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Lifecycle Information Management in a Product Information Model

Master's Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology.

Espoo, September 23, 2017

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Abstract of the master's thesis

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In modern, global manufacturing business, value is increasingly created by services related to products rather than the products themselves. In industries related to the built environment, various products installed in the buildings are a major asset for the operators and managers of buildings. Product Lifecycle Management (PLM), managing and exploiting product-related information throughout the lifecycle of the product, has become both a requirement and an important tool for effective service business development.

Extensive and interactive PLM requires a universal system for information exchange across the lifecycles of buildings and products. The objective of the study is to define and implement the minimum requirements set by a product-centric information exchange system in an IFC-based product information model, based on use case of managing installed medical equipment in hospital environment.

The study comprises a literature analysis and a use case. Late literature was reviewed to analyse developments of intelligence and lifecycle management in products and buildings. It was found that major challenges exist in exchanging lifecycle information between stakeholders and across lifecycle stages. Based on the analysis, it is proposed that using the technologies of building information modelling and a product-centric information exchange system could provide novel solutions to the identified challenges. In the use case, a method was developed for incorporating an open, product-centric PLM information exchange system into the existing IFC standard.

It was found that an URI-based, product-centric information exchange system using external databases and product servers satisfies the requirements of effective PLM information exchange. Additionally, it was found that using IFC for product information modelling can effectively support such a system by linking virtual building and product information models into the lifecycle information stored in external servers.

Keywords: PLM, CL2M, IFC, BIM, BLM, PIM, Revit, lifecycle

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Nykyaikaisessa, kansainvälisessä valmistavan teollisuuden liiketoiminnassa arvoa luodaan entistä enemmän tuotteisiin liittyvillä palveluilla kuin itse tuotteilla. Rakennettuun ympäristöön liittyvässä liiketoiminnassa rakennuksiin asennetut tuotteet muodostavat suuren pääoman rakennusten käyttäjille ja hallinnoijille. Tuotteiden elinkaaren hallinta (Product Lifecycle Management, PLM), eli tuotteisiin liittyvän tiedon hallinta ja hyödyntäminen tuotteen elinkaaren aikana, on muodostunut sekä vaatimukseksi että tärkeäksi työkaluksi tehokkaiden liiketoiminnallisten palvelujen kehittämisessä.

Laaja-alainen ja vuorovaikutteinen PLM edellyttää yleismaailmallista tiedonvaihtojärjestelmää rakennusten ja tuotteiden elinkaarten varrelle. Työn tavoitteena on määritellä ja toteuttaa tuotekeskeisen tiedonvaihtojärjestelmän asettamat vähimmäisvaatimukset IFC-pohjaiseen tuotetietomalliin käyttötapauksessa (use case), jossa kiinteästi asennettavia lääkinnällisiä laitteita hallitaan sairaalaympäristössä.

Työ koostuu kirjallisuustutkimuksesta ja käyttötapauksesta. Tuotteiden ja rakennusten elinkaaren hallinnan ja älyn kehitystä analysoitiin kirjallisuuslähteiden perusteella. Elinkaaren aikaisen tiedon vaihtamisessa osapuolten ja elinkaaren vaiheiden välillä havaittiin merkittäviä haasteita. Analyysin perusteella työssä esitetään, että tietomallintamisen teknologioiden ja tuotekeskeisen tiedonvaihtojärjestelmän käyttäminen voivat tarjota uusia ratkaisuja tunnistettuihin haasteisiin. Käyttötapauksessa kehitettiin menetelmä avoimen, tuotekeskeisen PLM-tiedonvaihtojärjestelmän yhdistämiseksi nykyiseen IFC-standardiin.

Työssä havaittiin, että URI:in perustuva, ulkoisia tietokantoja ja tuotepalvelimia hyödyntävä tuotekeskeinen tiedonvaihtojärjestelmä täyttää tehokkaan PLM-tiedonvaihdon vaatimukset. Lisäksi havaittiin, että tuotteiden tietomallintaminen IFC:ia käyttämällä tukee järjestelmää tehokkaasti linkittämällä virtuaaliset rakennus- ja tuotetietomallit ulkoisilla palvelimilla sijaitsevaan elinkaaritietoon.

Avainsanat: PLM, CL2M, IFC, BIM, BLM, PIM, Revit, elinkaari

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KHK out.

Helsinki, September 23, 2017

Kalle-Heikki Koskinen

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Abbreviations

AEC	Architecture, Engineering and Construction
AECO	Architecture, Engineering, Construction and Owner-operated
BIM	Building Information Model/-ling
BMS	Building Management System
CAD	Computer Aided Design
CAFM	Computer Aided Facilities Management
CAM	Computer Aided Manufacturing
CL2M	Closed Loop Lifecycle Management
CEN	European Committee for Standardization
FM	Facilities Management
ID	Identifier
ICT	Information and Communications Technologies
IFC	Industry Foundation Classes
IoT	Internet of Things
LCA	Life Cycle Assessment
LCIM	Life Cycle Information Management
MEP	Mechanical, Electrical and Plumbing (engineering)
PIM	Product Information Model/-ling
PLC	Product Life Cycle
PLM	Product Lifecycle Management
QLM	Quantum Lifecycle Management
GUI	Graphical User Interface
URI	Universal Resource Identifier

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1 Introduction

Motivation and background for this study are discussed in this chapter. Furthermore, the research question and additional research objectives are identified. Finally, the framework and structure of the thesis are outlined.

1.1 Motivation

Information, advanced technology and advanced information technology have revolutionized the world during the last decades. Growing amounts of data is created, collected and exchanged in increasing speeds every year. The Internet has completely changed the way we interact with other people, organizations and material around us; anyone can be contacted anytime without delay, autonomous drones fly deliveries to customers and self-diagnosing engines automatically contact maintenance services.

In tandem, increased global competition and the maturation of developed markets have directed manufacturing companies to pursue a vantage over their competitors by switching from manufacturing products to providing services. Contemporary examples include providing a car or a jet engine as-a-service, pervasive after sales services for products or centralized asset management services. Understanding and tracking how products are designed, built, used and recycled is increasingly important for manufacturing companies seeking to develop intelligent services. This discipline, management of information related to products over their whole life span, is at the heart of this thesis.

In the building sector, sustainable and economic management of buildings and their equipment over their life cycles have risen as a modern standard. Creating virtual representations of facilities through building information modelling has emerged as a vital tool for effective asset management by centralizing and visualizing information. Especially in the public sector, financial scarcity and political ambitions have directed to pursue controlled, cost-effective and fault-preventive operation of built environment.

Due to the fast pace of technological evolution and immaturity of markets, many applications of Internet of Things and intelligent products are still young, unstandardized or prototypes driven by pioneering corporations. However, standardization and open source practises for modern information technologies are under constant development by researchers and international working groups. Unifying the practises information is managed and exchanged is vital for the development of international, cross-organizational life cycle services and new business opportunities.

Effective management of products as assets across their life cycles is an essential task for owners and operators of special buildings with significant installed equipment, such as factories and hospitals. This thesis aims to contribute to the applications of product lifecycle information exchange in a built environment by exploiting and amplifying open standards and matured technologies.

1.2 Research objectives and framework

The thesis is settled into the intersection of two broad topics, building information modelling and product lifecycle management. The empirical part of the thesis is formulated as a use case analysis. As the main guideline for the study, the following research question is to be answered:

> *How could product lifecycle information management be considered in product information modelling as part of a building information modelling process?*

The following two partial research questions are also asked to narrow and guide the scope of the thesis:

> *What technologies should be used to store and exchange product lifecycle information?*
>
> *Can building information modelling standards support the exchange of product lifecycle information?*

To address the research questions, following research objectives were defined:

- Based on a literature review, study the relevant aspects of intelligence, life cycle management and information modelling of products and buildings
- Identify the requirements for product lifecycle information exchange in a virtual product model

- Based on a use case, develop a method to allow product lifecycle information exchange in a building information modelling process.

1.3 Structure of the thesis

The thesis consists of five chapters. In chapter 2, a literature review is carried out to identify current developments in Internet of Things and intelligence of products and buildings. Furthermore, product lifecycle management is discussed, followed by a perspective towards lifecycle management and information modelling of buildings.

Chapter 3 provides insight into the requirements of product lifecycle information exchange, followed by an introduction to and definition of the use case, as well as details of the building information modelling standard.

In chapter 4, a method is developed for enabling product lifecycle information exchange in a virtual product information model using the standards of building information modelling.

Chapter 5 gathers and analyses the findings, achieved results and challenges identified in chapters 2–4. Finally, contributions, achievements and limitations of the thesis are discussed in chapter 6.

Figure 1.1 provides a visual insight into the structure of thesis.

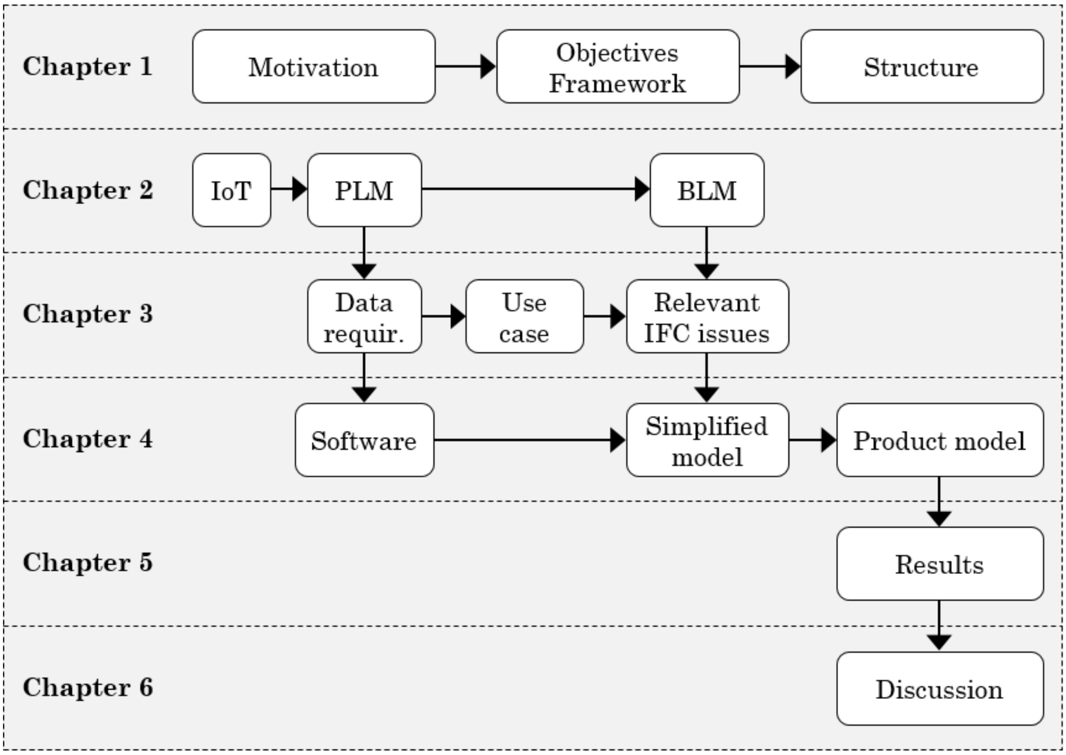


Figure 1.1: Structure of the thesis

2 Literature review

This chapter analyses and discusses the topics covered in the thesis based on current research proceedings and literature. First, issues and developments related to the Internet of Things and intelligence in products and buildings are discussed. Second, the concept of product lifecycle management and related information exchange are described. Finally, building lifecycle management and the late developments of products in building information modelling are discussed.

2.1 Internet of Things and intelligent objects

Today, the concept and applications of the Internet of Things (IoT) are an important area of focus in several research domains. As the name states, IoT is a paradigm that combines physical, tangible objects ("things") and the Internet. In general, the basic idea of IoT has been described as *"the pervasive presence around us of a variety of things or objects – such as - - RFID tags, sensors, actuators, mobile phones, etc. – which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach common goals."* In IoT, pre-existing Internet protocols are used to create a connecting web between objects. (Atzori et al., 2010)

The ability of objects to gather, manage and exchange information forms the basis of IoT and are also the main reason for its popularity and economical potential. Alternatively, IoT is a system that adds intelligence to otherwise inert objects and enables human beings to communicate with them. In this domain, such objects are defined as intelligent, although the level of intelligence may vary. By processing and utilizing the information created by the IoT, it is possible to develop endless applications that improve the efficiency of economical systems and the quality of life. (Atzori et al., 2010; Kiritsis, 2011)

In IoT context, an object is an umbrella term for any tangible artefact that exists in the world. In this thesis, concepts of an intelligent product and an intelligent building are studied in detail.

2.1.1 Intelligent products

Traditionally, a product is a tangible object that has a value and can be bought or sold. In modern business framework, the concept of a product is extended to cover also intangible aspects, such as the benefit of using the product and the information related to the product. Thus, a product is a combination of a physical object and various intangible properties. (Liu et al., 2010)

As a tangible, physical product is conceptualized, created, used, maintained and discarded, information of all the properties and activities relating to the product is created, exchanged and stored. Historically, products and information relating to them have been managed separate from another, as the information has been dispersed to different stakeholders across time. The development of modern and pervasive information and communication technologies (ICT) has greatly increased the potential and effectiveness of managing product information within the product itself. This basic concept of a physical item, combined with an information-based representation of itself, is described as an intelligent product. (Yang et al., 2009; Främling et al., 2013)

Further definitions for intelligent products are provided in resent research and literature. However, common properties and requirements can be identified. In general, an intelligent product should have the following capabilities:

- Possessing an identity
- Acquiring data related to manufacturing and disposal of the product
- Acquiring data related to distribution, usage and maintenance of the product during life cycle
- Providing a means to store, access and maintain the data.

Several technologies to manage intelligent product data have been studied and applied. In intelligent product is typically equipped with an ICT device, such as an RFID chip, that can either store the data or communicate with an external database storing the data, or both. (Yang et al., 2009)

In this thesis, an intelligent product is defined broadly as a product that has a unique identity, communicates and exchanges information with an external database and expresses a part-whole hierarchy, as described by Främling et al. (2007). This concept is further described in section 2.2.3.

2.1.2 Intelligent buildings

Trivially, a building can be considered as a structure providing the human shelter from undesirable environmental conditions. Today, however, buildings are complex constructions that address multiple scientific fields in creating, using and discarding them. Understanding and developing building as a concept is increasingly important as most of the world population already live in urban areas. (Lilis et al., 2017)

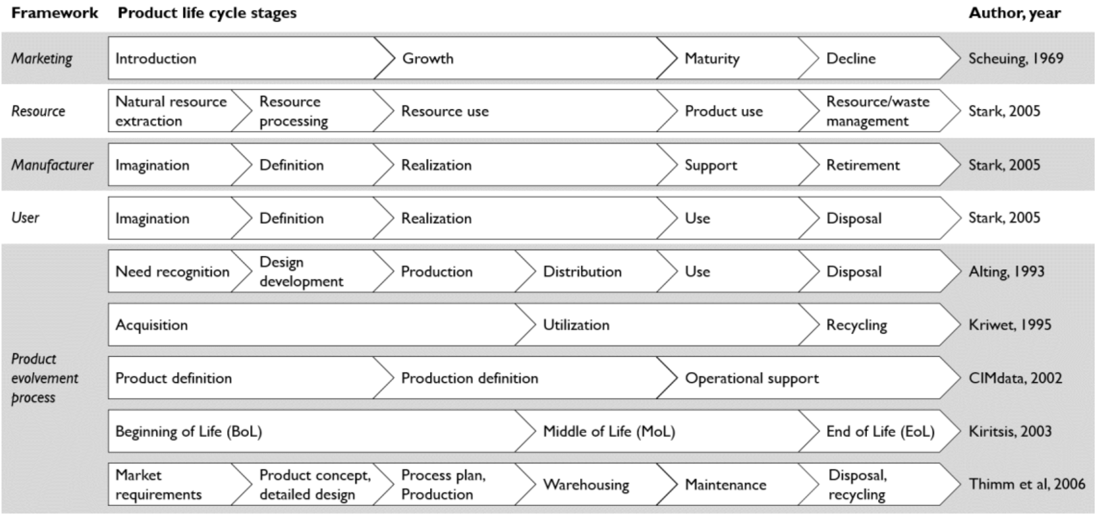
Ghaffarianhoseini et al. (2016) provide a very comprehensive analysis on the various domains, research and definitions of intelligent buildings through time. Intelligent buildings emerged as a concept in the 1980s primarily in a technological domain, such as automation of MEP systems. In the 1990s, the development of automated computing, measurement and building control systems provided a basis for a human-centred concept of intelligent building, in which the ability to create and maintain a user-friendly environment was the focal point. However, focusing merely on technology and people eventually lead to an increase in building energy consumption. In the research of this millennia, energy economy and sustainability are considered as essential factors of intelligent buildings (Ghaffaranhoseini et al., 2016).

Today, in conclusion, intelligent buildings can be described as buildings that use modern technology to provide an optimal environment for people as efficiently and sustainably as possible. Interestingly, a similar definition was provided by the International Council for Research and Innovation in Building and Construction (CIB) already in the 1990s: *"a sustainable intelligent building can be understood as a complex system of inter-related three basic issues: People (owners; occupants, users, etc.); Products (materials; fabric; structure; facilities; equipments; automation and controls; services); and Processes (maintenance; performance evaluation; facilities management) and the inter-relationships between these issues"* (AlWaer & Clements-Croome, 2010). Inter-relationships require information to be created and exchanged. Information management is one of the central issues and requirements of intelligent buildings.

Thus, similar to intelligent products, an intelligent building can also be considered as a combination of a physical building and an information-based representation of itself. This definition, combined with an ability to communicate and express information with an external database, serves as a basis for this thesis and is further described in section 2.3.1.

2.2 Product Lifecycle Management (PLM)

The lifecycle of a product, or Product Life Cycle (PLC), is a concept defining the different stages of existence and interaction of a product from creation to destruction. The PLC concept has been studied, used and defined in various business and research domains, such as marketing and manufacturing management, as illustrated in figure 2.1.



