UNIVERSITY OF TWENTE.

BIM WITHOUT A 3D IN EARLY DESIGN STAGES

Master's Thesis | Emmanouil Patsoumadakis
Department of Construction Management and Engineering
University of Twente and ABT

<This page is intentionally left blank>

COLOPHON

Personal Details

Name	Emmanouil Patsoumadakis
Student number	s2406608
E-mail	mpatsoum@gmail.com

University Information

Educational Institution	University of Twente
Faculty	Engineering Technology (ET)
Address	Drienerlolaan 5, 7522 NB Enschede, The Netherlands
Master	Construction Management and Engineering (CME)

Graduation Thesis

Title of research	BIM Without A 3D In Early Design Stages
1st University supervisor	dr. J.T. Voordijk (Hans)
2nd University supervisor	dr.ir. F. Vahdatikhaki (Faridaddin)
3rd University supervisor	dr. X. Yin (Xianfei)
Document	Report
Date	16 Dec 2021

Graduation organization

Organization name	ABT BV
Address	Arnhemsestraatweg 358, Velp, Gelderland, The Netherlands
1st Company supervisor	ir. S. Droste (Stefan), Senior Advisor, Constructions
2nd Company supervisor	ir. W. Heuver (Widy), Architect Engineer, BIM

UNIVERSITY OF TWENTE.

abt adviseurs in bouwtechniek

ACKNOWLEDGMENTS

First of all I would like to thank my academic supervisors dr.ir. Faridaddin Vahdatikhaki, dr. Hans Voordijk and dr. Xianfei Yin for their support, valuable insights and guidance throughout my master's thesis development.

I would also like to thank my supervisors from ABT bv Stefan Droste and Widy Heuver for giving me the opportunity to pursue this research and of course for their advice and help. Particularly, Widy's continued guidance and insightful meetings provided me with the tools that I needed to successfully complete my dissertation, from which I gained valuable experience and knowledge.

I want to thank Michiel Van Der Elst and Martin Bijsterbosch for their contribution to development phase of the thesis, and all ABT colleagues who assisted me in this research.

Finally, I would like to express my gratitude to my family and friends for their unconditional support, understanding and encouragement throughout my studies.

TABLE OF CONTENTS

EXCECUTIVE SUMMARY

Collection, management and use of information is considered one of the most important aspects within the built environment management. While projects in the construction industry are becoming more challenging and complex with many disciplines involved in, efficient exchange and use of information among domain professionals is fundamental for successful results. This requirement is even more evident during preliminary phases, which are decisive for the outcomes of subsequent phases of the lifecycle. The introduction of Building Information Modelling (BIM) has been one of the most significant efforts concerning data management within the built environment. BIM, which advocates the consistent and continuous use and re-use of data in digital format throughout the entire lifecycle of a built facility, has improved information flows between stakeholders thus resulting better communication and collaboration.

Nevertheless, it can be observed that despite its advantages, BIM practices are not really used in early design phases. The main reason is that current structures do not address early design phase information requirements while at the same time a common language to exchange information is absent. Shared 3D objects and models are the foundation of BIM implementation strategies, whereas not all disciplines of early phases are working in an object-based way. Additionally, in early design there are no 3D models that are needed to share and reuse data. Consequently, professionals are unable to work in a shared way using centralized data. Hence, they collect and manipulate information in isolated platforms. This practice hinders the seamless flow of information between project members and various design stages and leads to information loss.

Given that context, this research intends to develop a framework and a workflow for structuring information in the early stages of a project, in such a way that project members can efficiently and consistently work with centralized data and later integrate them seamlessly into the final design phase. The engineering company ABT bv provides the context of this study. The scope covers the Early Design stages and part of the initiation of the Final Design. Moreover, in order to include a considerable part of building data six disciplines of ABT are taken into consideration namely, cost estimation, building physics, sustainability assessment, fire safety, architectural and structural engineering departments.

In order to address the main research objective, the conceptual part of the research proposes an ontology that enables information integration among different disciplines during the early design stages and later on facilitates the information flow towards the final design. The proposed ontology results from the enrichment of the current IFC schema with additional concepts that particularly address the needs of preliminary phases. Furthermore, a novel workflow around this ontology is established. During the development phase, the findings of the previous step are implemented in a case study project. For that reason a working prototype tool is developed, which is a demonstration of how the ontology can be used in practice.

The evaluation outcomes indicate that the proposed ontology has the potential to contribute towards an efficient and consistent use of centralized data during the early design stages. At the same time, it can enable a smooth incorporation of information in later design stages. Overall, this study concludes that BIM without a 3D and a new way of working based on centralized information in preliminary phases of the lifecycle can be accomplished.

