“FROM GEOMETRY-ONLY TOWARDS FM-READY BIM”

Master Thesis

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Construction Management & Engineering

GloBLD

3DGeosolutions

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This thesis is dedicated to:

My wonderful parents, who never stop giving of themselves in countless ways,

My beloved brother,

My friends who encourage and support me,

And all the people in my life who touch my heart,

Contents

List of Abbreviations:

AECO - Architecture, Engineering, Construction and Owner-Operated

API - Application Programming Interface

A/S - Activity/Space

BIM - Building Information Modelling

BRep - Boundary representation

CAD - Computer Aided Design

CAFM - Computer Aided Facility Management

CMMIS - Computerized Maintenance Management Information System

CMMS - Computerized Maintenance Management System

COBie - Construction Operation Building Information Exchange

CSG - Constructive Solid Geometry

EPM - Energy Performance Monitoring

FM - Facility Management

FMT - Facility Management Team

GIS - Geographic Information System

ICT - Information and Communication Technology

IFC - Industry Foundation Classes

ISO - International Standard Organization

LoD - Level of Detail/Development

M&O - Maintenance and Operation

REM - Real-Estate Management

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1. Introduction

In a project's lifecycle, the Maintenance and Operation (M&O) phase accounts for the greatest share of the project's cost and value, i.e., between 60% to 85% of the project turnover [1]. Accordingly, the M&O strategies and practices have a great influence on the overall success/failure of projects. M&O of the projects are commonly delegated to the Facility Management (FM). There is no consensus on the scope and definition of FM in the literature [2], but, based a dominant notion, FM is a discipline concerned with maintaining the acceptable level of service and ensuring the maximum value for the asset [2]. FM practices are very diverse and the efficient FM strategy must be customized and tailor-made for each specific project.

In recent years, FM has benefitted from Information and Communication Technologies (ICTs). Such solutions as Computer Aided Facility Management (CAFM), Computerized Maintenance Management System (CMMS), and Computerized Maintenance Management Information System (CMMIS) have emerged as a result of incorporating ICT in FM practices. Building Information Modelling (BIM) has recently emerged at the forefront of ICT developments in the construction industry. Although the definitions and perceived scope of BIM vary greatly [1], it is commonly viewed as a new paradigm for the collaboration, planning, and monitoring of projects throughout their lifecycle using a central digital model. Because of its lifecycle approach, BIM is believed to have a strong potential for facilitating FM practices and substituting the conventional FM support systems [6]. However, the widespread adoption of BIM in the industry has only taken off recently and its application is currently limited to the design and construction phases [8]. Accordingly, while the BIM penetration in the market is on the rise, the integration of BIM and FM is still not fully achieved in practice [7].

Even if BIM-FM integration is fully materialized in the market, it will be mostly applied to new projects. On this premise, a large number of existing buildings, which do not have a BIM model and are in a stage of their lifecycle that needs strong maintenance support, cannot benefit from BIM. As a result, many researchers started to investigate the technologies and practices for what is known as "as-built modelling" [3].

As-built modelling refers to the process of developing a BIM model for existing buildings. As-built modelling consists of two main steps: (1) data collection and (2) data modelling. The data collection refers to practices of using advanced surveying technologies such as laser scanners to generate the input for the BIM model. The second step is to convert the raw surveying data, e.g., point clouds, into an object-oriented BIM model [3]. Because most of the modelling is done manually, the as-built modelling is currently a labor-intensive, time-consuming, and error-prone process. There are some efforts in automating this process in the recent years, but the automation is only possible for some basic objects [4]. The existing as-built models, therefore, only contain a simplified geometric representation of the buildings and lack some of the essential pieces of information needed for efficient FM practices, e.g., spaces [3].

The GloBLD company, i.e., the host of this research, is interested in moving towards the automation of as-built modelling and preparing FM-ready BIM with minimal human intervention.

1.1. Research Problem

As stated above, the current as-built BIM models are not suitable for FM. The data needed for FM practices are not easily found using the produced models.

The FM practices would need specific data which are not explicitly modelled in primitive as-built BIM models. The current models merely contain basic objects in terms of geometry and title, which is not enough for efficient FM practices; the data regarding the energy performance [5], safety [6] and specific quantity take-offs [7] are mentioned as instances in previous research works. In addition to physical objects, FM requires information about non-physical entities, e.g., spaces and their intended use. As a result, for the as-built BIM models to become ready for FM practices, the existing as-built models need to be expanded to include these non-physical entities. The process of adding, or inferring, the non-physical entities from the physical objects (i.e., geometry) will be referred to as *semantic expansion* in the remainder of this research. It is called semantic expansion because it will lead to the generation of an extra layer of abstract information (semantics) to the existing model.

The semantic expansion can be a manual or automated process. The manual process is time-consuming, expensive and error-prone in comparison to the automated processes. The automation of semantic expansion requires to establish relationships between physical objects and non-physical entities. These relationships might be extracted from geometrics and architectural, structural, mechanical, electrical, piping related rules and relationships. The lack of explicit rules between physical objects and non-physical entities makes the automation process difficult.

Additionally, non-physical entities in each building may be identified and categorized differently considering the specific FM needs. Especially, when it comes to spaces and their intended uses, different perspectives among architects, BIM modelers and FMTs may cause inconsistency of explicit data in BIM models in comparison to the data needed for FM practices. The fragmentation among the Facility Management Teams (FMTs) and as-built BIM modelers would be a barrier to specify the needed explicit data as the representative of spatial semantics.

To conclude, the research problem may be summarized as: ***"the lack of automation in extracting the non-physical objects from the primitive as-built BIM models because of the absence of explicit relationships between physical objects and non-physical entities"***. The research problem is illustrated in ***Figure 1***.

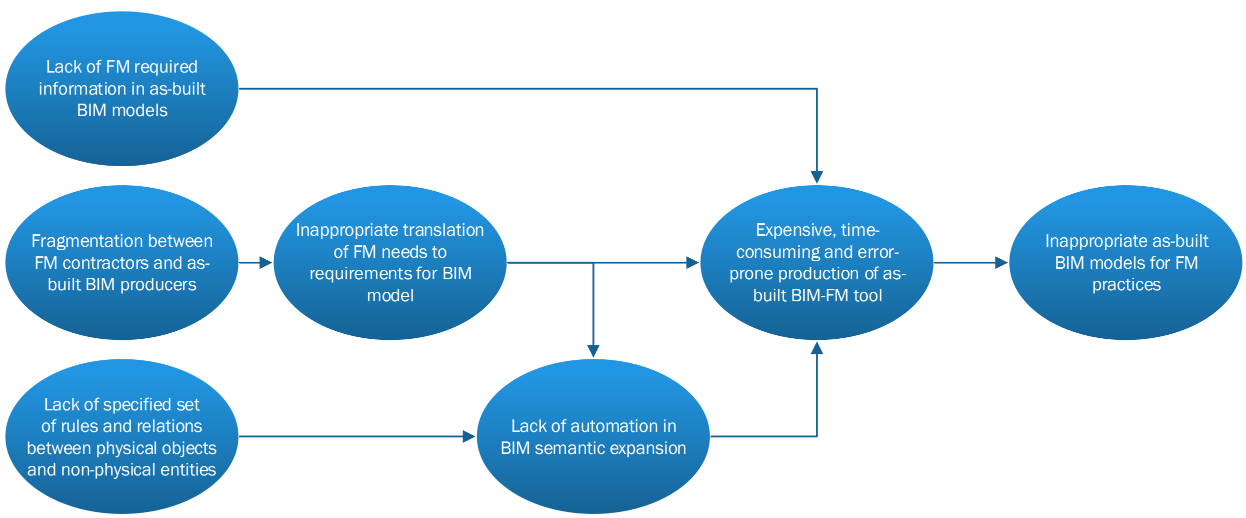


Figure 1: Research Problem

1.2. Research Objective

As addressed by the research problem, the lack of automation in extracting non-physical objects from primitive as-built BIM models is partly due to the fragmentation between the as-built BIM producers and FM contractors and, partly, because of the absence of automation in semantic expansion. To overcome this problem, the primitive as-built model should be upgraded with a set of heuristic rules in order to enable automatic semantic expansion.

This research aims to:

"design a semi-automated process to extract non-physical entities necessary for FM to produce a FM-ready model from the current primitive as-built BIM model by establishing the relationships between the physical objects and non-physical entities."

This objective can be further decomposed into the following sub-objectives:

1. ***"define and refine a well-tailored structure of non-physical entities required for facility management in general"***,
2. ***"find and formulate the relationship between the modelled physical objects and non-physical entities"***,
3. ***"Use the relationships to develop a semi-automated process for semantic expansion as-built BIM model "***.

1.3. Research Questions

Based on the research objective described above, the main research question would be: ***"How can a model containing required non-physical entities be developed automatically from as-built BIM model?"***

The research sub-questions will be:

1. What are the non-physical entites required for FM?
   - 1.1. How would a proper FM approach use the explicit data regarding non-physical entities?
   - 1.2. How can these non-physical entities be classified and prioritized for automation according to their inter-relationships and importance?
   - 1.3. Which non-physical entities are the most important/underlying among all non-physical entities? i.e. from which point should semantic expansion start?
2. How can the non-physical entities identified in 1 be defined by a primitive BIM model?
   - 2.1. What rules can be used to define the new non-physical entites using the basic objects?
   - 2.2. Which of those required data are available in an ordinary primitive as-built BIM model (among the objects with the BIM model)?
   - 2.3. To what extent is there a need to extend the as-built BIM model?
   - 2.4. How can the other required data be extracted from or using the physical objects and their geometric and non-geometric attributes?
3. What is the process of developing the new spatial semantics out of the current model?
   - 3.1. What is the procedure of extracting the implicit data out of the existing BIM model? (How to apply the rules gained as the answer to research question 2.d. in a BIM medium?)
   - 3.2. How can the current model be updated?/How to store the new extracted semantics?

1.4. Contribution

The research scope is framed such that it fits the available timeframe. The expected contributions of this research are as follows:

The research will contribute to the automation of as-built BIM models; the actual as-built models may merely produce primitive models with limited explicit data and only for a narrow scope of use. The proposed semantics expansion method can be a leap forward in making FM-ready as-built BIM models. Additionally, the relationships between physical objects and non-physical entities can be further used in the design phase of new buildings to assist the modelers in quick preparation of FM-ready models. Finally, an expansion of the spatial semantics can contribute to design a model supporting decision making especially in intervention planning.

2. Theoretical Background

2.1. Information Requirements for FM

The first section of the literature study aims to introduce the FM, BIM, the integration of BIM and FM (BIM-FM) and the information requirements of FM especially the information regarding non-physical entities. This section also aims to provide an answer to the first research question by finding the most underlying non-physical entity in BIM-FM models as the start point of semantic expansion and scope of the design work in current research.

2.1.1. Facility Management

FM has different definitions in the literature; as mentioned in the introduction, based a dominant notion, FM is a discipline concerned with maintaining the acceptable level of service and ensuring the maximum value for the asset [2,8]. FM has evolved into a stand-alone discipline and profession in the construction industry since the 80's. However, the emergence of FM has been reported from 60's, 70's and even 1800's by different sources. Through many years, FM scope and capabilities have been extended[8].

Nowadays FM is concentrated on several fields, also covering the M&O practices of physical assets' lifecycles [9]. According to the literature, FM almost covers all of the post-construction activities. FM requires a big diversity of detailed and rich data [10,11]. In the conventional method of data management in the construction industry, much of the needed data for FM are scattered [12].

FM has been benefited from the advantages of the ICT to facilitate the data management. A range of ICT solutions from emails to computer systems such as CMMS and CAFM are developed and used [13–15]. The specific information exchange systems CAFM and CMMS are the most used information systems which help FM managers have easier access to information needed for the better management of facilities. While the use of FM-support systems are very common in the industry, the use of BIM for FM, as the most recent data management medium is still not widespread [16]. BIM can, however, significantly improve the status quo of FM because of its support for data visualization, topological analysis, and work orders [17].

2.1.2. BIM

BIM has become a growing trend in the Architecture, Engineering, Construction and Owner-Operated (AECO) sector both in academia [18] and industry [19,20]. However, there is no single unified definition for BIM [2,21]. It has been a research topic since 70's [22], however, the specific term BIM has been suggested in 1992 for the first time [23]. The practices and activities of BIM is also labeled differently in the literature; namely: Asset Lifecycle Information System, Building Product Models, Integrated Design Systems, Integrated Project Delivery, nD Modelling, Virtual Building™, Virtual Design and Construction & 4D Product Models Organisation, Integrated Model, Object Oriented Building Model, Single Building Model, etc. [24]. while for some BIM is merely a technology that facilitates the sharing and dissemination of the building lifecycle information [25], for others BIM encompasses the technology and the process that goes along with the effective adaption of the technology [26], and others consider BIM as an Integration of policies, technologies and processes [14,24].

Figure 2 illustrates the three fields of BIM activities with their players (shown in boxes) and deliverables. Derived from these prevalent definitions, there are numerous other definitions where the overlap between any two (or all) dimensions of BIM is considered to be "the best practices"[24] or the "True BIM"[14]. A general definition for BIM has been suggested in the ***Introduction*** of this research: "*a set of policies, processes and technologies revolving around a digital representation of buildings/asset that can be used as **an object-oriented data repository** to **facilitate the collaboration**, planning, monitoring of projects **through their lifecycles**.*"

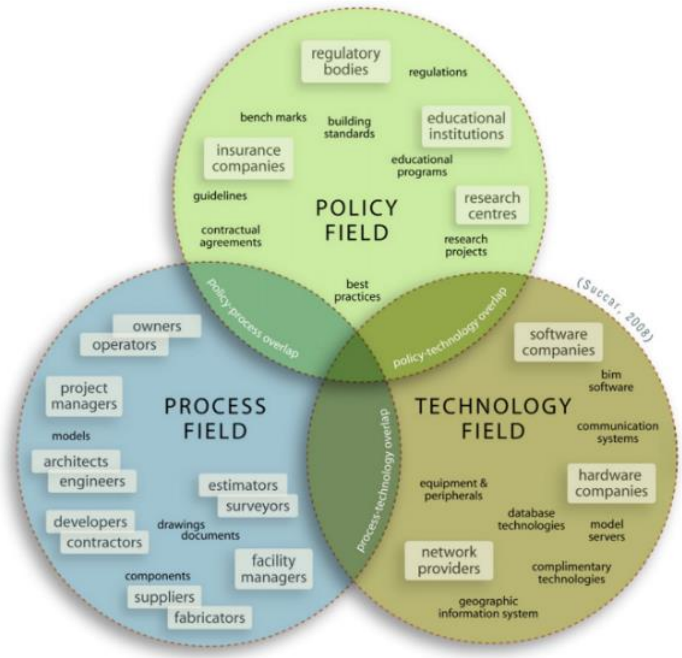


Figure 2: The interlocking fields of BIM activities – Venn diagram. [1]

A very important keyword in BIM definition is the object-orientedness. BIM software and models contain parametric objects representing building components [25]. BIM models may contain both geometric and non-geometric data about building components/elements [12]. The richness and accuracy of the data has an important role in the functionality of BIM models [12]. As stated above, BIM models are object-oriented models representing different types of building-related data. These data might be modelled implicitly, i.e., not understandable by the machine and only extractable by intensive human interventions, or modelled explicitly but in a way which is hard to be accessed by the FM managers [7].

Another keyword in the definition of BIM is "collaboration". Collaboration among stakeholders in the construction industry is linked to the "interoperability" [18]. "*Interoperability can be defined as the ability of diverse systems and organizations to work together (interoperate)"* [27].

Several standards have been used to facilitate the interoperability. Industry Foundation Classes (IFC) is known as the most widely-used standard in BIM software [28]. IFC is the subject of International Standard Organization (ISO), document ISO 16739:2013, Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries [13]. IFC is the only object-oriented 3D "vendor-neutral BIM data format for the semantic information of building objects" [29].

2.1.3. Integration of BIM and FM

By definition, BIM is able to offer lots of advantages to construction industry, such as integration of information flow, reduction of the fragmentation in the industry, and provision of a central data repository for all stakeholders over the whole project's lifecycle [13,22,24], Most saliently, the capability of BIM to support the entire project life cycle is stated to be the most significant advantage of BIM [17,30]. However, such a comprehensive use of BIM is rare in practice. For instance, although the post-construction phases of construction projects (M&O) are believed to account for the biggest part of the lifecycle costs [1,12], the BIM has hardly been implemented over these phases[17,30].

To make the integration of FM tools and BIM plausible and effective, the interoperability of the databases/models is critical. Construction Operation Building Information Exchange (COBie) has been introduced in the US in 2007 and adopted later in the UK in 2014 as an information exchange standard for

FM [31]. COBie might be used as spreadsheets and captured in IFC [13,32]. COBie aims to enhance the information flow from early stage stakeholders to FM managers, enabling the designers, clients, and contractors to put the created data in a machine interpretable format to prevent the data recreation in the post-construction phases [33]. A proper use of COBie can be a step towards the integration of BIM and FM [17].

2.1.4. Non-Physical Entities in BIM-FM

Although the application of BIM for FM is starting to receive interests in academia, significantly since 2013 [18], it remains to be an understudied field [34]. The integration of BIM and FM (BIM-FM) is found to be beneficial if the proper conditions are met [2,13,14,16,17,31,32,35]. The two main requirements of the successful implementation of BIM-FM are (1) the model should include more facilities-related data, and (2) the data should be explicit and easy-to-access [7].

As discussed before, FM tasks are quite various and need a big diversity of information. The first challange in BIM-FM integration according to the investigation done by Mc. Arthur [35] is the identification of critical information neded for FM tasks.

According to Mc Arthur's work [35] although the FM information requirements may differ by project specifications, it roughly lays in three general fields of (1) space planning, (2) maintenance activities, and (3) front-of-house. He further suggests for incremental and iterative data addition in small useable steps which are prioritized by the user. In his process of incremental data adding, he puts the floorplans and spatial layout in the cenral circle which represents the core of information required for proper BIM-FM integration (***Figure 3***).

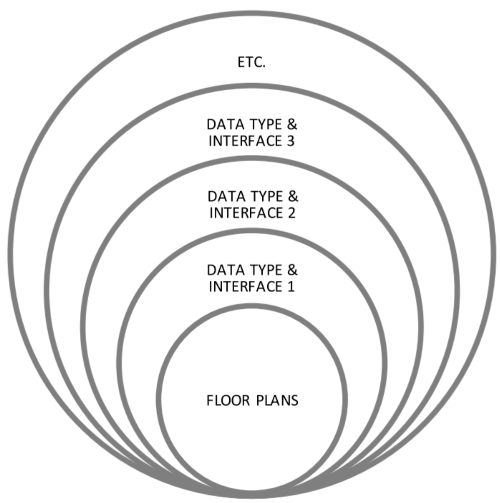


Figure 3: incremental data adding,[35]

Stated by Cavka et al. [36], referenced to Liu et al. [37], spatial layout (floor plans and design specifications) are the most important facility related data. Clayton et al. [38] enumerate room and equipment identification and location as of key content for FM related information.

General Services Administration (GSA), which is a leader organization of BIM implementation in north America, considers spatial program (i.e. accurate geometric as-built for equipment) as the first tier of BIM-based project information requirements [36].

Becerik-Gerber et al. [12] provided a substantial list of non-geometric data, which they argue to be an essential information required for succesful implementation of BIM-FM, required for the proper FM practice (see ***Figure 4***). They suggest that these data should be put in the model from top to bottom through the project's lifecycle. The application of BIM for the visualization and topological analysis of non-physical objects, such as spaces and zones, is considered the first tier after the identification of equipments and shown in the litereture [5,12,17].

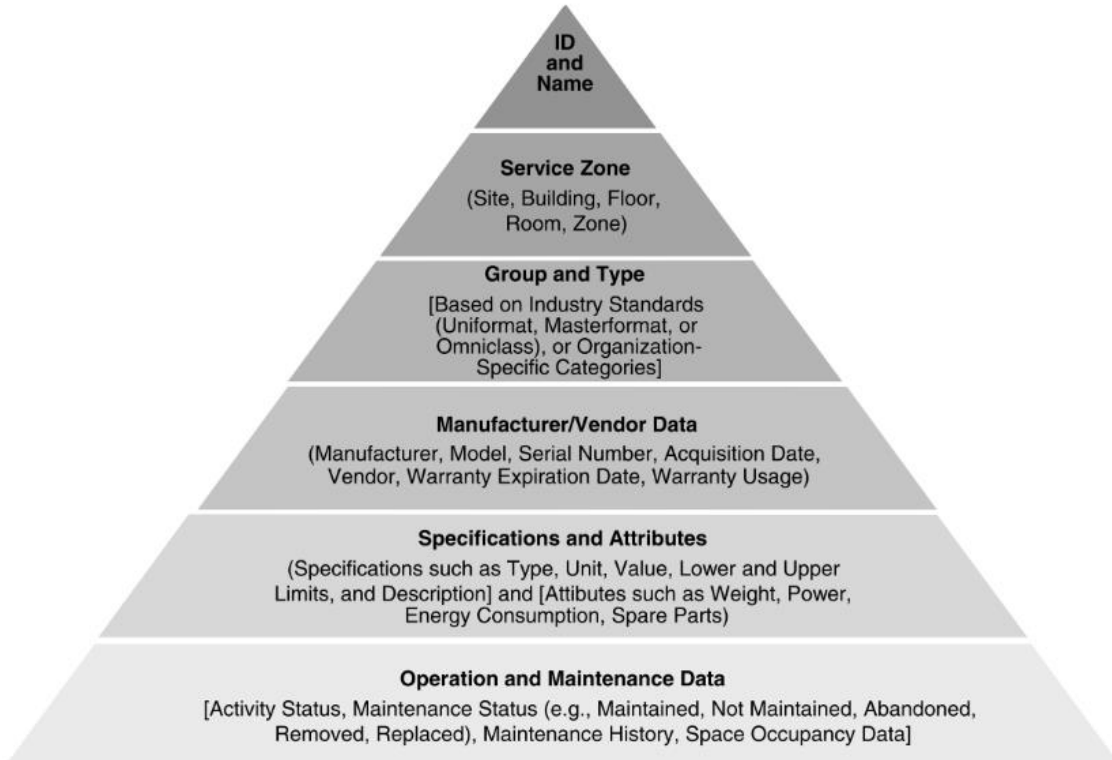


Figure 4: Data structure of non-geometric data requirements, [12]

2.1.5. Spatial Elements in BIM-FM

As discussed in the former section, the spatial layout is considered the first tier of non-geometric entities needed for proper and successful implementation of BIM-FM. In this section, some of the researches using spatial information for BIM-FM are reviewed.

Becerik-Gerber et al. [12] have defined specific organizational FM functions (such as energy management, M&O, space management, quality assurance and monitoring, noncapital construction, commissioning and closeout, real estate management, etc.) and the potential areas to use BIM for FM use (e.g. locating building components, facilitating real-time data access, visualization and marketing, checking maintainability, creating digital assets, space management, planning and feasibility studies for noncapital construction, emergency management, controlling and monitoring energy, personnel training and development, etc.) based on interviews with professionals. They have found spaces as an attribute of equipment accommodated by those spaces and/or providing service to those spaces. Further, they suggest the classification and visualization of spaces based on the specific FM guidelines; however, this research doesn't go further in the specifications of these classifications and their related FM guidelines/uses.

Akcamete et al. [17] have investigated the potential utilization of BIM models for M&O practices. Pointing the advantages of BIM against the other available FM information systems such as CAFM and CMMS, they have tested their argument by entering annual M&O work orders in a BIM model and analyzing their spatial relationships to develop a dataset for FM uses. However, they didn't produce their used model by themselves. Further, they have put the architectural (factual) room boundaries to distinguish the spatial information regarding the work orders and didn't add any subspace for such a use.

In another research, Cavka et al. [36] have developed the owner's information requirements. According to their work, the information requirements of the owner (who are considered to be the main users of FM tools) need to be identified and formalized according to the unique conditions of the project (internal information needs) in addition to general requirements according to the regional, municipal, and/or national (external information needs). First of all, the information users should be classified by their position, scale, and category, then their specific information requirements should be identified and translated to quantities which can be modelled and computed by machines, and finally these quantitated requirements should be modelled or added to the available BIM model.

Also in the requirements landscape, according to their work, the spatial information of the project in four sorts such as (1) the space program and list, (2) overall access adjacency and circulation requirements, (3) architectural descriptions and requirements and (4) Mechanical, Structural, Civil, Electrical systems descriptions and requirements are seen as the requirements at the project requirements level. This can later be translated into the project-specific BIM spatial data requirements to be mounted on the model [36].

In another industry-oriented research [39], the spatial elements have been standardized and involved in BIM-FM adoption in Sydney Opera House project. They have produced their own spatial hierarchy in their master model and defined by the human users and hosted furniture/ equipment. They later have used this information to sort and classify spatial elements and their hierarchies for several different tasks of data extraction such as benchmarking and documentation of the services provided to each space, zone etc.

