features provide a mind mapping like platform for the end user who can define and organize their own data structure in the application directly from the UI. The integration of the node-link diagram with the BIMServer made VisuaLynk an application which is able to handle and process the standardized building data such as COBie and IFC, and also present the flexibility to the end user to build-up on top of the existing standardized data sources and IT solutions with its scalable and flexible data generation and management functionalities.

7.2 Contribution to Knowledge

This research makes a methodological, theoretical and technical contribution towards the understanding and utilization of IT standards in AEC-FM industry, corresponding to the detailed research questions, and by examining the usability challenges behind the COBie standard as case standard.

In terms of the methodological contribution, this research employs the design thinking and agile development methodologies together with the various supportive research approach, paradigm and validation approaches. In particular, conducting hackathons with the case company has been a promising experiment to understand how design thinking and agile development techniques can be performed within an iterative research and development cycle. Conducting hackathons as the part of the research methodology is fairly new, when compared to the existing research approaches in the AEC-FM domain.

The lack of investigation into the usage and usability factors associated with AEC-FM standards is a critical gap in the literature. This research built on the premise that this gap is a potentially significant factor in the adoption as well as effective utilization of advanced solutions in the AEC-FM industry. Therefore, from a conceptual and theoretical viewpoint, this research contributed to the existing knowledge by understanding, presenting, and enhancing the usability aspects of the AEC-FM standards such as COBie.

This research tried to reach a balance between AEC-FM standards that are applicable to the wider domain and still meet the unique requirements specific to each user and the diverse requirements of the fragmented industry. Therefore, one of the objectives of this research was to augment the AEC-FM standard by IT solutions that allow customization and extended functionalities on top of the standards. The technical contribution of this research can be viewed in terms of the need for a digital platform that can not only process, manage, and utilize standardized approaches and data structure, but can also present a flexible and scalable
layer for the specific needs of the users in terms of data integration, exchange, management, etc.

### 7.3 Limitations of the Research

While the key theoretical and technical contributions have been adequately validated, the following limitations of the current research must be noted, which should be accounted for in the future research plans.

In the beginning phases of this research there was limited opportunity to gather first-hand COBie usability feedback directly from the expert COBie users, because of very limited use of COBie in Finland. Hence, the first-hand feedback from Finnish companies that indicated why COBie is not used, was taken as a starting point. However, this has been a relevant research question within the scope of the thesis. In addition, to overcome this limitation, the researcher reviewed industry reports and existing academic studies about COBie and user experience with large spreadsheets. The researcher also obtained preliminary feedback through demonstrations with national/international research groups and meetings with industry participants in Finland. A detailed review of the discussions about COBie on the social web platforms was also conducted to help researcher define initial problem statements. Nonetheless, a detailed survey with first-hand expert COBie users could expand the problem statements and bring new solution proposal, and hence new functionalities to VisualCOBie approach. Although it was a limitation in the beginning of this research, the results of the iterative process of design thinking methodology eliminated this limitation and validated the relevance of the identified challenges in COBie spreadsheet during the focus group meetings.

Although the initial tests and feedbacks have been collected during the focus group meetings and hackathons, a detailed and systematic first-hand user experience test for VisualCOBie approach is still underway. By the time of the submission of this thesis, two pilot studies have been conducted while a third one is still in progress. In the completed pilot studies, the VisualCOBie platform (and revised version, VisuaLynk) has been implemented and tested by the researchers and the case company representatives who have been closely involved in the implementation. Nonetheless, since the development has not yet been deployed online and open to industry-wide use, the wider user-test with industry actors are still to be conducted. Through the demonstrations of VisualCOBie for ease of data comprehension, navigation as well as the scalable and flexible data generation and management of VisuaLynk has already been found to be validated during these case studies. However, a more comprehensive and systematic user experience test has the potential to reveal the established usable features as well as the hidden challenges. Besides, these tests should be performed to identify what are the time and cost savings for the industry practices. Therefore, the lack of such tests can naturally be seen as a limitation in this research. However, these tests are also part of the iterative feedback-revise loop of the design thinking and agile development methodologies. On the other hand, by the time this research has been submitted, several lessons have been learnt, leading to a detailed to-do list for further refinement of the implementation with relevant theoretical and technical perspectives.