LIST OF ABBREVIATIONS

Abbreviation	Full Name
AEC	Architecture Engineering Construction
API	Application Programming Interface
BIM	Building Information Modelling
BIMDO	BIM Design Ontology
BIMSO	BIM Shared Ontology
BHOM	Buildings and Habitats Object Model
BOT	Building Topology Ontology
CDE	Common Data Environment
DO	Definitief Ontwerp *(Final design)*
FM	Facility Management
ICT	Information and Communication Technology
IFC	Industry Foundation Classes
JSON	JavaScript Object Notation
LOD	Level of Detail
OWL	Web Ontology Language
POC	Proof Of Concept
QTO	Quantity Take Off
RDF	Resource Description Framework
SO	Structuurontwerp *(Masterplan design)*
SPARQL	SPARQL Protocol and RDF Query Language
SQL	Structured Query Language
SWRL	Semantic Web Rule Language
VO	Voorontwerp *(Preliminary design)*
XML	Extensible Markup Language

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1 RESEARCH CONTEXT

Building design is a multidisciplinary process, involving collective efforts from architects, structural, mechanical, electrical engineers and many other specialists. Designers usually employ various design tools to complete their own design tasks in connection with different characteristics of these fields (Deng, et al., 2019). This inevitably requires cooperation among different disciplines for which the central issue is the use and exchange of data. It is no doubt that construction industry relies heavily on the use of information exchange between different professional disciplines for design, analysis, construction, operations and maintenance activities (Amoah & Nguyen, 2019).

Moreover, projects in the construction industry are becoming progressively large and complex, with new construction technologies and methods developing rapidly. Furthermore, owners of construction projects are making increasingly diverse sets of demands while all related laws and regulations undergo rapid change. As a result of such advancements in construction technology and the growing complexity of the construction industry, efficient management of the diverse information generated from construction projects is becoming increasingly necessary (Lee, et al., 2017). Building information is generated and managed throughout the lifecycle of a building, from the conceptual design stage up to construction and maintenance (Choi, et al., 2020).

Nevertheless, it can be acknowledged that preliminary design is a critical phase of a project's lifecycle, since at that point fundamental decisions are taken which affect the latter stages of the process. Improved insight into the early phase allows better understanding of value generation, stronger industrial involvement in the early phase, improved decisions, and thus better project execution. This implies that the early phase of a project development is the most important time for innovative activities and for planning an execution that will optimize project value generation. (Kolltveit & Grønhaug, 2004). Preliminary phases (programming and pre-design) may determine up to 80% of building operational costs, as well as of environmental impacts (Bogenstätter, 2000). Well-informed decisions based on proper information are essential in order to achieve project's objectives and avoid consequences such as re-designs or budget and time overruns. Therefore, there is an emergent need for versatile and flexible information management already from the very early design stages of a project.

Construction is currently undergoing a fundamental change thanks to the emergent development of Building Information Modelling (BIM), which in conjunction with team-effort collaborative design perhaps represents one of the most useful approaches in achieving cost-effectiveness as well as high-quality design results (Deng, et al., 2019). BIM is a method that fosters closer cooperation between all the various technical teams involved in different stages of a construction project's life-cycle where at the same time integrates the information inputs from all teams involved in a project (Grilo & Jardim-Gonçalves, 2010). Thus, it is rapidly transforming complex building processes -speeding project completion, resolving design conflicts, lowering costs and improving overall quality at the same time (Borrmann, et al., 2015).

1.2 PROBLEM STATEMENT

However, in spite of the advantages of BIM in the construction sector, it can be acknowledged that there is limited implementation of BIM during the early project phases. A considerable obstacle is that during these stages there are not sufficient implementation strategies that enable engineers to work based on centralized information. As such, for the execution of their tasks, project members collect data from several scattered sources like sketches, drawings in various formats like pdf, or spreadsheets. Moreover, they use their own, fragmented platforms for managing and using information. Accordingly, the outputs of their work are shared in multiple heterogeneous file formats.

Therefore, the acquired information is not organized and data flow is becoming sub-optimal, which means that the working team is not able to capture and exploit it in a desired level. In this desired level, it is expected that all generated data during these stages are stored and reused by specialists for different tasks where at the same time information loss is minimized. In addition, professionals that are engaged in this process claim that during preliminary stages there are individual interpretations of a design by different disciplines, due to the unstructured nature of data that often result in false assumptions and inconsistent outcomes. Moreover, the seamless flow of data into later design phases is hindered. Thus, the development of the BIM model starts without any information already available from preceding phases. As a result, there is a considerable period until the model reaches the information level that can be used as the communication platform for the project.

The diagram of Figure 1, gives an indication regarding the information level progression of different sources throughout a project's lifecycle. It has to be mentioned though, that the modelling (red line) does not necessarily start with the initiation of the Final Design (DO). It may start later or even on earlier phases like the Preliminary Design (VO) phase.