2.2. Spatial Elements in Modelling

As argued in the last section, the spaces are the most important/underlying non-physical entities which are to be used by FMTs. Also, it is discussed that BIM, as a 3D representation of Buildings has its significant advantage in comparison to the other data management and ICT tools commonly used in FM. In this section, the definition of spaces, the process of modelling spaces, and their attributes in BIM are reviewed.

2.2.1. in Pre/Early-BIM context

"Space" as a concept is rather older than the BIM. In general, the word "Space" is used to refer to several concepts. The Latin root "Spatium" refers to different concepts such as "area", "room", and "interval of space or time" [40]. "Space" as a concept may be a reference or representation according to semantics theory. In other words, "Space" can be seen as an object itself (reference) or an attribute to an object (representation) [41]. Space can be considered as a mutual property of multiple objects (which have spatial or separation relation) or an attribute of a single object (such as an internal void). Spaces can be open or boundary-less (the geometric and mathematical abstract concept) or may be enclosed by boundaries. The boundaries of spaces can be factual or experimental. Factual boundaries enclose factual spaces and might be open to some things while closed to some others. Experiential spaces are a mutual property of the spaces and the experiencing observers. i.e. any space may have different boundaries or been divided into different sub-spaces according to the perspective of any person. Therefore, an experiential space may have more or less objective and subjective boundaries according to the needs and experiences of the user [40].

"Space" has a specific definition in construction. Ekholm et al. [40] define the space in construction industry as *"An aggregate of things, including construction entities or their parts, with a materially or experientially enclosed void that may accommodate users or equipment."* This definition emphasizes on two main points: (1) the enclosing entities/objects (i.e. the boundaries) and (2) the activity which is going to be accommodated in the space. A similar definition can be inferred from ISO 12006-5 document, where space is defined by its boundaries (art. 3.1.8) or activity(s) (art. 3.1.9)[42].

Björk et. al. [43] reviewed four disciplines of space modelling with different perspectives to draw a general sketch of spatial modelling and topological relations. The work of Björk et al. [43] offers in-depth understanding of the geometric representation of spaces by categorizing and listing space boundaries. However, their work has only investigated the physical (factual) boundaries and didn't go in depth addressing the experiential boundaries. It also lacks the proper notice to the accommodated activities which are aimed to be hosted by the spaces and sub-spaces. ***Figure 5*** illustrates the structure of the spaces, space boundaries and enclosing structures. As it can be seen in ***Figure 5***, the experiential (imaginary) boundaries are left without any further attributes in downstream while the factual (physical) boundaries have been further investigated and their entities and geometrical representation are specified.

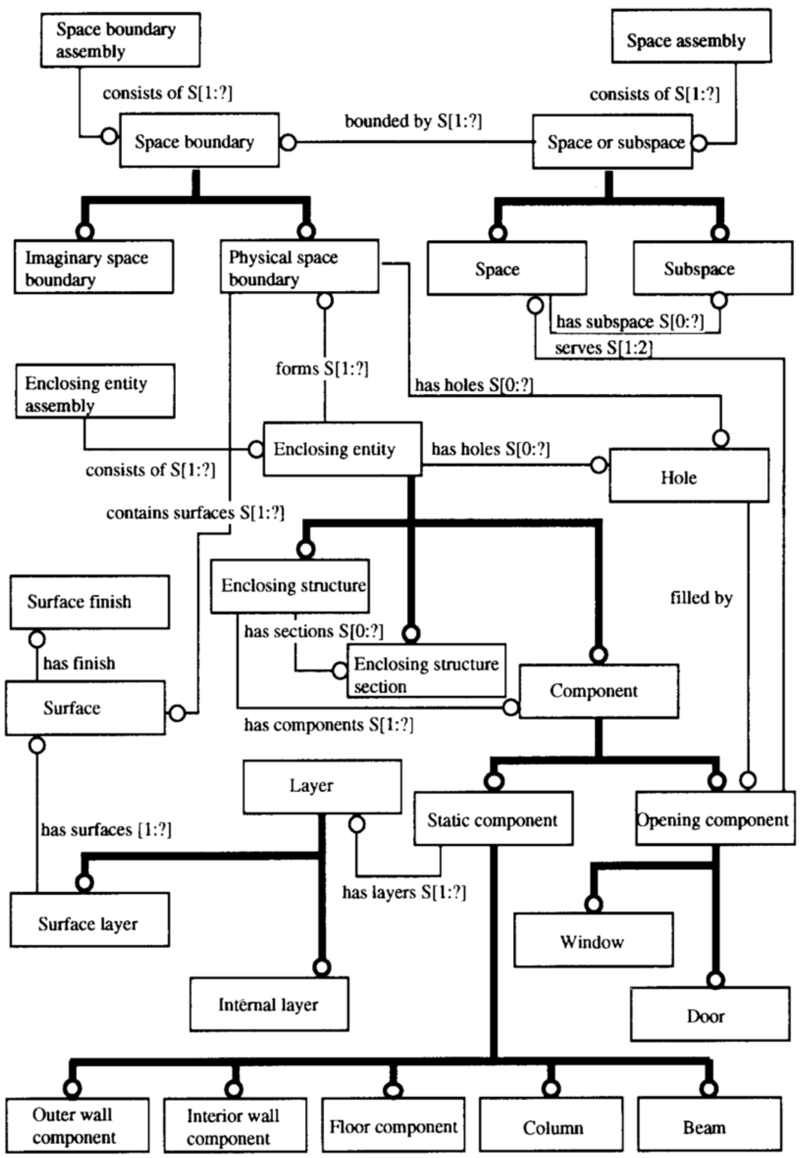


Figure 5: The schema for spaces, space boundaries and enclosing structure [43]

However, activities which are hosted by a space have also a centric role in the definition of that space. Mahler et al. [44] investigated the notion of space and put the activities in the center of their attention. They have used the intended space usage and its needed equipment and users to form spatial activity envelops and form their Activity/Space (A/S) model (see ***Figure 6***). Although their aim was to design a spatial envelope, their research contributes to this research by formalizing the relationship of the spaces and their hosted activities.

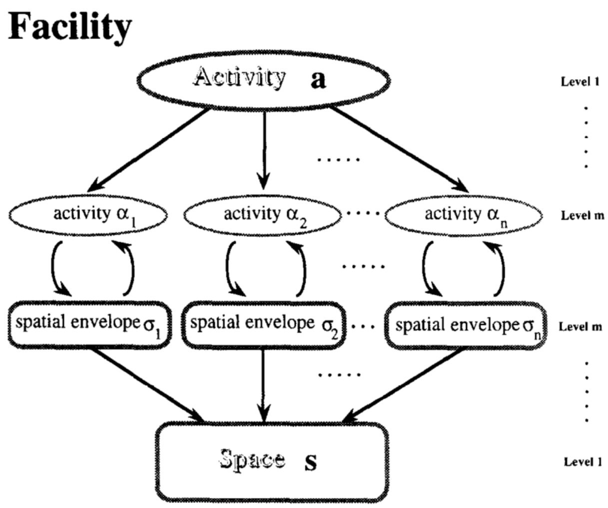


Figure 6: A general outline of the A/S model (for spatial singularity) [44]

The work of Eastman et al. [45] is somewhat an accumulation of the two above-mentioned research works, defining and modelling spaces considering both space boundaries and accommodated activities. They have suggested a generic building model which aims to facilitate the information exchange and correction within architectural and building designing process. They defined a building as "*a basic type of man-made structure, whose purpose is to provide space for human activities and to regulate the environment in the space provided*." Such a building is containing the "constructed form" which refers to the physical elements of a building, "activities" which are to be accommodated in the building spaces as the purpose of building, and the "bounded spaces" which mediate between the latter two and define the human occupancy and use in buildings. An analytic diagram has later been developed by Ekholm et al. [15] to illustrate relationships of "constructed form", "bounded spaces" and "activities" (see ***Figure 7***).

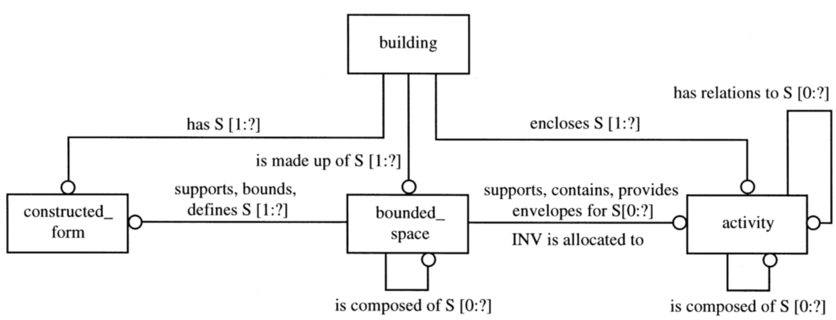


Figure 7: An analysis of basic concepts in Eastman et al. article [40]

Eastman et al.'s [45] method mainly relies on solid geometric modelling to serve any architectural or building design with proper extensions as a kernel backend repository. In their model, the activity has three properties: (1) a general brief is summarized in each bounded space as activity categories and spaces allocated to them, (2) a compulsory level of details highlight the name, location, shape (space) of the area occupied by the equipment and the prop-shape or the shape of the bounded space hosting the activity, and (3) the third level of further details use the furniture, fixed equipment, area occupied by the sub-activities and environmental conditions/properties. They further discuss the level of detail for activities which can vary from high for specific building with specific uses (such as a hospital or university) to low for some other (such as housing in which the activity of each area is to be decided upon after the occupancy by tenants). A detailed compositional diagram is picked from their paper (***Figure 8***).

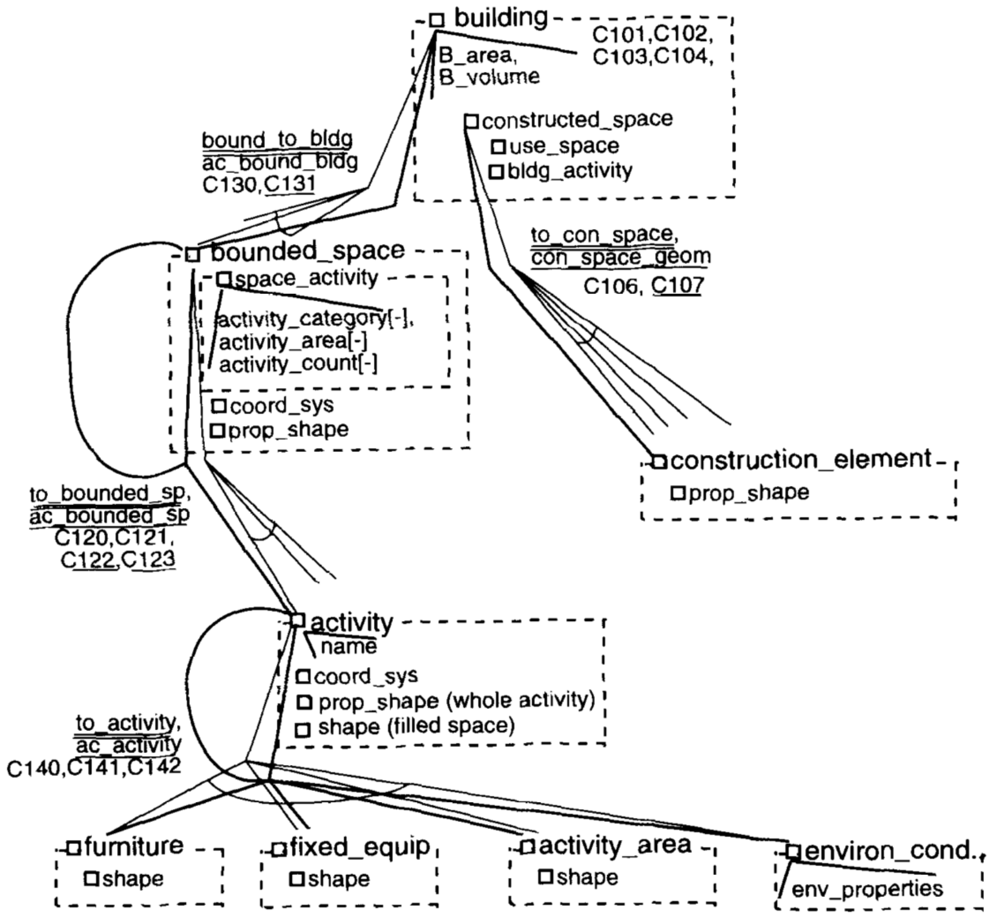


Figure 8: The overall compositional structure of Generic Building Model, picked from [45]

These research works show that the spatial elements are well defined and formalized for modelling even prior to the introduction of BIM in its actual format. A review of these research works provides a basis for formulizing spaces for automatic modelling in the current research. According to these works, spaces can be defined by their boundaries and activities. The space boundaries might be factual or experiential. The factual boundaries can be formulated according to the building constructed elements and their geometric attributes and topological relations while the experiential boundaries need to be defined according to the specific user needs (e.g. FMTs in this research). Spaces are designed and built in form of buildings to accommodate activities. These activities can be used in order to identify the space intended uses. The accommodated activities in each space can be identified by the furniture, fixed equipments, loose spaces required for each specific activity, and the environmental conditions (i.e. the attributes of each space in terms of position, relationships with other spaces and/or building constructed elements).

2.2.2. Spatial Elements in BIM

2.2.2.1. Space in 3D BIM Models

BIM models can contain a variety of information. Thus, BIM models may be classified by the information they contain in form of nD models [24]. 3D object(-oriented) models shape the core body of BIM models nowadays. If a BIM model contains the "time" and is used for planning and scheduling of the project, the model is considered 4D. "Cost" is another important variable in projects. Modelling cost information with the 4D BIM models will extend the model to a 5D BIM. Addition of information about Facility management (FM), Sustainability and safety can further generate 6D,7D, and 8D BIM, respectively. [46].

The role of spatial elements is the most visible in the 3D BIM modelling. Suter [47] developed a spatial layout as a graph representation which can be used for further analysis of the topologic relations and placements of spaces and assets (equipment) in the building envelopes. In this work, the definitions of space hierarchy and their boundaries, both linguistically and geometrically, are developed. The author, also, developed definitions for topological relations such as adjacency, access, touching (clashes) and closeness between spaces, their boundaries and (fully/partially) accommodated elements. Moreover, a list of spatial layout constraints, e.g. the instances which may bring failure(s) and inconsistencies to the model, both with regard to layout elements and their relations, is presented. Also, a resolve-inconsistencies operation is suggested based on BIM architectural design system and client applications. The whole layout is modelled using C++ programing language and presented in a schematic graph and later in both 2D and 3D. However, the research work lacks a linkage with IFC and constructive solid geometry representation (CSG).

2.2.2.2. Space in IFC

Spaces are seen as entities (e.g. objects) in IFC. In this study, IFC 2x3, as the most popular, and IFC 4, as the most recent version of IFC, are investigated. According to International Alliance for Interoperability (IAI), space contains (1) the "physical or notional" boundaries, (2) accommodating certain areas or spaces for certain functions (which is added form IFC version 1.5). In IFC, spaces might be interior or exterior which can be a subset of IFCBuildingStorey or IFCSite, respectively. They might be Complex (a space group), Element (space) or Partial (a partial space). The relation of these three is defined as spatial composition and decomposition. [48,49].

IFC has defined a list of properties which are commonly used to analyze information of space elements. [48,49]. In IFC, each space may be represented by different solid forms. Solid modelling of a space can be done by its footprint as a 2D poly Curve, Swept Solid Geometry or Body Clipping Geometry. 2D Poly Curves are the polygons made by projection of the wall centerline (surfaces) on the floor of the space (***Figure 9***). Swept Solids are extrusions from enclosed solid areas (which may contain voids as Poly Curves) (***Figure 10***). Body Clipping Geometries are the Swept Solid Geometries subjected to a Boolean expression (***Figure 11***) [57,58].

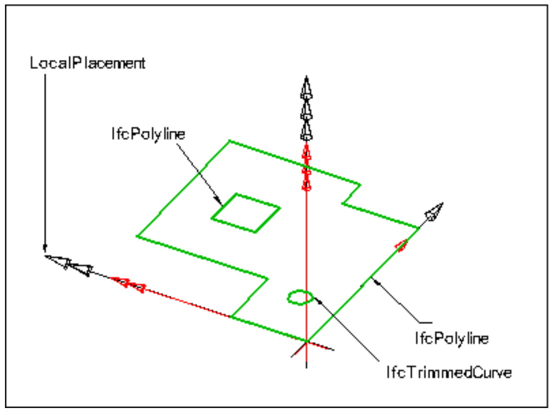


Figure 9: "2D Footprint" representation [37]

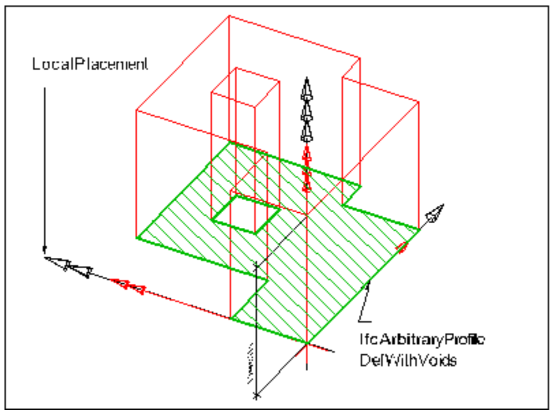


Figure 10: "Swept Solid" representation [37]

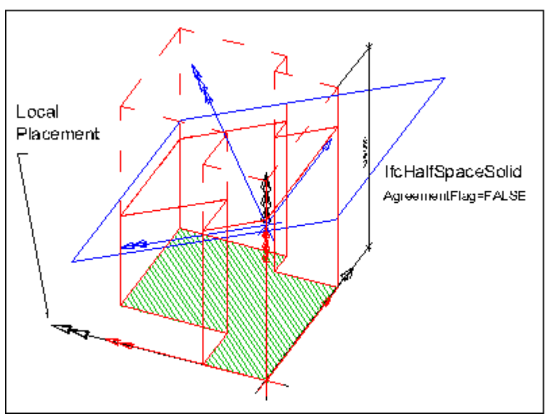


Figure 11: "Body Clipping" representation [49]

However, some other modellings of space are also suggested by the literature. In early/ pre-BIM, Björk [43] suggests 4 different ways for modelling the geometry of 3D objects (such as spaces) as illustrated in ***Figure 12***. Patraucean et al. [3] suggest Constructive Solid Geometry (CSG) modelling or Boundary representation (BRep) for volumetric modelling. Venugopal et al. [27] suggest four methods (***Figure 13***) as shape methods available in IFC; 3D shapes can be represented by (1) their boundary surfaces (boundary representation), (2) by a 2D polygon and extrusion for prismatic shapes (polygon face extrusion), (3) by joining simple 3D shapes such as cuboids, spheres etc. (unionization), and (4) by Boolean subtraction of simple 3D shapes.

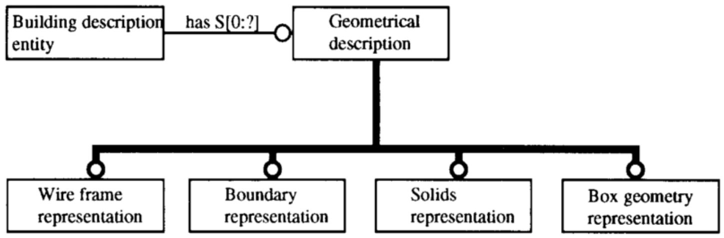


Figure 12: Basic principle to attach geometric information product description [43]

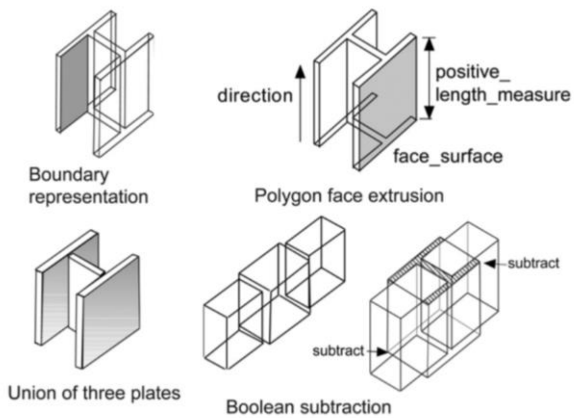


Figure 13: Shape methods available in IFC [27]

2.2.2.3. Space in Revit: Rooms

Autodesk Revit, as one of the most common BIM software packages, defines spaces by instance of rooms. In Revit, rooms are specified by their boundaries which can be building elements or imaginary/user-defined surface(s) (named as room separation walls) [50,51]. Since Revit offers rooms as the only instance for IFCspace, it can be concluded that Revit is originally compatible with indoor spaces. Although outdoor spaces can still be modelled using imaginary surfaces (room separation lines/surfaces) by a human user on Revit, these new (outdoor) spaces may not comply with an accurate definition of IFCsite.

Rooms are placed selecting a floor span in a Revit model [52]. However, Revit doesn't have any rule checker for the rooms. Rooms may be extended (in order to span several floors and levels and/or walls and separators) or trimmed (when needed to add an experiential room boundary) [52,53]. Room (physical) boundaries are aimed to take the role of being a room boundary by checking/unchecking the relevant box in properties of each building element [54].

Rooms, like any other family instances, may contain several properties. These properties are categorized in constraints (physical limitations addressing other building elements and/or levels), dimensions (area, perimeter, unbounded height, and volume), identity data and phasing [55]. Rooms may acquire tags which are identical information added by the user to be shown on floor/section plans [56].

2.3. As-built Modelling

As discussed above, the enrichment of data in BIM models is important for FM applications. Incomplete and/or low-detail models are not suitable for FM. Rich BIM models can be gained in three cases: (1) updating the as-planned BIM model through the construction phase, (2) updating the pre-existing BIM models of the facility with the changes after a period, and (3) preparing a new BIM model for the existing facilities which may not have a pre-existing BIM models or have an incomplete and/or inadequate models [30] of which the third is the subject of the current research.

The development of as-built BIM is still a largely manual and thus expensive process [57] and it is also prone to error [58]. The development consists of two main steps: (1) data collection and (2) data modelling. The objective of data modelling is to generate the rich 3D semantics containing the objects, their relations, and attributes in a BIM model [59]. ***Figure 14*** illustrates the process of data modelling in development of as-built BIM models. In this process, as-built modelling aims to use the geometric specifications and architectural rules to generate object-oriented models out of generated and pre-processed point clouds [3].

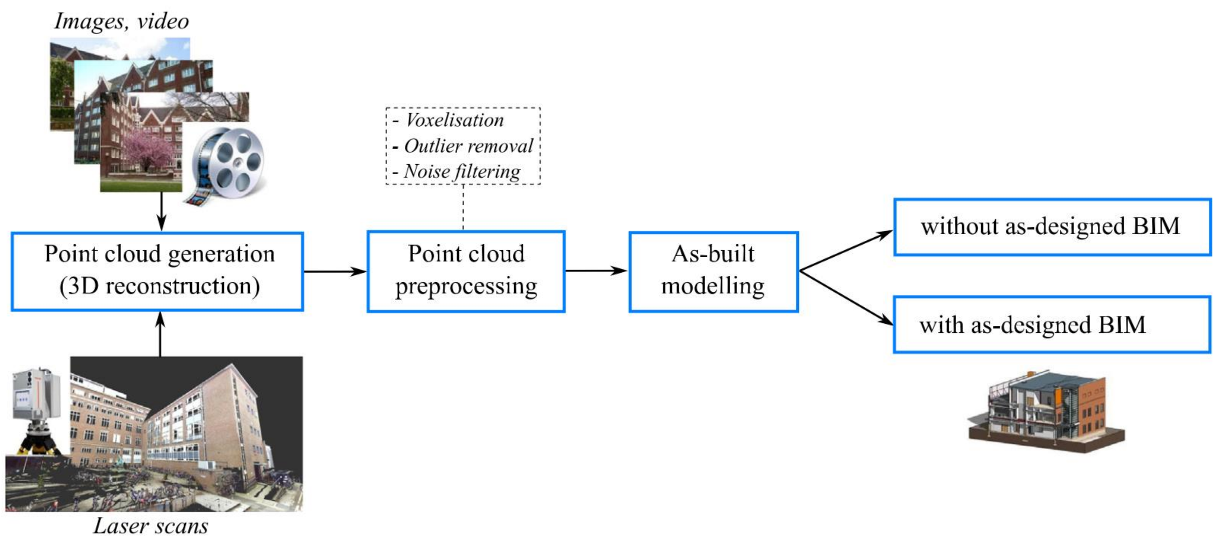


Figure 14: The schematic process of data modelling [10]

As-built modelling may follow different approaches; namely: heuristic, context-based, prior knowledge-based, and ontology-based [59]. Heuristic approaches use the human knowledge codification from the architectural field. Context-based approaches use same heuristic set of rules and use the relation between components based on the context. For instance, the upper horizontal surface recognized in a point cloud generated from an interior laser scanning of a room is recognized as the ceiling [4]. Prior knowledge-based approaches use the pre-existing BIM models to compare the geometries with the point clouds and recognize the objects. In case an initial BIM model is not available, the development of an accurate as-built modelling is a challenging process because it still heavily depends on human experts or [3]. Finally, the ontology-based approaches are based on knowledge ontology. Inspired by semantic web, This approach uses a priori knowledge of objects and context which are extracted from other mediums such as Geographic Information System (GIS), Computer Aided Design (CAD) drawings, expert knowledge etc. [59].