Framework	Product life cycle stages						Author, year
Marketing	Introduction		Growth		Maturity	Decline	Scheuing, 1969
Resource	Natural resource extraction	Resource processing	Resource use		Product use	Resource/waste management	Stark, 2005
Manufacturer	Imagination	Definition	Realization		Support	Retirement	Stark, 2005
User	Imagination	Definition	Realization		Use	Disposal	Stark, 2005
Product evolvement process	Need recognition	Design development	Production	Distribution	Use	Disposal	Alting, 1993
	Acquisition			Utilization		Recycling	Kriwet, 1995
	Product definition		Production definition		Operational support		CIMdata, 2002
	Beginning of Life (BoL)			Middle of Life (MoL)		End of Life (EoL)	Kiritsis, 2003
	Market requirements	Product concept, detailed design	Process plan, Production	Warehousing	Maintenance	Disposal, recycling	Thimm et al, 2006

Figure 2.1: Various PLC definitions
(Adapted from Liu et al., 2010; Maharjan, 2013)

Regardless of the domain, the fundamental idea behind lifecycle approach to products is understanding that qualitative and economical value is created by different business processes and interactions with and around a product across time. To facilitate and control value creation, such interactions should be managed effectively during the life cycle. This management process is called Product Lifecycle Management (PLM).

As PLC, PLM also has various definitions depending on the context it is studied in. In general, PLM is described as management of all activities related to a product during the whole life cycle of a product. Historically, PLM emerged as an explicit concept in the beginning of 21st century. Before then the different life stages of products typically were managed in an implicit, discontinuous manner across business organizations and departments. The fragmented, unmanaged approach often resulted in ineffectiveness and negative business outcomes. (Stark, 2011)

The need to overcome business and product development problems, as well as the general development of ICT, resulted in the emergence of PLM.

As described by Stark (2011), *"PLM manages a company's projects to innovate and develop products, and their related services, all the way across the lifecycle. Without new products, company revenues will decline. Innovation activities are the source of growth and wealth generation in a company, and PLM makes them more effective."* In addition to addressing a single business, PLM also offers macroeconomic benefits as it increases overall efficiency and reduces monetary and environmental waste. In general, PLM can be seen as *"- - a holistic business activity addressing not only products but also organisational structure, working methods, processes, people, information structures and information systems. It's a new paradigm, a new way of looking at the world of products"* (Stark, 2011).

2.2.1 Closed Loop Lifecycle Management (CL2M)

In near future, PLM will support an increasing number of business activities. Managing a product across the life cycle requires managing the data, information and knowledge created in all stages of the life cycle (Kiritsis, 2011). Traditionally, a transition from one life cycle stage to another, which often equals also a transition from one actor to another, creates challenges and disruptions in the flow of information. Finding solutions to minimize and eliminate such disruptions, "closing the information gaps", has been under great interest in late research.

Closed Loop Lifecycle Management (CL2M) is a paradigm for ensuring seamless, bi-directional flow of information across the actors and phases of a product during the life cycle (Kiritsis, 2011). The concept of CL2M and an example of information flow is presented in figure 2.2. Closing the information gaps and creating loops of information exchange provide, for example (Jun et al., 2007):

- data about the methods and state of use, retirement and disposal of the product to the actors in the early stages of life cycle, such as designers, helping to develop new generations of products
- data about actual product usage conditions for the actors in the middle stages of life cycle, such as service and maintenance experts, helping to extend the life cycle of products
- data about the resources and materials originally used in manufacturing to the actors in the end stages of life cycle, such as recycling experts, helping to maximize the potential of re-use and recycling of materials.

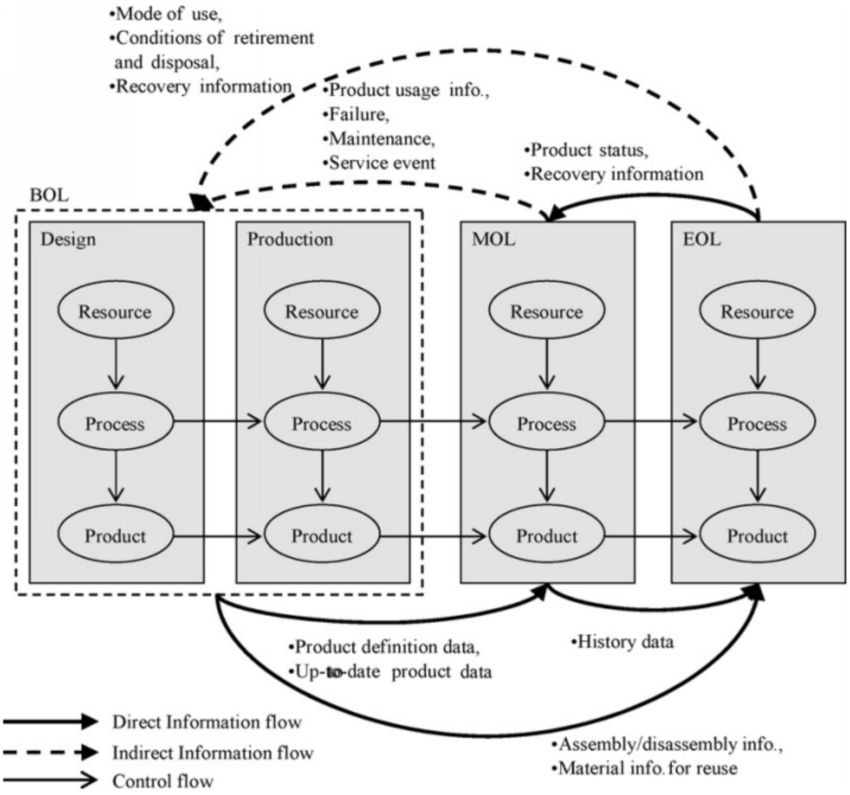


Figure 2.2: Example of CL2M information flow (Jun et al., 2007)

2.2.2 Product-centric PLM information exchange

Today, business models and supplier networks have become increasingly complex and global. PLM information is created by multiple organizations that usually focus on a limited aspect during a limited life cycle phase of a product. Information systems are traditionally rather organization or production-centric which leads to great amounts of product information to be pushed forward in a manual and unidirectional way to the downstream supplier network (Kärkkäinen et al., 2002). Such a system easily leads to information overflow and inefficiency in the supply chain. To introduce full potential of PLM, information flow needs to be bi-directional and easily accessible between organizations during the whole lifetime of a product (Främling et al., 2007).

Another important driver for a change in information systems is the increasing demand for product variation and customization. Products need to be managed on item rather than type level. This exponentially multiplies the amount and complexity of information and creates requirements that traditional data management systems do not meet. (Främling et al., 2007)

Product-centric information systems have been introduced as a solution to the challenges of modern PLM. Such systems are composed of three key elements, an intelligent product, a PLM agent and a PLM system. A PLM agent gathers lifecycle data from various intelligent products using mobile readers. The data is sent to a PLM system where they are processed and composed. The PLM system makes decisions on whether data should be updated and communicates such updates to products and PLM agents if necessary (Kiritsis, 2011). The system is illustrated in figure 2.3.

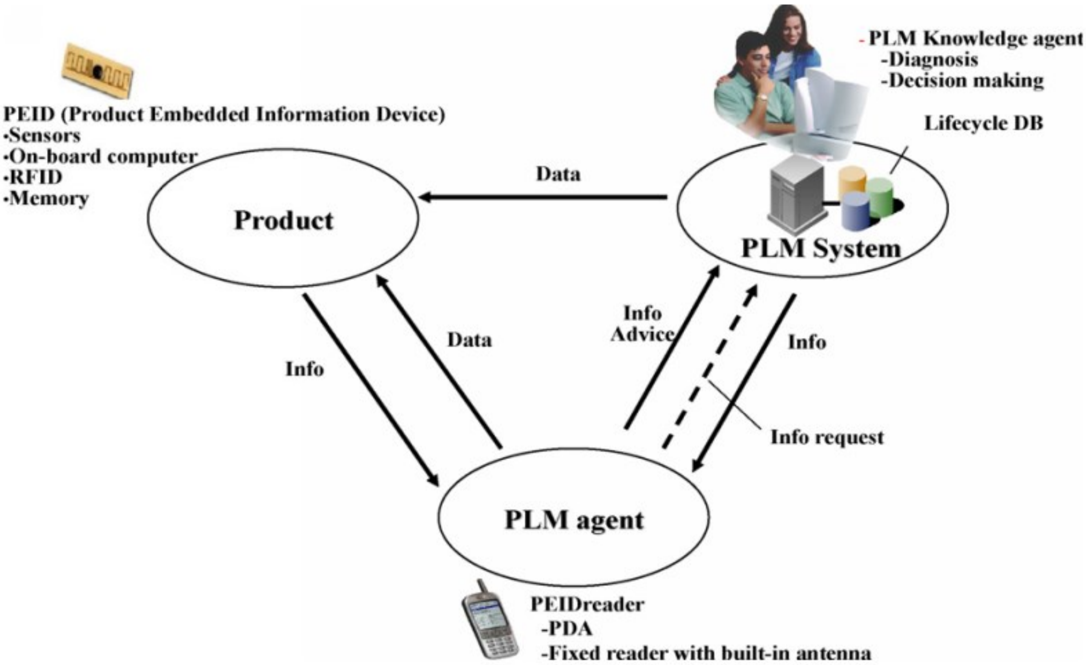


Figure 2.3: A product-centric PLM information exchange system (Kiritsis, 2011)

Several applications of a product-centric PLM information architecture have been developed, based on both centralized and distributed PLM systems. Late research has been mainly focused on distributed, open systems that use existing communication protocols (the Internet) to meet the discussed challenges of dispersed supply networks and complex production structures (Kiritsis, 2011). In open systems, there is no need for a centralized information database as the data is stored by multiple organizations and databases and shared via an open peer-to-peer technology. The information is transmitted directly between the place it is needed and the place it is stored, thus removing the need for unnecessary copies of information to the organizations in the supply network or for intermediate, centralized databases operated by third-party organizations. As the data is retrieved and composed from multiple sources, a universal reference system using unique identifiers must be defined. (Kärkkäinen et al., 2002)

2.2.3 The DIALOG system

The DIALOG (Distributed Information Architecture for Collaborative Logistics) is a software platform developed in Helsinki University of Technology by Kärkkäinen et al. (2002) for research purposes in PLM information exchange. DIALOG is an open system that uses peer-to-peer communication to exchange product information. DIALOG introduces the concept of a product agent (not to be confused with PLM agent) that is a virtual representation of a tangible object. (Främling et al., 2007)

In DIALOG, an intelligent product and a product agent containing the product related information are connected bi-directionally over the Internet using unique product references. Although standards for globally unique identifiers have been developed, such as GTIN (Global Trade Item Number), GLN (Global Location Number) and EPC (Electronic Product Code), they have proven to be problematic as the number of intelligent product items is rapidly increasing. In DIALOG, an ID@URI notation has been proposed for unique referencing. In ID@URI notation, the ID identifies a product and the URI identifies a resource. Thus, the uniqueness of a reference is guaranteed by definition and it becomes possible to use company-specific IDs. (Främling et al., 2007)

Other key features in the DIALOG system are the two design patterns called Composite Products and Observers. The intention of Composite design pattern is to *"- - compose objects into tree structures to represent part-whole hierarchies, where individual objects and compositions can be treated uniformly. - - This signifies that physical product items become parts of each other, so the information related to them becomes interconnected. The construction of composite products usually does not change too much during the life cycle of most products, but it is a vital piece of information to manage when changes occur"* (Främling et al., 2007). An example of a composite structure is illustrated in figure 2.4.

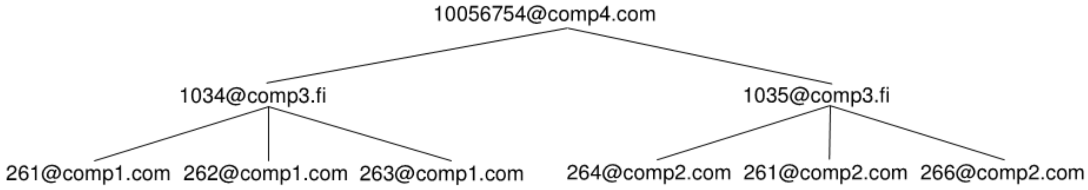


Figure 2.4: Example of composite product hierarchy (Främling et al., 2007)

The intention of Observer design pattern is to *"define one-to-many dependencies between objects so that when one object changes state, all its dependents are notified and updated automatically"* (Främling et al., 2007). An example of the use is when information has to be transferred to multiple companies related to the product, such as a logistics company handling spare part replenishments in the case of a break-down. Figure 2.5 is an example of an observer design pattern where *"- - an information update could be propagated through "Observer" references. Items 13456@comp3.com, 151@comp2.com and 456@comp4.com observe item 10056754@comp1.com. Items 13456@comp5.com and 543@comp6.com observe item 13456@comp3.com. Therefore the information update message shown in the figure will be sent to the corresponding product agents*" (Främling et al., 2007):

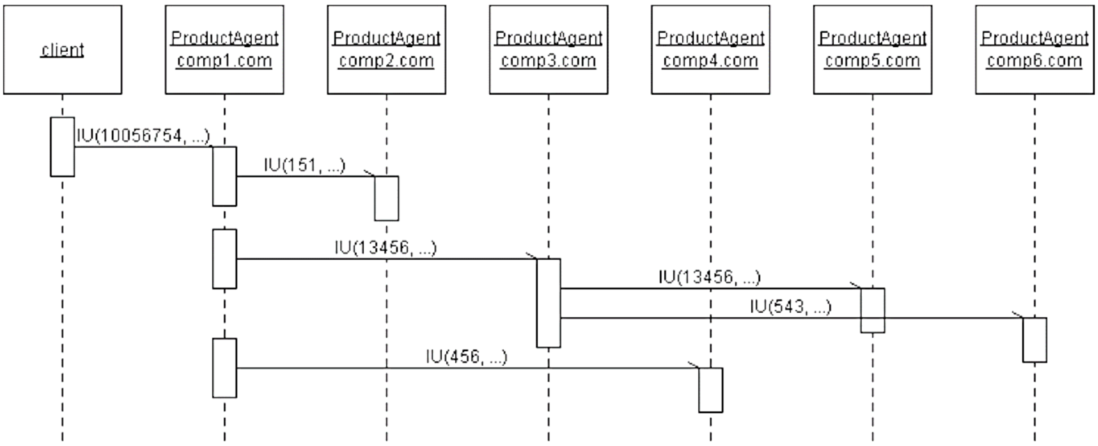


Figure 2.5: Example of observer product hierarchy (Främling et al., 2007)

Although the DIALOG system was developed as a research platform, it has been applied to various business-oriented proceedings during the last decade, such as the PROMISE (PROduct lifecycle Management and Information tracking using Smart Embedded systems) architecture

(CL2M.COM, 2009), Quantum Lifecycle Management (QLM) messaging (Främling & Maharjan, 2013) and Open Messaging interface (O-MI; (Kiritsis, 2011). Thus, the novel idea of DIALOG has been proven feasible on various occasions.

2.3 Building Lifecycle Management (BLM)

Building Lifecycle Management (BLM) is a loosely-defined paradigm that aims to apply PLM methodology to the building and construction domain. Similar to products, the life cycle of buildings can be separated into several phases.

Little literature can be found on building life cycle phasing as a topic. The most common method divides the life cycle into three trivial stages: for a building to exist in the first place, it must first be designed and constructed. Once the construction is completed, the building is operated and maintained. After the use, the building is either demolished or refurbished for another use. These stages are addressed as the Embodied phase, Operational phase and End-of-life phase (Eleftheriadis et al., 2017). The division into three stages can also be associated with the phasing into BOL, MOL and EOL in PLM domain.

Historically, the general interest towards life cycles of buildings has emerged from the environment and sustainability megatrend. Construction and operation of buildings consume increasing amounts of natural resources and energy as the world population grows and the general level of infrastructure rises. Life Cycle Assessment (LCA) is an internationally standardized technique to evaluate environmental impacts of a product, such as a building, during the life cycle (CEN, 2006). LCA has been commonly used in the building domain since the 1990s and it can effectively cover the whole lifespan of a building, both time-wise and phase-wise (Geng et al. 2017). From a total BLM point of view, however, LCA is inadequate as it only focuses on estimating environmental impacts. As PLM is described as a holistic, complete business activity, so should BLM be understood in a broad manner.

Another paradigm, Facilities Management (FM), is *"an integrated approach to maintaining, improving and adapting an organisation's buildings to promote a fertile environment that supports the organisation's primary objectives"* (Pärn et al., 2017). Many alternative definitions are also provided in late business and construction domain literature. In general, FM can be addressed as both a business approach and a set of tools and processes to effectively manage a building in the Operational, or MOL, phase of a building. FM has been a popular research topic as the costs generated in the MOL phase occupy more than 60–80% of an average building life cycle expenses (Pärn et al., 2017; Guillen et al., 2016). Decisions made in BOL Embodied phase, or design and construction phase of a building, have a great influence in MOL costs. In combination with strict environmental regulations and the global financial austerity megatrend, this has resulted in an increasing need for effective resource management in AECO (architecture, engineering, construction, owner-operated) sector and a cross-phase information flow between EOL to MOL information systems. (Pärn et al., 2017)

Information is crucial for efficient and effective BLM, from design and construction of a building to supporting building use and maintenance operations. Mature technologies exist for both, such as computer aided design (CAD) systems for engineering and computer aided facilities management (CAFM) systems for operation and maintenance. However, the fragmentation of information, strict focus on specific engineering domains and lack of interoperability typically result in knowledge loss between AECO operators and in transitions from BOL to MOL of a building (Pärn et al., 2017).

Building life cycle information management faces similar challenges as PLM. Closing the information gaps and acquiring information feedback between operators and stages of life cycle is important. An integrated BLM solution should provide a platform for the requirements of both BOL and MOL, as well as EOL stage of a building. Building information modelling has emerged as a solution to such challenges.