Though two completed and one on-going case studies with the industry participants in Finland have been conducted, due to privacy restrictions this research only presents one of the case studies in detail. This can be seen as a limitation because the details of the other case studies could provide further validation of the arguments in this research. However, the in-
dustrial relations of these companies alleviates this limitation. Since the FM software developer company’s products are being actively used by the other two companies, the researcher got similar feedbacks and requirements that have been obtained from the FM software developer company. Similarly, the results may seem to reflect the outcomes of Finnish construction industry only. Further studies conducted in other countries where COBie is more frequently used could give additional insights into the arguments and practical applicability of this research.

Conducting a doctoral research that requires system implementation, and empirical data is demanding within the constraint of the limited research timeline. System implementation takes time, especially when it is a novel system which is expected to provide unique usability and technical features, and often detailed empirical studies may have to continue beyond the period of the doctoral study. Besides, during the research timeline, there have been some offers to conduct a case study with the local standardized data structures. This kind of case study could also provide opportunities for the researcher to understand the dynamics of AEC-FM industry in Finland. However, the lack of familiarity of the researcher with the local language, and the narrow-scope of the results of the potential case study, could be viewed as a limitation.

In an ideal scenario, we would have liked to have feedback from UI experts who have strong familiarity with AEC-FM industry as well. However, there is dearth of people with this combination of skills in Finland. Thus, expert feedback either comes from the UI domain or AEC-FM domain. However, the lack of cross-domain contextual knowhow was evident in experts approached during this study. On the other hand, this also demonstrates how UI and usability has generally been overlooked in the AEC-FM domain.

The VisualCOBie and VisuaLynk systems implemented in this research employed existing technologies, such as open source BIMServer, Neo4j graph database for property graph representation of data, radial force-layout with edge-bundling graphs for visualization, etc. There are many alternative technological stacks that are available and can provide similar functionalities. The researcher made initial reviews and investigations to choose the appropriate components of the development stack during the research. A detailed comparison of the selected development stack with other alternative technologies could provide a better understanding to evaluate usability and functionality aspects. Design thinking and agile development cycle aims to handle these kinds of limitations to enhance and further drive the research with future studies, development phases applied for other domains than FM (see Section 7.4).

7.4 Future Studies

The potential future studies are expected on further review of COBie and other standardized data formats in AEC-FM industry from a usability point of view. This research classifies the potential future studies according to (1) methodological, (2) theoretical, and (3) technical outcomes of this research.

For the methodological contribution, as mentioned in the limitations of this research (Section 7.2), the most essential future study can contribute the missing detailed and systematic first-hand user experience test for VisualCOBie approach with the implemented VisuaLynk application. The outcomes of such a research has the potential to reveal additional challenges that the research team has not identified yet, and further enhance the validity of the underly-
ing theoretical concepts. Therefore, this kind of research should also be performed in a country where COBie is actively employed or mandated for the AEC-FM industry. This kind of research also has the possibility to reveal the potential advantages of VisuaLynk from the perspectives of time and cost savings, and the data organization, generation and management techniques when the research is supported with a case study that covers the lifecycle phases of COBie. In addition to the detailed and systematic user experience tests, such research should also include the UI experts who have strong familiarity with AEC-FM industry. If such experts are identified and their collaboration extended to the future research, the outcomes can be powerful because it will reflect both the perspective of the VisualCOBie approach and the implemented VisuaLynk application.

This research employed Gestalt’s visual perception principles and conceptual mapping as the fundamental theoretical arguments to build the research framework. Both arguments have been facilitative to build the results of this research. However, the revised VisuaLynk implementation indicates opportunities for revising theoretical insights for validity of the enhanced features as well as the identify the theoretical and technical perspective for the iterative development process. For example, the focus group discussions that followed the VisuaLynk implementation often pointed towards the potential for effective management of distributed knowledge and information within FM organizations. That is, focus group participants reiterated that the VisuaLynk visualization and mapping of dependencies can help in knowing who knows what, where what information resides, and how to access the distributed information when needed. These characteristics suggest that the VisuaLynk approach can also be seen as the enhancement of the FM organization’s Transactive Memory Systems (TMS), facilitated by visualization. Thus, further theoretical work is possible in exploring the concept of Visual TMS.