The performance of the as-built modelling process needs to be evaluated in order to track the improvements of the new designs in regard to the process. As pointed before, one of the ways to address the accuracy and richness of BIM models is the use of Level of Detail/Development (LoD). Different functionality-related LoDs are defined in the literature[30] such as for general modelling [60]. Tang et. Al. cluster the evaluation measures to three categories of measures (1) related to the design of the algorithm, (2) related to environmental and sensing conditions, and (3) of modelling performance [60]. This evaluation process can be helpful to compare different approaches and investigate whether the new designed (automated) as-built modelling practices are conveniently accurate or not.

The previous research works have been mainly focused on the object recognition rather than the development of relations and attributes. Previous research works have mainly used the geometries from the point clouds rather than the explicit geometrics and heuristic rules [4] from a primitive BIM model containing the basic objects. Currently, the industrial need of as-built modelling is mainly satisfied by loading point clouds in BIM software packages and creation/development of a model by human experts [58].

2.4. Semantic Expansion

As stated before, BIM models are object-oriented. However, the order of semantics in BIM models can vary a lot. They may vary from the basic building elements such as walls, floors, ceilings, doors, and windows to spatial elements, the tasks assigned to each zone and space and several other data [35]. Such a diversity of data might also be produced by fragmented stakeholders [61,62]. This causes excessive time and human resource allotment to develop the as-built BIM models to be used for FM practices considering that the semantics can be developed unlimitedly. However, some of the needed data such as the spatial elements of the buildings can be extracted using the primitive BIM models and a set of heuristic (geometric and architectural) rules. In this research, this process is named as “semantic expansion”.

The extraction of semantics using heuristic rules has been addressed in the as-built modelling literature. Looking among the as-built modelling literature, creation of as-built BIM models in absence of as-designed BIM models, the main focus is on the geometric data gained from the point clouds as the input [3,63]. The main constraint of these research efforts relies on the input; the input of these efforts is the (geometrics extracted from) point clouds. The heuristic rules in these cases are mainly considering the topological relationships of surfaces and lines extracted from point clouds rather than specification of objects. However, by using the primitive objects and their explicit geometric data, a step of object recognition is skipped and the speed of the process is to increase while the complexity decreases.

The semantic expansion may occur within or beyond the IFC’s predefined libraries. The main semantic expansion research works aim to expand the semantics over the IFC libraries. These works have used ontology approach extracting the explicit data from IFC logs by parsing IFC logs [64] and added the new relationships by several tools such as protégé [7,65]. While the inputs in these processes are the ordinary IFC determined objects, the outcome is new and its relationships and dependencies to the other objects can be defined according to the designer of the new object.

When the semantic expansion takes place within the current IFC boundaries, it usually happens by the intervention of human experts. When the semantics are to be linked to some other set of data formats such as CityGML, the neutral format for data exchange between GIS models, transitional ontologies are used. Another example can be found about the safety management, energy performance, specific quantity take-offs etc.

While the use of spatial elements in the BIM models have been addressed to be beneficial for different FM uses, such as space management [12], energy performance monitoring [63], and M&O management [17], the spatial elements has been assumed to be present in the available model rather than to be developed through the research [5,17].

2.4.1. Space Extraction

As discussed, an instance of semantic expansion could be producing spatial elements. Such a process, named space extraction, may take place from building object-oriented models in 2D or 3D format or point clouds.

Space extraction was a subject to a stream of research works done in order to analyze the indoor navigation. These studies use IndoorGML standard as their reference [66]. IndoorGML is a reference for Geographic Information System (GIS) tools with a high level of detail e.g. LoD4. This standard aims to classify the indoor spaces and some of their topological relations as Node-Relation Graph (NRG). In IndoorGML, the indoor spaces are semantically sorted in a hierarchy as illustrated in ***Figure 15.***

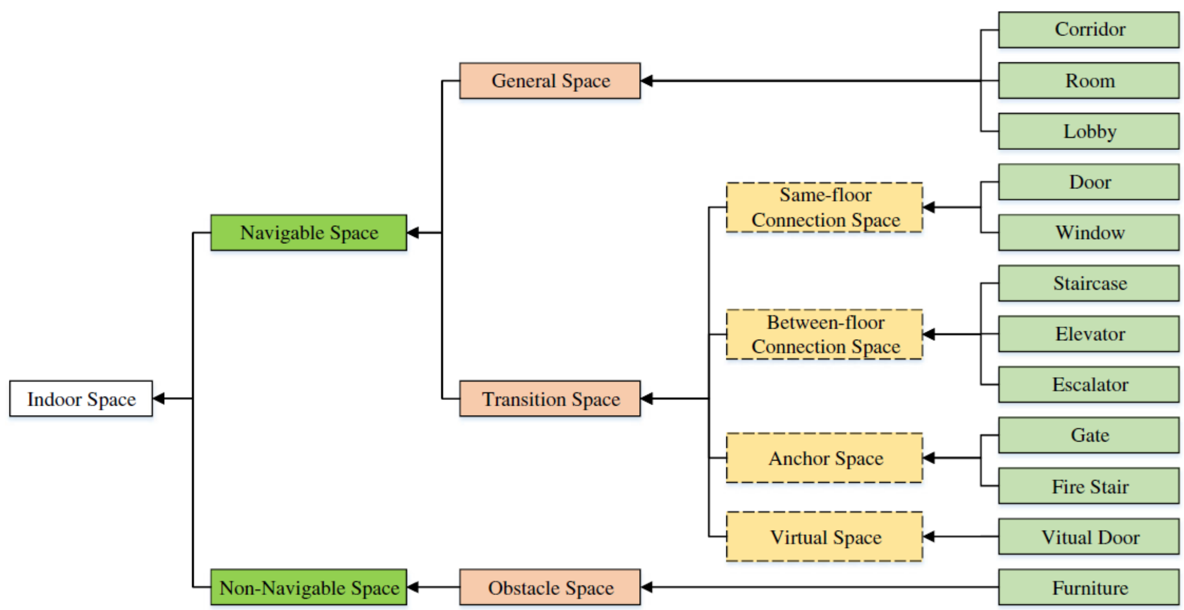


Figure 15: Hierarchy of semantic information of indoor spaces in IndoorGML, picked from [67]

According to the IndoorGML, the indoor spaces might be non-navigable (e.g. obstacles such as furniture) or navigable. The navigable spaces are broken down into general spaces consisted of rooms, corridors and lobbies and transition spaces. Finally, the transition spaces are classified in (1) same-floor transition spaces as doors and windows, (2) between floor transition spaces such as stairs, elevators, and escalators, (3) anchor spaces such as gates and fire escape stairs and virtual spaces as virtual doors (e.g. openings in the walls. It is important to note that all these elements are not really spaces but are used to relate to spaces and their topologic relations. Although the spatial relations of spatial elements and spatial attributes of building elements are well defined by IndoorGML, these are mainly used for indoor navigation analysis. It should be checked with the FMTs if they need extra types of spaces or any other modification [66,67].

To produce the indoor spaces according to the IndoorGML code, the researchers have taken different approaches. Abou Diakité et al. [68] have designed and implemented a process which extracts the intersection of walls and floors to find the bounded spaces from IFC file of a building model. The final result is produced as a water-tight 3D object representing the inner surface of spaces. However, their work does not identify the experiential boundaries of spaces nor identifies the space uses. In order to extract the spaces and their uses according to the IndoorGML classification in complex buildings, Xiong et al. [67] have developed a process which automates the space extraction and classification to be used in indoor navigation in complex 3D models of buildings in CityGML format with LoD 4. In their work, they use voxelization and triangulation in order to simplify bounded spaces into smaller particles and join them to form a space in a 2D/3D model. The outcome of their work also represents a watertight geometric solid which represents the inner surface of a space. Therefore, their work lacks the topological relationships of the constructed spaces and also the classification is limited to the IndoorGML classes. In another research, Yousefzadeh [63] has used point clouds to produce spaces for energy analysis. The outcome of his designed process represents a boundary representation of indoor space of which the surfaces represent the centerline surface of boundary objects. Although his work has a superiority of not being dependent to the presence of 3D object-oriented models, the outcome doesn't show experiential boundaries and according to the use of point clouds, the accuracy is considerably lower. Further, the constructed spaces are not classified based on their intended use.

While the spaces may be extracted from basic building objects, the spatial network may be refined by extracting sub-spaces out of present or extracted spaces. This process is called sub-spacing in the literature. Sub-spaces might be produced according to the physical, logical and functional constraints [69]. In order to execute sub-spacing based on all sorts of constraints, the spatial layout must be enriched with the space uses and boundaries. However, the physical and geometric constraints can be extracted in parallel with space extraction. Jung et al. [69] have implemented sub-spacing on a present spatial network enriched with space uses. However, the function constraints in their model only include the "stay" and "transition" spaces since they attempt to analyze the pedestrian circulation in a shopping center. Also, their work only subspaces the pedestrian corridors and main lobbies of common indoor spaces. As mentioned Xiong et al. [67] have used voxelization in order to find enclosed spaces. This approach enables them to identify the complex patterns in the shape of space such as niches and to identify the sub-spaces.

2.5. Discussion

In the light of the presented literature review, it can be concluded that while BIM implementation is gaining popularity among designers and contractors, the full-fledged use of BIM that covers the entire life-cycle of the project is still missing. Such a comprehensive use of BIM would benefit the facility management of the buildings more than any other discipline. The current FM practices require the management of a huge amount of data. This data is usually scattered across many disciplines and, in the current practice, several data management tools are being used to consolidate and manage these data.

The integration of BIM and FM can offer the advantage of having a central object-oriented model where facilities-related information is seamlessly embedded in the building elements. This integration can streamline the process of data retrieval and query, which in turn can result in an enhanced management of the facilities. However, the major issue with the BIM-based FM is that while the approach can be theoretically adopted for the new project, it cannot be applied to the majority of the old buildings for which BIM model either does not exist or is incomplete.

To address this issue, many researchers and contractors started to apply the as-built modelling, where the laser scanners are used to generate the point cloud of the buildings. This point cloud is later processed, manually or semi-automatically, to extract geometric objects (e.g., walls and windows) and consequently generate the BIM model. Nonetheless, to prepare the as-built model for the FM applications, the designer needs to manually add the facilities related data to the model to enhance the semantics of the model. This process is time-consuming and error-prone.

Therefore, it is essential to devise a method that can facilitate the process of semantic expansion in the as-built models. It is argued that many of the facilities related semantics (basically spaces and zones) can be derived from basic geometric relationships between the building elements. While the space extraction has been a subject to some research works, they had merely considered FM perspective for their outcome. This research is dedicated to this end and tries to propose methods that can use the geometric information of the as-built model and (semi-)automatically generate the FM works related semantics.

3. Research Methodology

The research will be broken down into four phases in addition to phase zero: research setup. Research setup phase will cover preparation of the research proposal and the development of theoretical background reviewing the previous research works.

In the following sections, the research phases are described separately by addressing the research approach used. The fourth and final phase is used to prepare the final report for the green light session and presentation during the colloquium.

The research will use a case study of the primitive as-built model to test the workability of the process and validity of the findings.

3.1. Phase I

In this phase, an exploration will be conducted to gain a proper understanding of the FM needs and their relation to spatial semantics. A semi-structured interview with the FM contractor of the case study project will be supported by the theoretical background. The aim of this exploration is to find the best set of boundaries and explicit data by which the spatial semantics can be addressed through the upgraded as-built BIM model. The literature review might be updated by new findings through interviews.

3.2. Phase II

The second research phase would aim to use the outcome of the first phase as the design requirements in addition to a review of the case study model to define a set of heuristic rules, mainly addressing the geometric and architectural specifications of the building objects/elements.

This phase will consist of two sub-divisions; the first sub-division aims to use the results of phase I to design a set of heuristic rules which can be hired to extract the required spatial semantics from the primitive BIM models. The second sub-division would then consist of a review of the as-built model produced by 3DGeosolutions (3DGS) as the case study, exploring the accuracy, limitations and the Level of Details (LoD). The rule set produced by the first sub-division will also fix to match the specific limitations and needs of the produced model. Some unstructured interviews with as-built BIM model developers and minor rehabilitation/downgrades of the current BIM model might also be necessary to finalize the design phase.

3.3. Phase III

After setting the geometric and architectural rules in phase II, the extraction of the spatial semantics will be modelled in the third phase. The third phase will be broken down into three sub-divisions:

The first sub-division contributes to the automated extraction of the spatial semantics. “Dynamo”, an add-on of the Autodesk Revit will be used to model the process of extraction and to produce the spatial semantics. Using Dynamo is selected due to the following advantages:

1. The current as-built model is produced by Revit. Although the use of the model in several other formats is possible (each model can be exported as an IFC file and then be imported in any other BIM based software or be used with IFC parser and viewer), such an export-import approach would result in some data loss. The probable rehabilitation of the primitive BIM model would also be much more time-consuming and less probable which may threaten the feasibility of the research in the desired time span. Since the licenses for Revit are provided both by Autodesk for educational uses and by the research client for industrial uses, the use of Revit won’t result in extra costs.

2. Dynamo is an open-source free add-on to Revit that has been beneficial to a large number of users and large web-based forums. It facilitates the debugging of the developed procedure and serves for maximal feasibility.
3. Being limited to use of Revit might not be good in regard to interoperability, however, the use of Dynamo will decrease the workload eliminating the need for the programming in order to use the .IFC files. On the other hand, .IFC files can be exported for other users after the extraction of the spatial semantics, so it will not cause other restrictions according to the interoperability. Moreover, storing the found information as data is considered out of scope for this research.

The second sub-division is related to the validation of the outcomes. The validation will be expert-based by the industrial supervision of the research client, GloBLD and the primitive as-built BIM producer, 3DGS. The FM contractors may also be involved in this part.

3.4. Phase IV

The final phase will aim to finalize the research project, reporting the research, holding the green light session and preparation and presentation of the colloquium. Recommendations on future research and discussion of the findings will also be prepared in this phase.

A brief illustration of the research framework is provided in ***Figure 16***.

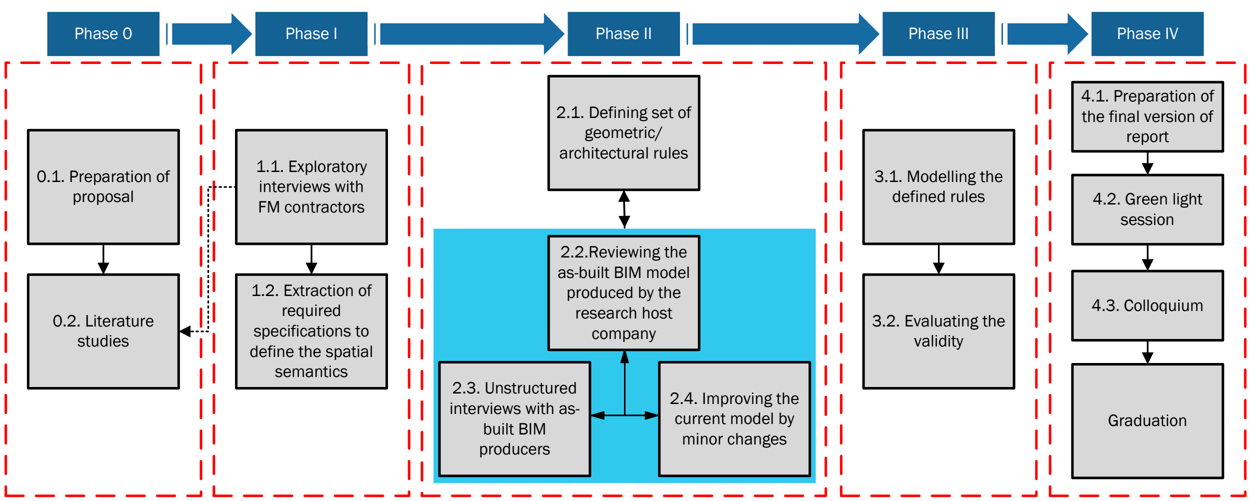


Figure 16: Research Framework

4. Spatial Information Requirements of the FMTs

This chapter is dedicated to further investigating the role of spatial information requirements of FM. These requirements are discussed with few interviewees with different functions in the industry using a series of semi-structured interviews about BIM and FM. FM tasks may vary essentially in detail based on the project specifications. However, some spatial elements (and some specific attributes of them) are commonly used by FM managers. These interviews are designed to identify the most relevant spatial element/attributes used in the FM tasks.

4.1. Interview Design:

A real-estate and facility manager of an educational complex, a head manager responsible for minor M&O projects for a post-construction services company, a head manager of an M&O company responsible for major M&O works in residential buildings, and an architect were interviewed. For these interviewees, two questionnaires were designed, one for the facilities managers and one for the architect. However, based on the responses, additional questions were asked on the fly.

The interview consisted of 5 different parts; the first two parts was about the introduction of the project and researcher to the interviewee and the general information of the projects and FM tasks in the interviewees' organization. The third part explored the current procedures of data/information management over FM managers in terms of: (1) the employed information management systems, (2) data formats, (3) presence or absence of BIM, (4) the type of models (as-designed or as-built), (4) internal (organizational) or external (municipal, provincial, national, or international) standards and codes in use, and (5) the process of data extraction to support decision making, planning and pricing, execution, and any other possible case that are added by interviewees. The next part aimed to explore the variety of disciplines serving M&O, and the collaboration and data exchange among them. The fifth part was about the investigation of the spatial data used in different maintenance and operation areas, the hierarchy of spatial elements, the different spatial hierarchical structures used for the disciplines of M&O and their relations, space boundaries, topological relations, space classification by type, space classification by the activity, and the relationship between space, furniture and fixed equipment. The architect interviewee did not have to answer these questions. The final part, which was only for the architect, was almost the same as the previous part but with the centric view on space design and classification in architecture which is to be used in collaboration with FM and especially M&O tasks. The designed questionnaire is provided in ***9.1***.

4.2. Findings

The findings of Interviews are summarized in ***Table 1***. The general findings in regard to the usage of BIM in FM and M&O are addressed in the following paragraphs.

Table 1: Findings from interviews

NO.		1	2	3	4
Position		Senior designer	REM & FM Manager	M&O Manager (for Minor interventions)	M&O Manager (EPM)
Specialization		Architecture	Mechanical Eng.	Construction	N/A
Company type		Consultancy and design	Service provider for FM and REM	Service provider for M	Service provider for M&O in regard of energy management, focused on design and placement of special building materials and elements
Project type		Residential	Residential/ Educational	Residential	Residential
Reference spatial layout		Architectural (floor) plans	Architectural (floor) plans	1.Architectural (floor) plans 2.Pictures taken by expert	1.Architectural (floor) plans 2.Pictures taken by expert and/or tennant
Space hierarchy		Based on Bouwbesliut standard	Based on the use and rent policy/price mentioned in the document	N/A	Inner and outer spaces sanitary(ies) and kitechen(s) activity spaces
Distinction of spaces/ sub-spaces according to:	Physical specifications	1.Constructed boundaries 2.Height 3.Light conditions 4.Padding 5.Colors and painting	Constructed boundaries	Constructed boundaries	1.Constructed boundaries 2.Height
	Activity	Space usage and type according to bouwbesluit standard	Space usage (to be referenced to the inter-university standard*)	N/A	Intervention activity (e.g. specific spatial requirements for work estimated by human expert)
Topologic relations		N/A	Accessibility and circulation	Adjacency to the other spaces	1.Position in the building (exteriority vs. interiority) 2.Adjacency to the other spaces

The interviews have shown that BIM models are still rarely employed by FM and M&O in the industry. In spite of their awareness of the great share of M&O and FM in projects' economic turnover, none of the interviewees is currently using BIM models in their decision making. The interviewees have stated that they still mainly use the traditional 2D floor plans, spreadsheets, and pictures to manage their data. However, three interviewees (except interviewee responsible for Energy Performance Monitoring (EPM) and M&O) have expressed their interest in employing BIM models in the future. The scope of projects of three interviewees were mainly around residential buildings (all except #2 who focused mainly on educational buildings). In order to manage the information about their projects, the interviewees have used different data management tools.

The first interviewee (the architecture and design company) has used BIM modelling tools such as Revit and Archi CAD only in the design phase and didn't develop an instruction for implementation of BIM through post-construction phases.

The Real Estate and FM manager (Interviewee #2) uses an Integrated Workspace Management System (IWMS) which was an expanded CAFM/CMMS with the capability to import/export BIM data and models.

However, this interviewee pointed that this capability is still not operational because BIM models of their assets with sufficient information for FM are not available.

In the third case, the interviewee is being called by the owner if minor maintenance interventions are needed. This company barely has a structured documentation and benchmarking system.

The fourth company developed their own data management platform which is based on spreadsheets. The diversity of maintenance and operation tasks in the interviewed companies were also different from none (the architecture and design company) to low (M&O companies) to highly diverse (Real Estate Management and FM contractor of the university). The conversations are recorded and included in ***Appendices 9.2, 9.3, 9.4,*** and ***9.5.***

With regard to the spatial information used in the projects, the findings are sorted into four main classes; namely: (1) reference spatial layout, which is the main source of spatial information for FM managers, (2) space hierarchy, (3) the boundaries and activities which are important in order to classify the spaces according to the space hierarchy, and (4) the topologic relation of spaces which are important for FM.

4.2.1. Reference spatial layout

As discussed before, FM decisions need to be supported by information extracted from an enriched BIM model. FM managers need spatial layout as a reference to extract their needed information to support their decisions. In this regard, interviewees were asked about the reference spatial layout they tend to receive as the outcome of as-built modelling. All interviewees indicated that such a reference should be the architectural spatial layout. This means that the architectural spaces (the spaces bounded between walls and floors and ceilings) are the reference spaces. Other specific sub-spaces such as workspaces are extracted by such as a human expert subcontractors and/or project coordinator.

4.2.2. Space hierarchy

Different spaces (and/or subspaces) should be categorized and classified in order to facilitate the information extraction. A breakdown structure of spaces and/or sub-spaces in form of a hierarchy facilitates the information extraction process. The only general reference that interviewee #1 has mentioned as a reference to space hierarchy was the Dutch national building codes named “Bouwbesluit”. Bouwbesluit barely contains a hierarchy of spaces and mainly has classified the building types. In the residential buildings, only a minimum area and height are discussed. However, some mandatory conditions have been pointed for specific room types. For instance, the living places must receive the natural daylight, which obliges the designers and constructors to put a window in such rooms. Further, specific rooms such as toilet, bathroom, and exterior storage are bound by minimum dimensions. These spaces do not need to have windows. While bouwbesluit is generally in use for construction, some organizations may have their own space classification and hierarchy according to their organizational goals. Interviewee #2 indicated that they are classifying and sorting their spaces into different classes according to their intended use (i.e. the use according to which space is designed and constructed). The third interviewee listed a number of architectural spaces which are taken into account for M&O interventions between different tenants of a rental unit. This list contains bedrooms, bathroom, toilet, kitchen, hallway, staircase, living room, attic, closets and storage, installation rooms and exterior spaces such as a balcony, front, and back-yard. Interviewee #4 has pointed to the sanitary spaces such as toilets and bathrooms, kitchens and the rest.

4.2.3. Space Boundaries

The spaces and sub-spaces might have different types of boundaries. These boundaries might be physical (i.e. the constructed building objects and/or geometrical attributes of spaces) or can be imagined according to the spatial needs of M&O activities in each space. In regard to physical boundaries, two of interviewees has only pointed to the constructed building objects (factual boundaries) such as walls and floors and ceilings. Height, as a physical attribute of the space, was mentioned by other two interviewees as the most important experiential boundary. Some other attributes such as the lighting condition, the finishing of the building elements etc. have also been mentioned by the architect. The activity spaces were also mentioned by all FM and M&O interviewees but no instruction and standard have been found. Such an activity/space structure is present in the industry by the human experts as project coordinators/organizers and might be different according to the specifications of each project.

4.2.4. Topological relations

Another important information for FM uses is the topologic relation of spaces and sub-spaces. Topologic relation of the spaces and sub-spaces can be seen as their adjacency, aggregation, accessibility, and circulation, etc. The interviewees have enumerated the adjacency, accessibility of the spaces, circulation, and position of the space in the building envelope (whether space is adjacent to other interior spaces in all directions or not) as important topological relations.

4.3. Reference Spatial Layout for FM in Residential Buildings-Specifications of the Final Product

As the result of the semantic expansion process, the primitive as-built BIM model shall be updated with higher-order non-physical entities, e.g., spaces. As discussed in the theoretical background, FM managers need a spatial element in two forms: first, the geometric representation of spaces and second, as a non-geometric attribute (location) of other elements and facilities. In other words, the product should enable the user to query the topological location (such as aggregation, adjacency etc.) of each element modelled as well as all geometric attributes of spatial elements.