2.3.1 Building Information Modelling (BIM)

Building information modelling (BIM) is a novel discipline, technology and platform for managing and exchanging building information during the whole life cycle. BIM is defined as *“a digital representation of physical and functional characteristics of a facility. A building information model is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition”* (BuildingSMART, 2017a). BuildingSMART, founded in 1995, is an international working group developing BIM that provides several descriptions explaining the holistic nature and various dimensions of BIM (Guillen et al., 2016):

- BIM is a digital representation of physical and functional characteristics of a facility. Not only graphical information of the building elements but also the rest of information types that can be used to manage all the life cycle phases: manufacture and vendor data, service and use requirements, operation and maintenance data, performance parameters, energy consumption, etc.
- BIM is a shared knowledge resource for information about a facility, forming a reliable base for decision during its life cycle.
- BIM is a platform for collaboration by different stakeholders at different phases of the facility life cycle in order to insert, extract, update or modify information in the BIM support reflecting different roles according to each stakeholder's interest.
- BIM is a shared digital representation founded on open standards for interoperability. In addition to the standardization needs, this point highlights the open character of BIM conception, to allow the combined use of different software an application (3D design, FM software and others) and to support the successive software updates.

The AECO industry has employed specific terms to illustrate the multiple dimensions of BIM, based on an n-dimensional representation of a building, as presented in table 2.1.

Table 2.1: Dimensions of BIM
(Adapted from Guillen et al., 2016; Pärn et al., 2017)

Term	Relation	Description	Stakeholder impact
2D	from analog to digital	Classical 2D CAD model data to represent the building design.	Engineer Designer
3D	2D + Z-axis	3D CAD model data to represent the building design.	Designer team Supplier
4D	3D + time	Scheduling and project sequencing. Links time related information to control project and construction execution.	Contractor
5D	3D + cost	Cost estimation. Adds cost related information to enable early cost estimation and quantity take offs.	Quantity surveyor
6D*	3D + sustainability	Sustainability assessment. Adds environment related information to estimate environmental impact of construction and operation.	Facility manager Building owner
7D*	3D + FM	FM and building life cycle information integration. Adds information management useful for operation and maintenance planning and execution.	Facility manager Building owner
nD	3D + …nD	Other possible dimensions associated with the BIM model.	Any

* no general consensus on order or naming have been reached in the literature

BIM has been widely adopted by AEC industries and is the modern standard for building design and construction. BIM has revolutionized the way information is managed, exchanged and transformed as it provides an open platform for collaboration between stakeholders via a single integrated model. As discussed in section 2.3, effective BLM and FM rely upon continuous and reliable information on the inventory, condition and performance of building elements. In BIM, *"such non-geometrical information can be gathered and integrated with existing geometrical data retrievable in the BIM environment. This affords ease of access for information retrieval and enhanced visual recognition when locating facility assets. - - Implementing BIM in FM also allows asset owners to formulate intelligent decisions on facility related activities, and consequently optimise the outcome"* (Pärn et al., 2017). Figure 2.6 illustrates AECO stakeholders, dimensions and information flows around BIM during BOL and early MOL of a building.

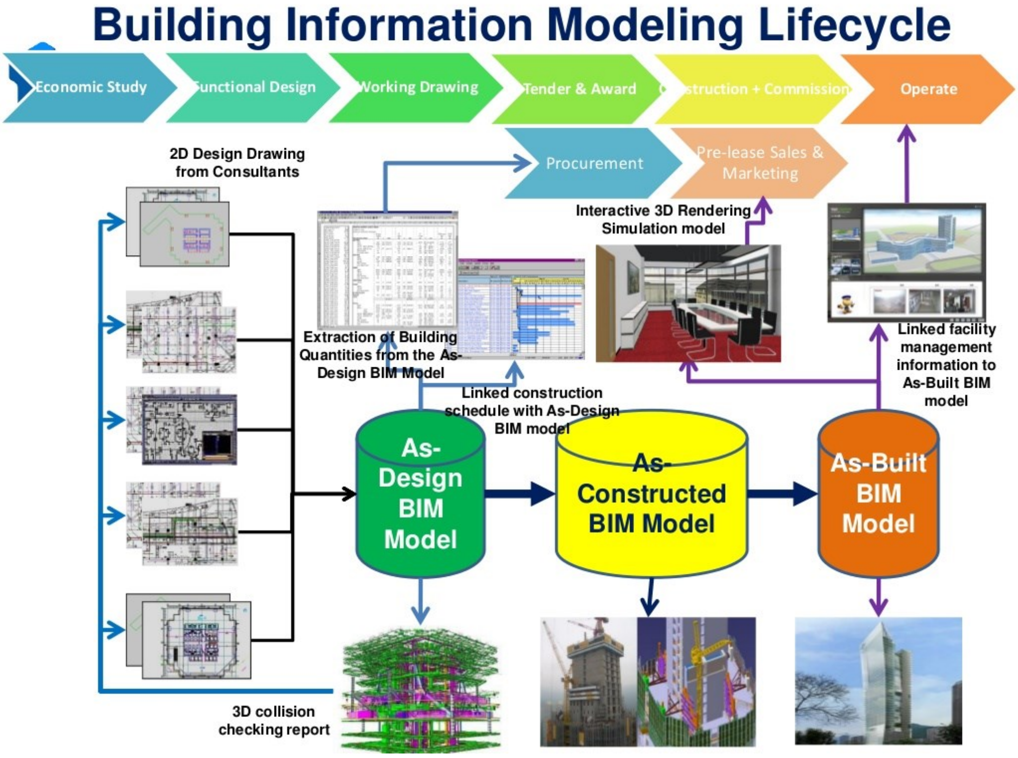


Figure 2.6: Illustration of BIM properties and information flows (Au, 2017)

From BLM point of view, extending the potential of using BIM to MOL and EOL of a building via an integration to FM information management systems is crucial. Methods and value of BIM-FM integration define a contemporary and popular area of research that argues several improvements to effective FM from integration to BIM (Pärn et al., 2017):

- automation of current manual processes of information handover
- increased accuracy of FM data
- increased accessibility of FM data
- increased efficiency in work order execution.

As in CL2M, a bi-directional information flow, or an information loop, has been recognized as a key element in an effective BIM-based BLM system. Figure 2.7 illustrates such an information loop and some of the identified BIM-FM benefits argued in the literature.

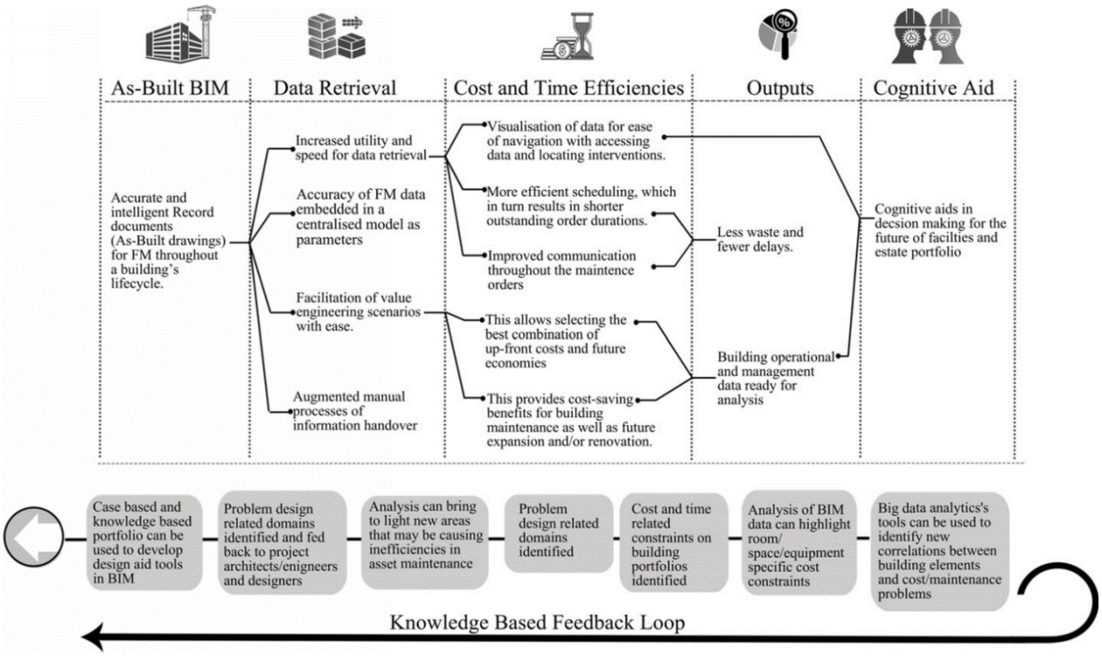


Figure 2.7: Information loop potential in BIM-FM data integration (Pärn et al., 2017)

As the origins of BIM lie in the AEC sector, current mature commercial applications of BIM, such as various information management and design software, have been developed mainly to be used for the design and construction of buildings. Depending on the business or engineering domain, several modelling software platforms have been developed. However, interoperability and information exchange between commercial software has proven difficult and resulted in the development of a BIM standard, Industry Foundation Classes.

2.3.2 Industry Foundation Classes (IFC)

BuildingSMART aims to drive a transformation of the built asset economy through creation and adoption of open international standards. The origins of buildingSMART lie in two key conclusions reached by the founding companies (BuildingSMART, 2017b):

- interoperability is viable and has great commercial potential
- standards must be open and international, not private or proprietary.

A major achievement of buildingSMART has been the introduction of Industry Foundation Classes (IFC). IFC is an open international standard (ISO 16739:2013) for "- - *BIM data that is exchanged and shared among* *software applications used by the various participants in a building construction or facility management project"* (CEN, 2013). IFC is linked to the International Framework for Dictionaries (IFD; ISO 12006-3; CEN, 2007), an open library in which concepts and terms are semantically described and given a unique identification number, and the Information Delivery Manual (IDM; ISO 29481-1:2016; CEN, 2016), an information exchange method for IFC.

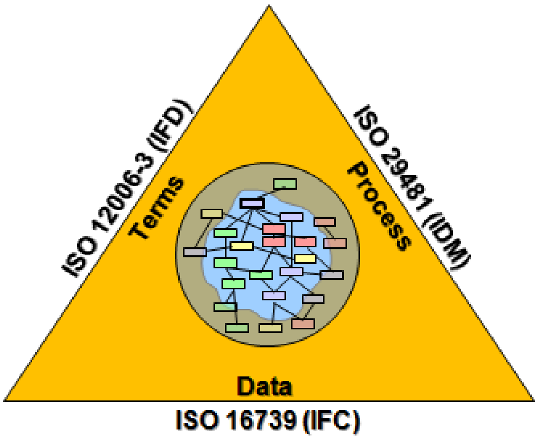


Figure 2.8: IFC related standards (BuildingSMART, 2017c)

IFC is an open and neutral data file format for sharing and exchanging data within design, construction and FM. IFC provides improved integration between BIM software vendors and is the only object-orientated, vendor-neutral BIM data format for the semantic information representation of building objects. IFC is under continuous development with multiple versions and addendums published. The most recent version is IFC4 Addendum 2 (IFC4 Add2; Kang, 2017; BuildingSMART, 2017c). However, the preceding, matured and finalized version IFC2x3 Technical Corrigendum 1 (IFC2x3 TG1) has been widely adopted and is currently used as a commercial standard in several countries (BuildingSMART Finland, 2012).

IFC has become the global standard for transferring BIM data due to the lack of interoperability between vendors. Currently, IFC is supported by circa 150 software applications. The interoperability provided by IFC data format allows all stakeholders of a building project to utilise different software through the building life cycle. However, as IFC is developed by a vendor-neutral alliance, it also induces that no commercial BIM software is currently able to produce IFC as a native file type. (Pärn et al., 2017)

IFC is a business-driven data format. An IFC file consists of objects and semantic connections between objects. Objects have attributes that describe the business-related properties of the related real-life object. Connections between objects are represented by "relation elements". An IFC model represents both tangible building elements, such as walls, doors or beams, and abstract concepts, such as schedules, activities, spaces or construction costs in the form of entities. Currently, IFC provides over 700 entity data types. Each entity can have multiple properties, such as name, geometry, materials or relationships. (Pärn et al., 2017; Kang, 2017; Motamedi et al., 2016)

IFC describes information schema in the object-oriented EXPRESS language. IFC can be implemented for all kinds of objects, or building elements, including site, walls, mechanical equipment, electronical devices or special equipment (Vanlande et al., 2008). The IFC technology (IFC4) consists of (Kang, 2017; BuildingSMART, 2017c):

- The IFC kernel
- 3 core data schemas (basic extension packages extended from the kernel)
- 5 shared element data schemas (common extension packages for AEC/FM domains, in which some concepts are added from the extension packages)
- 8 domain specific data schemas (AEC/FM domain-specific packages)
- 21 resource definition data schemas (resource packages in which basic entity data types, such as quantity resources and material resources, are defined by type to define the attributes of the building elements).

An example of an IFC2x3 file is presented in figure 2.9 as an actual building used by a company in food processing industry, located in Northern Finland. Sections of the corresponding file structure are presented in Appendix A.

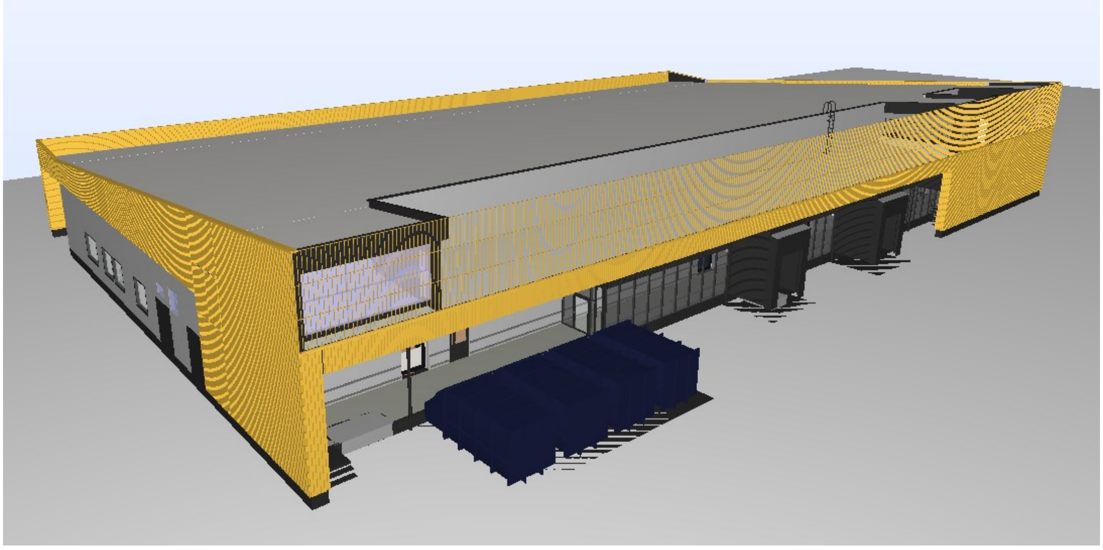


Figure 2.9: Example of IFC representation of an actual building (ALT Arkkitehdit Oy, 2017)

Eventually, IFC4 will replace IFC2x3 TG1 as the standard version for BIM exchange, similar to how IFC2x3 has replaced the older versions in history. For this reason, the latest IFC release, IFC4 Add2, was chosen to be used in this thesis.

2.3.3 Product information modelling in IFC

Increasing use of BIM technologies in the AEC field has led to a need for BIM-feasible objects of building-related products. Today, both open source and commercial web-based product libraries are available, for example BIMobject (2017) for standard architectural and MEP system products and a community-based RevitCity (2017) for virtually any products the users upload to the service. (Gao et al., 2017)

As IFC can describe, both visually and semantically, all elements and processes of a building, it can also be used to describe any product installed or located in a building. However, as explained in section 2.3.2, IFC is currently not used as a native filetype by any software vendor. Current online BIM resources, such as BIMobject and RevitCity, offer BIM models primarily in their native file format dependent on various software vendors. The models typically include relevant product data, for example their functions, dimensions, materials, performances and manufacturers (Gao et al., 2017). The models are embedded as part of a BIM and typically converted into a single IFC model containing all products on a storey or a building (BuildingSMART Finland, 2012). Such an IFC file includes the product models and their data, depending on the software and method of conversion. Typically, all BIM software provide an IFC exporter with varying customization properties.

An IFC model represents building elements and other products in the form of entities. Each entity can have multiple properties such as a name, geometry, materials and relationships. Currently, IFC supports only a limited number of use cases in the AECO industry. IFC is under continuous development and new entities are proposed and constantly developed by buildingSMART. However, IFC also offers methods to describing non-standard, customized product entities if needed. The two mechanisms are:

- using proxy elements
- using property sets or types.

These mechanisms require implementation agreements about the definition of the property sets and proxy elements if they are to be used to exchange data with other BIM software (Motamedi et al., 2016).

An example of a customized IFC model is provided in figure 2.10. It represents an IFC2x3 file that contains special production equipment of the food processing facility presented from the same direction of view in figure 2.9.