Both the initial VisualCOBie prototype and the enhanced VisuaLynk implementation provided novel technical contribution for this research study with the employed technologies in the background. Graph databases is one of the important components of the presented developments because they provided the opportunity to define the semantic relationships among data entities. As presented in Section 6.4, the WoBD has similar logic and underlying data management principles with a different syntax and a few technical details. Therefore, WoBD is seen as a potential research and development area for the VisualCOBie approach and the VisuaLynk application. Although the first initial integration with VisuaLynk and DRUMBEAT platform has been established to only visualize the data in the proposed node-link diagram, there are many research and development areas still to be explored. Such future studies can take the initial visualization integration of VisuaLynk and DRUMBEAT and configure the development for the relevant SPARQL-based queries which can support the proposed functionalities of VisuaLynk with WoBD. Besides, both WoBD and VisuaLynk supports the enriching the life cycle data with various relevant data sources. Such future studies can also focus on this topic to enhance the IFC, COBie or any other standardized data structure and enrich them with the other ontologies and RDFs developed by the linked data community. Such study will have the potential to make the VisuaLynk implementation a full-scale linked data application.
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Conclusion, Limitation and Future Research

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Appendix-A: A Sample of Coded Segments from Focus Group Meetings
Appendix-A: A Sample of Coded Segments from Focus Group Meetings

This appendix presents sample sentiments with the applied protocol analysis classification. The presented sentiments are not in chronological order and aimed to represent the applied classification logic based on the applied protocol analysis methodology.

<table>
<thead>
<tr>
<th>Role</th>
<th>Type</th>
<th>Context</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suggestion/Idea</td>
<td>Concern/Doubt</td>
<td>Opinion/ViewPoint</td>
</tr>
<tr>
<td>It will be better for you to talk with the other companies and get a user feedback about the usability</td>
<td>CEO</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>From my perspective there are many companies who don’t know what they are looking for in terms of facility management</td>
<td>CEO</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>But they are looking for something easy to use and understand</td>
<td>CEO</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>We should also deliver the IfcZone information to show the service areas on the 2D and 3D floor plan</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>From my point of view, this approach is quite innovative</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Instead of searching information from tables or tree structures with lots of long texts, this one is more easy</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>All information in one place, and all of them queried at the same time with their relationships</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Otherwise, in the tabular forms, there is a repetitive process to search the information with lots of text and numbers</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>We can send the detailed component specifications to VisualCOBie</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
### Appendix-A: A Sample of Coded Segments from Focus Group Meetings

<table>
<thead>
<tr>
<th>Role</th>
<th>Type</th>
<th>Context</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suggestion /Idea</td>
<td>Concern /Doubt</td>
<td>Opinion /ViewPoint</td>
</tr>
<tr>
<td>to link and even get the design requirements from the end-user</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>But all information should be connected with spaces and relationships should be shown</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Space will be the center point from the ABCDE system as well</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Normally our mechanical models do not include any spaces</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Integration of mechanical components and spaces in one time will be quite important with the relationships</td>
<td>Operations Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Because the mechanical components are not associated with architectural elements at all</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>We just export the mechanical components and spaces separately and merge in a separate file</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>We can associate them in the property sets but in this case, the data is not in the correct IFC entity that a software can read and show</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Better approach will be to show these data in the software by itself with less text but more relationships</td>
<td>Operations Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In our application the data is not in the IFC and we dont prefer to put them in the IFC. And keep the IFC files for individual domains</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>This both makes the management of files easy. and also we dont allow everyone sees every data. So it is because for authoring the data</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Instead of showing the walk-in model, I think it will be better to show only three dimensional model and two dimensional floor plan</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The system should also show the what are the other spaces which may have potentially similar problems in the floor plan</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Role</td>
<td>Type</td>
<td>Context</td>
<td>Content</td>
</tr>
<tr>
<td>-----------------------</td>
<td>------------</td>
<td>---------</td>
<td>---------</td>
</tr>
<tr>
<td>Operations Manager</td>
<td>Suggestion/ Idea</td>
<td>Initiated</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Concern/Doubt</td>
<td>Question</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Opinion/Viewpoint</td>
<td>Follow Up</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Observation/Analysis</td>
<td>Reply</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Query</td>
<td>Technical/Computational</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Strategy</td>
<td>Cultural/Work Practice</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td>Request</td>
<td>Data Organization</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Use Case</td>
<td>X</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Business Case</td>
<td>X</td>
</tr>
</tbody>
</table>

We also need a status section in our application to show the work status with different colors.

It is also necessary to show the zones in the three dimensional model.

So when the user opens the air handling unit node in VisualCOBie, he needs to see what other spaces are served by the same air handling unit.

And those spaces should be shown in both three dimensional and two dimensional model in VisualCOBie.

So he can see the duct work of that room and other related data components of the room.