As concluded from the interviews, the most common spatial layout is the architectural layout. This means that locating FM activities and building facilities/elements are almost always taking place in the architectural plan. Furthermore, due to the importance of floor areas in residential buildings, it is commonly accepted that the floors are nearly always used as a reference for spaces.

Interviews revealed no particular information on the classification and categorization of indoor spaces of the building. However, two spatial hierarchies were found in the reviewed literature. In IFC, indoor spatial elements are put in the hierarchy. According to the IFC, the IFCSite contains IFCBuilding (which may represent a whole or a part of a building), and IFCBuilding is decomposed to IFCBuildingStorey, IFCStair, and IFCTransportElement (for elevators) and each IFCStory is decomposed to IFCSpaces or rooms. To be consistent with the nomenclature in the discipline, the hierarchy of spatial elements in IndoorGML standard is used as the basis for this research. However, the non-navigable spaces are eliminated from the hierarchy since we are working with primitive as-built BIMs in which only a few kitchen equipment and sanitary facilities might be modelled. Further, based on the importance of each space for FM, add a few items are added to the general spaces in the current research; while the sub-categorization of general spaces remains the same, the rooms may be tagged as a residential room or non-residential room. The non-residential room is assigned to storage places, sanitary spaces, kitchen(s), built-in wardrobes etc. All three categories of corridors, lobbies and rooms may also be tagged as an attic if located underneath a Gable roof. Transition spaces will be represented and distinguished in the same way suggested by the IndoorGML hierarchy. Since most of these elements are presumed to be modelled separately in a primitive as-built BIM model, the process will only distinguish the type of the doors (doors vs. gates which are access doors to exterior spaces).

To conclude, the final product will contain a network of general and transition spaces. General spaces will be classified in (residential and non-residential) rooms, corridors and lobbies. The access to another floor (s) and being an attics is tagged as extra features.

5. Design of the Process

The semantic expansion process is explained in this chapter. The semantic expansion process aims to augment the primitive as-built BIM model with the spaces and their intended uses. This final product is to be used as a reference spatial layout for FM uses. As illustrated ***Figure 17***, the semantic expansion process starts from the point that a primitive as-built BIM model is produced from point-clouds of laser scanned assets. These models, as an input to the semantic expansion process, will be augmented through (1) space extraction and (2) space use recognition. The space extraction part aims to build up the spaces according to the geometric attributes of the physical objects available in the primitive as-built BIM model. Later, the space use recognition will use the intersection of the spaces with each other and with other building elements, and the geometric attributes of spaces according to the set of heuristic rules to determine the intended use of the spaces.

The current chapter consists of two sections. In the first section, the space extraction process, its operations, and associated algorithms are explained. The second section will discuss the heuristic rules and the design of the space use recognition module.

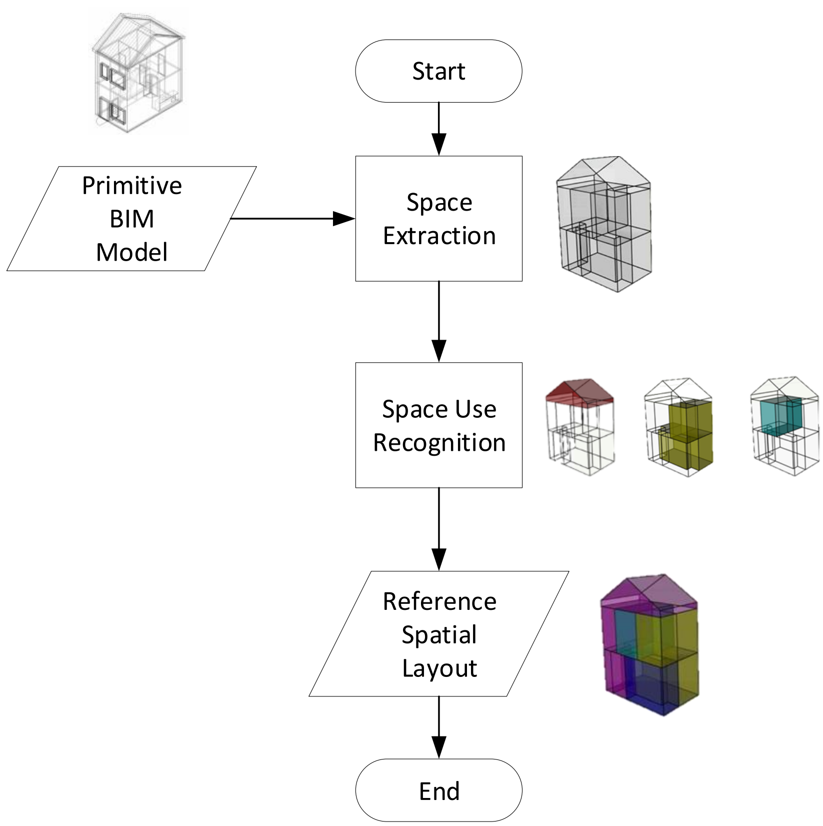


Figure 17: Schematic Flowchart of Semantic Expansion Process

5.1. Space Extraction

In order to produce the reference spatial layout for FM out of the primitive as-built model, the spaces must be built in the first step. The generated space should be built based on the boundary elements e.g. walls, floors, roofs and should enable the users to query the aggregation/containment relationships for each element.

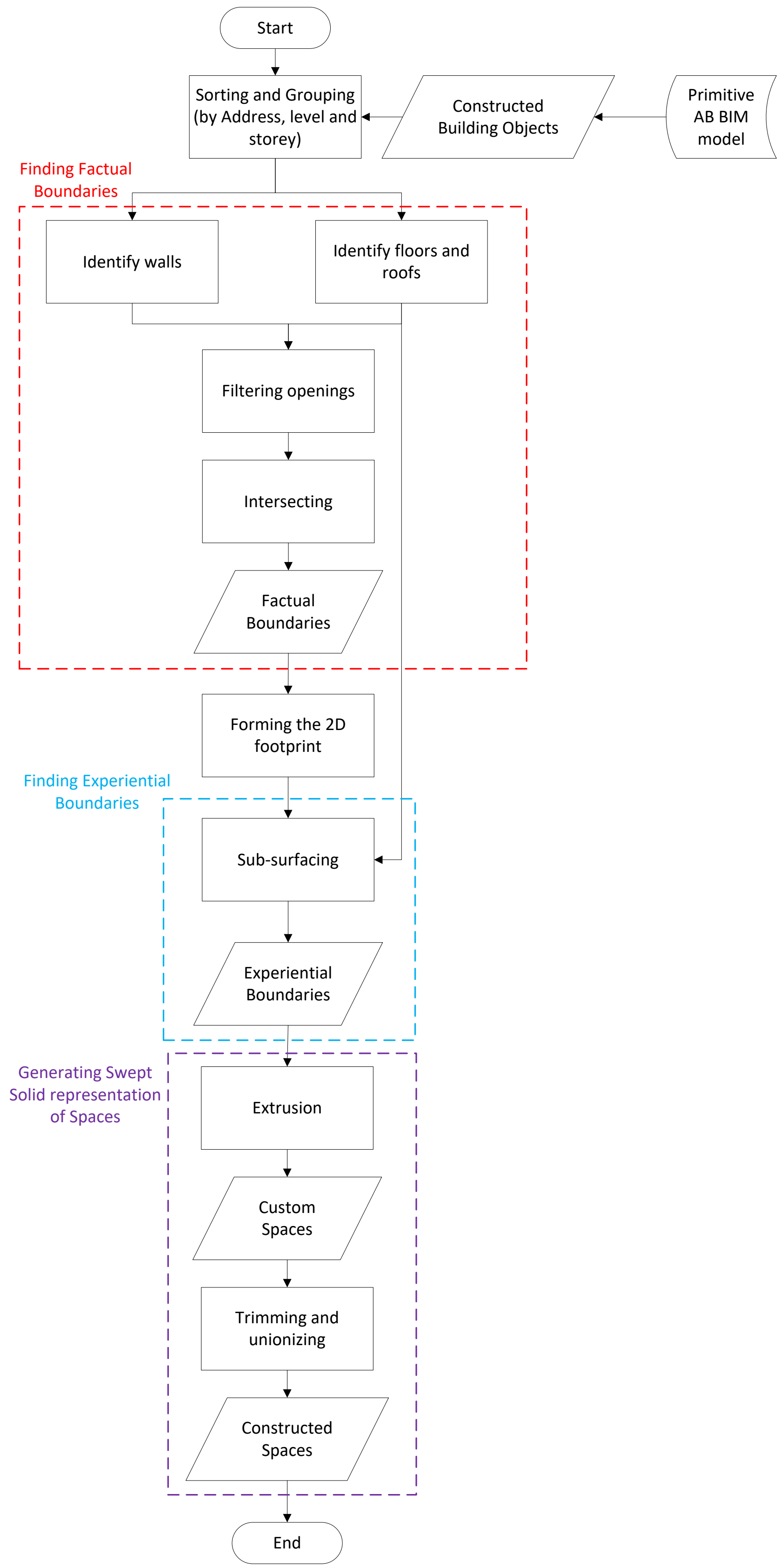


Figure 18: Flowchart of space extraction process

As discussed in Chapter 2, these boundaries might be factual i.e. the constructed building elements such as walls, floors, ceilings, etc. or experiential, e.g., height. As illustrated in ***Figure 18***, the space extraction starts from extracting all relevant building objects (e.g. walls, floors, and roofs), and then sorting and grouping according to their addresses (in the case the model contains more than a single building) and elevation. The grouped objects and their geometric attributes will be used in order to find the factual boundaries. The generated factual boundaries are "grouped" in order to shape the polygons which represent factual space boundaries and 2D space footprints are generated. Then, the 2D footprints are exploded to sub-surfaces which represent the height difference or change in top boundary (i.e. when the top boundary is represented by roof element than a simple floor or slab). This step also gives a unique quantity for extrusion. When these surfaces and sub-surfaces are all extruded, the elements which are under roof elements are trimmed by roof's top poly-surface and solids produced from sub-surfaces are unionized to form complex spaces. In the following sections, these steps are discussed in detail.

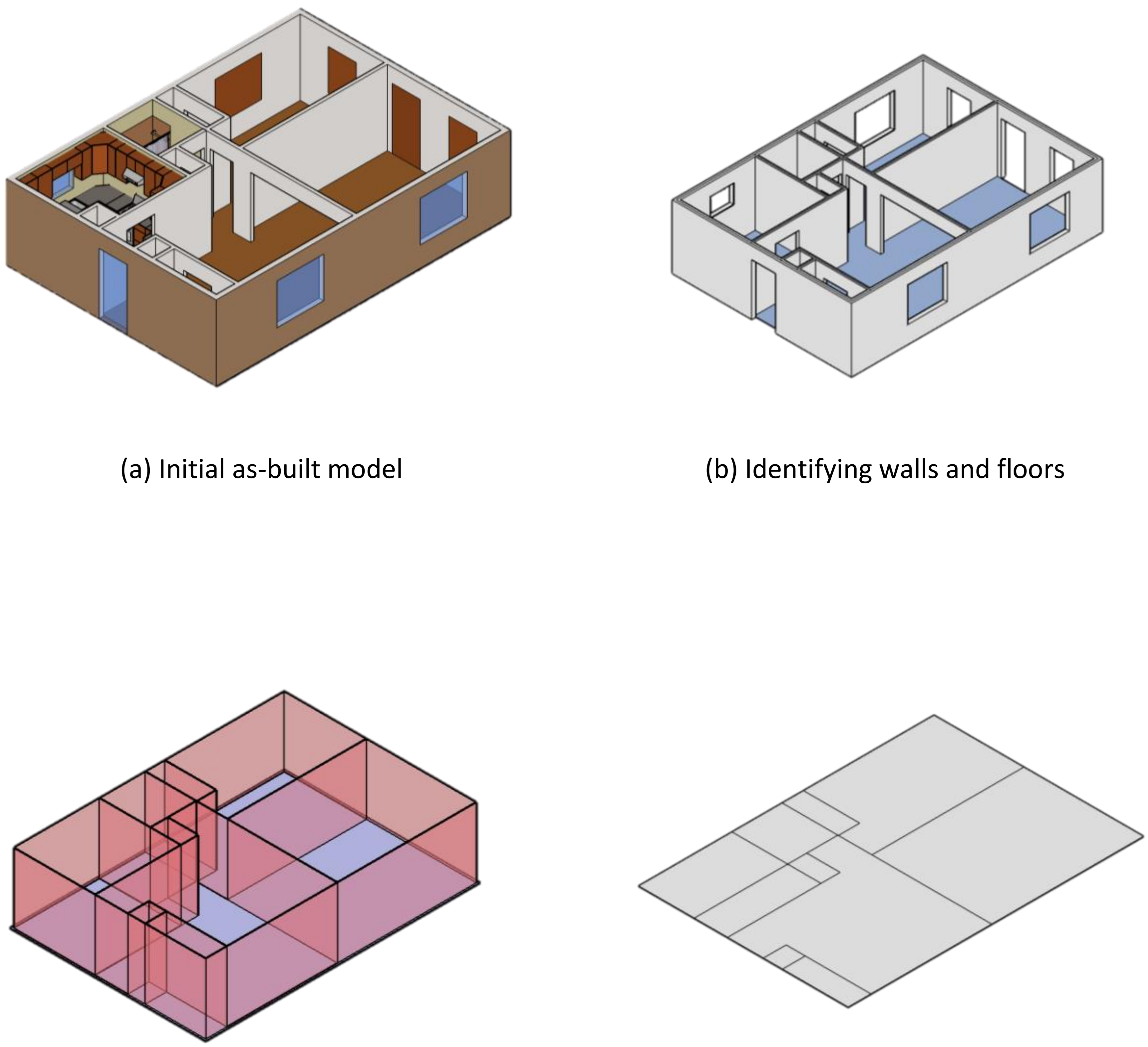
5.1.1. Recognizing Factual Boundaries

As mentioned in the theoretical background, the spaces may be represented as 3D geometric solids. These 3D geometric solids can be produced in several ways such as finding all the limiting surfaces, wire-frame boundaries etc. In order to simplify the production of 3D space elements, they may also be produced by extruding the 2D footprints of spaces, a process which is known as 2.5D analysis [70]. Such an approach will reduce the computation efforts especially when the final products have a prismatic shape with parallel faces on top and bottom. A similar approach is mentioned by IFC standard for representing spaces.

The factual boundaries of space's 2D footprint can be defined as the intersection of walls with their host floor(s). In order to reduce the computation effort, the floors can only be intersected with the walls which have the same level of base constraint. As it is shown in ***Figure 20*** in form of a flowchart, the walls and floors of each building floor should be intersected with one another. Sometimes the intersection lines may not be explicitly produced on the floors, for instance, when walls are not covering the complete height of a building floor e.g. the cases in which the wall is only attached to the ceiling (openings and arches) and/or walls which are representing a kitchen counter which is not attached to the ceiling, or where there are some openings in the walls (like the doors, windows, and door-less openings). These may cause an inconsistency in the intersection lines. In order to overcome this issue, the centerline surface of walls and floors need to be produced. The use of centerline surfaces tends to filter all the openings and disconnection of walls and floors which has already been addressed as a problem in previous research works [68]. Also, to solve the matter of walls which are hosted by a building floor but not attached to the actual floor element, the centerline surfaces of these walls should be projected to the centerline surface of the floor which is located on their base constraint.

Another advantage of using centerline surfaces relates to the final product. The previous space extraction procedures tend to produce the water/air tight spaces bounded by inner faces of their physical boundaries which may be called the architectural space [67,68]. This has two constraints: first, the cases in which the attachment of wall and floors/ceilings are not water/air tight, and second, the final product will include void spaces which are representative of bounding elements; The spaces produced from the centerline surfaces will also cover half of their bounding elements' thicknesses. This will later facilitate the process of relating the building elements which are not physically located in the space itself but are located in their bounding wall/floor etc. In other words, these "custom spaces" will enable the FM managers to query the relation of "being accessible" from a space element.

When all the intersections between walls and their host floors are found, these intersection lines should be stored for further process of grouping and forming the 2D footprints, discussed in next chapter. The process of identifying factual boundaries of spaces is illustrated in ***Figure 19*** for a simple one-floor residential building.



(a) Initial as-built model

(b) Identifying walls and floors

(c) Generating wall and floor centerline surfaces (Filtering all openings in walls and floors)

(d) Projected wall centerlines on floor's planar

Figure 19: Recognizing factual boundaries, an example

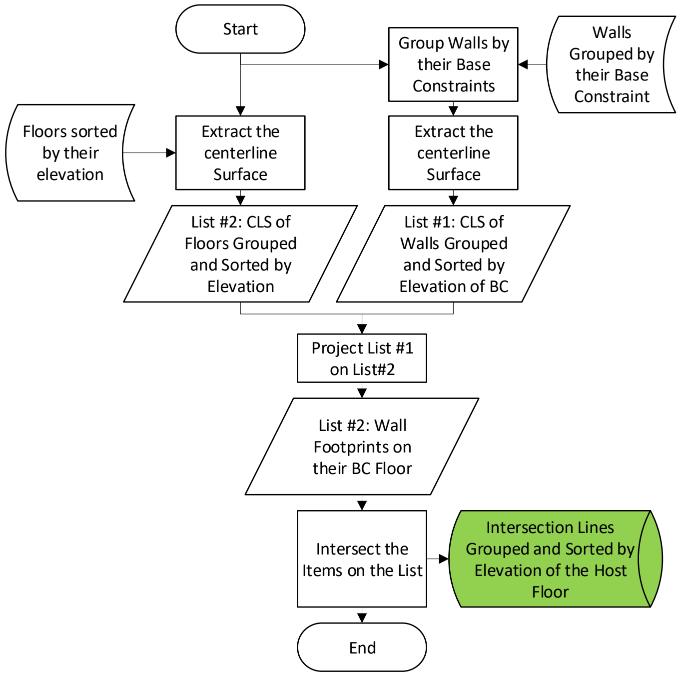
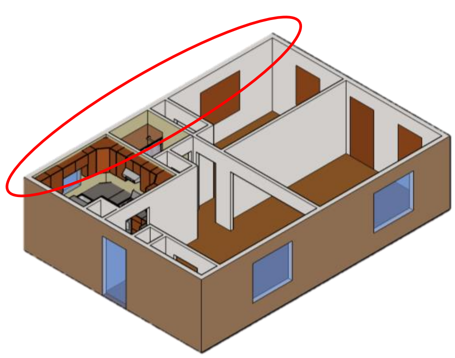


Figure 20: Flowchart: Recognizing factual boundaries

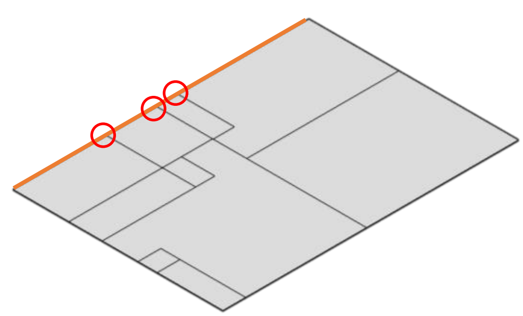
5.1.2. Grouping and Generation of 2D Space Footprints

When the baselines of physical boundaries have been extracted by the processes explained in section5.1.1, these lines should be grouped and merged as 2D footprints.

The former step provides a nested lists of lines. These lines are sorted and grouped by their host floor and their elevations. In the first step, it is important to notice that some walls may now only bound two spaces (one space at each side) but more. This happens when a wall element bounding three or more spaces in a row is modelled as one wall. This will be represented in presence of long lines which have intersections with other lines not on their end but in middle (see ***Figure 21***). In order to find the closed polygons as 2D footprint boundaries, it is important to break these big lines to the smaller parts. To solve this matter, the lines should be exploded into smaller particles at each intersection point and duplicates should be eliminated.



A omplex wall in the sample model



Intersection points in the middle of the line representing complex wall

Figure 21: Complex wall centerlines

The next step is grouping. In this step, the closed polygons should be made as the boundary of the 2D footprint of spaces. In order to find the lines which can bound a space's 2D footprint, graph theory is used. In this way, a matrix of adjacency for points is made and the floor plan is taken as a dot-arch graph. By using Johnson's algorithm[71,72], all simple cycles are found and then the repetitive cycles are eliminated**.** By using Johnston's algorithm, the simple cycles in a directed 2D graph can be found. As a result, this algorithm produces a duplicate string of points for every single surface. It also produces adjacent points as a cycle. In order to filter these items, the strings with less than 3 points which cannot represent a surface are removed from the result. The surfaces which have at least one shared vertex and the same average of perimeter vertices are identified as duplicates.

In the second step, the cycles are used to form surfaces. As pointed, these cycles may represent the boundaries of the complex surface, whereby the surfaces consisting of adjacent surfaces as a simple space. In this step, the extra cycles are removed. Another way to filter duplicates could be to filter all strings which can produce a surface with a normal vector of (0,0,-1).

When the duplicate surfaces are eliminated, the rest of surfaces should be checked against representing unwanted spaces. Unwanted spaces may be complex spaces or spaces which contain another (smaller) space without any mutual boundary, e.g. like an island in between. If two spaces from this list have an overlap with positive area value, and they also have a mutual vertex, the surface with the bigger area is representing a complex space and thus should be eliminated from the list. If they have an overlap area but no mutual vertex, the surface with smaller area represents one space and this surface should be subtracted from the surface with the bigger area. An example of the possible surfaces produced by the outcome of Johnson's algorithm and desired answers are illustrated in ***Figure 22***.

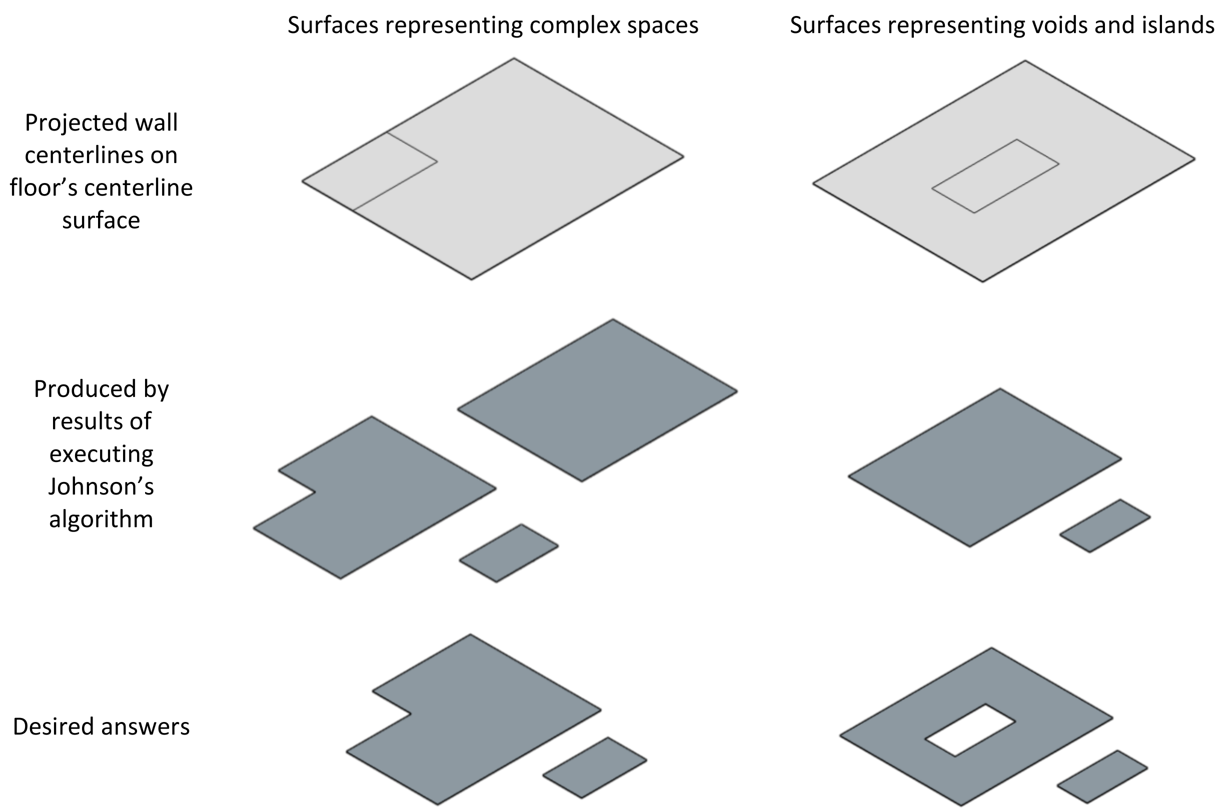


Figure 22: Generated surfaces vs. desired instances of 2D footprints

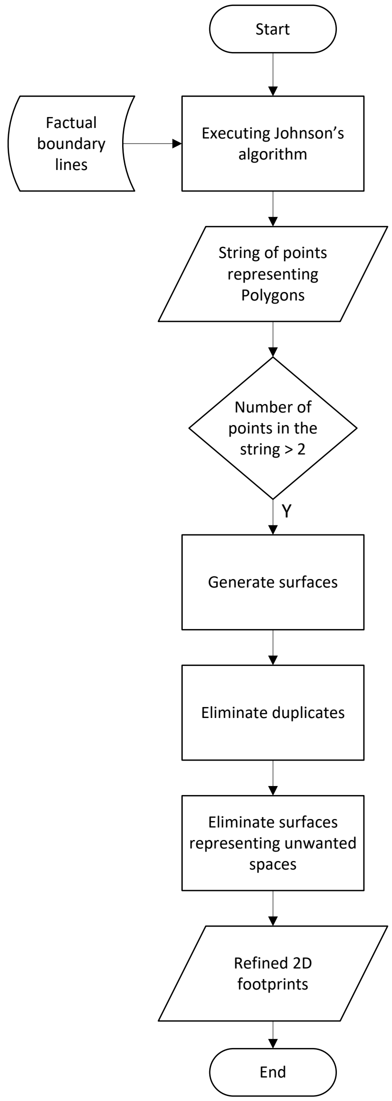


Figure 23: Flowchart: Grouping and generation of 2D footprints,

5.1.3. Sub-Surfacing and Finding Experiential Boundaries

The 2.5D analysis for space extraction means that each 2D footprint must be extruded by a specific height. Thus we need to distinguish the sub-spaces which have differences in height for each generated 2D footprint. Further, as discussed before, the height of each space is also important for M&O works. For this reason, the height is the only type of experiential boundaries considered in this research. By an operation called Sub-surfacing, each floor will be decomposed into sub-floors which have a unique elevation difference with the next higher floor/roof. The sub-surfacing operation is illustrated by a simple example of one-room building which has two roof elements (***Figure 24***).