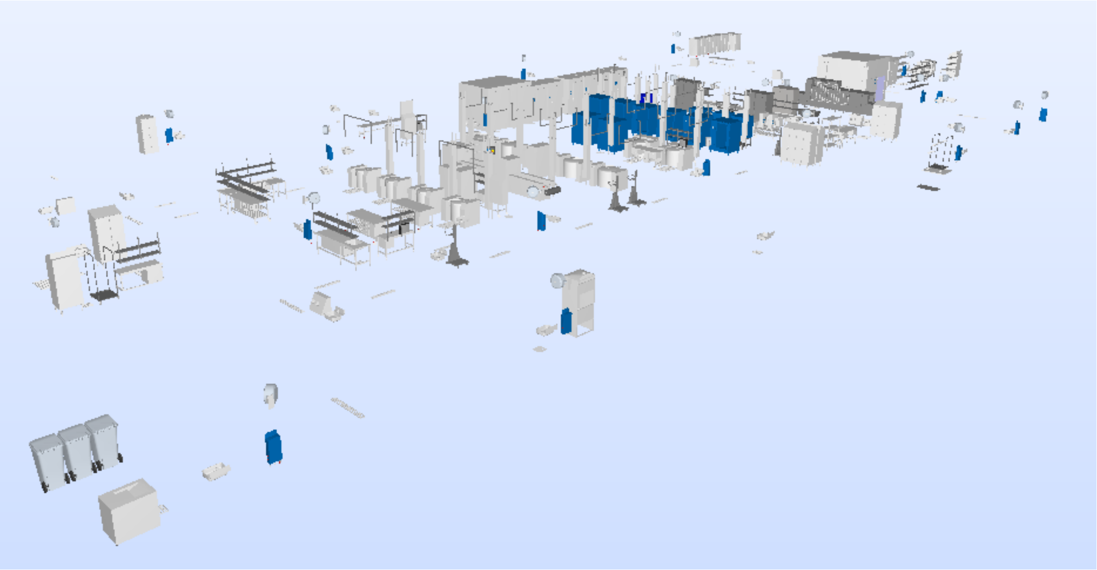


Figure 2.10: Example of IFC representation of production equipment (Saircon Oy, 2017)

The objects representing production equipment have been modelled using commercial BIM software and converted to IFC by an additional, built-in IFC exporter. In the IFC file, the products are described using proxy elements (IfcBuildingElementProxy) combined with custom property sets and types. Sections of the corresponding file structure are presented in Appendix B. By definition, *"IfcBuildingElementProxy is a proxy definition that provides the same functionality as subtypes of IfcBuildingElement, but without having a predefined meaning of the special type of building element, it represents. - - IfcBuildingElementProxy can be used to exchange special types of building elements for which the current specification does not yet provide a semantic definition"* (BuildingSMART, 2017c). Numerous other common and domain-specific proxies are also included in the standard.

The IFC standard includes mechanisms for internal and external representation of product-related, non-spatial information. Both structured, machine-readable and unstructured, human-readable data can be described as standard or custom properties and property sets, depending on the IFC schema or entity. The fundamental concepts and core data schemas provide, for example, methods for relating processes, costs, time and people to objects or presenting physical (aggregation) and non-physical (nesting) composite structures. (BuildingSMART, 2017c)

Active development and expandability, openness and the support of major software vendors have led to the success and adoption of IFC in BIM. As PLM and PIM continue to develop, IFC will increasingly support these functions and predictably act as the standard for lifecycle modelling of products utilized in BLM. (Vanlande et al., 2008; Motamedi et al., 2016; Gao et al., 2017)

3 An IFC-based PLM addressing system for a medical device

In this chapter, the background, general setting and requirements of the use case are defined. First, the necessary information management structure of an ID@URI based PLM system are derived from the theory. Second, the environment and setting of the use-case are described. Additionally, specific features and limitations of the IFC standard in relation to the use case are discussed.

3.1 Minimum data requirements

IFC, by standard, defines property sets and human readable properties for product related information, such as manufacturer, model, serial number or acquisition date of an object. This thesis, however, focuses on implementing properties that are required to create a universal, product-centric addressing system using ID@URI notation. Such properties do not exist in current version of IFC standard.

Derived from the theory presented in sections 2.2.2 and 2.2.3, the data scheme of a universal addressing system should at the minimum be able to describe product identity, a composition design pattern and an observer design pattern. Also, if the model is used as an information platform, it should be able to store history information of at least the latest modification within the platform itself. All other data it is assumed to be modified using an external server or software. To describe these four minimum features, several attributes must be defined.

Figure 3.1 presents a graphical visualization of the minimum attributes and sample values of a PLM addressing scheme, further described in detail in table 3.1.

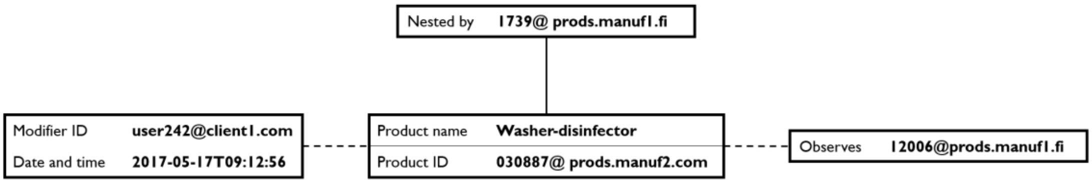


Figure 3.1: Minimum data attributes of the product model

Table 3.1: Minimum data attributes of the product model

	Attribute	Description	Example value
Identity	**Product name**	Human readable, universal name of the product.	Washer-disinfector
	Product ID	Identifier of the product. Unique inside the product server URI.	030887@prods.manuf2.com
Composition	**Nested by**	Identifier of another “whole” product that the product is partly composed of. Unique inside the “whole” product server URI.	1739@prods.manuf1.fi
Observer	**Observes**	Identifier of another product that the product observes but does not share a composition with. Unique inside the product server URI.	12006@prods.manuf1.fi
History	**Modifier ID**	Identifier of the user that has last modified the attributes. Unique inside the user server URI.	user242@client1.com
	Date	Date when the user last modified the attributes. Presented in IFC format “YYYY-MM-DD”.	2017-05-17
	Time	Time when the user last modified the attributes. Presented in IFC format “hh:mm:ss-00:00”, where the last digits indicate time zone difference to UTC.	09:12:56+03:00

3.2 Description of use case environment

Healthcare industry is a technology intensive industry, in both private and public sector. A study performed in the United States found that from 1995–1997 to 2008–2010, the average number of mobile medical devices, related to treating a patient, per a staffed hospital bed rose by 62% from 8 to 13 (Horblyuk et al., 2012). Late research in the field of medical equipment has also found that during an approximately equivalent time period from 1998 to 2006, global expenditures on medical equipment and devices increased 52% from US$145 billion to US$220 billion (Castro et al., 2013) and were expected to keep growing in near future. Medical equipment is a major asset for healthcare organizations and an interesting terrain for PLM.

3.2.1 Medical device management in Finnish hospitals

As an example, the largest public hospital district in Finland, the Hospital District of Helsinki and Uusimaa (HUS), has over 100 000 medical devices involved in their asset management system (Sofor Oy, 2017). Due to the increasing costs and number of devices, effective management of medical equipment is crucial for private and public healthcare service providers.

Software vendors have been developing asset management software for medical equipment since 1980s. Today, multiple choices are available with varying levels of PLM features included. In the Finnish public healthcare sector, a study concluded that all 20 public healthcare districts were using a modern asset management software to manage medical device related information and maintenance tasks (Lehtoviita, 2016). Another important reason for the wide adoption of medical device management systems is the Finnish *Law on healthcare devices and equipment* (FINLEX, 2010). The law obliges healthcare service providers (named “professional users of medical devices” in the law) to use a system to, for example,

- maintain information devices and their location
- track use and maintenance history of devices
- track information related to situations that have endangered users or patients.

Also, the law states that every healthcare unit must have a person in charge of fulfilling the requirements of the law when the devices are used, and a person appointed in charge of medical devices. As new devices are acquired to a healthcare unit, an acceptance inspection is performed to the devices as they are added into a device register. In the inspection process, devices are granted a unique identifier specified by the professional user (FINLEX, 2010). The fulfilment of the law is supervised by the National Supervisory Authority for Welfare and Health (Valvira). In addition to supervision, Valvira also guides healthcare organizations and medical professionals using medical devices. Valvira is entitled to inspect organizations to ensure the fulfilment of the law.

Medical device management involves multiple people and systems across organizations. Even though information management systems exist, they are typically designed for a special narrow use. Typically, both the manufacturer and user of a device have a system for PIM, or even PLM, but the systems are completely separated from each another. Figure 3.2 represents typical actors, actions and systems around a medical device, as well as the potential of CL2M and product-centric information management.

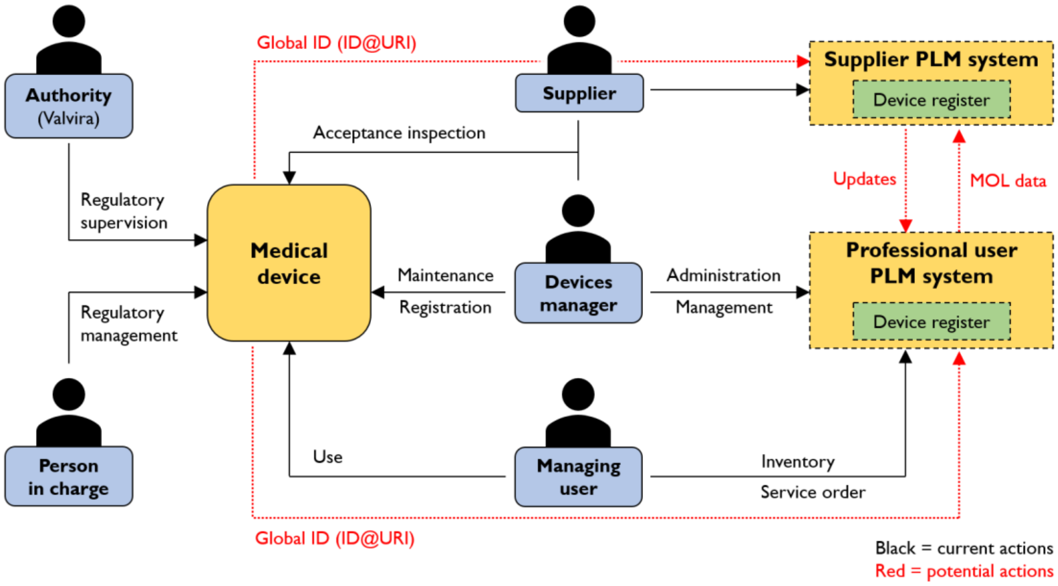


Figure 3.2: Medical device management system in Finnish hospitals

From product-centric PLM point of view, medical devices represent a typical scenario where gaps in information, missing interoperability and lack of globally defined unique identifiers would benefit all parties in the PLM environment.

3.2.2 BIM in Finnish public hospital sector

As in most Scandinavian countries, specialized healthcare sector is currently in turbulence in Finland. Most of public hospital infrastructure were built in 1960–70s, reaching the end of technical life cycle in near future. Currently, major renovation and new build projects are under development and construction throughout the country. A total investment of over 3 billion euros to new hospital buildings and infrastructure has been estimated to realize during 2012–2021 (NHG, 2014).

BIM has been widely adopted in Finnish public construction, especially after the release of Common BIM Requirements (YTV2012a; BuildingSMART Finland, 2012). YTV2012a describes the national methods, processes and best practices of building information modelling in

Finland and is typically used as a reference in all public building projects. A recent study published by buildingSMART Finland and the association of Finnish Hospital Engineering (SSTY), *Building information models for maintenance – a preparatory study*, found that IFC-based BIM is already extensively used in hospital construction projects and is expected to be a minimum requirement in all future projects (Kiviniemi, 2017). BIM has become a standard in modern hospital building engineering in Finland.

The fundamental theme in the study by Kiviniemi (2017) was the current state, restrictions and possibilities of utilizing BIM into operation and maintenance of hospitals. The study involved several interviews and workshops with BIM professionals, hospital property managers and hospital engineers in major Finnish healthcare districts. The study argues several established benefits of BIM in hospitals:

- Utilizing BIM has helped information and construction process management in transitions from design phase to construction phase and partially to operation phase
- BIM models offer great potential in operation and maintenance of hospital infrastructure through semantics and visual representation of complex information
- BIM models could offer a platform for storing identification data of building systems, elements and equipment, as well as transferring the data from BOL to MOL.

The study also identifies several challenges related to the use of BIM:

- Lack of detailed, sector-specified national modelling standards result in inconsistent BIM data
- Current BIM models serve well in construction process but are poorly applicable and lack functionality for the operation and maintenance
- Incorporating BOL and MOL data to building elements is seen important, but currently extremely difficult and ineffective due to the lack of universal data schemes and interoperability between software.

The current situation of infrastructure development in Finnish public hospital sector represents a typical scenario and challenges described in the literature in chapter 2. BIM and IFC have been identified as a potential platform for improved building and product lifecycle management, but the fragmentation of information, lacking interoperability of systems and incompleteness of international standards impede comprehensive, commercial adoption and implementation.

3.2.3 User setup and system limits

This section describes the general setting of the use case to be implemented in chapter 4. The objective is to develop a method for implementing the product-centric ID@URI concept in an IFC modelling process of a medical device in a hospital building project.

As a BIM oriented hospital construction project proceeds to the end of construction phase, an as-built combination BIM model of the hospital is delivered, along with the separate domain-specific IFC models. For the device manager of a hospital, a model representing all medical devices (device model) is of most importance. In the use case, this model is expected to include product information models of the medical devices in the hospital. Each product information model should incorporate information of the product ID and URI of relating product server. This would enable using the complete IFC model as a platform for product-centric information management in the medical device management system of the hospital.

The device model is created either by a medical device designer or the supplier of the devices. In both cases, a native modelling software is first used to create PIMs of single devices (products). As no software vendors currently use IFC as a native format, native PIMs are first deployed in a commercial BIM modelling software to create a native device model containing all devices in a project. Next, the native device model is exported as an IFC device model and delivered to be combined with other partial models of the project.

In the use case, the person creating the PIM and the device models needs a method for incorporating the necessary ID@URI data into the final IFC device model. As a single hospital project may include up to thousands of medical devices, the method should be simple and automatically exportable from native format to IFC. No manual modification of the IFC model should be necessary. The final IFC model should describe the identities, visual representations, part-whole hierarchies and external resource information for all devices separately.

Figure 3.3 describes typical phases, actions and actors of the process in black. The figure also shows potential actions and systems related to a product-centric PLM system in red. The boundaries of the use case are shown in lilac.

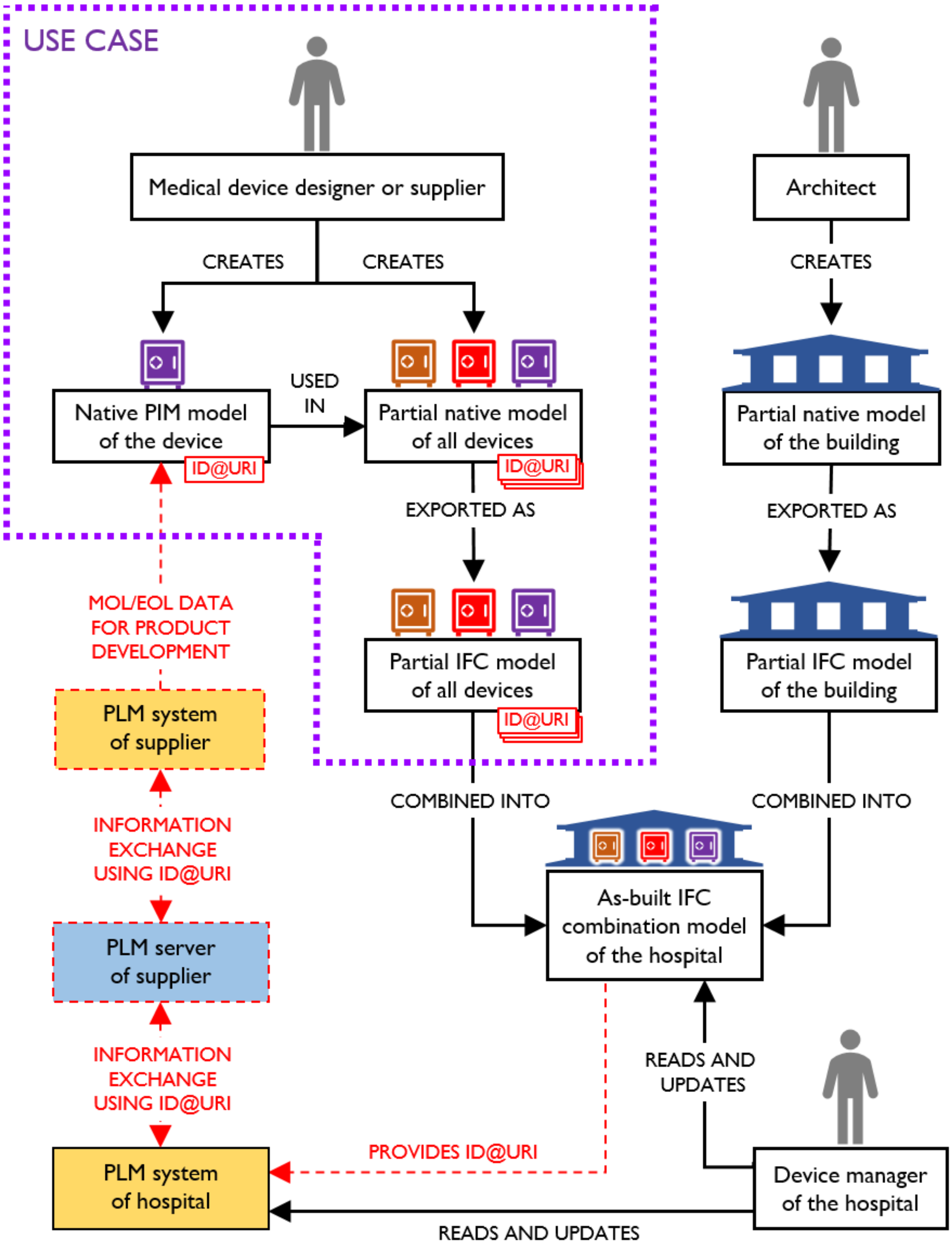


Figure 3.3: Use case diagram of the study

3.2.4 The product system

For the use case, a high capacity, automated washer-disinfector system is selected as a product system to be modelled. A washer-disinfector is later abbreviated as a disinfector. Disinfectors are common medical devices that can be found in all hospitals around the world and are purposed to safely wash and disinfect instruments, tools and equipment used in hospitals.

Automated, high capacity disinfector systems are typically used in central sterile services department (CSSD). CSSDs are centralized, integrated hospital units that perform washing, disinfection and sterilization on medical devices, equipment and consumables. An automated disinfector system typically composes several disinfectors, automated loading and unloading conveyors, return conveyors and carts. A single disinfector is shown in figure 3.4 and an automated disinfector system with various conveyors in figure 3.5.