VisualCOBie should also get the data from the building automation system as well.

But with all these, the service areas should be visualized and shown in both the three and two dimensional model.

Currently, the mechanical components and zones, spaces are not linked with each other.

Those data is stored in different IFC files. And it is very important to show that relationship between components and spaces, zones.

When the data is visualized and identified, the problematic area should be reported as the work order.

In the work order, the location of the problematic area and who created the work order should be identified.

I want to connection starts from space.

From space the zone, from zone to system, and from the system.
<table>
<thead>
<tr>
<th>Role</th>
<th>Type</th>
<th>Context</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>we should find the equipments</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>If the equipment is under the system, I should see the relationship explicitly</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>How do you make these links. Is it manual work? Should we update the code to change them? Can we generate our own links from the user interface?</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>This user interface is quite great. I have never seen an interface like that. I was wondering what kind of information we can store in this system</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>I know COBie does not solve everything</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The first thing should be a data drop to check whether the system is handling all the data we give</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>If we integrate the designer application, we can click one of the node and access the designer data from VisualCOBie</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>But this is a good interface for that idea to work with</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>This is also related who is using the application. There should be different roles on the application</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>With this interface, I think the service man use case is good. So the service man can check all the root causes of a problem, check other components from VisualCOBie</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>For example if I have the space, what air handling unit is serving the space</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>I also need to know what is the system that air handling unit belongs to and I would like to see this system in three dimensional model</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Role</td>
<td>Type</td>
<td>Context</td>
<td>Content</td>
</tr>
<tr>
<td>------------------------------</td>
<td>--------------------------</td>
<td>---------</td>
<td>-----------</td>
</tr>
<tr>
<td>and I would like to see this system in together with the other linked data on three dimensional model</td>
<td>Operations Manager</td>
<td>Initiated</td>
<td>Question</td>
</tr>
<tr>
<td>There information is graphically colored where are service are in the spaces</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>So the problematic spaces in the center as the service area</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>And from there I can access the air handling unit</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Than I connect the internet of things system to see the sensor readings</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>And also connect the designer platform to see the detailed attributes.</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Currently the service man has no information at all in the hand when they are trying to fix any problem. They only have the street address</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>They go and check and try to figure out what we can make it, and other come back and ask us we need this</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>So VisualCOBie interface will be quite useful to dig in the data and explore what is needed and what should be done</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>But I am still wondering how can we fit all these information inside VisualCOBie</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>For big projects such as shopping malls, there are five million objects already and no one is mapping this data in tables</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>But if we define that structure, it will make our work quite easy for many task. Can we define the structure ourselves?</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>What happens when the graphical model change and you change the model in IFC</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>We can use the BIM server also uploading IFC files as well</td>
<td>Operations Manager</td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
### Appendix-A: A Sample of Coded Segments from Focus Group Meetings