Figure 24: Sub-surfacing and finding experiential boundaries

In this step as elaborated by a flowchart in ***Figure 25***, a sorted list of all floors in a building which are sorted by their elevations is used. As illustrated by flowchart, for each generated 2D footprint, the lowest floor is projected on the 2D footprint. The projected surface is then identified as a sub-surface. The sub-surfaces will be subtracted from the original 2D footprint and if there is a remaining, the next lowest floor/roof will be projected on the remainder. This loop continues until the remainder equals to zero or all floor/roofs are checked. IF there is a (sub-)surface of a 2D footprint which is not covered by any projection, this (sub-)surface is eliminated as an exterior space 2D footprint.

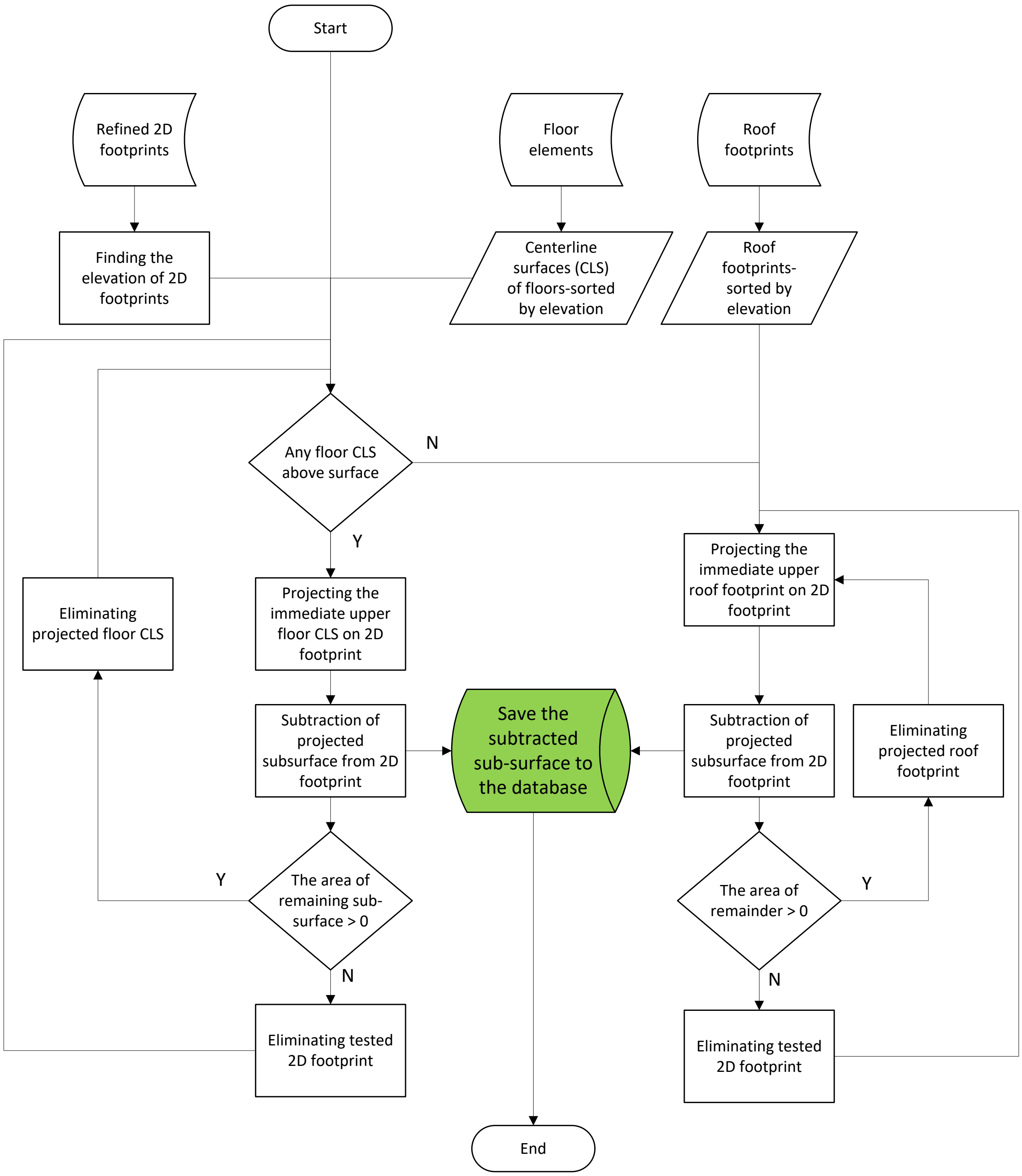


Figure 25: Flowchart: Sub-surfacing and finding experiential boundaries

5.1.4. Extrusion, Trimming, and Unionization

While the footprints are made, refined and divided to sub-surfaces, the nearest floor above them is used as a reference of extrusion. When there is no floor above the 2D footprint, the maximum height of the roof element above the footprint is taken as the reference of extrusion. The result of extrusion for both aforementioned examples in this chapter are provided in ***Figure 26***.

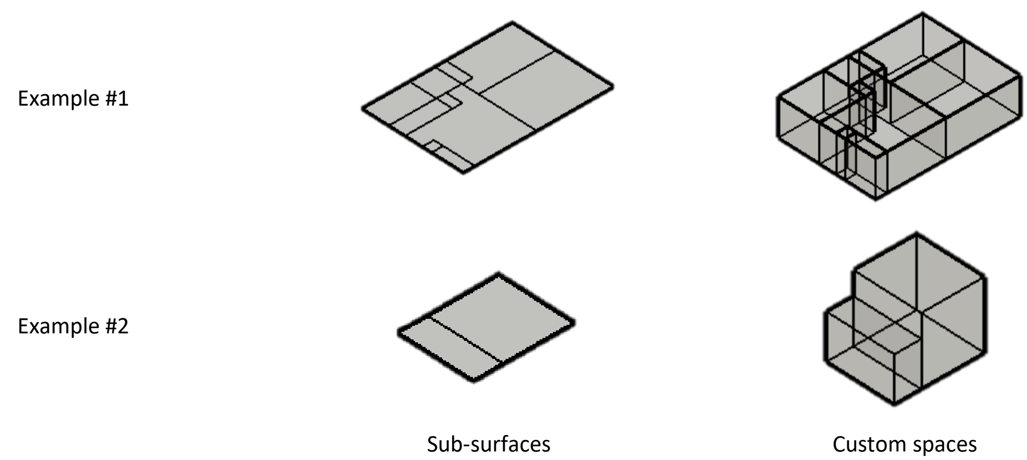


Figure 26: Extrusion of sub-surfaces

After the extrusion, the custom spaces are produced. Since custom spaces are produced through extrusion, they are represented as cuboids or any other prismatic shape. In the case that the extrusion is taken place up to the maximum height of a roof element, the generated cuboid should be trimmed by the top poly surface of the roof in order to represent the correct shape of the space (See ***Figure 27 (b), (c), and (d)***).

After the trimming, the solids which are generated from sub-surfaces of a unique 2D footprint need to be unionized. The unionization of these sub-spaces is important to identify the space intended use and the sub-spaces can be stored and later be used for sub-spacing when the height difference is important for FM jobs. The total process of extrusion, trimming, and unionization is illustrated in ***Figure 27***.

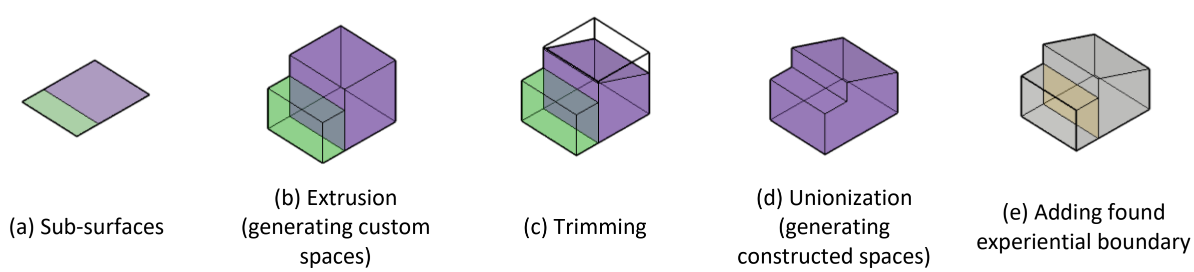


Figure 27: A schematic example of extrusion, trimming, and unionization

5.2. Space Use Recognition

When the custom spaces are built, the space uses should be recognized. As defined in the IndoorGML standard, the indoor spaces can be categorized into navigable and non-navigable spaces. This module is designed to identify the custom spaces which represent typology of constructed spaces as discussed in chapter 4.

Space use recognition takes place through a hierarchical decision tree that classifies spaces into the categories as discussed in Chapter 4. Space classification may take place according to the geometrical specifications of spaces, their topologic relationships with each other, and fixtures and equipment.

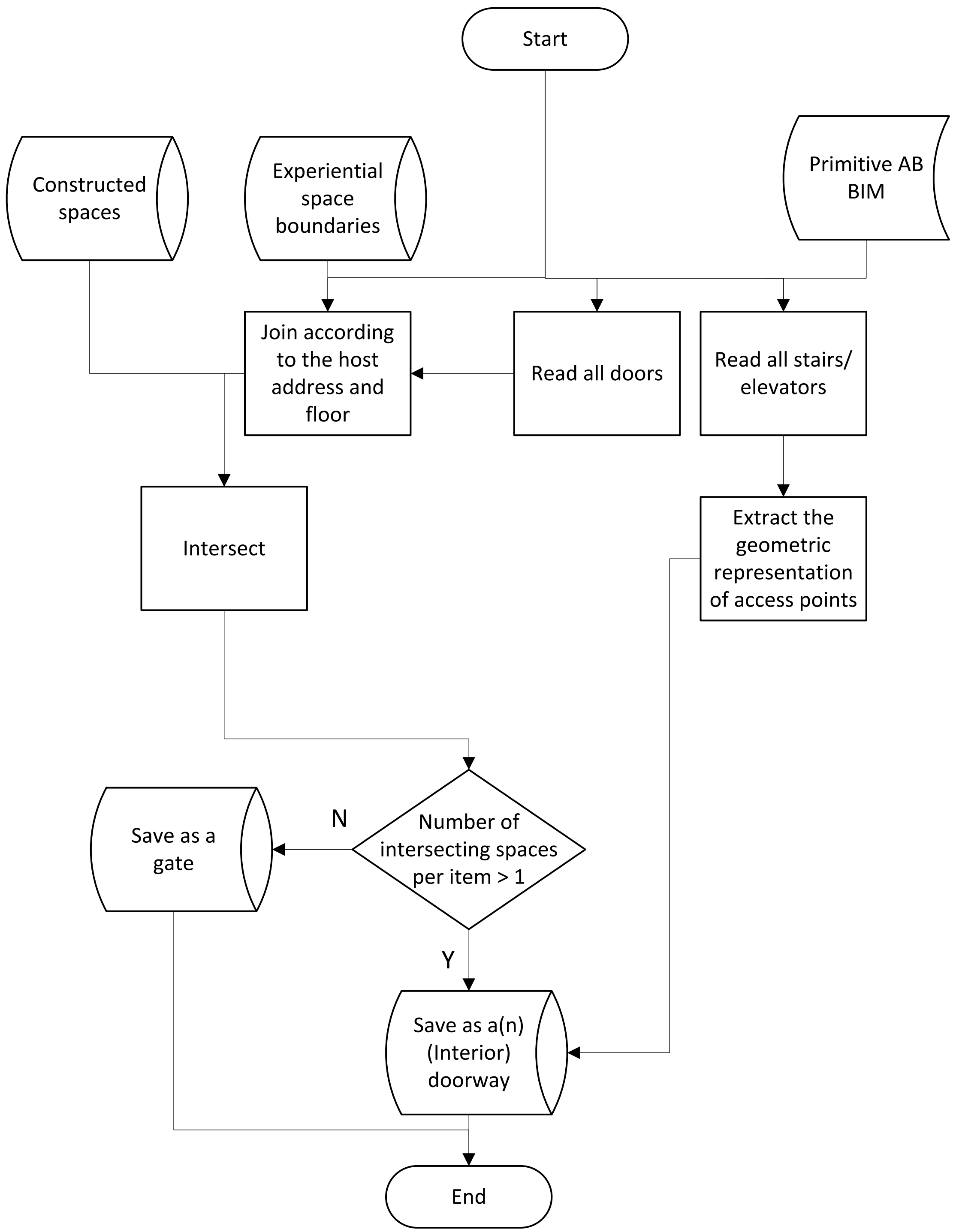
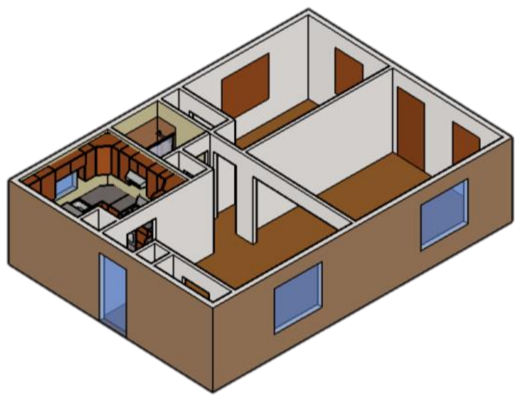


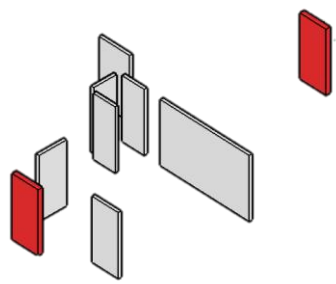
Figure 28: Flowchart: Listing all interior access points

In order to use the topological relations of spaces, the transition spaces need to be identified. The gates (doors with access to exterior spaces), (interior) doors, virtual doors (openings in walls and height differences), windows, stairs, elevators and (probably) escalators should be located in the same workspaces and the aggregation of each (transitional space) should be checked through intersection of them with the constructed spaces.

The simplest space type is the room. Rooms and lobbies/corridors can be distinguished based on their accessibility in the very first step. While the corridors and lobbies tend to provide access to more than one space, rooms may only have one access point. In order to find the access points of each space, we need to specify all access points and sort them by the spaces with which they intersect. To classify the access points, as illustrated in ***Figure 28***, we first need to query all the doors in the model and intersect them with the constructed spaces. The interior doors will intersect with two spaces while the gates intersect with only one. In addition, all the experiential boundaries (height in this case) can be nominated as interior access points. Categorization of doors in the sample model #1 is illustrated in ***Figure 29***, in which the external doors (gates) are marked with the red color. Finally, the between floor transition spaces represent two virtual doors in the two space they connect in different floors. When all the interior access points are merged into a list, its intersection with the list of constructed spaces provides a table which can show the number of access points per space. The spaces which only intersect with one access point will be the first candidates for the room.



Sample model #1



Doors, categorized into interior (grey) and exterior (red)

Figure 29: classification of doors

Rooms might be residential (such as bedrooms, living rooms, etc.) or non-residential (such as sanitary, storage or built-in wardrobes). These room types can be distinguished by both geometrical and topological attributes of the representing space. First of all, all residential rooms need to have natural light, as mandated in the building permit regulations of the Netherlands. Second of all, each residential space may have a minimum dimension that can host living equipment of a tenant, such as a bed. The latter condition calls for the minimum width of 2 meters (length of a bed) and a minimum area of 6 square meters for a residential room (according to Dutch normative). If space doesn't meet both these conditions, it may be a non-residential space which could be a storage, sanitary, built-in wardrobe, etc.

However, some rooms may have their private sanitary room or built-in wardrobe or storage. These rooms will be listed as candidates for lobbies/corridors. In order to filter this error, the access points to non-residential rooms should be eliminated from the list of access points of each lobby/corridor candidate and if the rest of list contains only one access point, the space should be checked as a room candidate and added as a residential/non-residential room to the other recognized spaces. In ***Figure 30(b)*** illustrates the process of intersecting classified access points and windows with constructed spaces of sample model #1, classification of one of the spaces is illustrated in ***Figure 30(c)***, and the refinement of results according to accessibility with a non-residential space is illustrated in ***Figure 30(d)***.

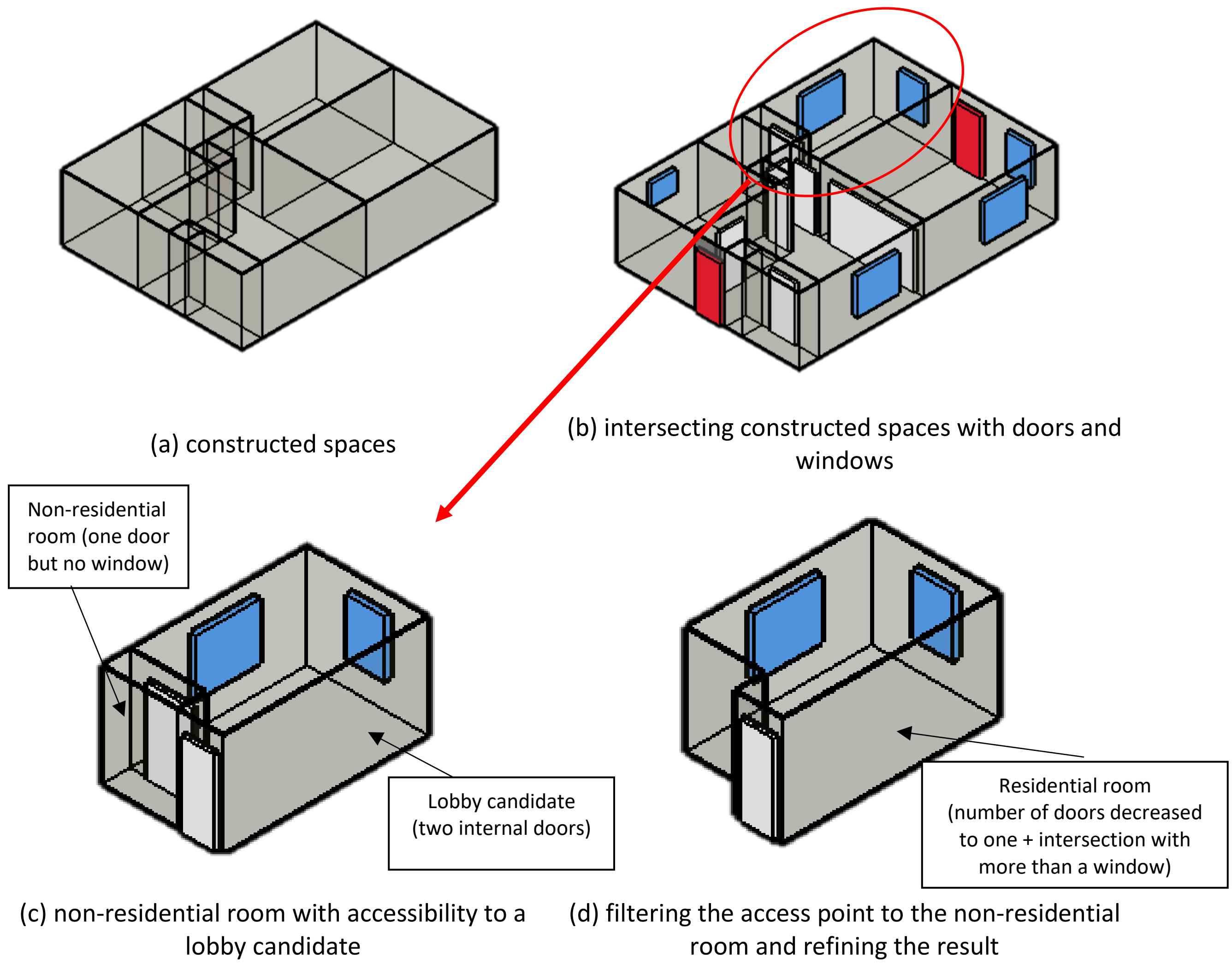


Figure 30: Classifying spaces into rooms/lobbies and refining the results by filtering access points to non-residential rooms

The rest of spaces, i.e. lobbies/corridors will be classified based on their shape. While both lobbies/corridors are multi-access spaces, corridors are usually shaped as narrow spaces. In order to check the narrowness of a space, we can divide the perimeter by the square root of the perimeter. The minimum of this coefficient is equal to $2\sqrt{\pi}$ for a circle and when the shape becomes narrower, the coefficient increases. A minimum of 4.62, which is the coefficient for a rectangle with length 3 times bigger than its width is considered as the threshold for classification of lobbies and corridors. The flowchart of space classification using the interior access points, natural light and geometric attributes is illustrated in ***Figure 31***.

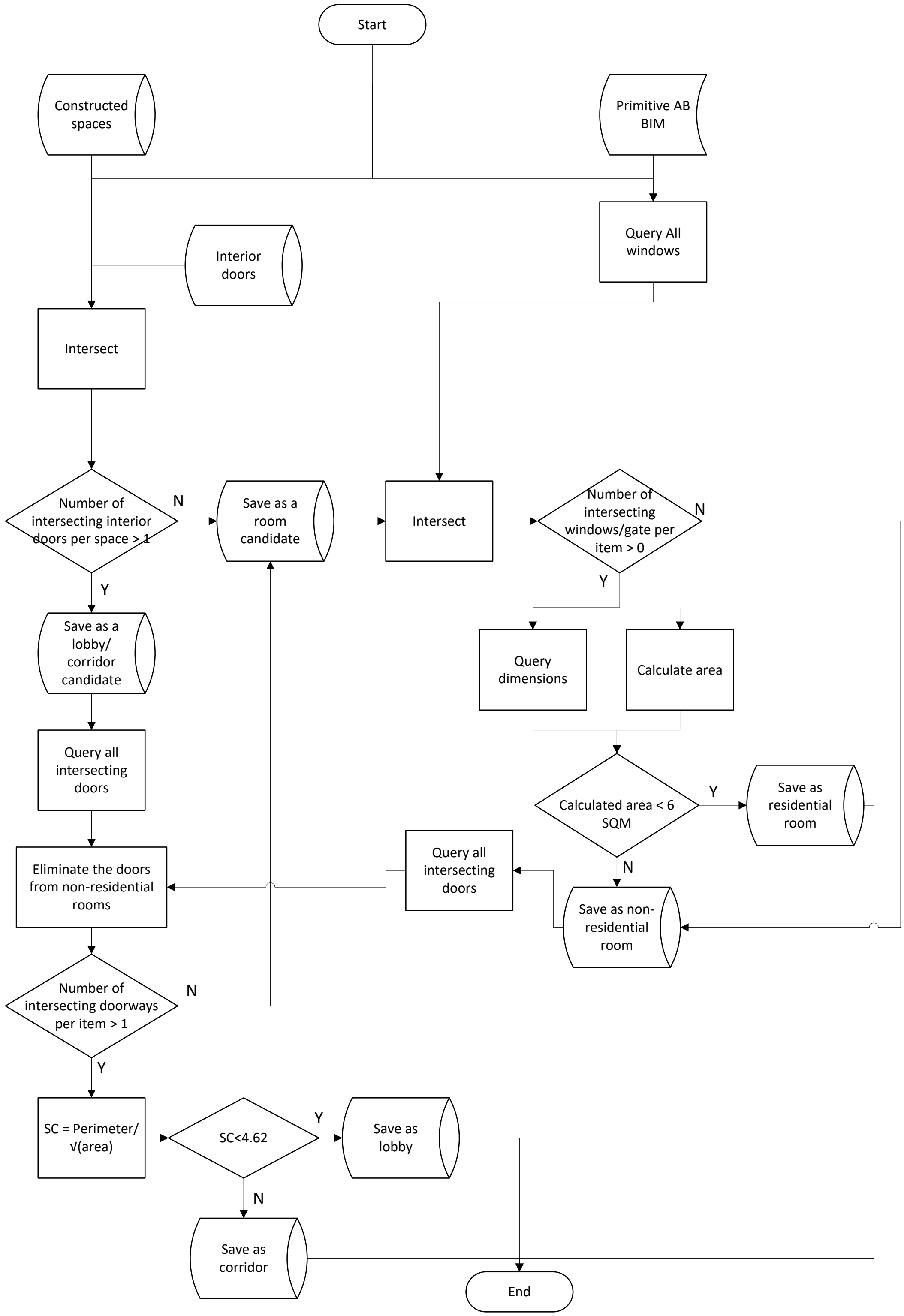


Figure 31: Flowchart: space classification using the interior access points, natural light and geometric attributes

6. Implementation

The designed process is implemented and tested on a sample model from 3DGS company. The model contains a common residential Dutch house with three floors produced in Autodesk Revit© in accordance with the Dutch Revit modelling standard, NLRS. The LoD of the model is 200 (***Figure 32***), so the model contains only the geometric representation of constructed building elements. The process has been implemented through Dynamo, which is a Python-based visual programming software. Dynamo has the advantage of calling different building elements from Revit model and manipulating different commands as an API on Revit.