Figure 3.4 (left): A typical pass-through disinfector
Figure 3.5 (right): An automated disinfector system
(Belimed AG, 2017)

A healthcare unit typically purchases the disinfector system as a whole from a single supplier. However, different products or components, such as conveyors or carts, may originally be manufactured by multiple companies and composed by the supplier to a single delivery. Thus, the system represents a typical real-life composition, or a part-whole hierarchy, as described in the literature. In the use case, a simplified system composed of three product types is implemented, containing:

- two disinfectors
- two loading conveyors (one for each disinfector)
- two unloading conveyors (one for each disinfector).

The product system represents a logical hierarchy from the point of view of a medical device manager. The system is acquired as a single unit and will thus be addressed with a product ID. The system hosts two disinfectors. In the system, conveyors are attached to and serve a single disinfector. Thus, both disinfectors host two sub-products, a loading conveyor and an unloading conveyor. Composition of the system is shown in figure 3.6.

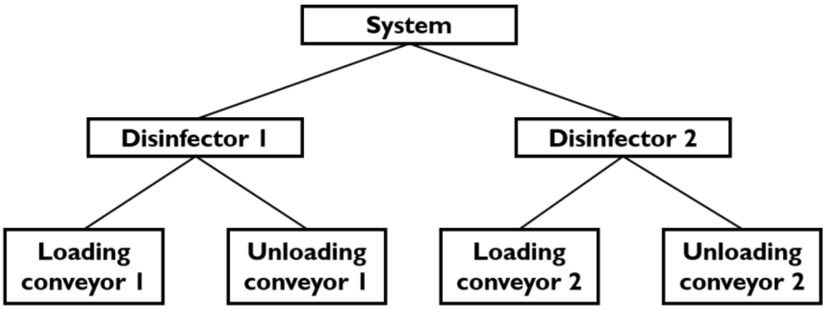


Figure 3.6: Use case system composition

In the PLM-feasible IFC product model, each component of the system must be able to store the necessary data described in section 3.1.

3.3 Description of relevant IFC issues

Although the IFC standard is well developed in AECO sector, it only supports a limited number of use cases. Many building element and product types are not explicitly defined or lack functionality in special applications such as healthcare. For both the products and the required PLM data, custom entities and properties need to be applied.

3.3.1 Medical devices in IFC standard

Modern medical devices are complex and highly technical apparatuses. Although primarily operating on electricity and always being connected to an electricity network, many medical devices also require a connection to other systems, such as plumbing, HVAC, steam, medical gases or ICT networks. From a mechanical, electrical or plumbing (MEP) engineering point of view, a medical device may be a simple terminal unit of relating domain. However, from facility management, healthcare and or medical device manager point of view, a medical device is always a single entity. If an as-built BIM is to be used in the operation and maintenance phase of a building, the product models must be built according to the needs of the end user. For this reason, in healthcare projects, medical devices need to be modelled as whole products that have an ability to connect to multiple MEP networks.

Currently, IFC does not provide an entity for medical devices or any other corresponding, industry specific specialty equipment. IFC4 HVAC domain extension (IfcHvacDomain) describes an entity called *IfcMedicalDevice*, but only as part of a medical gas system: *"A medical device is attached to a medical piping system and operates upon medical gases to perform a specific function"* (BuildingSMART, 2017c). Less than 10 predefined device types are listed, all only related to medical gases. Similarly, the electrical domain extension (IfcElectricalDomain) describes an entity called *IfcElectricAppliance* as *"- - a device intended for consumer usage that is powered by electricity. Electric appliances may be fixed in place or may be able to be moved from one space to another. Electric appliances require an electrical supply that may be supplied either by an electrical circuit or provided from a local battery source"* (BuildingSMART, 2017c). Several predefined types of electric appliances are described but only for household and office appliances, such as cookers, photocopiers and vending machines.

Thus, neither domain extension provides predefined solutions for special equipment or devices that directly connect to multiple MEP networks. For example, as a household dishwasher can primarily be addressed as an electric appliance as it is infrequently used and connected to plumbing systems via a mixer or a tap (an independent terminal unit), a professional washer disinfector is used continuously and has direct connections to electrical, steam and plumbing networks and a built-in mixer. In the scope of IFC schema, a medical device should not be domain specific but rather a shared element.

In future, as the standard develops, IFC is expected to support a growing number of special product applications and types. New extensions, for such as an entity for RFI tags (Motamedi et al., 2016), are usually proposed by industry representatives or academic researchers. However, proposing an extension for incorporating medical devices into the IFC standard falls out of the scope of this thesis. Instead, the use case will utilize a general proxy element *IfcBuildingElementProxy*, as explained in section 2.3.3.

3.3.2 Composition structures

Object composition is one of the fundamental concepts in IFC: *"objects may be composed into parts to indicate levels of detail, such as a building having multiple storeys, a framed wall having studs, or a task having subtasks. Composition may form a hierarchy of multiple levels, where an object must have a single parent - -"* (BuildingSMART, 2017c).

Composition is divided into two composition types, aggregation and nesting. An aggregation indicates an internal, unordered part composition relationship between the whole structure, referred to as "composite", and the subordinate components, referred to as "parts". A nesting indicates an external, ordered part composition relationship between the hosting structure, referred to as "host", and the attached components, referred to as "hosted elements". The relationship from the hosting structure to its attached components is called nesting and the relationship from the components to their containing structure is called hosting. In other words, a "whole" *nests* "parts" and "parts" are *hosted* by "whole". However, the related object attributes are called *Nests* (nesting) and *IsNestedBy* (hosting).

In relation to the ID@URI concept, only nesting is relevant as it, by definition, describes an ordered structure. Thus, nesting could be used to describe the composition structure of PLM feasible product information models. However, nesting being an IFC backend feature, it is not a solution as such for the ID@URI concept. IFC nesting uses GUIDs as a reference and is primarily intended to describe relationships within the model file, rather than offering an externally or human readable reference structure for part-whole hierarchies. Further development of a general, PLM-feasible nesting feature falls out of scope of this thesis.

In the use case, the composition structure of a product model is described using custom properties for nesting and hosting. To allow future development, the properties will be named according to the IFC naming methodology (nesting, hosting).

3.3.3 Custom property sets

IFC defines a difference on object attributes and properties. Most IFC objects can have properties attached to them that have little or no relationship to other objects. In an IFC model, attributes are directly attached to the object as attribute of the entity. Properties, grouped in a property set, are assigned to the object by a relationship. Property sets can be related to both object occurrences (instances) or object types. Property sets for types define the common properties for all occurrences of the same type. Identical properties directly assigned to an object occurrence always override properties assigned to the object type.

Properties and property sets, as all IFC elements, are defined as entities. By definition, IfcProperty is “an abstract generalization for all types of properties that can be associated with IFC objects through the property set mechanism.” An IfcPropertySet is “a container class that holds properties within a property tree. These properties are interpreted according to their name attribute.” Properties are usually defined by a name, value, unit triple. (BuildingSMART, 2017c)

Using properties and property sets is recommended as a method to extend applicable properties. The IFC schema supports storing and transmitting user defined, custom properties in named sets. The standard defines and recommends many property sets but also states that regional adoptions and applications may define more if necessary.

The minimum data attributes defined in section 3.1 will be incorporated into the IFC product model as custom properties and compiled into a custom PLM property set. This will allow for an explicit, external data inquiry and exchange as the IFC model relates the visual elements into the PLM property set, which in turn relate the products into PLM composite and observer structures using an ID@URI addressing system.

4 Development of an IFC product information model

In this chapter, a method and an automated process is developed to create a native product model and export it as an IFC product model capable of product-centric information exchange. The chapter is divided in three parts. First, main features of commercial BIM software and IFC exporting are described. Second, a method is explained to create a simplified, general product system model. Last, a finalized product system model for the use case is presented.

4.1 Modelling software and related issues

A variety of commercial BIM software are available. Most of the software are designed for domain specific use or have gained a foothold in certain market areas. Some examples are ArchiCAD and Vectorworks for architectural and interior design, MagiCAD for MEP engineering, especially in Northern Europe, and Tekla Structures for structural engineering in Finland. Some vendors have developed BIM software families that cover all engineering domains and the whole design process a building. The most important BIM vendor with the largest international market share is Autodesk with their Revit software, covering architectural, MEP, structural and interior design domains.

As IFC has become a widely adopted standard, all BIM software are today able to import and export BIM as IFC, typically by using a built-in IFC exporting module. Typically, software extensions are also provided either by vendors or open source communities. BuildingSMART hosts and updates a comprehensive list of IFC-compatible BIM software (BuildingSMART, 2017d).

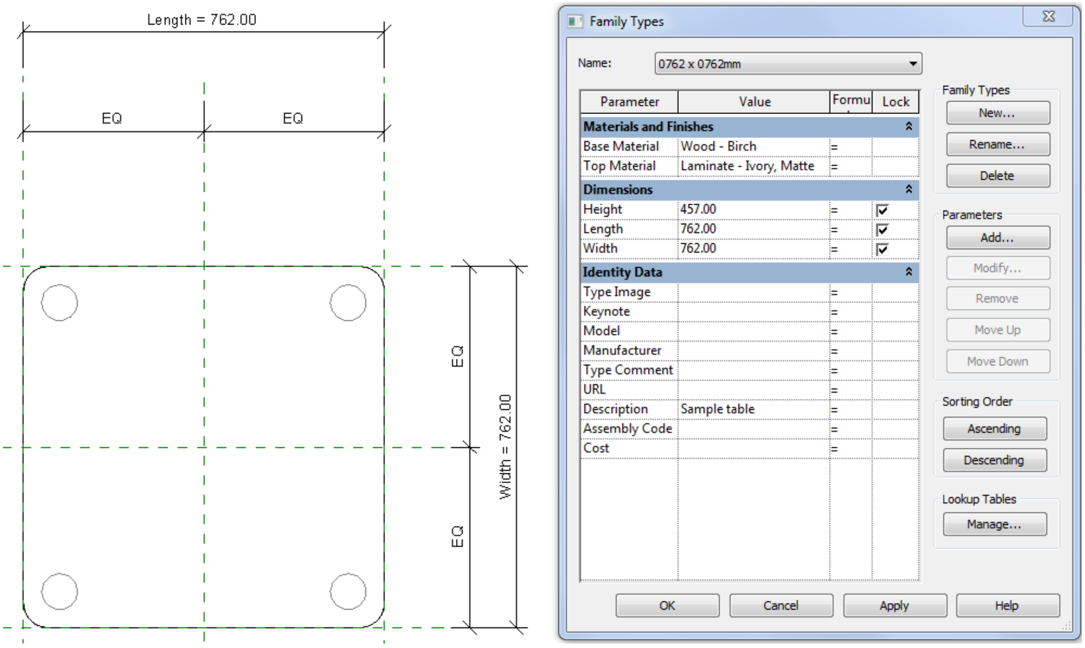
4.1.1 Autodesk Revit

In the use case, Autodesk Revit was selected as the native BIM software for product and project modelling. A major reason behind this decision was gaining universality because of the wide adoption and market share of Revit in all engineering domains. In Finland, many major architectural and engineering offices specialized in healthcare use Revit for BIM. Also, many hospital device manufacturers already provide native product models for Revit.

Another important reason for choosing Revit is the ease of creating parametric objects, such as virtual product models. Revit was one of the first software to introduce parametric, "component-based" modelling in building engineering. In Revit, parametric components are created using a graphical editor rather than a programming language. All relationships between components, views, and annotations are automatically captured by the model so that a change to any element automatically propagates and keeps the model consistent. The graphical user interface is a great benefit considering a building life cycle, as the users of product models are not required to master programming languages to create, edit or use the models.

In Revit, a parametric component is called a *family*. A family can represent any element within a building project, such as a wall, a window, a person, an appliance, a special device or an annotation. Each family can have one or many *types*. A single occurrence of a family is called an *instance*. Parameters can be created for both types and instances of a family. A *type parameter* affects all instances of a family and an *instance parameter* affects a single instance. In families, parameters can be used for infinite applications, such as topology, relations, annotations or general information. Revit also features *shared parameters* that can be defined in an external text file. Shared parameters are intended to be used across families and projects and can be applied on multiple categories. This allows for a predefined parameter structure that is necessary for a universal PLM attribute definition, as later explained in detail in section 4.2.1.

Figure 4.1 shows a floor plan view of a sample Revit furniture family in left and the parameter editing window in right. The family has various parameters defined, for example "Length" and "Width" for table geometry and "Description" for human readable information.



Name: 0762 x 0762mm

Parameter	Value	Formu	Lock
Materials and Finishes			
Base Material	Wood - Birch	=	
Top Material	Laminate - Ivory, Matte	=	
Dimensions			
Height	457.00	=	☑
Length	762.00	=	☑
Width	762.00	=	☑
Identity Data			
Type Image		=	
Keynote		=	
Model		=	
Manufacturer		=	
Type Comment		=	
URL		=	
Description	Sample table	=	
Assembly Code		=	
Cost		=	

Figure 4.1: Sample family view and parameter editor in Autodesk Revit

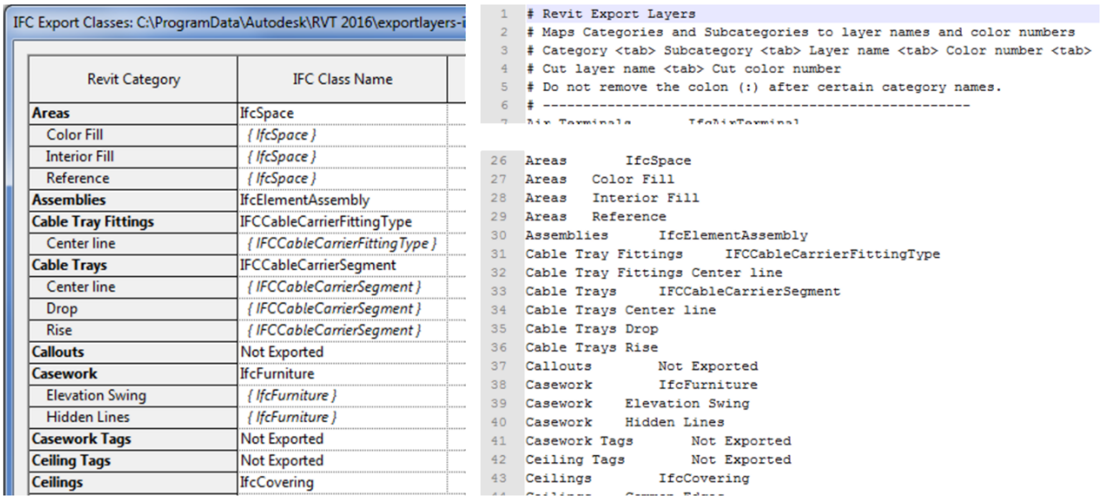
Families are always assigned to a single *category*. Categories are used to specify the intended domain or use of a family. Examples of categories include Casework, Electrical Fixtures, Generic Models, Specialty Equipment and Windows. Subcategories can also be created. Different categories have different family parameters based on how Revit expects the component to be used. Using the correct categories is required in IFC export phase, as Revit defines IFC classification using family categories, as further explained in section 4.1.2.

Revit enables *nesting* of families. Complex product models can be created by loading a family into another family, thus creating a *nested family* as a hierarchical structure. Nesting can also be used to change the category of a family as a family of one category can be nested into a family of a different category. Revit also enables a choice to either hide the parameters of a nested family or to show them in the hosting family. This feature is called *sharing*. If the nested family is shared, it can be selected, tagged and scheduled separately from the host family. If the nested family is not shared, components created by the host family and nested family act as a single unit. The sharing feature is essential in this use case.

In Revit, the BIM model of a room, floor or an entire building is called a *project*. A project defines every aspect of a building or part of a building, such as general information, scheduling, location, levels and topology. Families are loaded into a project as instances and associated with necessary semantical level, space, room, scheduling and resource data. A project represents the virtual model of a partial or whole building and can be exported into an IFC file.

4.1.2 Built-in IFC exporter of Revit

A built-in IFC exporter is provided in Revit. The exporter maps the Revit project and family instances into IFC entities and writes an IFC file of the project. Basic configuration options are provided in the exporter, such as choosing which version of IFC standard is used, which parts of the project are exported and how base quantities and spatial boundaries are treated. A method for configuring IFC classification is also provided in the exporter. Each Revit family category is mapped into a corresponding IFC class according to an *IFC Mapping File*, which is stored in text format. The IFC mapping file is loaded into Revit and shown in a graphical user interface (GUI). The GUI and sections of the corresponding mapping text file are presented in figure 4.2.