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<tr>
<th>Role</th>
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<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Suggestion</td>
<td>Concern</td>
<td>Opinion</td>
</tr>
<tr>
<td>Import one IFC file to BIM</td>
<td>Suggestion</td>
<td>Concern</td>
<td>Suggestion/ViewPoint</td>
</tr>
<tr>
<td>server and put the data also</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>into the ABCDE systems and</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>integrate with each other in</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VisualCOBie</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>And in both systems, we can</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>have the same information</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>coming from two different</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>platforms together with</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>COBie output and visualized</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in the VisualCOBie application</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>directly</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>When we are dealing with the</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>IFC files, we have all sorts</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>of information which we dont</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>need</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>So we can retrieve the specific</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>information sets from different</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>datasets and merge in one place</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Usually spaces is the connection</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>point for the different</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>information sets</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From the end-user point of</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>view, this user interface is</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>quite good, but looks like</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>not flexible</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>We have many information</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>sets coming from many different</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>systems and this node-link</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>diagram showing all of them at</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>the same time in one single</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>user interface</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>What will be the plan for this</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>application. Are you going to</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>focus only on the facility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>management. Or is there going</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to be something like a to do</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>task list</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dependencies will be the power</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>for any user. Because they will</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>find the all information in one</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>hand</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>We were lacking with these</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>kind of user interface to</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>make the data more explicit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>with each other</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>From the space VisualCOBie</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>should connect the sensor</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>information directly</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VisualCOBie should be</td>
<td>Operations</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>connected with many other</td>
<td>Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>systems based on the service</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>persons individual</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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<tr>
<th>Role</th>
<th>Type</th>
<th>Context</th>
<th>Content</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Initiated</td>
<td>Question</td>
</tr>
<tr>
<td>In mechanical design, we always miss the zones, and focusing only for the space level.</td>
<td>Operations Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>But the zone information is quite important</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>So the VisualCOBie should show the zones as well.</td>
<td>Operations Manager</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Components are related to system. But spaces are related with service area</td>
<td>Operations Manager</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>The facility managers who understands and checks the building automation systems is already expert level guys</td>
<td>Operations Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>But the service guys on the site are already low level guys who do not understand anything</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>The information should be served to them with a simple user interface like VisualCOBie</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>We have static data to start the link. We have the sensor reading data together with the design specifications</td>
<td>Operations Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>How about integration augmented and virtual reality. Is it possible to integrate it?</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>When you are reading the sensor information, there has nothing with COBie, and that should be done additionally</td>
<td>Operations Manager</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In this case we will integrate two different datasets at the same time. One will be COBie and the other our sensor data coming from our servers</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>When he clicks the work order data, the system will forward to the VisualCOBie and it will identify the user location</td>
<td>Operations Manager</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>When we click the components from 3D model, can we see the</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Role</td>
<td>Type</td>
<td>Context</td>
<td>Content</td>
</tr>
<tr>
<td>------</td>
<td>---------------------------------------------------------------------</td>
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</tr>
<tr>
<td></td>
<td>related information in node link diagram</td>
<td></td>
<td></td>
</tr>
<tr>
<td>If we try to connect the location, that can be the connection of many other information</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>I see the good thing here is the connection to other data through spaces</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Three dimensional model is fancy. When the user walks in the model, it is fine. But maybe it is complex and not needed that much</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Is there any way that we define the data groups and figures?</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>In the graphics, is there anyway that we can choose multiple components? Maybe showing relationships on the 3D model can be nice</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The space should be one of the nodes should be opened and the main connection point</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>VisualCOBie should show the components from systems. and also vice-versa, we should find the systems from components as well</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Spaces in the three dimensional model should be colored to show the problematic area. And there should be a mechanism to show their relationships also in the 3D model</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Have you tried VisualCOBie with another model. Can there be any other problem with another big building</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>How close the VisualCOBie to the linked building data? Can we use RDF data with VisualCOBie?</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Can this visual query system be expandable if we integrate new data sets in addition to COBie? Does source code need modification?</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Role</td>
<td>Type</td>
<td>Context</td>
<td>Content</td>
</tr>
<tr>
<td>----------------------</td>
<td>-------------------------------------------</td>
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</tr>
<tr>
<td></td>
<td>Suggestion / Idea</td>
<td>Concern / Doubt</td>
<td>Opinion / ViewPoint</td>
</tr>
<tr>
<td>Different projects have different data and if we have to change data structure each time, it will not be efficient. Can we make it dynamically customizable?</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Actually we don't have a predefined classification. Usually all the work requests are three or four words. And we need to define the information dynamically from the user interface</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>So I imagine that either through two or three dimensional view data and relationships should be visualized in addition to node link</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>So can you make the connection with the node-link diagram over the three dimensional model</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>We need, when the user selects the component from node-link, than the served spaces should be seen from the 3D model as the related data</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Can we define specific attributes for components dynamically? Because components and design requirements usually change a lot during the project</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>When the zones are defined, than we can show the service areas as well. Directly from the 2D and 3D model</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>How can we link different data sets with COBie without pre-defined relationships? This can be a flexibility issue</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Does it save your selections in the system, is there any historical record of the users?</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Can we show the service areas, components and zones as a result of the work order with relationships on the 3D model?</td>
<td>Research &amp; Innovation</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>The start point can be contextualized based on your role and on the</td>
<td>Research Expert</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
organizational structure. So the start point can be based on what my role is

All we need is that data structure, and we will be implementing that structure in there to generate the links and link with COBie data

One question about graphics. This is running on top of WebGL. And the IFC file, you probably translated with IfcOpenShell. So what format you translated the IFC?

Now you have the graphical user interface for traversing through the nodes and relationships via the web service to access the data. So how do you follow the links of a node. Do you connect other web services?

How do we access this platform. Is there any user login and access management platform here? Does information open for everyone or limited for different user roles?

How the server-side of the implementation can be expanded for flexible and dynamic data generation? You have to link those data to BIM models as well.

The two dimensional floor plan really is crucial for this case rather than walk-in model