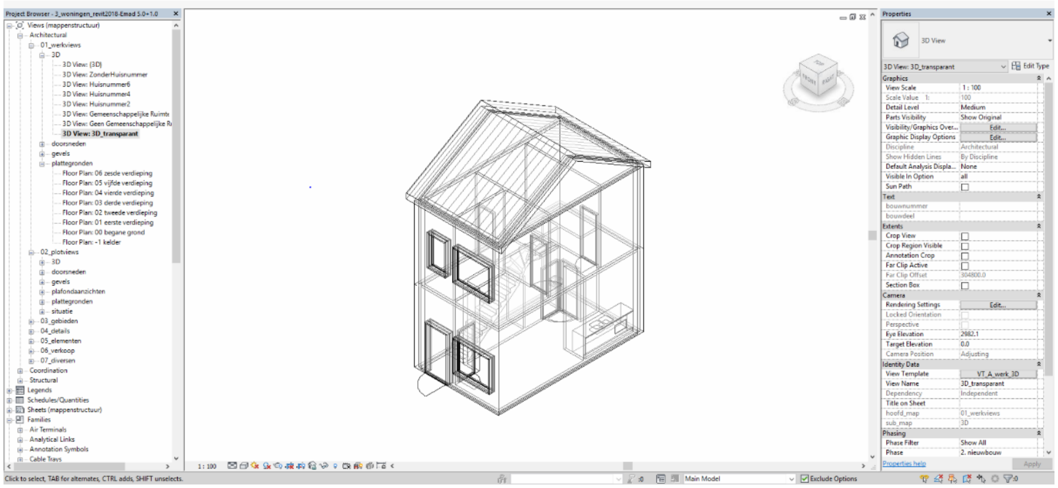


Figure 32: Case study, transparent 3D view in Revit

In the first step, the building floors and walls are called, sorted and grouped by the building floor (***Figure 33***). For the walls, their base constraint has been taken as a reference of their host building floor (***Figure 34***). Also, the walls have been categorized into masonry walls, curtain walls, and interior walls (***Figure 35***). This is important since in the common as-built modelling in the Netherlands, the exterior walls are usually modelled as two parallel walls: the basic walls (interior layer) and masonry walls (the exterior layer). Also, in Dutch as-built modelling protocol windows are commonly modelled as curtain walls since it can reduce the modelling time considerably.

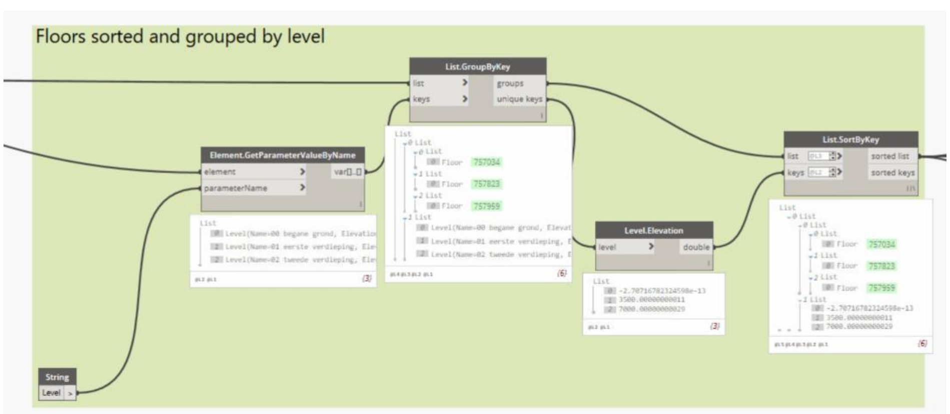


Figure 33: Floor elements sorted and grouped according to the elevation

Figure 34: (Basic) Wall elements sorted and grouped according to the elevation

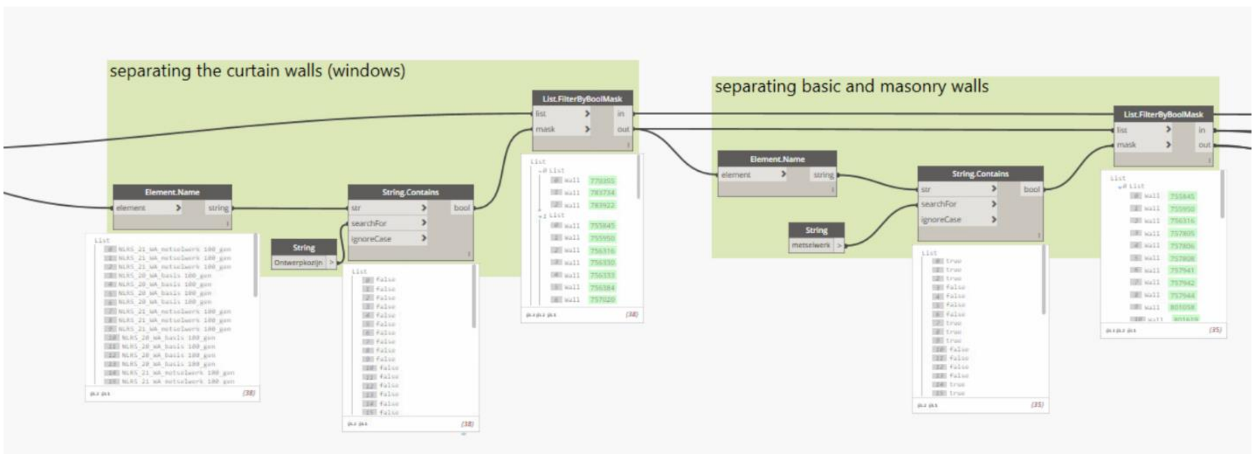


Figure 35: Distinguishing different wall types in the model

In the second step, the openings in walls and floors are filtered and the centerline of walls with the base constraint of each building floor is projected to the floor's planar. then, these centerlines have been intersected with each other and lines are decomposed into smaller parts. From these lines, the repetitive lines have been eliminated (***Figure 36***).

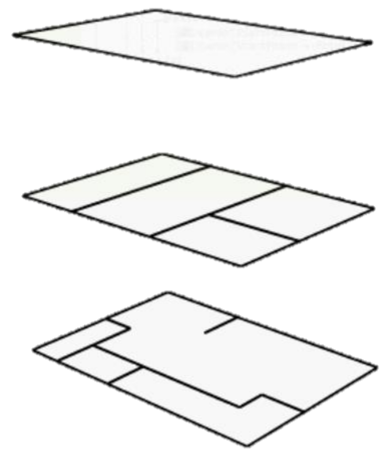


Figure 36: Refined wall centerlines projected on host floor planars

In order to recognize the space boundaries, a point to point connection table is formed and a 2D graph of point adjacency is made. The graph is mapped as a “dictionary” data set and used as an input to Johnston algorithm, which is developed as a custom node in Dynamo using python scripts (***Figure 37***). The python script is available in ***Appendix 9.6*** Final 2D footprints of spaces in the case study are shown in ***Figure 38***.

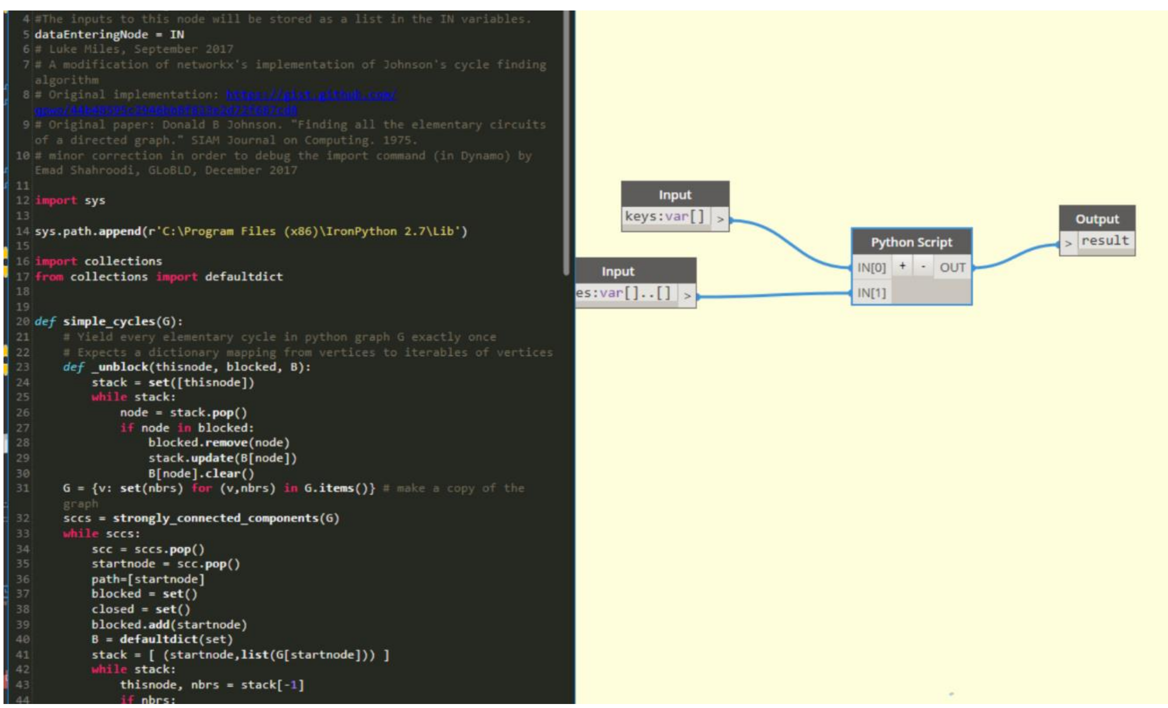


Figure 37: Dynamo custom node "SimpleCycles" producing dictionaries and executing Johnson’s algorithm

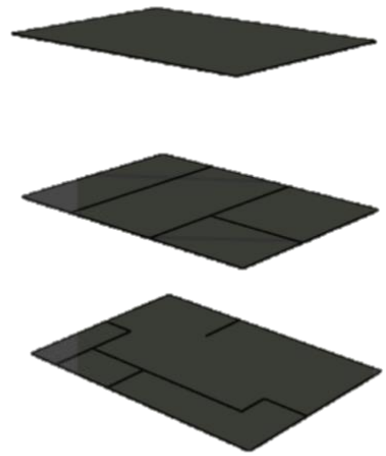
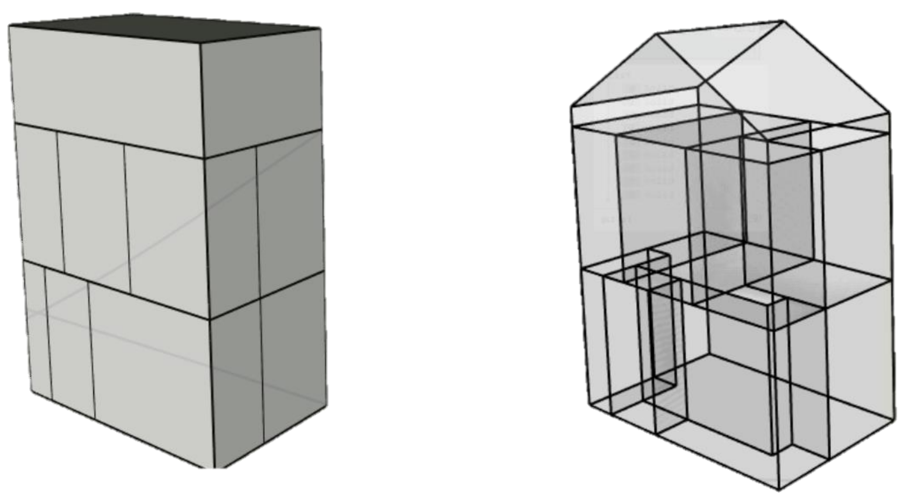
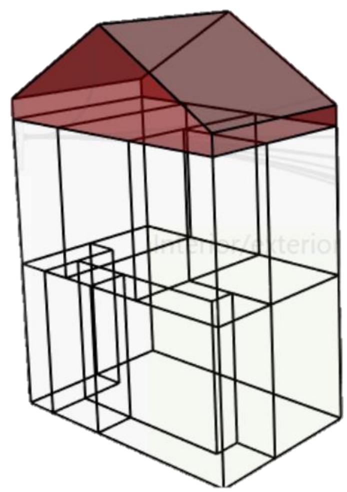


Figure 38: 2D footprints of spaces, outcome of grouping process

The extruded solids (***Figure 39 (a)***) which intersect a roof element are then trimmed by the top poly-surface of the roof(***Figure 39 (b)***). All these trimmed solids may also be marked as attic spaces (***Figure 39 (c)***).



(a) (b)



(c)

Figure 39: Extrusion and Trimming

After the space extraction part and generation of constructed spaces, the space recognition phase starts. By checking the number of access points of each space and their dimension, the rooms are classified into residential and non-residential rooms(see ***Figure 40***). In this case study, the stairway was the only instance of the virtual access points. These virtual access points (stair's start and end geometric representations) and spaces with access to other floors are illustrated consequently in ***Figure 41 (a) & (b)***

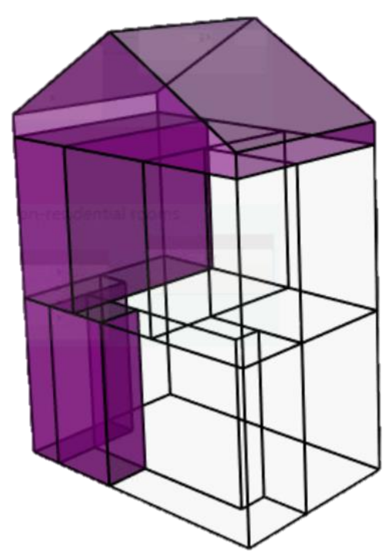
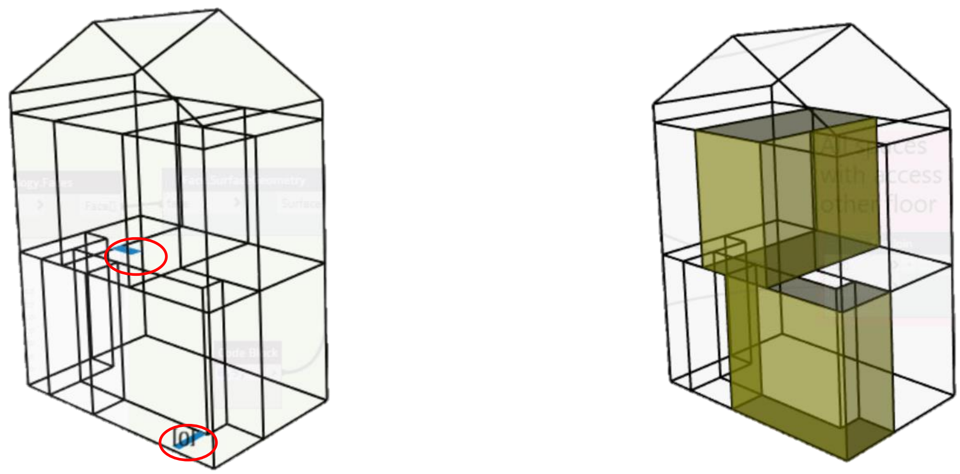


Figure 40: Non-residential rooms



(a) (b)

Figure 41: Spaces including a virtual access point

In the same time, the lobbies and corridor candidates are checked against the narrowness. Spaces with the coefficient bigger than 4.62 are taken as corridors (***Figure 42)***.

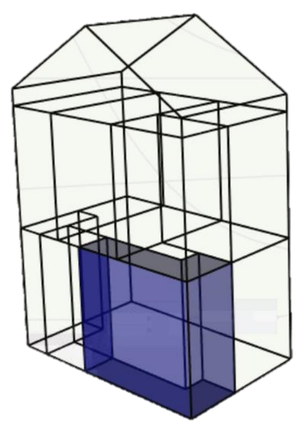
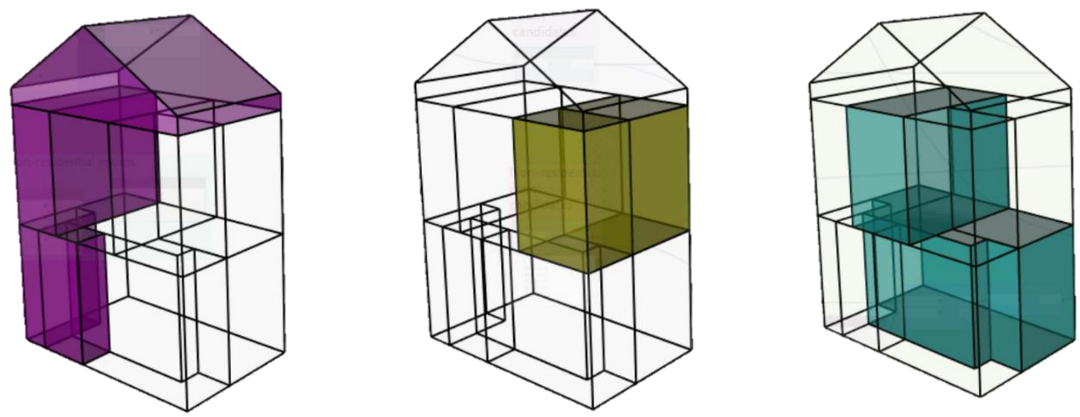
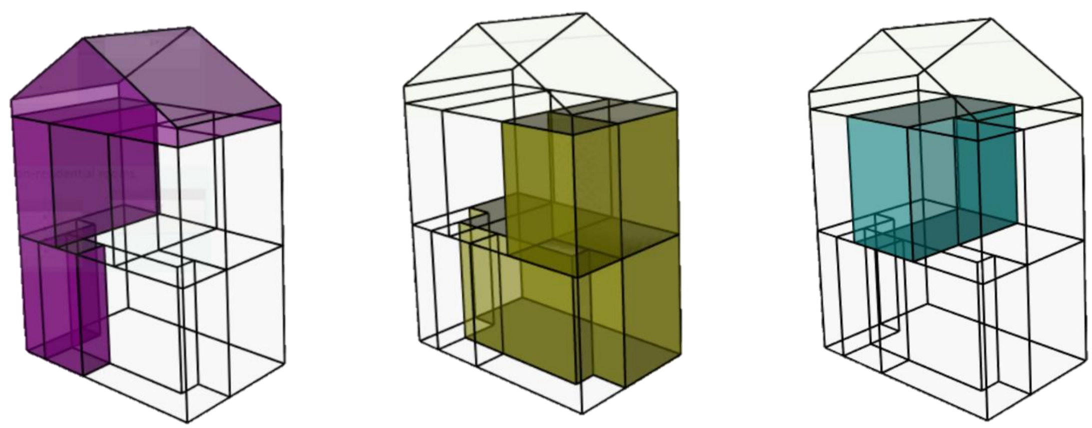


Figure 42: Corridors

As discussed, the room candidates may increase in number based on their accessibility to non-residential rooms. ***Figure 43*** illustrates the first residential/non-residential room candidates and lobbies ***(a)*** after the first classification by the access points and ***(b)*** after elimination of the mutual access points with non-residential rooms and iteration of room classification process.



(a)



(b)

Figure 43: Refining room/lobby candidates according to the accessibility with non-residential spaces

Finally, the recognized spaces are visualized in Dynamo (***Figure 44***). The residential rooms are shown in yellow, non-residential rooms in purple, corridors in blue and lobbies in cyan.

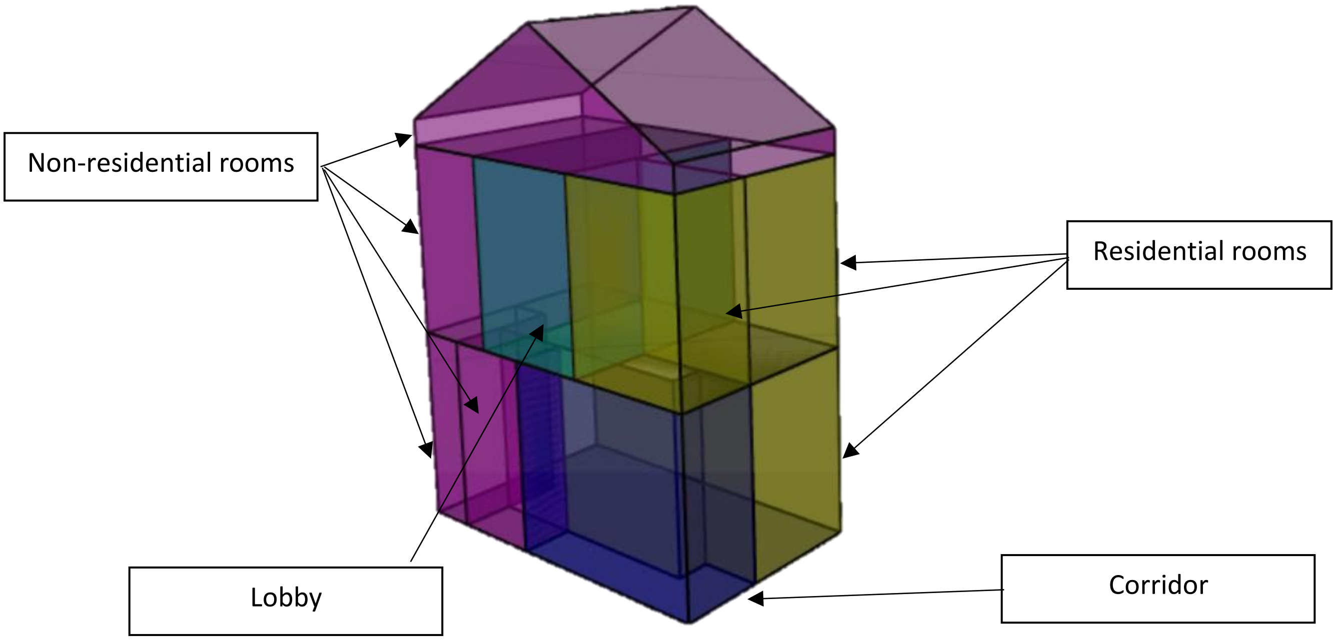


Figure 44: Visualized Space recognition

7. Conclusion

This research addressed the lack of automation in augmentation of as-built BIM for FM uses. This lack of automation specifically points the presence of non-physical entities in the as-built BIM models. The main objective of this research was to the gap between current primitive as-built models and the useable models for FM.

The objective of this research was broken down into three research questions/objectives. The first research question/objective was to find the non-physical entities to be used by FMTs, classifying them and finding the basic and general non-physical entities to initiate the automation process. The second research objective/ question was to find the relation of modelled building elements in the primitive as-built BIM models and the information regarding selected non-physical entities. Finally, the last research objective/question was to design a process of automatic augmentation of geometry-only as-built BIM models towards an augmented version which facilitates the usage of the model for FMTs.

In the first phase of this research, the information needs of FM are reviewed from previous research works. Although the required information for FM is very diverse and specific to project, they have general basics. The very first and important instance of non-physical and non-geometrical information to be used by FMTs is the spatial layout consisted of spaces and their intended use. Thus, the automation of space extraction and identification of their intended uses are picked as the scope of this research.

Then, a further review has taken place in order to investigate the space modelling in construction. The previous space modelling approaches have been reviewed and the current standards for defining a space in BIM models have been studied.

Finally, a set of semi-structured interviews with professionals in design and FM sector has brought an insight to the important sorts of data for FMTs. As the finding of this part, the needed features of the final product have been clarified. As result of this phase, the automatic generation of spaces (space extraction) and identifying their (intended) uses have been picked as the key outcome of the augmentation process.