IFC Export Classes: C:\ProgramData\Autodesk\RVT 2016\exportlayers-i

Revit Category	IFC Class Name
Areas	IfcSpace
Color Fill	*{ IfcSpace }*
Interior Fill	*{ IfcSpace }*
Reference	*{ IfcSpace }*
Assemblies	IfcElementAssembly
Cable Tray Fittings	IFCCableCarrierFittingType
Center line	*{ IFCCableCarrierFittingType }*
Cable Trays	IFCCableCarrierSegment
Center line	*{ IFCCableCarrierSegment }*
Drop	*{ IFCCableCarrierSegment }*
Rise	*{ IFCCableCarrierSegment }*
Callouts	Not Exported
Casework	IfcFurniture
Elevation Swing	*{ IfcFurniture }*
Hidden Lines	*{ IfcFurniture }*
Casework Tags	Not Exported
Ceiling Tags	Not Exported
Ceilings	IfcCovering

```
# Revit Export Layers
# Maps Categories and Subcategories to layer names and color numbers
# Category <tab> Subcategory <tab> Layer name <tab> Color number <tab>
# Cut layer name <tab> Cut color number
# Do not remove the colon (:) after certain category names.
# ---------------------------------------------------
```

```
Areas       IfcSpace
Areas   Color Fill
Areas   Interior Fill
Areas   Reference
Assemblies      IfcElementAssembly
Cable Tray Fittings     IFCCableCarrierFittingType
Cable Tray Fittings Center line
Cable Trays     IFCCableCarrierSegment
Cable Trays Center line
Cable Trays Drop
Cable Trays Rise
Callouts        Not Exported
Casework        IfcFurniture
Casework    Elevation Swing
Casework    Hidden Lines
Casework Tags       Not Exported
Ceiling Tags        Not Exported
Ceilings        IfcCovering
```

Figure 4.2: IFC mapping tool in Revit

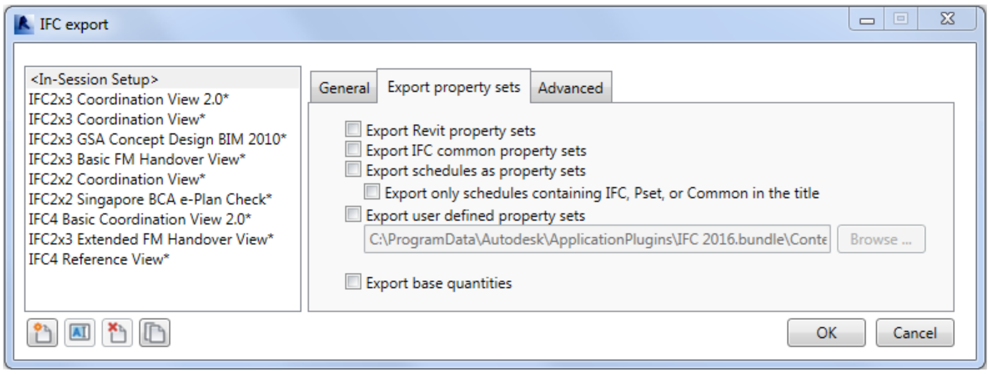
A default mapping is provided for most typical categories. Custom mappings can easily be created to cover user defined subcategories or special applications. For example, should the IFC standard have multiple defined classes for different medical device types in the future, corresponding types could be created using subcategories and mapped into correct IFC classes or types.

However, the built-in IFC exporter lacks functionality for property set definition. Even though it is possible to create custom parameters in Revit, they are disregarded in the IFC export and not written into custom properties or property sets. The built-in exporter does not allow to incorporate the necessary attributes of product-centric PLM into an IFC model without manually editing the IFC file. Hence, a software extension must be used to define the necessary property sets.

4.1.3 IFC for Revit extension

IFC for Autodesk Revit (IFCfR) is a software extension published and distributed by Autodesk. The early versions were originally developed by an open source community and the extension is still provided as freeware. IFCfR significantly enhances and extends import and export capabilities of Revit and is an officially recommended tool for all Revit users that depend on the quality and accuracy of IFC files (Autodesk Inc., 2017).

IFCfR replaces the built-in tool and provides a GUI that allows detailed specification on what information is exported and how the IFC is written. In addition, it also enables for comprehensive definition and creation of custom properties and property sets. Various methods are available but using Revit schedules as property sets or a user defined property set definition file provide for greatest flexibility. Figure 4.3 shows the IFCfR GUI for property sets.



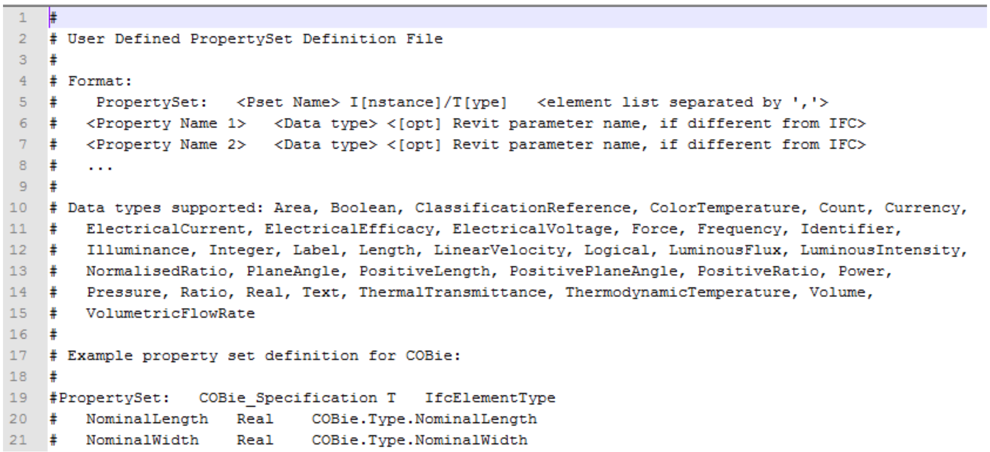
<In-Session Setup>
IFC2x3 Coordination View 2.0*
IFC2x3 Coordination View*
IFC2x3 GSA Concept Design BIM 2010*
IFC2x3 Basic FM Handover View*
IFC2x2 Coordination View*
IFC2x2 Singapore BCA e-Plan Check*
IFC4 Basic Coordination View 2.0*
IFC2x3 Extended FM Handover View*
IFC4 Reference View*

☐ Export Revit property sets
☐ Export IFC common property sets
☐ Export schedules as property sets
  ☐ Export only schedules containing IFC, Pset, or Common in the title
☐ Export user defined property sets
C:\ProgramData\Autodesk\ApplicationPlugins\IFC 2016.bundle\Conte

☐ Export base quantities

Figure 4.3: IFC for Revit property set definition GUI

The user defined property set definition (UPD) file is a human readable text file that maps Revit parameters as IFC properties, writes them into custom property sets and addresses them to IFC elements. This feature is the key improvement to the built-in IFC exporter as it allows controlled exporting of parameters in a native Revit product model into properties of an IFC product model. A UPD file is defined in the use case as a tool for automatically writing the attributes of product-centric PLM into an IFC model. Figure 4.4 shows the syntax and an example section of a UPD file.



```
#
# User Defined PropertySet Definition File
#
# Format:
#    PropertySet:   <Pset Name> I[nstance]/T[ype]   <element list separated by ','>
#   <Property Name 1>   <Data type> <[opt] Revit parameter name, if different from IFC>
#   <Property Name 2>   <Data type> <[opt] Revit parameter name, if different from IFC>
#   ...
#
# Data types supported: Area, Boolean, ClassificationReference, ColorTemperature, Count, Currency,
#   ElectricalCurrent, ElectricalEfficacy, ElectricalVoltage, Force, Frequency, Identifier,
#   Illuminance, Integer, Label, Length, LinearVelocity, Logical, LuminousFlux, LuminousIntensity,
#   NormalisedRatio, PlaneAngle, PositiveLength, PositivePlaneAngle, PositiveRatio, Power,
#   Pressure, Ratio, Real, Text, ThermalTransmittance, ThermodynamicTemperature, Volume,
#   VolumetricFlowRate
#
# Example property set definition for COBie:
#
#PropertySet:   COBie_Specification T   IfcElementType
#   NominalLength   Real    COBie.Type.NominalLength
#   NominalWidth    Real    COBie.Type.NominalWidth
```

Figure 4.4: User defined property set definition file syntax

The objective of the modelling process was to achieve an IFC product model that hosts the minimum PLM attributes according to section 3.1. In the first stage, a method was developed for producing a simple, universal IFC concept model template and an automated IFC export method. Visual reality or composite structures were not considered in this phase.

4.2 Simplified functional model

The native model template should present a parameter structure that can be exported to IFC properties. The parameters, corresponding the PLM attributes, were defined as a set and named, conforming to the IFC naming syntax, as *PlmProperties*. Table 4.1 shows the mapping from PLM attributes to parameters or properties and the corresponding data formats.

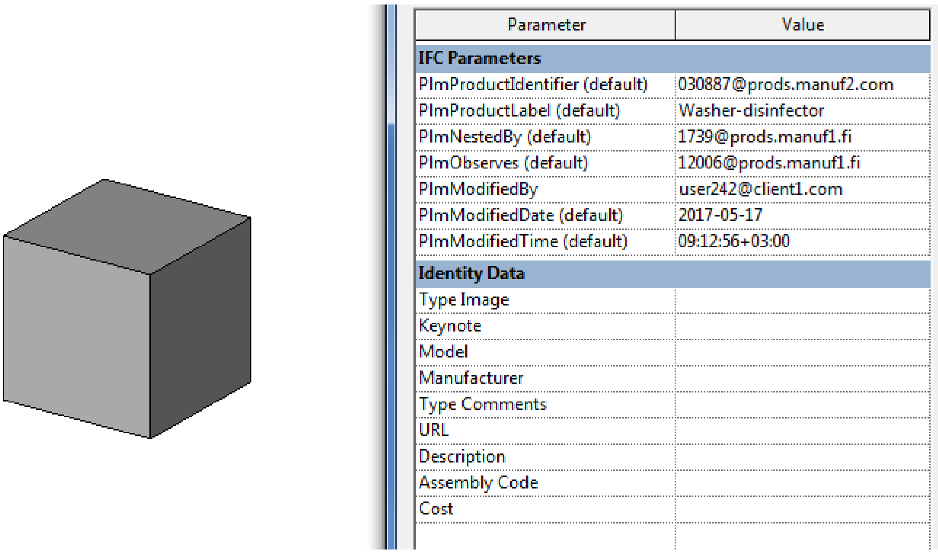
Table 4.1: PLM attribute mapping

PLM attribute	Name of Revit parameter or IFC property	Revit data format	IFC data format	IFC entity
Product name	PlmProductLabel	Text	String	IfcLabel
Product ID	PlmProductIdentifier	Text	String	IfcIdentifier
Nested by	PlmNestedBy	Text	String	IfcIdentifier
Observes	PlmObserves	Text	String	IfcIdentifier
Modifier ID	PlmModifiedBy	Text	String	IfcIdentifier
Date	PlmModifiedDate	Text	String	IfcText
Time	PlmModifiedTime	Text	String	IfcText

4.2.1 Single product template and parameter mapping

Shared parameters offer the best universality and applicability as they can be used by any Revit category. Shared parameters are also written in an external text file which would allow, for example, a standardized parameter definition in future. Thus, a shared parameter file was created and the parameters were defined according to table 4.1 under a parameter group named *PlmProperties*. The resulting shared parameter file structure is presented in Appendix C.

First, a standard Revit family template *Metric Specialty Equipment* was selected as a basis for the native product model and a cube was extruded as a generalization of product geometry. The family was defined as shared to allow hierarchical representation of parameters later in nesting phase. The shared PLM parameters were assigned to the family and grouped under *IFC Parameters*. All parameters were set as instance parameters as they are always product or instance specific rather than common for all similar products. Figure 4.5 shows the simplified Revit family and the corresponding parameter table with example values.



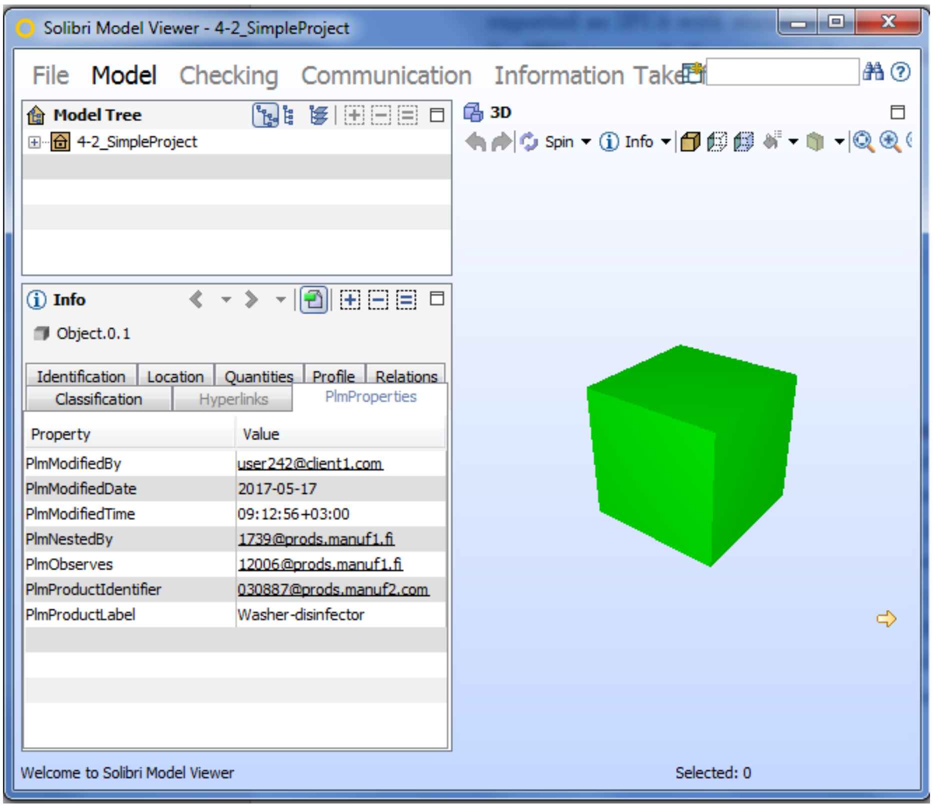
Parameter	Value
IFC Parameters	
PlmProductIdentifier (default)	030887@prods.manuf2.com
PlmProductLabel (default)	Washer-disinfector
PlmNestedBy (default)	1739@prods.manuf1.fi
PlmObserves (default)	12006@prods.manuf1.fi
PlmModifiedBy	user242@client1.com
PlmModifiedDate (default)	2017-05-17
PlmModifiedTime (default)	09:12:56+03:00
Identity Data	
Type Image	
Keynote	
Model	
Manufacturer	
Type Comments	
URL	
Description	
Assembly Code	
Cost	

Figure 4.5: Simple Revit family with PLM parameters

As an experiment, the family was loaded into an empty project and exported to IFC4 using only the Revit built in IFC exporter with standard settings and default classification for IFC. Thus, Specialty Equipment families were mapped to the class IfcBuildingElementProxy. The resulting IFC was analyzed using a general graphical IFC viewing software (Solibri Model Viewer). The topology of the product model exported correctly but was found to miss all user defined parameters, such as the set of PLM parameters. This confirmed the need to use IFCfR and a UPD file to map the Revit parameters into IFC properties correctly.

Next, a UPD file was written to achieve controlled mapping of shared Revit parameters to IFC properties. The property set to be created was named *PlmPropertySet* and defined for a *IfcBuildingElementProxy*. Parameters were mapped according to table 4.1 and IFC properties were named identically to Revit parameters. The final UPD file structure is presented in Appendix D.

IFCfR was utilized to export the project to IFC4. All other functionalities of the extension were disabled and only the UPD file was used to export the PLM parameters. A review using the IFC viewer showed that the IFC product model exported correctly and incorporated the PLM properties contained in a custom property set *PlmProperties*, as shown in figure 4.6.



Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	1739@prods.manuf1.fi
PlmObserves	12006@prods.manuf1.fi
PlmProductIdentifier	030887@prods.manuf2.com
PlmProductLabel	Washer-disinfector

Figure 4.6: Simple Revit family exported as IFC

The resulting IFC file was further analysed using a source code editor to confirm the successful export and found to represent correct and compact EXPRESS syntax:

```
...
#185= IFCBUILDINGELEMENTPROXY('1aQtz6DsrA9hoaVEL2QuwE',#42,
   'PlmProductTemplate:PlmProductTemplate:309519',$,'PlmProductTemplate',#183,#175
   ,'309519',$);
#200= IFCPROPERTYSINGLEVALUE('PlmProductLabel',$,
   IFCLABEL('Washer-disinfector'),$);
#206= IFCPROPERTYSINGLEVALUE('PlmProductIdentifier',$,
   IFCIDENTIFIER('030887@prods.manuf2.com'),$);
#207= IFCPROPERTYSINGLEVALUE('PlmNestedBy',$,
   IFCIDENTIFIER('1739@prods.manuf1.fi'),$);
#208= IFCPROPERTYSINGLEVALUE('PlmObserves',$,
   IFCIDENTIFIER('12006@prods.manuf1.fi'),$);
#209= IFCPROPERTYSINGLEVALUE('PlmModifiedBy',$,
   IFCIDENTIFIER('user242@client1.com'),$);
#210= IFCPROPERTYSINGLEVALUE('PlmModifiedDate',$,IFCTEXT('2017-05-17'),$);
#211= IFCPROPERTYSINGLEVALUE('PlmModifiedTime',$,IFCTEXT('09:12:56+03:00'),$);
#212= IFCPROPERTYSET('3HLJO7rYz0nvSNjv4yD$Ow',#42,'PlmProperties',$,
   (#200,#206,#207,#208,#209,#210,#211));
#226= IFCRELDEFINESBYPROPERTIES('11sm9bqSPD1gOqwVzCivfQ',#42,$,$,(#185),#212);
...
```

The Revit family was named *PlmProductTemplate.rfa* as it was intended to be used as a product model template for all PLM feasible native product models in the next phases. The UPD file was named *PlmUserDefinedPropertySets.txt* and used as the definition set for IFC exports in the next phases.