In the second phase, the process of semantic expansion is designed. The process takes place in two main steps, i.e., space extraction and space use recognition. Both these main steps have been designed based on the geometric attributes of primitive building elements and their topologic relations with each other and with the outcomes of the first step, space extraction. The outcome of space use recognition, e.g. rooms, lobbies, attics, and corridors, have been defined based on the IndoorGML classification. While modelled furniture and fixed equipments in each space have been stated in both literature and by professionals to be helpful for a more accurate space use recognition, this type of rules is excluded from the process because of the low LoD of input models.

Finally, in the third phase, the rules produced in the second phase have been arranged in a process to augment primitive as-built BIM models with the space elopements and their intended uses. The designed process is implemented on a case study of sample as-built BIM model which has LoD of 200-250 from a common residential Dutch house. The model is created in Revit and the implementation has taken place through DynamoThe space categories and their attributes can be exported as an excel sheet or imported to Revit model.

In the end, this report has successfully provided an answer to all the aforementioned research questions. The following of this chapter is designated to a further discussion about the limitations and challenges in this research and as well as future works.

7.1. Limitations and Challenges

The limitations and challenges in this research can be classified into two main categories: limitations and challenges in the process, and limitations and challenges in the case study and tools.

7.1.1. Limitations and challenges in the process

7.1.1.1. In space extraction

In space extraction part, the main limitations are in recognizing experiential boundaries. The only experiential boundary mentioned by interviewees was the height of the space, while the shape inconsistencies (e.g., niches in the walls, changing the width of corridors, etc.) are not considered as experiential boundaries. While these may not be present in a majority of residential units, they are important in educational buildings, hospitals, airports, etc.

7.1.1.2. In space use recognition

because of the lack of fine categorization and classification in the literature and architectural sources, a generic space use network is used. In order to classify the spaces, a set of heuristic rules are developed which uses geometric attributes and topological relations of building objects and spaces. Although the specifications of each class (i.e. space type/intended use) are taken from common sense and building codes of the Netherlands, they may vary in different countries considering their regulations and culture. Further, according to the relatively low LoD of as-built BIM models, these rules do not take the equipment and mechanical/electrical/structural installation into account. Therefore, the space recognition cannot be considered as a guaranteed result and should still be supervised by a human. This matter may be solved by integrating piping/electrical/structural plans and/or supervised machine learning processes after running the process for several cases supervised by an expert.

7.1.2. Limitations and challenges in case-study and tools

7.1.2.1. In case study-model

The case study has been picked from sample models of as-built BIM models produced by 3DGS company. These models provide a low level of detail which may only provide a geometric representation of main building objects and some fixed equipment of kitchen and sanitary. However, according to the probability of absence of these fixed fixtures, the heuristic rules have skipped them and only geometric attributes and topologic relationships of constructed spaces and basic building objects are used. The models contain some errors; while most of these errors are according to the absence of a real building (these errors were according to architectural details of a building e.g. the attic room in the model doesn't have any entrance and is an isolated room in the top floor.), the windows were mainly defined as curtain walls according to the simplicity of modelling in comparison to modelling of windows. While curtail walls are not essential building objects in residential houses, they might be present in other building types. To overcome this limitation in the cases which contain both curtain walls and windows, some heuristic rule should be defined to find the windows out of curtain wall objects.

Further, the model didn't contain some of the defined conditions such as height difference in building floors. This might not be a common case for residential units. Therefore, the module of recognizing experiential space boundaries has not be implemented in the implementation section while designed.

7.1.2.2. In tools

The tools used for implementation were Autodesk Revit, as the host environment and Dynamo, as the programming tool. While the use of Dynamo and Revit had a great added value according to their large user community and helpful forums which contribute minimizing the workload in implementation phase, it is important to consider that the implementation codes prepared by dynamo may be optimized to better performance in comparison to Python or C Application Programming Interfaces (APIs) in Revit or IFC logs.

7.2. Future Works

In order to fully implement the designed process for industrial use, these steps might be done in future works. First, the categorization of the spaces might be refined by a survey study of space definition through FM teams and architects. Second, in order to improve the quality of outcomes, an added module of sub-spacing may help to divide the constructed space to simpler sub-spaces. This will improve the process by enabling the machine to filter niches and other unwanted dimensions of each constructed space to increase the performance of the process. Finally, the process may be used under human supervision in machine learning in order to reduce the flaws in the outcome.

Further, the outcomes of this research may be a subject to future research works. In 8D BIM analysis, BIM and safety, the accessibility of constructed spaces can be defined and by building a graph of accessibility, the disaster relief in buildings can be simulated. Also, by querying the connectivity of spaces (i.e. having mutual or overlapped faces) the interior and exterior spaces can be found. This data can be used in energy analysis.

8. Bibliography

[1] B. Hardin, D. McCool, BIM and construction management : proven tools, methods, and workflows, Second edi, Wiley Publishing, Indianapolis, Indiana, 2009.

[2] N.D. Aziz, A.H. Nawawi, N.R.M. Ariff, Building Information Modelling (BIM) in Facilities Management: Opportunities to be Considered by Facility Managers, Procedia - Soc. Behav. Sci. 234 (2016) 353–362. doi:10.1016/j.sbspro.2016.10.252.

[3] V. Patraucean, I. Armeni, M. Nahangi, J. Yeung, I. Brilakis, C. Haas, State of research in automatic as-built modelling, Adv. Eng. Informatics. 29 (2015) 162–171. doi:10.1016/j.aei.2015.01.001.

[4] X. Xiong, D. Huber, XIONG, HUBER: AUTO-CREATION OF SEMANTIC 3D MODELS Using Context to Create Semantic 3D Models of Indoor Environments, in: 2010. doi:10.5244/C.24.45.

[5] T. Gerrish, K. Ruikar, M. Cook, M. Johnson, M. Phillip, C. Lowry, BIM application to building energy performance visualisation and managementChallenges and potential, Energy Build. 144 (2017) 218–228. doi:10.1016/j.enbuild.2017.03.032.

[6] E.M. Wetzel, W.Y. Thabet, The use of a BIM-based framework to support safe facility management processes, Autom. Constr. 60 (2015) 12–24. doi:10.1016/j.autcon.2015.09.004.

[7] H. Liu, M. Lu, M. Al-Hussein, Ontology-based semantic approach for construction-oriented quantity take-off from BIM models in the light-frame building industry, Adv. Eng. Informatics. 30 (2016) 190–207. doi:10.1016/j.aei.2016.03.001.

[8] A.H. Mohammed, Facility Management History and Evolution, Int. J. Facil. Manag. 5 (2014).

[9] What is FM - Definition of Facility Management, (n.d.). http://www.ifma.org/about/what-is-facility-management (accessed July 3, 2017).

[10] B. Atkin, A. Brooks, Total facility management, 4th ed., John Wiley & Sons, Inc., 2015.

[11] P.M. Teicholz, IFMA Foundation., BIM for facility managers, John Wiley & Sons, Inc., Hoboken, New Jersey, 2013.

[12] B. Becerik-Gerber, F. Jazizadeh, N. Li, G. Calis, Application Areas and Data Requirements for BIM-Enabled Facilities Management, J. Constr. Eng. Manag. 138 (2012) 431–442. doi:10.1061/(ASCE)CO.1943-7862.0000433.

[13] A.J. Guillen, A. Crespo, J. Gómez, V. González-Prida, K. Kobbacy, S. Shariff, Building Information Modeling as Assest Management Tool, IFAC-PapersOnLine. 49 (2016) 191–196. doi:10.1016/j.ifacol.2016.11.033.

[14] R. Williams, H. Shayesteh, L. Marjanovic-Halburd, Utilising Building Information Modelling for Facilities Management, Int. J. Facil. Manag. 5 (2014) 1–19. https://www.bartlett.ucl.ac.uk/graduate/programmes/postgraduate/mscdiploma-facility-environment-management/documents/Richard_Melhuish-Williams_82242_assignsubmission_file_BENVGBE4_-_BIM_Dissertation_-_Richard_Williams.pdf.

[15] N.D. Aziz, A.H. Nawawi, N.R.M. Ariff, ICT Evolution in Facilities Management (FM): Building Information Modelling (BIM) as the Latest Technology, Procedia - Soc. Behav. Sci. 234 (2016) 363–371. doi:10.1016/j.sbspro.2016.10.253.

[16] A. Kiviniemi, Value of BIM in FM/OM–why have we failed in attracting owners and operators?, presentation in “BIM and Facility Management” seminar, April 4th, in: Aalto Univ. Espoo, 2013. https://scholar.google.com/scholar?q=Value+of+BIM+in+FM/OM+—+why+have+we+failed+in+attracting+owners+and+operators? (accessed July 5, 2017).

[17] a Akcamete, B. Akinci, J.H. Garrett, Potential utilization of building information models for planning maintenance activities, Proc. Int. Conf. Comput. Civ. Build. Eng. (2010) 151–157.

[18] R. Santos, A.A. Costa, A. Grilo, Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015, Autom. Constr. 80 (2017) 118–136. doi:10.1016/j.autcon.2017.03.005.

[19] M. Construction, The business value of BIM in North America: multi-year trend analysis and user ratings (2007-2012), 2012.

[20] M. Construction, Value of BIM for Construction in Major Global Markets: How contractors around the world are driving innovations with Building Information Modelling, 2014.

[21] S. Azhar, Building Information Modeling (BIM): Trends, Benefits, Risks and Challengees for the AEC Industry, 11 (2011) 241–252.

[22] H. Penttila, M. Rajala, S. Freese, Building Information Modelling of Modern Historic Buildings, Predict. Futur. 25th eCAADe Konf. Frankfurt Am Main, Ger. (2007) 607–614. http://cumincad.architexturez.net/system/files/pdf/ecaade2007_124.content.pdf.

[23] G.A. van Nederveen, F.P. Tolman, Modelling multiple views on buildings, Autom. Constr. 1 (1992) 215–224. doi:10.1016/0926-5805(92)90014-B.

[24] B. Succar, Building information modelling framework: A research and delivery foundation for industry stakeholders, Autom. Constr. 18 (2009) 357–375. doi:10.1016/j.autcon.2008.10.003.

[25] R.S. Weygant, BIM content development : standards, strategies, and best practices, John Wiley & Sons, Inc., 2011.

[26] J. Carmona, K. Irwin, BIM: who, what, how and why - Facilities Management Software Feature, (2007). http://www.facilitiesnet.com/software/article/BIM-Who-What-How-and-Why--7546 (accessed June 25, 2017).

[27] M. Venugopal, C.M. Eastman, R. Sacks, J. Teizer, Semantics of model views for information exchanges using the industry foundation class schema, Adv. Eng. Informatics. 26 (2012) 411–428. doi:10.1016/j.aei.2012.01.005.

[28] C. Eastman, P. Teicholz, R. Sacks, K. Liston, BIM Handbook A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers, and Contractors, John Wiley & Sons, Inc., Hoboken, New Jersey, n.d.

[29] V. Thein, I.P. Manager, Industry Foundation Classes (IFC) BIM Interoperability Through a Vendor-Independent File Format A Bentley White Paper Industry Foundation Classes 2 Executive Overview, 2011. http://consultaec.com.au/consultaec/wp-content/uploads/2014/07/WP_IFC.pdf (accessed July 5, 2017).

[30] R. Volk, J. Stengel, F. Schultmann, Building Information Modeling (BIM) for existing buildings - Literature review and future needs, Autom. Constr. 38 (2014) 109–127. doi:10.1016/j.autcon.2013.10.023.

[31] E.A. Pärn, D.J. Edwards, M.C.P. Sing, The building information modelling trajectory in facilities management: A review, Autom. Constr. 75 (2017) 45–55. doi:10.1016/j.autcon.2016.12.003.

[32] Louise Sabol, Building Information Modeling & Facility Management, 2008. https://pdfs.semanticscholar.org/cb40/288c07f9351120447f872a2e815f5f1a8db5.pdf (accessed July 6, 2017).

[33] E. William East, Construction Operations Building Information Exchange (COBIE): Requirements Definition and Pilot Implementation Standard, Champaign, IL, 2007.

https://www.wbdg.org/files/pdfs/erdc_cerl_tr0730.pdf (accessed July 5, 2017).

[34] Q. He, G. Wang, L. Luo, Q. Shi, J. Xie, X. Meng, Mapping the managerial areas of Building Information Modeling (BIM) using scientometric analysis, Int. J. Proj. Manag. 35 (2017) 670–685. doi:10.1016/j.ijproman.2016.08.001.

[35] J.J. McArthur, A Building Information Management (BIM) Framework and Supporting Case Study for Existing Building Operations, Maintenance and Sustainability, Procedia Eng. 118 (2015) 1104–1111. doi:10.1016/j.proeng.2015.08.450.

[36] H.B. Cavka, S. Staub-French, E.A. Poirier, Developing owner information requirements for BIM-enabled project delivery and asset management, Autom. Constr. 83 (2017) 169–183. doi:10.1016/j.autcon.2017.08.006.

[37] L.Y. Liu, A.L. Stumpf, S.S. Kim, F.M. Zbinden, Capturing as-built project information for facility management, in: Comput. Civ. Eng., 1994: pp. 614–621. cedb.asce.org/CEDBsearch/record.jsp?dockey=0088544%0A (accessed March 12, 2018).

[38] M. Clayton, R. Johnson, Y.S. building materials and components, undefined 1999, Operations documents: Addressing the information needs of facility managers, in: Durab. Build. Mater. Components, 1999. http://www.irbnet.de/daten/iconda/CIB2205.pdf (accessed March 12, 2018).

[39] CRCC Innovation, Adopting BIM for facilities management: Solutions for managing the Sydney Opera House, Qld, 2007. https://eprints.qut.edu.au/27582/1/27582.pdf (accessed July 3, 2017).

[40] A. Ekholm, S. Fridqvist, A concept of space for building classification, product modelling, and design, Autom. Constr. 9 (2000) 315–328. doi:10.1016/S0926-5805(99)00013-8.

[41] M. Bunge, Sense and reference, Reidel, 1974. https://search.lib.virginia.edu/catalog/u484702 (accessed September 20, 2017).

[42] ISO 12006-2:2015(en), Building construction — Organization of information about construction works — Part 2: Framework for classification, 2015. https://www.iso.org/obp/ui/#iso:std:iso:12006:-2:ed-2:v1:en (accessed September 22, 2017).

[43] B.C. Björk, A conceptual model of spaces, space boundaries and enclosing structures, Autom. Constr. 1 (1992) 193–214. doi:10.1016/0926-5805(92)90013-A.

[44] M.L. Maher, S.J. Simoff, J. Mitchell, Formalising building requirements using an Activity/Space Model, Autom. Constr. 6 (1997) 77–95. doi:10.1016/S0926-5805(96)00171-9.

[45] M. Eastman, A. Siabiris, A generic building product model incorporating building type information, Autom. Constr. 3 (1995) 283–304.

[46] P. Smith, the 5D Project Cost Manager, Procedia -Social Behav. Sci. 119 (2014) 475–484. doi:10.1016/j.sbspro.2014.03.053.

[47] G. Suter, Structure and spatial consistency of network-based space layouts for building and product design, Comput. Des. 45 (2013) 1108–1127. doi:https://doi.org/10.1016/j.cad.2013.04.004.

[48] IfcSpace IFC2x3, (n.d.). http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/ifcproductextension/lexical/ifcspace.htm (accessed October 17, 2017).

[49] IfcSpace IFC4, (n.d.). http://www.buildingsmart-tech.org/ifc/IFC4/final/html/schema/ifcproductextension/lexical/ifcspace.htm (accessed October 17, 2017).

[50] About Room-Bounding Elements | Revit LT | Autodesk Knowledge Network, (n.d.).

https://knowledge.autodesk.com/support/revit-lt/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/RevitLT-Model/files/GUID-241430FC-8084-43A1-AA3A-681B2883B0FC-htm.html (accessed November 9, 2017).

[51] Room Boundaries | Revit LT | Autodesk Knowledge Network, (n.d.). https://knowledge.autodesk.com/support/revit-lt/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/RevitLT-Model/files/GUID-C7338362-6D35-471B-90B0-6A893534FFE2-htm.html (accessed November 9, 2017).

[52] Selecting a Room | Revit LT | Autodesk Knowledge Network, (n.d.). https://knowledge.autodesk.com/support/revit-lt/learn-explore/caas/CloudHelp/cloudhelp/2014/ENU/Revit-LT/files/GUID-40DDBA89-885E-4BAF-93AC-1E5756A2BCE4-htm.html (accessed November 7, 2017).

[53] Rooms Spanning Floors or Levels | Revit LT | Autodesk Knowledge Network, (n.d.). https://knowledge.autodesk.com/support/revit-lt/learn-explore/caas/CloudHelp/cloudhelp/2014/ENU/Revit-LT/files/GUID-50C282D8-2856-4B5C-88E8-5A2A92774F0B-htm.html (accessed November 7, 2017).

[54] About Rooms | Revit LT | Autodesk Knowledge Network, (n.d.). https://knowledge.autodesk.com/support/revit-lt/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/RevitLT-Model/files/GUID-DD74A51D-A0B0-4461-A4BA-0F9CCC191CDB-htm.html (accessed November 10, 2017).

[55] Room Instance Properties | Revit LT | Autodesk Knowledge Network, (n.d.). https://knowledge.autodesk.com/support/revit-lt/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/RevitLT-Model/files/GUID-21326970-0037-41C6-A996-980C24EE019F-htm.html (accessed November 10, 2017).

[56] Room Tags | Revit LT | Autodesk Knowledge Network, (n.d.). https://knowledge.autodesk.com/support/revit-lt/learn-explore/caas/CloudHelp/cloudhelp/2018/ENU/RevitLT-Model/files/GUID-6DB755B9-1830-4CCA-A358-511AC9D48FC6-htm.html (accessed November 10, 2017).

[57] I. Brilakis, M. Lourakis, R. Sacks, S. Savarese, S. Christodoulou, J. Teizer, A. Makhmalbaf, Toward automated generation of parametric BIMs based on hybrid video and laser scanning data, Adv. Eng. Informatics. 24 (2010) 456–465. doi:10.1016/j.aei.2010.06.006.

[58] J. Jung, S. Hong, S. Jeong, S. Kim, H. Cho, S. Hong, J. Heo, Productive modeling for development of as-built BIM of existing indoor structures, Autom. Constr. 42 (2014) 68–77. doi:10.1016/j.autcon.2014.02.021.

[59] N. Hichri, C. Stefani, L. De Luca, P. Veron, G. Hamon, FROM POINT CLOUD TO BIM: A SURVEY OF EXISTING APPROACHES, in: ISPRS - Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci., Copernicus GmbH, 2013: pp. 343–348. doi:10.5194/isprsarchives-XL-5-W2-343-2013.

[60] P. Tang, D. Huber, B. Akinci, R. Lipman, A. Lytle, Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques, Autom. Constr. 19 (2010) 829–843. doi:10.1016/j.autcon.2010.06.007.

[61] C. Eastman, P. Teicholz, R. Sacks, K. Liston, A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors: BIM Handbook, Wiley, 2011.

[62] R. Codinhoto, A. Kiviniemi, S. Kemmer, BIM-FM Implementation: An Exploratory Invesigation, in: Int. J. 3-D Inf. Model., 2013: pp. 1–15. doi:10.4018/ij3dim.2013040101.

[63] M. Yousefzadeh, E. Technology, AS-BUILT MODELING FOR ENERGY SIMULATION, Enschede, 2016.

[64] G. Gao, Y.S. Liu, P. Lin, M. Wang, M. Gu, J.H. Yong, BIMTag: Concept-based automatic semantic annotation of online BIM product resources, Adv. Eng. Informatics. 31 (2017) 48–61. doi:10.1016/j.aei.2015.10.003.

[65] E.P. Karan, J. Irizarry, Extending BIM interoperability to preconstruction operations using geospatial analyses and semantic web services, Autom. Constr. 53 (2015) 1–12. doi:10.1016/j.autcon.2015.02.012.

[66] J. Lee, L. Ki-Joune, S. Zlatanova, T.H. Kolbe, C. Nagel, T. Becker, OGC IndoorGML. Draft specification OGC, Open Geospatial Consort. Inc. v.0.8.2 (2014). doi:http://www.opengeospatial.org/.

[67] Q. Xiong, Q. Zhu, Z. Du, S. Zlatanova, Y. Zhang, Y. Zhou, Y. Li, Free multi-floor indoor space extraction from complex 3D building models, Earth Sci. Informatics. 10 (2017) 69–83. doi:10.1007/s12145-016-0279-x.

[68] A. Abou Diakité, S. Zlatanova, Valid Space Description in BIM for 3D Indoor Navigation, Int. J. 3-D Inf. Model. 5 (2016) 1–17. doi:10.4018/IJ3DIM.2016070101.

[69] H. Jung, J. Lee, Indoor subspacing to implement IndoorGML for indoor navigation, Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci. - ISPRS Arch. 40 (2015) 25–27. doi:10.5194/isprsarchives-XL-2-W4-25-2015.

[70] A.K. Turner, What's the differente among 2-D, 2.5D, 3-D and 4-D?, Appl. Geosci. Forum. (1997). www.geoplace.com/gw.

[71] D.B. Johnson, Finding All the Elementary Circuits of a Directed Graph, SIAM J. Comput. 4 (1975) 77–84. doi:10.1137/0204007.

[72] R. Tarjan, Depth-First Search and Linear Graph Algorithms, SIAM J. Comput. 1 (1972) 146–160. doi:10.1137/0201010.

9. Appendices:

9.1. Designed Questionnaire:

0. Introduction of the research/researcher
1. General information about the interviewee/the project
    a. Name
    b. Position of the interviewee: Facility Manager/Owner
    c. Field of Expertise: Architecture, Data Science, Management, MEP Technical etc.
    d. General project specifications:
        i. Type: Residential, Educational, Hospital, etc.
        ii. Area in total
        iii. Value of the project (LCCA)
        iv. Value of the FM contract (if applicable)
        v. Maintenance and operation fields to be listed by task
        vi. Value of the maintenance contract (if applicable)
2. Information on the employed FM database:
    a. Do you use an information management system such as CAFM, CMMS etc.?
    b. What data formats do you use? .csv, .pdf, .dwg, .rvt, etc.?
    c. In the case of using BIM models, do you use the as-designed BIM models or as-built BIM models? How often do you update the models of your facility?
    d. What standards and codes for implementation of the model do you use: Internal (organizational/institutional)or external (international/national/provincial/municipal/etc.)?
    e. Querying procedure; how do you extract the supportive data for your decision making/planning and price estimation/execution/etc. (any other case?)?
3. Maintenance and operation of facilities:
    a. What are the disciplines involved in the maintenance and operation of your organization?
    b. How are these disciplines exchanging data among each other? Are they using, updating their data on the same model?
4. Spatial elements in use for maintenance
    a. What spatial data do you use for maintenance planning (what spaces/sub-spaces)? Do you take only the location of equipment or the geometrical specifications (or any other attribute) of spaces into account for maintenance planning?
    b. Do you use same spatial elements for different disciplines? Mechanical, Electrical, Plumbing repair, Fire Safety, Disaster Relief, etc.
    c. In the case of upgrading a primitive as-built BIM model, How can we meet your spatial needs such as as-designed, as-built models you have currently in use or desire to implement in the future? Are you able to define the spatial layout requirements for the maintenance disciplines?
        i. What physical building elements you use to separate spaces? Walls, floors, etc.
        ii. What geometrical specifications do you use to classify spaces? Height for example.
    d. What do topological relations (e.g. adjacency, aggregation, etc.) you take into account for maintenance planning? (in which direction(s))
    e. Do you use the room/space types for classification of spaces? Can you enumerate those types?

f. Do you use the accommodated furniture and/or specific (fixed) equipment in the room for classification of spaces? Can you list those items?

5. Spatial elements in use for maintenance (Architect interviewee specifically)
    a. How do you sort spaces and sub-spaces in a hierarchy for facilitating the data extraction for FM and especially for M&O?
    b. What attributes of spaces into account for classification of spatial elements?
    c. Do you use same spatial elements for different disciplines? Mechanical, Electrical, Plumbing repair, Fire Safety, Disaster Relief, etc.
    d. Are you able to define the spatial layout requirements for the maintenance disciplines?
        i. What physical building elements you use to separate spaces? Walls, floors, etc.
        ii. What geometrical specifications do you use to classify spaces? Height for example.
    e. What do topological relations (e.g. adjacency, aggregation, etc.) you take into account for maintenance planning? (in which direction(s))
    f. Do you use the room/space types for classification of spaces? Can you enumerate those types?
    g. Do you use the accommodated furniture and/or specific (fixed) equipment in the room for classification of spaces? Can you list those items?