4.2.2 Introducing composite hierarchy

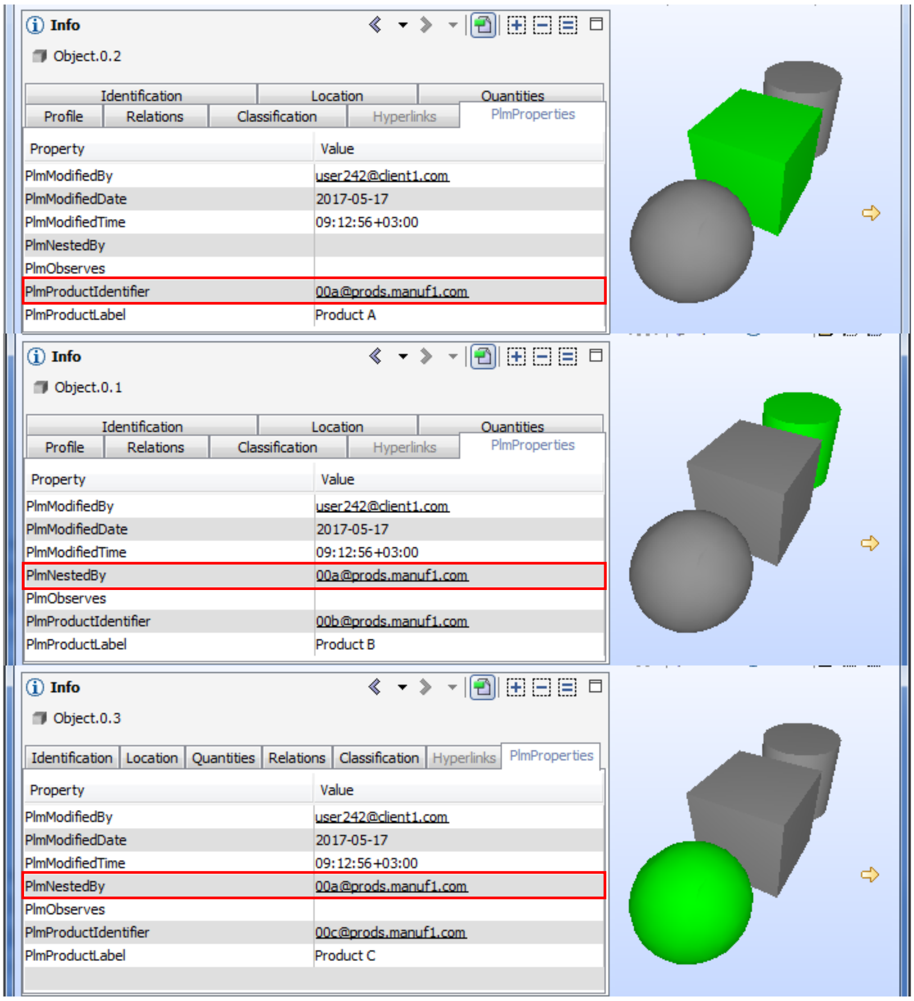
The next phase was to develop and test a method for incorporating composite design pattern into the simplified model. For this purpose, three simplified product models were created using the product model template:

- family A, visualized as a cube, as a hosting product (whole)
- family B, visualized as a cylinder, as a nested product (part)
- family C, visualized as a ball, as another nested product (part).

Nesting of families was used to represent the hierarchy of a product system. Two parallel “part” families, B and C, were nested into the “whole” family A. All families were assigned with PLM parameter values manually except for the *PlmNestedBy* parameter. Linking of parameters was used to link the *PlmNestedBy* parameter of families B and C (parts) to the *PlmProductIdentifier* parameter of family A (whole). Linking is a Revit feature that copies any changes made to the parameter value in the hosting family to the linked parameter in the nested family.

The nested composite family ABC was loaded into an empty project. As a nested family, user can use and modify ABC as a single unit (a product system), while still being able to select and view the parameters of all nested parts separately. This allows for controlled positioning and relations between elements of the system as they can be predefined. ABC acting as a single unit also enables mass modifications as changes made in a single instance of type ABC are copied to the other instances of type ABC.

To test exporting the nested family, IFCfR was utilized using the UPD file to map the PLM parameters. The resulting IFC file was studied using an IFC viewer and found to successfully represent the part whole hierarchy through the nesting attribute, showing correct properties for all products A, B and C, as shown in figure 4.7.



Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	
PlmObserves	
PlmProductIdentifier	00a@prods.manuf1.com
PlmProductLabel	Product A

Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	00a@prods.manuf1.com
PlmObserves	
PlmProductIdentifier	00b@prods.manuf1.com
PlmProductLabel	Product B

Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	00a@prods.manuf1.com
PlmObserves	
PlmProductIdentifier	00c@prods.manuf1.com
PlmProductLabel	Product C

Figure 4.7: Simple nested Revit family exported as IFC

4.3 Realistic product system model

In the next phase, the product model template was used as a starting point and extended with geometrical and titular reality to achieve finalized product models for the use case. Using a template guaranteed all models to host identical PLM parameters. To represent the parts of the system, four individual product models were required:

- a loading conveyor
- an unloading conveyor
- a disinfector
- a system (representing the limits of a product system or a delivery).

4.3.1 Introducing realistic geometry

Standard geometrical forming tools of Revit family editor were used to create correct product topology for each model. In product modelling, the level of detail is a considerable issue. Revit allows for almost microscopic accuracy if necessary as the smallest length of a profile, an edge or a line can be as little as 1/256 inches (circa 0,1 millimetres). This enables modelling, for example, individual bolts, fasteners or buttons if necessary. However, increased detailing simultaneously increases the amount of data and thus the size of a final BIM or IFC file. For instance, in medical building projects BIM file sizes have been found problematic and have often resulted in inefficiency in information transfer. The level of detail should be set according to the needs of intended model users.

In the use case, high level of detail was not considered as a primary objective. For the medical device manager, a product model should represent the actual product only to such detail that it is visually recognizable and easily found in an IFC model. Another feature, that is also important to a medical device designer, is an approximate visual location of control panels and maintenance hatches. For an architect or any actor involved in a building design process, the product model should also represent realistic measurements as it affects other elements nearby.

These were set as guidelines while modelling the individual products. The geometrical modelling resulted in three families, named subsequently *Disinfector.rfa*, *LoadingConveyor.rfa* and *UnloadingConveyor.rfa*, each hosting the PLM parameters and being able to be used as an independent product model or as a part of a composite structure. Next, the loading and unloading conveyor families were nested into the disinfector family and named *AutomatedDisinfector.rfa* and as in the simplified model, the PlmNestedBy parameters of conveyor families were linked to the PlmProductIdentifier parameter of the disinfector family to create a parametrical composite hierarchy. To validate the results of this step, all the models were loaded into a project and exported as IFC. The results are presented in figure 4.8.

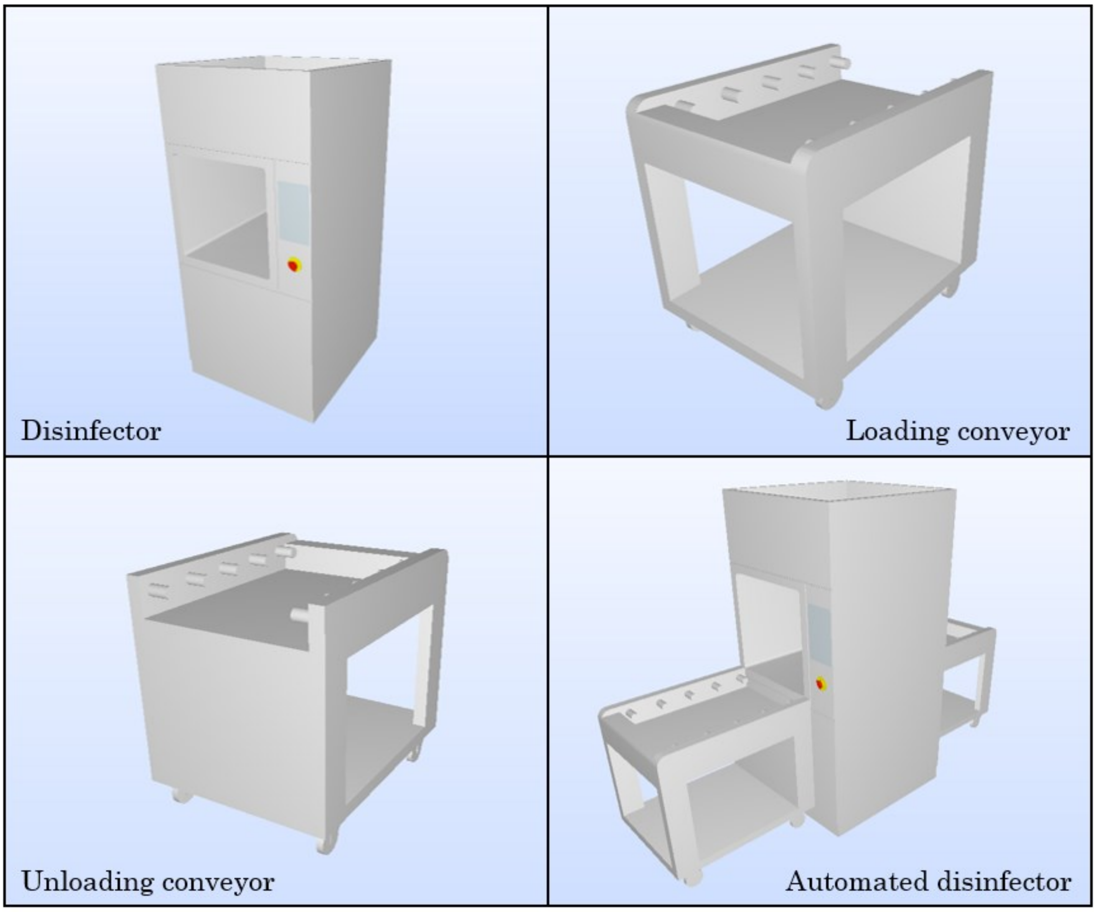


Figure 4.8: Individual product models exported as IFC

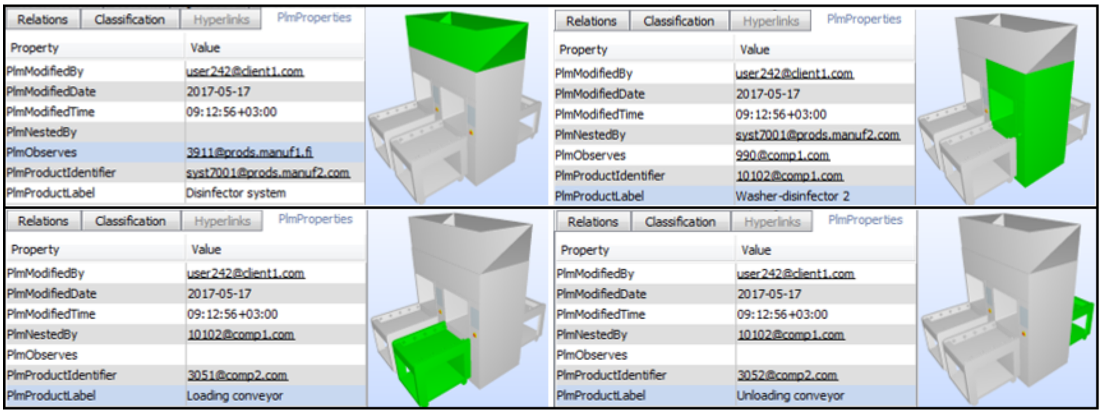
4.3.2 Finalizing the product system

To represent the limits of a typical project delivery and the whole composite, a system model family *DisinfectorSystem.rfa* was created using the product model template and given sample PLM values. Two automated disinfectors were nested into the system family and named disinfectors 1 and 2. Hierarchy parameters of nested families were linked to the hosting system family as in prior sections. The end result was a system family that hosted two automated disinfectors as defined in section 3.2.4.

The system family was loaded into an empty project and exported as IFC using IFCfR and the UPD file. Unexpectedly, studying the model with an IFC viewer revealed that while the model hosted parameters of individual products correctly, all parameters of the composite system were missing. Further investigation revealed that both the native IFC exporter of Revit and IFCfR extension fail to export all information that is not hosted by either the project or a geometrical element within the project. To solve the problem, two alternative methods were developed depending on the indented use of the BIM:

- If the system itself is not relevant as a PLM product to the user or a simple system ID is sufficient, a system ID can be fed to the *PlmNestedBy* parameters of top-level parts in the composite hierarchy
- If the system itself should exist as an entity hosting PLM parameters, some actual or artificial geometric elements should be included in the composite model to host the PLM parameters of the system.

In the use case, the latter method was used as enabling identification for collecting information of the use of the whole disinfector system would be beneficial to the manufacturer and a medical device manager. As a solution, a typical part of the system delivery, fascia panelling on top of disinfectors, was added to the system family. The system was reloaded into the project and exported to IFC. The resulting IFC model of the product system was found to host all the correct parameters. The final IFC model along with the parameter values is presented in figure 4.9.



Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	
PlmObserves	3911@prods.manuf1.fi
PlmProductIdentifier	syst7001@prods.manuf2.com
PlmProductLabel	Disinfector system

Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	syst7001@prods.manuf2.com
PlmObserves	990@comp1.com
PlmProductIdentifier	10102@comp1.com
PlmProductLabel	Washer-disinfector 2

Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	10102@comp1.com
PlmObserves	
PlmProductIdentifier	3051@comp2.com
PlmProductLabel	Loading conveyor

Property	Value
PlmModifiedBy	user242@client1.com
PlmModifiedDate	2017-05-17
PlmModifiedTime	09:12:56+03:00
PlmNestedBy	10102@comp1.com
PlmObserves	
PlmProductIdentifier	3052@comp2.com
PlmProductLabel	Unloading conveyor

Figure 4.9: Finalized product system IFC model with PLM properties

The final model was also analysed using a source code editor. PLM-related sections of the final EXPRESS file are provided in Appendix E.

5 Results

This chapter reviews the results and findings of the study. First, the achieved issues and results of use case model development are analysed. Second, the research questions and objectives are answered based on the findings on literature and empirical study.

5.1 Findings from the model development

The objectives of model development process, described in chapter 4, can be condensed into two topical areas: whether an IFC product model can host necessary attributes of a product-centric PLM system and how well the modelling process can be automated.

As result, it was found that a combination of utilizing IFCfR extension, defining a custom UPD file and using the features of family nesting and parameter linking is an effective and solid method for incorporating PLM information exchange attributes into an IFC product model. It was also found that necessary definitions can be stored in external, central data files or as template files of the modelling software, which allows for a coordinated and standardized modelling practice. Once the settings have been made, the data files and templates can easily be used to automatically create consistent PLM-feasible IFC models for virtually any product.

Also, it was found that the built-in nesting feature of modelling software allowed the user to modify the composite product as a single unit, while still being able to select and view the parameters of all nested parts separately. This feature was found to represent an actual design scenario of the use case, as both the medical device manager and the designer need simultaneous information of the composite and the parts within. In addition, nesting was found to enable automated linking of attributes to represent a composite design pattern.

The final product system IFC model, presented in figure 4.9 and Appendix E, was found to successfully host the necessary attribute structure of a product-centric PLM system. Since the individual products are successfully identified with an ID@URI notation and IFC is based on a semantic and simple coding language, further editing, updating and extending of the product model using external PLM systems is easy.

5.2 Answering the research questions

The following partial research question was asked in chapter 1:

> *What technologies should be used to store and exchange product lifecycle information?*

Utilizing information flow between intelligent products using Internet based protocols provides a source of benefits and revenues on both micro and macro-economic level. Value is increasingly created not by products themselves, but by the information related to them over their life cycles. Effective PLM requires a universal management and addressing systems for the information generated and exchanged during the life cycle.

Traditionally, systems have been dispersed and focused on limited applications or market actors. Company centric information systems have been found inadequate to fulfil the needs of information exchange between actors across different stages of product life cycles. In contrast, modern product-centric systems, such as the DIALOG using the ID@URI notation, have been found to effectively meet the requirements of a business-oriented PLM solution and are a preferable technology for the development of future applications.

A product-centric information exchange system relies on external databases as information storages and external product servers as managers of the information exchange. This network structure, alongside the URI reference based addressing scheme, guarantees high scalability and allows corporations to create domain or business specific applications while still using a universal, open system.

In detail, using a product-centric information exchange system implies that products must be intelligent, that is they must carry a virtual representation themselves. It was found that at the minimum such an intelligent product should be able to host information of an identity, a hierarchical position inside a composite structure, a link to another product to be observed and a modifier log.

Furthermore, a second partial research question was set as following:

> *Can building information modelling standards support the exchange of product lifecycle information?*

The open standard for BIM, IFC, has matured and been widely adopted by AECO industries around the world. From start, IFC has been designed to be highly customizable and extendable for all building related information modelling. IFC already supports functions alongside the traditional architectural or MEP engineering tasks, such as scheduling installations, planning human resources on construction site and sustainability assessment.

In the use case, it was found that IFC can also be effectively used for product information modelling as it can effectively describe both visual and informative features of any element. Custom properties and property sets were used to incorporate the necessary attributes into the IFC product models. As the analysis of resulting models showed expected results, it can be argued that the IFCs standard can easily be extended to support the exchange of information in a product-centric PLM system by using simple methods defined in the standard. The IFC product system model can be used as a partial FM tool as it provides both a visual guide and a platform for identifying product information.

In conclusion, the main research question was set in chapter 1 as following:

> *How could product lifecycle information management be considered in product information modelling as part of a building information modelling process?*

Based on the study, it can be argued that there are no technological restrictions of incorporating product lifecycle information into the building information modelling process. Also, automated procedures for incorporating PLM information exchange attributes into product models can be defined for current commercially available building information modelling software. To verify the quality of models, such automated processes should be developed and be consistently used.

However, as universal or standardized methods are currently non-existent, the end users of building information models and PLM systems are required to predefine the objectives, level of detail and attribute structures according to their local needs. In future, national or international definitions should be developed to support a global PLM information exchange system.

6 Discussion

This chapter discusses contributions and limitations of the thesis. Achieved new findings are also reviewed and future research topics proposed.

6.1 Implications of the study

This thesis sets into the intersection of product information management and building information modelling. While both are popular research topics, little topical research was found to have been made in combining the two. A considerable amount of literature on building information management was also found to be written on an abstract level. Even though building information modelling has been in commercial use for decades, it is still a developing practise and requires new applications.

This thesis proposes a new functionality into the existing IFC standard and simultaneously provides a practical, real-life application around medical devices. The proposed method for combining product-centric lifecycle data management into an IFC model provides major benefits to multiple parties in building construction projects. In general, key challenges relate to information management and exchange between parties and stages of complex building projects. These information gaps influence various parties in various ways, all of which can be fixed using the proposed method.

Architects and engineers designing a building require versatile and, most of all, flawless information about manufactured products to be installed and used in the building in order to provide for sufficient spaces and commodities. Typically, such information is dispersed and in an impractical format that requires manual refinement. Additionally, history data of both good and bad applications and practices is usually lost between projects or relies merely on personal knowledge of experts involved. Standardized information linking using IFC product models and ID@URI notation, as proposed in this thesis, could provide a simple and robust method for filling the gaps of information exchange and improving the flow of knowledge between experts, projects and parties across time.