9.2. Interview #1:

0. Introduction of the research/researcher
1. General information about the interviewee/the project
    a. Name
    b. Position of the interviewee: Facility Manager/Owner
    c. Field of Expertise: Architecture, Data Science, Management, MEP Technical etc.
    d. General project specifications:
        i. Type: Residential, Educational, Hospital, etc.
        ii. Area in total
        iii. Value of the project (LCCA)
        iv. Value of the FM contract (if applicable)
        v. Maintenance and operation fields to be listed by task
        vi. Value of the maintenance contract (if applicable)

Answer:

General introduction by the interviewee:

a. ONLY ACCESSSIBLE TO AUTHORIZED REVEIWERS ACCORDING TO CONFIDENTIALITY
b. Senior Architect responsible for design and consultation tasks
c. Studied M.Arch
d. N/A

2. Spatial elements in use for maintenance (Architect interviewee specifically)
    h. How do you sort spaces and sub-spaces in a hierarchy for facilitating the data extraction for FM and especially for M&O?
    i. What attributes of spaces into account for classification of spatial elements?
    j. Do you use same spatial elements for different disciplines? Mechanical, Electrical, Plumbing repair, Fire Safety, Disaster Relief, etc.
    k. Are you able to define the spatial layout requirements for the maintenance disciplines?
        i. What physical building elements you use to separate spaces? Walls, floors, etc.
        ii. What geometrical specifications do you use to classify spaces? Height for example.
    l. What do topological relations (e.g. adjacency, aggregation, etc.) you take into account for maintenance planning? (in which direction(s))
    m. Do you use the room/space types for classification of spaces? Can you enumerate those types?
    n. Do you use the accommodated furniture and/or specific (fixed) equipment in the room for classification of spaces? Can you list those items?

Answer:

The architectural design takes place according to the 1. Demands from client and 2. National standards of Bouwbesliut. The type of rooms and their placement doesn't follow a predetermined formula and is thus deeply dependent to the client's desires.

a. Such a hierarchy is not predefined. This workflow asks the architect always to move from the outer and bigger spaces such as parcels to the smaller elements such as rooms. However, we need to follow the standard of the bouwbesliut standard to check whether the specific spaces are following the regulations or not. This is about the lighting, ventilation, etc. in order to receive the permit. However, this is not going through a structured procedure and is mainly dependent to the experience of the designer and will be later checked by a responsible office in the municipality.

However, in the design phase, the circulation and accessibility is the first thing which is taken into account for the daily use and disaster relief. After the decision on the circulation and general placings according to the environmental factors are made, the apartment or house indoor spaces are to be placed.

Some spaces, however, are obligatory to be designed for each apartment. Balcony, storage space of at least 6 SQM are of instances. Also, certain sorts of buildings have much more restrictions from a regulatory perspective. For example, hospitals should follow the specific tight requirement of the national regulations mentioned in bouwbesluit.

b. Several attributes are important to us; colors and painting, furniture, plants, paddings, etc. are taken into account. The position of a space is also important but these all are mainly done by the desire of the client and according to the experience of the designer and also the environment of the building like the placing of the streets etc.

c. We are mainly in charge for the only architectural part and for the rest we will receive some advices from professionals from other disciplines. In this case, either, we share the architectural plans and sketches with them and this (architectural plans) will be taken as the reference.

d. Lighting (both natural and artificial), padding, colors, and painting are other examples aside from the physical constructed elements and height. However, these elements might be translated differently to different individuals according to their culture, expertise etc.

e. As far as you take care of proper circulation and accessibility, the rest is not of the importance.

f. N/A

g. Furniture and fixed equipment can for sure be employed for recognition of the space type if present in the model and scene. This depends to the level of detail and level of development of the model and whether you view an as-designed or as-built model.

Other important points:

- The rental price is maybe the most important factor in the design according to the owner aside from the construction costs. Thus the floor plan and area is the reference for all the disciplines. After that, the energy costs are the most considered in the architectural design phase.
- 10-20-30 codes which are the national codes which are obligatory for design in order to be eligible for receiving building permit.
- The recommendation is to gather unit-specified information from tenants to classify the space in each housing units.
- The documentation in regard of client desires are thrown and not recorded for any housing project.

9.3. Interview #2:

0. Introduction of the research/researcher
1. General information about the interviewee/the project
    a. Name
    b. Position of the interviewee: Facility Manager/Owner
    c. Field of Expertise: Architecture, Data Science, Management, MEP Technical etc.
    d. General project specifications:
        i. Type: Residential, Educational, Hospital, etc.
        ii. Area in total
        iii. Value of the project (LCCA)
        iv. Value of the FM contract (if applicable)
        v. Maintenance and operation fields to be listed by task
        vi. Value of the maintenance contract (if applicable)

Answer:
General introduction by the interviewee:

a. ONLY ACCESSSIBLE TO AUTHORIZED REVEIWERS ACCORDING TO CONFIDENTIALITY
b. The manager responsible for Real Estate and Facility Management of a university, both the renting and maintenance and operation tasks. Also a board member for the BIM employment in a national scope in the Netherlands.
   At the moment in a horizontal connection with the project management department which will later be a vertical relation (the project management will be a branch of REM and FM) as a result a soon coming re-organizing.
c. Studied mechanical engineering.
d. 44 buildings for educational and residential purposes.
   250,000 SQMin total of which 180,000 SQM is being rented.
   The estimated value of 630,000,000 Euros for all buildings by insurance.
   300,000,000 Euros the annual turnover of the university 12 percent of which is spent on housing.
   4,400,000 Euros annually to be received from Dutch government
   The total expense of 7,700,000 Euros spent on overall executive maintenance for building-related part.

2. Information on the employed FM database:
    a. Do you use an information management system such as CAFM, CMMS etc.?
    b. What data formats do you use? .csv, .pdf, .dwg, .rvt, etc.?
    c. In the case of using BIM models, do you use the as-designed BIM models or as-built BIM models? How often do you update the models of your facility?
    d. What standards and codes for implementation of the model do you use: Internal (organizational/institutional)or external (international/national/provincial/municipal/etc.)?
    e. Querying procedure; how do you extract the supportive data for your decision making/planning and price estimation/execution/etc. (any other case?)?

Answer:

a. Planon is used for maintenance data management*. Planon contains several modules integrated and prepared upon request such as the space management platform. Planon is also able to integrate with BIM by built-in Revit and IFC adaptors.
   Prognatis**? (Couldn't find any further information on this on www.) as the main data repository. Prognatis provides the over-yearly schedule for maintenance based on the inspection held by the maintenance and operation employees on site.
b. Mainly PDF and CSV as the written data sheets, in combination with 2D drawings in PDF and DWG are used in the Prognatis which is the main data repository for our uses. RVT models are used for the new buildings. We aim to hire IFC later to integrate the data repositories on Planon and Prognatis.
c. As-designed BIMs are used for the new buildings but the existence of updated as-built models are questionable. No BIM for old buildings is existent.
d. A list of international, national and specific intra-consortium/organizational standards are prepared for the interview ***.
e. Several drawings need to be made providing an as-is situation of the facilities such as MEP facilities (in XRF) and these should be overlaid with the spatial layout for executive planning (in PDF and/or DWG). The querying procedure is done by the project coordinator or the technician within the shared dataset and coordinated under human supervision. All are desired to be transported into Planon according to the strategy of the company. Currently, this procedure is taking place in 2D but with a strategy to do so in 3D according to the abilities of Planon using the 3D spatial data provided by a Revit model/IFC log.

3. Maintenance and operation of facilities:
   a. What are the disciplines involved in the maintenance and operation of your organization?
   b. How are these disciplines exchanging data among each other? Are they using, updating their data on the same model?

Answer:

a. 1.5 electrical engineer, 0.5 building construction expert, 0.5 energy performance monitoring and coordination, 2 mechanical engineering, 1 person for building maintenance.
b. By Prognatis, the clashes of works are detected and further discussion and coordination take place in the gatherings with other disciplines. However, the prioritization is not taking place in a fully automated manner; the outcome of the Prognatis is used as the premier data considering the criticality of the assets but the budget considerations and clash detection are to be considered by the experts.

4. Spatial elements in use for maintenance
   a. What spatial data do you use for maintenance planning (what spaces/sub-spaces)? Do you take only the location of equipment or the geometrical specifications (or any other attribute) of spaces into account for maintenance planning?
   b. Do you use same spatial elements for different disciplines? Mechanical, Electrical, Plumbing repair, Fire Safety, Disaster Relief, etc.
   c. In the case of upgrading a primitive as-built BIM model, How can we meet your spatial needs such as as-designed, as-built models you have currently in use or desire to implement in the future? Are you able to define the spatial layout requirements for the maintenance disciplines?

i. What physical building elements you use to separate spaces? Walls, floors, etc.
ii. What geometrical specifications do you use to classify spaces? Height for example.

d. What do topological relations (e.g. adjacency, aggregation, etc.) you take into account for maintenance planning? (in which direction(s))
e. Do you use the room/space types for classification of spaces? Can you enumerate those types?
f. Do you use the accommodated furniture and/or specific (fixed) equipment in the room for classification of spaces? Can you list those items?

Answer:

a&b. Mainly the architectural layout is used as a reference of the maintenance planning; specific sub-spaces are not used generally for the decision making.

c. As the REM is the main critical reference for the budgetary matter, the floor area is the most important information regarding each space. A classification in regard of intended use is to be involved in the analysis. So in this case, the height is not of such an importance.

c. The circulation and accessibility are the most important data interesting to us.
d. Yes, a 7 categories list is to be referenced in which the spaces are classified by their intended (designed) usage.
e. It cannot be assured that the furniture or fixed equipment are modelled so this may not be applicable.

*Planon is a resilience platform for Real Estate and Facility Management consisted of several modules which can be implemented in a so-called manner. Planon offers its services as an integration of data management modules, e-learning, change management and consultancy. Planon as an Integrated Workplace Management System (IWMS) can be considered as a successor of CAFM which is integrated with the human resource management, enterprise resource management, and building management system. has the ability to be integrated with BIM and GIS. The main data exchange system among the Planon and BIM is COBie.

**I couldn't find any information about Prognatis on www. Am I typing the name wrong? Do you have any brochure or white paper for me as a reference?

***Would you please send the excel sheet containing the list of reference standards for the high-pressure lab model? (A2 sheet in blue and white cells)

Conclusion:

The interviewee was the best familiar with the BIM concept and technical considerations in regard of BIM integration with REM, FM and M&O uses among all the interviewees. Further, a specific hierarchy of spaces based on their rental price (which was in a direct relation to the intended use (as-designed use) by a consortium of universities in the Netherlands which may shape the structure of spatial hierarchy for heuristic rules. The most important benchmark for space distinction is the constructed boundaries (walls, floors and ceilings, and openings) but their main interest is the floor according to its importance in real estate use and height as an instance of a commonly accepted physical boundary or activity based spaces are not of their interests. Finally, their models do not contain the loose and/or fixed equipment.

9.4. Interview #3:

0. Introduction of the research/researcher
1. General information about the interviewee/the project
    a. Name
    b. Position of the interviewee: Facility Manager/Owner
    c. Field of Expertise: Architecture, Data Science, Management, MEP Technical etc.
    d. General project specifications:
        i. Type: Residential, Educational, Hospital, etc.
        ii. Area in total
        iii. Value of the project (LCCA)
        iv. Value of the FM contract (if applicable)
        v. Maintenance and operation fields to be listed by task
        vi. Value of the maintenance contract (if applicable)

Answer:

General introduction by the interviewee:

The interviewed company is a company for maintenance and operation which offers its services to housing corporations. They have two main departments of major and minor interventions known as construction and maintenance part. The first is responsible for major and mass interventions in big projects with higher value than 100,000 Euros which is mainly renovations or interventions for residential or other type complexes. The (minor) maintenance department is responsible for the threshold less than 100,000 Euros, responsible for the maintenance assignment repairs by call (simple and complex) or general services of renovation of service areas such as sanitary facilities between the different tenants renting a house.

a. ONLY ACCESSSIBLE TO AUTHORIZED REVEIWERS ACCORDING TO CONFIDENTIALITY
b. Manager responsible for Minor Maintenance and Operation called by the owner within the threshold of less than 100,000 euros per project
c. Studied Construction Engineering, with a professional career as a former consultant in innovative solutions.
d. Several housing projects mainly located in the western Netherlands. However, since the assignments are given by the housing corporation, a right estimation may not be provided by the interviewee.

2. Information on the employed FM database:
    a. Do you use an information management system such as CAFM, CMMS etc.?
    b. What data formats do you use? .csv, .pdf, .dwg, .rvt, etc.?
    c. In the case of using BIM models, do you use the as-designed BIM models or as-built BIM models? How often do you update the models of your facility?
    d. What standards and codes for implementation of the model do you use: Internal (organizational/institutional)or external (international/national/provincial/municipal/etc.)?
    e. Querying procedure; how do you extract the supportive data for your decision making/planning and price estimation/execution/etc. (any other case?)?

Answer:

a. The data regarding each project's information is collected and stored for later use. The documentation is not structured and happens according to the project manager of department manager at the very moment of documenting a specific project. These documents and their information may later be called if the manager remembers about a similarity. A documentation and benchmarking platform is to be designed and implemented from Bouwinfosys later on in their project.
b. Mainly PDF and CSV as the written data sheets, It is considered to be a rare case if the client can provide information in formats such as DWG of floor plans and Revit is just not used at all. In each project, a technical expert gathers needed information by visual inspection and capturing them in pictures.
c. N/A
d. This matter is mainly dependent to the clients and general municipal regulations.
e. This is dependent to the complexity and size of project. Each project is supervised by a technical expert accompanied by a work organizer which is rather a team leader. In the case of simple jobs the project coordinator provides each sector or external sub-contractor with the needed data. If the complexity calls or the presence of the other parties in querying and decision making, the data without the monetary information is shared with the sub-contractors and different specializations under supervision of a non-technical (team) leader.

3. Maintenance and operation of facilities:
   a. What are the disciplines involved in the maintenance and operation of your organization?
   b. How are these disciplines exchanging data among each other? Are they using, updating their data on the same model?

Answer:

a. A document for an intervention project is to be provided by the interviewee*. List of specializations and contractors they use. The budgetary and monetary info will remain confidential.
b. A project owner/coordinator is responsible for managing all data and information exchange as discussed in 2.e.

4. Spatial elements in use for maintenance
   a. What spatial data do you use for maintenance planning (what spaces/sub-spaces)? Do you take only the location of equipments or the geometrical specifications (or any other attribute) of spaces into account for maintenance planning?
   b. Do you use same spatial elements for different disciplines? Mechanical, Electrical, Plumbing repair, Fire Safety, Disaster Relief, etc.
   c. In the case of upgrading a primitive as-built BIM model, How can we meet your spatial needs such as as-designed, as-built models you have currently in use or desire to implement in the future? Are you able to define the spatial layout requirements for the maintenance disciplines?
      i. What physical building elements you use to separate spaces? Walls, floors, etc.
      ii. What geometrical specifications do you use to classify spaces? Height for example.
   d. What topological relations (e.g. adjacency, aggregation, etc.) do you take into account for maintenance planning? (in which direction(s))

e. Do you use the room/space types for classification of spaces? Can you enumerate those types?
f. Do you use the accommodated furniture and/or specific (fixed) equipment in the room for classification of spaces? Can you list those items?

Answer:

a. The floor plans are taken as the reference so the architectural spatial layout is the basic information we base our decision on. Also in the case of defect such as a leakage, the placement of the defect and its surroundings and access routes.
b. At this moment the traditional model of referring all task on the architectural layout is picked; however, in special projects such as “a bathroom in a day” a very detailed model or at least information about any object and geometric specifications of the bathroom or sanitary spaces are needed. The subspaces according to specific activities are taken into account by the experience and knowledge of the technical expert.
c. The extra attributes such as insulation of the walls and floor and ceiling is important; no specific attributes of spaces are on the top of our list.
d. The adjacency in all directions is very important. Aggregation is also considered important to us. The access way to supply raw materials is also important.
e. The rooms are classified by the use and the name of space; a document in this regard would be sent by Mr. Boers later.
f. N/A

Conclusion:

Although the BIM models are not used for the minor maintenance and operations done by this department of the company, it will be certainly helpful for them to identify the specific spaces which is their work zone, its position in the building envelop and the accessibility and adjacency of its to the other spaces. Some documents containing an example of a minor maintenance project and the classification of spaces in the regarded company is sent to the interviewer. According to the information form interviewee, a general spaces of a project which are taken into consideration by the project planner are:

- Bedrooms
- Bathroom
- Living room
- Toilet
- Staircase
- Hallway
- Kitchen(area)
- Attic
- Closets/storage
- Installation-room
- Balcony/garden front/back

9.5. Interview #4:

0. Introduction of the research/researcher
1. General information about the interviewee/the project
    a. Name
    b. Position of the interviewee: Facility Manager/Owner
    c. Field of Expertise: Architecture, Data Science, Management, MEP Technical etc.
    d. General project specifications:
        i. Type: Residential, Educational, Hospital, etc.
        ii. Area in total
        iii. Value of the project (LCCA)
        iv. Value of the FM contract (if applicable)
        v. Maintenance and operation fields to be listed by task
        vi. Value of the maintenance contract (if applicable)

Answer:

General introduction by the interviewee:

The company is mainly responsible for maintenance and operation of the outdoor spaces of residential projects such as façade, also concentrating on prediction of degradation of façade elements. They are currently working on the sustainable solutions for materials used to improve the quality of the rented units. They also hold a patent for specific wooden window and door frames.

a. ONLY ACCESSSIBLE TO AUTHORIZED REVEIWERS ACCORDING TO CONFIDENTIALITY
b. Manager responsible for Maintenance and Operation, also renovation concentrated on material and doors and windows, also renovation of kitchen and sanitary facilities.
c. Interviewee had held the chair of his own maintenance company for more than 4 decades.
d. Residential houses, 600 in total with average area of 100,000 SQMs 25 percent of the rent fee is spent on the maintenance and operation, outdoor building elements, kitchen, bathroom, central heating and roofs sometime.

2. Information on the employed FM database:
    a. Do you use an information management system such as CAFM, CMMS etc.?
    b. What data formats do you use? .csv, .pdf, .dwg, .rvt, etc.?
    c. In the case of using BIM models, do you use the as-designed BIM models or as-built BIM models? How often do you update the models of your facility?
    d. What standards and codes for implementation of the model do you use: Internal (organizational/institutional)or external (international/national/provincial/municipal/etc.)?
    e. Querying procedure; how do you extract the supportive data for your decision making/planning and price estimation/execution/etc. (any other case?)?

Answer:

a. The data regarding each project's information is collected and stored for later use. A mobile software has been developed for this company which enables the company to store and use their needed information from pictures taken by their expert and/or tenants.
b. PDF as 2D drawings are the most used as those are sufficient. The software stores the data in spread sheets like excel. No 3D representation is used.
c. N/A

d. N/A-everything is tailored according to the client desires and company's conditions. The only important materials in this regard are the regulations such as bouwbesluit. However, these basic standards are expected to be considered by experts and no instruction is modified in this case.
e. The decision making procedure is of responsibilities of the expert who is responsible for the project. The supportive data is extracted from the floor plans and data sheets provided by the client.

3. Maintenance and operation of facilities:
   a. What are the disciplines involved in the maintenance and operation of your organization?
   b. How are these disciplines exchanging data among each other? Are they using, updating their data on the same model?

Answer:

a. A document for an intervention project is to be provided by interviewee*.
b. In simple projects the project coordinator takes care of the information exchange. More complex projects will result in a meetings with representatives of all disciplines to share information and overcome possible frustration among the stakeholders.

4. Spatial elements in use for maintenance
   a. What spatial data do you use for maintenance planning (what spaces/sub-spaces)? Do you take only the location of equipments or the geometrical specifications (or any other attribute) of spaces into account for maintenance planning?
   b. Do you use same spatial elements for different disciplines? Mechanical, Electrical, Plumbing repair, Fire Safety, Disaster Relief, etc.
   c. In the case of upgrading a primitive as-built BIM model, How can we meet your spatial needs such as as-designed, as-built models you have currently in use or desire to implement in the future? Are you able to define the spatial layout requirements for the maintenance disciplines?
      i. What physical building elements you use to separate spaces? Walls, floors, etc.
      ii. What geometrical specifications do you use to classify spaces? Height for example.
   d. What topological relations (e.g. adjacency, aggregation, etc.) do you take into account for maintenance planning? (in which direction(s))
   e. Do you use the room/space types for classification of spaces? Can you enumerate those types?
   f. Do you use the accommodated furniture and/or specific (fixed) equipment in the room for classification of spaces? Can you list those items?

Answer:

a. Among the indoor spaces, the kitchen, sanitary spaces, attics and any other space which may have difficulties in regard of workability and accessibility is important to be known to our profession. Subspaces according to the specific jobs done by the executive team is also crucial for cost estimation and planning. However, no guideline is prepared for this matter. This is also assigned to the expert who plans the job and estimates the cost.
b. Mainly the architectural (floor) plans are the reference.
c. Height is sometime an important variant if exceeds normal amounts.

d. The position of each space in the whole building envelop, its outer surface's exposure to sun and other spaces in the case of being located inside (having other living spaces around) is important; however, most of these information are quite iterative and complying with housing normative in the Netherlands.
e. The other spaces (the spaces which are not listed as interesting) are of same importance and not interesting to us.
f. N/A

Conclusion:

Although the company was not interested to employ BIM in their current projects according to its exceeded complexity and low accuracy. The interviewee have pointed to interesting attributes such as position within the building envelop and sun exposure.

9.6. Python Script

```
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
#The inputs to this node will be stored as a list in the IN variables.
dataEnteringNode = IN
# Luke Miles, September 2017
# A modification of networkx's implementation of Johnson's cycle finding algorithm
# Original implementation: https://gist.github.com/qpwo/44b48595c2946bb8f823e2d72f687cd8
# Original paper: Donald B Johnson. "Finding all the elementary circuits of a directed graph." SIAM Journal on Computing. 1975.
# minor correction in order to debug the import command (in Dynamo) by Emad Shahroodi, GLoBLD, December 2017

import sys

sys.path.append(r'C:\Program Files (x86)\IronPython 2.7\Lib')

import collections
from collections import defaultdict


def simple_cycles(G):
    # Yield every elementary cycle in python graph G exactly once
    # Expects a dictionary mapping from vertices to iterables of vertices
    def _unblock(thisnode, blocked, B):
        stack = set([thisnode])
        while stack:
            node = stack.pop()
            if node in blocked:
                blocked.remove(node)
                stack.update(B[node])
                B[node].clear()
    G = {v: set(nbrs) for (v,nbrs) in G.items()} # make a copy of the graph
    sccs = strongly_connected_components(G)
    while sccs:
        scc = sccs.pop()
        startnode = scc.pop()
        path=[startnode]
        blocked = set()
        closed = set()
        blocked.add(startnode)
        B = defaultdict(set)
        stack = [ (startnode,list(G[startnode])) ]
```

```
    while stack:
      thisnode, nbrs = stack[-1]
      if nbrs:
        nextnode = nbrs.pop()
        if nextnode == startnode:
          yield path[:]
          closed.update(path)
        elif nextnode not in blocked:
          path.append(nextnode)
          stack.append( (nextnode,list(G[nextnode])) )
          closed.discard(nextnode)
          blocked.add(nextnode)
          continue
      if not nbrs:
        if thisnode in closed:
          _unblock(thisnode,blocked,B)
        else:
          for nbr in G[thisnode]:
            if thisnode not in B[nbr]:
              B[nbr].add(thisnode)
        stack.pop()
        path.pop()
    remove_node(G, startnode)
    H = subgraph(G, set(scc))
    sccs.extend(strongly_connected_components(H))

def strongly_connected_components(graph):
  # Tarjan's algorithm for finding SCC's
  # Robert Tarjan. "Depth-first search and linear graph algorithms." SIAM journal on computing. 1972.
  # Code by Dries Verdegem, November 2012
  # Downloaded from http://www.logarithmic.net/pfh/blog/01208083168

  index_counter = [0]
  stack = []
  lowlink = {}
  index = {}
  result = []

  def _strong_connect(node):
    index[node] = index_counter[0]
    lowlink[node] = index_counter[0]
    index_counter[0] += 1
    stack.append(node)
```

```
        successors = graph[node]
        for successor in successors:
            if successor not in index:
                _strong_connect(successor)
                lowlink[node] = min(lowlink[node],lowlink[successor])
            elif successor in stack:
                lowlink[node] = min(lowlink[node],index[successor])

        if lowlink[node] == index[node]:
            connected_component = []

            while True:
                successor = stack.pop()
                connected_component.append(successor)
                if successor == node: break
            result.append(connected_component[:])

    for node in graph:
        if node not in index:
            _strong_connect(node)

    return result

def remove_node(G, target):
    # Completely remove a node from the graph
    # Expects values of G to be sets
    del G[target]
    for nbrs in G.values():
        nbrs.discard(target)

def subgraph(G, vertices):
    # Get the subgraph of G induced by set vertices
    # Expects values of G to be sets
    return {v: G[v] & vertices for v in vertices}

    # Production of input dictionaries

def tolist(item):
            if hasattr(item,"__iter__"): return item


keys = tolist(IN[0])
elements = tolist(IN[1])
```

```
graph = dict(zip(keys,elements) )


#Assign your output to the OUT variable.
OUT = (tuple(simple_cycles(graph)))
```