Another potential benefit of the proposed method is the coordination of product-related information in both the handover phase from construction phase to the operational phase and later as the products start to wear out. Today, as a building project is completed, contractors gather and deliver documentation related to the installed products as individual electronic documents. The documents are usually stored in a database of the building operator. However, in complex buildings, such as hospitals, multiple operators and databases are typically involved, leading to ineffective or even nonexistent information exchange, inefficient use of labor and contradictory understanding of the state of key assets. Using a single source for all information regarding installed products, the IFC model, would allow various operators and parties using the same assets to only update their own databases while simultaneously providing the latest and correct information to the others.

For manufacturers, the study provides potential benefits in marketing, after sales and development of new products. As markets and products mature, increasing value is created not by products themselves but in services related to the products. Manufacturers could offer ID@URI-supported BIM product models for clients and building designers in trying to brand themselves as a market standard. Using such models could also create an easy method for collecting market and lifecycle data of installed products that would otherwise be either difficult or impossible to access. Such data would, of course, prove very useful in optimizing after sales and development of future products.

The most important potential of this study focuses in the end users of products. Typically, for most products that are installed in buildings, purchase costs are substantially exceeded by lifecycle costs. During the lifecycle, great amounts of information is created and stored related to the operation and maintenance of a product. Managing the lifecycle and information of the product effectively could reduce maintenance costs significantly, as faults and maintenances can be forecasted more accurately. Today, the information is often dispersed, leading to ineffectiveness and increased costs. Using BIM based product models and the ID@URI based addressing scheme, links to the information could be stored in a single location and evenly achievable to all users. Additionally, in complex environments such as hospitals, BIM would simultaneously work as an effective tool in locating and identifying the products.

The IFC-based PLM system developed in this thesis was studied in a restricted use case environment. However, the ID@URI notation and all methods that were developed are completely universal and easily applicable to other businesses and products. The combination of an open BIM standard and an open ID@URI addressing scheme can be used as an open platform to unlimited applications.

6.2 Limitations of the study

The use case was studied from a narrow viewpoint as it only considered the creating and viewing the model. While PLM attributes were successfully defined and introduced to the model, they only fulfil the needs of the actors that were included in the use case. Editing the attributes and controlling the modification and security of the model were not concerned. Concerning medical devices, legislation is strict and further analysis is needed to verify possible requirements regarding the trackability and security of the product model.

During the modelling process, an attribute was also excluded from the minimum requirements set. In a composite structure, parts could also host information regarding other parts that are nested by it. This feature was excluded for two reasons. First, it was revealed that Revit was not able to automatically compose the identities of nested parts into a single parameter. Second, a unidirectional definition the composite design pattern was considered to sufficiently represent the composite structure. However, a bi-directional definition could be beneficial or even necessary for other software in the PLM system.

Validity of some properties of the final IFC product model can also be argued. Attributes defining the date, time and user of last editor of the model were defined as text attributes in contrast to predefined entities *IfcPerson, IfcDate* and *IfcTime* that are provided in the standard. This resulted from the mapping deficiencies of IFCfR extension and keeping the final IFC file as simple as possible. In future, however, a method should be developed to enable using standardized entities and semantics.

6.3 Achieved new findings and future work

Surprisingly, it was found that the current definition of medical devices in IFC standard is insufficient for most uses. As building information modelling and IFC are becoming increasingly popular in development and operation of healthcare facilities, medical devices should be redefined to meet the requirements of intended users. Defining medical devices as shared element entities is thus proposed.

This thesis also serves as a basic study for IFC-PLM integration. In future, testing the achieved IFC model in a PLM software and validating the modelling process in a large project would provide necessary information for further development.

Another interesting topic for future research would be using the semantic references of IFC standard to replace some features that were defined using properties in the thesis. This would require advanced knowledge on core functionalities of IFC and a cross-domain testing environment.

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Appendix A:
Example of IFC2x3 building data

```
ISO-10303-21; HEADER;
FILE_DESCRIPTION(('Automatically generated IFC file.'),'2;1');
FILE_NAME('IFC_Example-building.ifc','2017-06-03T15:25:50',$,$,$,$,$);
FILE_SCHEMA(('IFC2X3'));
ENDSEC; DATA;
...
#9= IFCPERSON('SFn','Surname','First name',$,$,$,$,$);
...
#16= IFCPOSTALADDRESS(.USERDEFINED.,$,'Address',$,('Street'),$,$,'City','Code',$);
#18= IFCTELECOMADDRESS(.USERDEFINED.,$,'Tel.',('0'),$,$,('example@dot.com'),$);
#21= IFCORGANIZATION(' ','Business Name',$,$,(#16,#18));
#28= IFCPERSONANDORGANIZATION(#9,#21,$);
...
#341=
   IFCRELCONTAINEDINSPATIALSTRUCTURE('12pVfb1V6g_n2haPqqBM9G',#33,$,$,(#326,#431,#
   630,...,#7475),#204);
...
```

```
#402= IFCDIRECTION((1.,0.,0.));
#404= IFCDIRECTION((0.,0.,1.));
#406= IFCCARTESIANPOINT((0.,0.,0.));
#408= IFCAXIS2PLACEMENT3D(#406,#404,#402);
#409= IFCDIRECTION((0.,0.,1.));
#411= IFCEXTRUDEDAREASOLID(#401,#408,#409,1130.);
#412= IFCSTYLEDITEM(#411,(#301),$);
#415= IFCSHAPEREPRESENTATION(#85,'Body','SweptSolid',(#411));
#418= IFCCARTESIANPOINT((0.,0.));
#420= IFCCARTESIANPOINT((31179.9999995,0.));
#422= IFCPOLYLINE((#418,#420));
#424= IFCSHAPEREPRESENTATION(#311,'Axis','Curve2D',(#422));
#427= IFCPRODUCTDEFINITIONSHAPE($,$,(#415,#424));
#431= IFCWALLSTANDARDCASE('0_FjJIlgNGIPxRJ1t3iyEO',#33,'Wall
   Name',$,$,#390,#427,'3E3ED4D2-BEA5-D049-9EDB-4C1DC3B3C398');
```

section describing
a regular wall

```
...
#7496= IFCAXIS2PLACEMENT3D(#7494,#7492,#7490);
#7497= IFCLOCALPLACEMENT(#187,#7496);
#7498= IFCBUILDINGSTOREY('2zHO$cKquJJB1bQUw5kb61',#33,'1stFloor',$,$,
   #7497,$,$,.ELEMENT.,18200.);
```

section
describing
a storey

```
...
#8225= IFCAXIS2PLACEMENT3D(#8223,#8221,#8219);
#8226= IFCLOCALPLACEMENT(#7497,#8225);
...
#8299= IFCPOLYLINE((#8291,#8293,#8295,#8297,#8291));
#8301= IFCGEOMETRICCURVESET((#8299));
#8303= IFCSHAPEREPRESENTATION(#8290,'FootPrint','GeometricCurveSet',
   #8301));
#8306= IFCPRODUCTDEFINITIONSHAPE($,$,(#8285,#8303));
...
#8310= IFCSPACE('27W0ps2ciBJxneql_Jv6ya',#33,'Room Number',$,$,
   #8226,#8306,'Room Name',.ELEMENT.,.INTERNAL.,$);
#8315= IFCRELAGGREGATES('0tSq4utTCYeuQWeU1t$$NV',#33,$,$,#7498,
   (#8310,#9150,#110221,...,#1385741));
```

section describing
a room as a space

```
...
ENDSEC; END-ISO-10303-21;
```

Appendix B:
Example of IFC2x3 equipment data

```
ISO-10303-21; HEADER;
FILE_DESCRIPTION(('Automatically generated IFC file.'),'2;1');
FILE_NAME('IFC_Example-equipment.ifc','2017-06-03T15:38:12',$,$,$,$,$);
FILE_SCHEMA(('IFC2X3'));
ENDSEC; DATA;
...
#548055= IFCBUILDINGELEMENTPROXY('1tR6lPFuTErQT2k94b_5rl',#41,
   'Blast Chiller:2453877',$,'10xGN1/1 60kg',#548054,#548049,      A
   '2453877',$);
#548058= IFCPROPERTYSINGLEVALUE('Reference',$,
   IFCIDENTIFIER('Blast Chiller:10xGN1/1 60kg'),$);
#548059= IFCPROPERTYSET('2EQhsci9b58PU$lXLd1nWJ',#41,                     B
   'Reference Data',$,(#548058));
#548061= IFCRELDEFINESBYPROPERTIES('2xAW0suI53c8REGxCnIZVz',#41,
   $,$,(#548055),#548059);
...
#548068= IFCPROPERTYSINGLEVALUE('Position Number',$,
   IFCTEXT('175'),$);
...
#548114= IFCPROPERTYSET('1tR6lPFuTErQT2lf0b_5rl',#41,                     C
   'Identity Data',$,(#15704,#15705,#548068));
#548116= IFCRELDEFINESBYPROPERTIES('1tR6lPFuTErQT2lv0b_5rl',#41,
   $,$,(#548055),#548114);
...
ENDSEC; END-ISO-10303-21;
```

- **A.** Describes a piece of special equipment as IfcBuildingElementProxy, addressing it with a unique name, physical representation and location data.
- **B.** Describes a standard property set “Reference Data”, a related standard property type “Reference” and addresses a related parameter.
- **C.** Describes a custom property set “Identity Data”, a related property type “Position Number” and addresses a related parameter, all defined by the native BIM software.

Appendix C:
Revit shared parameters file structure

```
# This is a Revit shared parameter file.
# Do not edit manually.
*META  VERSION                               MINVERSION
META   2                                     1
*GROUP ID                                    NAME
GROUP  1                                     PlmProperties
*PARAM GUID                                  NAME                 DATATYPE  DATACATEGORY  GROUP VISIBLE  DESCRIPTION  USERMODIFIABLE
PARAM  1a586b0f-84ab-4087-a221-6ce5915c0a31  PlmModifiedBy        TEXT                    1     1                     1
PARAM  a743124c-188a-429a-9e7d-4d3bc142e2c3  PlmObserves          TEXT                    1     1                     1
PARAM  9aed545f-4bd6-446f-a7b7-a98d62e0c0a4  PlmProductIdentifier TEXT                    1     1                     1
PARAM  35ffba6b-9a10-402d-a01a-51c597fd9856  PlmModifiedTime      TEXT                    1     1                     1
PARAM  aa12d59c-8d74-4f38-809a-4ca3104e3901  PlmNestedBy          TEXT                    1     1                     1
PARAM  d2b630c0-5f04-4b61-897f-3f4e11d46888  PlmModifiedDate      TEXT                    1     1                     1
PARAM  878f0bd5-2d55-49f3-8f03-1c49e64cdb41  PlmProductLabel      TEXT                    1     1                     1
```

Appendix D:
User defined property set definition file for PLM

```
#
# User Defined PropertySet Definition File
#
# Format:
#    PropertySet:                            <Pset Name>          I[nstance]/T[ype]        <element list separated by ','>
#  <Property Name 1>                         <Data type>          <[opt] Revit parameter name, if different from IFC>
#  <Property Name 2>                         <Data type>          <[opt] Revit parameter name, if different from IFC>
#  ...
#
# Data types supported: Area, Boolean, ClassificationReference, ColorTemperature, Count, Currency,
#  ElectricalCurrent, ElectricalEfficacy, ElectricalVoltage, Force, Frequency, Identifier,
#  Illuminance, Integer, Label, Length, LinearVelocity, Logical, LuminousFlux, LuminousIntensity,
#  NormalisedRatio, PlaneAngle, PositiveLength, PositivePlaneAngle, PositiveRatio, Power,
#  Pressure, Ratio, Real, Text, ThermalTransmittance, ThermodynamicTemperature, Volume,
#  VolumetricFlowRate
#
#
PropertySet:                                 PlmPropertiesPset    I          IfcBuildingElementProxy
   PlmProductLabel                           Label                PlmProductLabel
   PlmProductIdentifier                      Identifier           PlmProductIdentifier
   PlmNestedBy                               Identifier           PlmNestedBy
   PlmObserves                               Identifier           PlmObserves
   PlmModifiedBy                             Identifier           PlmModifiedBy
   PlmModifiedDate                           Text                 PlmModifiedDate
   PlmModifiedTime                           Text                 PlmModifiedTime
#
```

Appendix E:
PLM sections in the final IFC4 model

```
...
#232= IFCBUILDINGELEMENTPROXY('00U9HXPlL12uOSO42pIygw',#42,'4-3-2_DisinfectorSystem:4-3-2_DisinfectorSystem:373948',$,'4-3-
   2_DisinfectorSystem',#230,#222,'373948',$);
#247= IFCPROPERTYSINGLEVALUE('PlmProductLabel',$,IFCLABEL('Disinfector system'),$);
#253= IFCPROPERTYSINGLEVALUE('PlmProductIdentifier',$,IFCIDENTIFIER('syst7001@prods.manuf2.com'),$);
#254= IFCPROPERTYSINGLEVALUE('PlmNestedBy',$,IFCIDENTIFIER(''),$);
#255= IFCPROPERTYSINGLEVALUE('PlmObserves',$,IFCIDENTIFIER('3911@prods.manuf1.fi'),$);
#256= IFCPROPERTYSINGLEVALUE('PlmModifiedBy',$,IFCIDENTIFIER('user242@client1.com'),$);
#257= IFCPROPERTYSINGLEVALUE('PlmModifiedDate',$,IFCTEXT('2017-05-17'),$);
#258= IFCPROPERTYSINGLEVALUE('PlmModifiedTime',$,IFCTEXT('09:12:56+03:00'),$);
#259= IFCPROPERTYSET('0$BmWg8Wv7wwimkXqT3UMF',#42,'PlmProperties',$,(#247,#253,#254,#255,#256,#257,#258));
#273= IFCRELDEFINESBYPROPERTIES('0p5$Wffo94LxHw5w1en3uE',#42,$,$,(#232),#259);
...
#7479= IFCBUILDINGELEMENTPROXY('00U9HXPlL12uOSO42pIygx',#42,'4-3_Automated_Disinfector:4-3_Automated_Disinfector:373949',$,'4-
   3_Automated_Disinfector',#7478,#7472,'373949',$);
#7482= IFCMATERIALLIST((#7433,#7444,#196,#7455));
#7484= IFCPROPERTYSINGLEVALUE('PlmProductLabel',$,IFCLABEL('Washer-disinfector 1'),$);
#7485= IFCPROPERTYSINGLEVALUE('PlmProductIdentifier',$,IFCIDENTIFIER('10101@comp1.com'),$);
#7486= IFCPROPERTYSINGLEVALUE('PlmNestedBy',$,IFCIDENTIFIER('syst7001@prods.manuf2.com'),$);
#7487= IFCPROPERTYSINGLEVALUE('PlmObserves',$,IFCIDENTIFIER('990@comp1.com'),$);
#7488= IFCPROPERTYSINGLEVALUE('PlmModifiedDate',$,IFCTEXT('2017-05-17'),$);
#7489= IFCPROPERTYSINGLEVALUE('PlmModifiedTime',$,IFCTEXT('09:12:56+03:00'),$);
#7490= IFCPROPERTYSET('3_lbiGz8L1KwEUZB4E8sCx',#42,'PlmProperties',$,(#256,#7484,#7485,#7486,#7487,#7488,#7489));
#7498= IFCRELDEFINESBYPROPERTIES('1Gg4fCQJDB_gFlLxNUSDFK',#42,$,$,(#7479),#7490);
...
#35443= IFCBUILDINGELEMENTPROXY('00U9HXPlL12uOSO42pIygv',#42,'4-3_Conveyor:4-3_Conveyor:373951',$,'4-
   3_Conveyor',#35442,#35436,'373951',$);
#35446= IFCPROPERTYSINGLEVALUE('PlmProductLabel',$,IFCLABEL('Loading conveyor'),$);
#35447= IFCPROPERTYSINGLEVALUE('PlmProductIdentifier',$,IFCIDENTIFIER('3051@comp2.com'),$);
#35448= IFCPROPERTYSINGLEVALUE('PlmNestedBy',$,IFCIDENTIFIER('10101@comp1.com'),$);
```

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#35449= IFCPROPERTYSINGLEVALUE('PlmObserves',$,IFCIDENTIFIER(''),$);
#35450= IFCPROPERTYSINGLEVALUE('PlmModifiedDate',$,IFCTEXT('2017-05-17'),$);
#35451= IFCPROPERTYSINGLEVALUE('PlmModifiedTime',$,IFCTEXT('09:12:56+03:00'),$);
#35452= IFCPROPERTYSET('3s_5x5l75B9hxCqHwl6hBv',#42,'PlmProperties',$,(#256,#35446,#35447,#35448,#35449,#35450,#35451));
#35460= IFCRELDEFINESBYPROPERTIES('1BPdxmU159cuIV_NW4AQ9Y',#42,$,$,(#35443),#35452);
...
#35474= IFCBUILDINGELEMENTPROXY('00U9HXPlL12uOSO42pIyh6',#42,'4-3_Conveyor:4-3_Conveyor:373952',$,'4-
   3_Conveyor',#35473,#35467,'373952',$);
#35477= IFCPROPERTYSINGLEVALUE('PlmProductLabel',$,IFCLABEL('Unloading conveyor'),$);
#35478= IFCPROPERTYSINGLEVALUE('PlmProductIdentifier',$,IFCIDENTIFIER('3052@comp2.com'),$);
#35479= IFCPROPERTYSINGLEVALUE('PlmModifiedDate',$,IFCTEXT('2017-05-17'),$);
#35480= IFCPROPERTYSINGLEVALUE('PlmModifiedTime',$,IFCTEXT('09:12:56+03:00'),$);
#35481= IFCPROPERTYSET('3fSaxi3rvCWuY33bagrfzd',#42,'PlmProperties',$,(#256,#35448,#35449,#35477,#35478,#35479,#35480));
#35487= IFCRELDEFINESBYPROPERTIES('1TC5$B$Qn4hvvMBnZTCq2y',#42,$,$,(#35474),#35481);
...
```