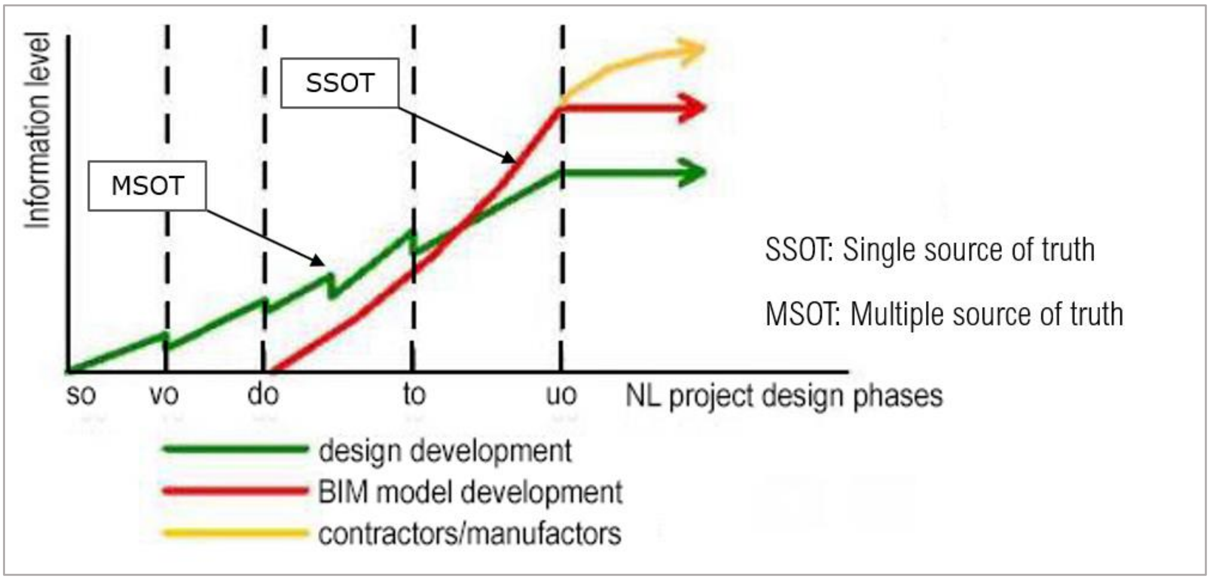

Figure 1: Current situation of information level in subsequent design stages.

Henceforth, in order to overcome the above-mentioned barriers and leverage the main benefit of a BIM process, which is the use of building information across the lifecycle, there is an emergent requirement for streamlining, combining, accessing and sharing building information from different disciplines, even before the development of a 3D model. Given that, it is indispensable to help engineers express information in such a way that it can be integrated with information of other members of a project team. Furthermore, it is essential to provide them with a common ''language'' that will also allow them to have a common understanding and interpretation of the acquired information and enable them to reuse it.

For this purpose, Semantic Web technologies are designed to solve the information integration problem by creating a web of structured and connected data that can be processed by machines, thus allowing the combination of information from different sources and its use by different specialists (Niknam & Karshenas, 2017). However, although Semantic Web can be perceived as a potential solution, currently an integrated and centralized information management is not available during the early stages. So, this research aims to confront that absence and propose an ontology together with an implementation plan oriented to preliminary design stages.

1.3 RESEARCH OBJECTIVE

According to the above-mentioned context and problem statement this research intends to ''develop a framework and a workflow for structuring information in the early stages of a project, in such a way that project members can efficiently and consistently work with centralized data and later integrate them seamlessly into the final design phase''.

The terms efficiency and consistency in this case are two close-related terms. Consistency implies that all disciplines are using the same measurement of variables throughout the datasets for their calculations/analyses, without having discrepancies over the same data. Efficiency, indicates that specialists retrieve and therefore manipulate consistent data without spending time collecting them manually from scatter sources. Consistency can be measured statistically by defining the range (i.e. largest value minus the smallest value between a data distribution). Efficiency can be assessed by comparing the time that professionals needs to collect a certain amount of information compared to a minimum threshold. Later on, during the validation of the study, these terms will eventually be assessed.

1.4 RESEARCH QUESTIONS

The main research question that derives from the problem statement is the following:

- How could data of early design stages be centralized in an information model from the very start of a project before the development of a 3D BIM model, in such a way that engineers can efficiently and consistently work with data and seamlessly integrate them into the final design afterwards?

Sub-questions have also been established:

1. What are the current practices of specialists in terms of capturing and using data in the early design stages?
    a. What data do different specialists need in order to perform their tasks?
    b. How do they retrieve and interpret these data?
    c. How do they report their calculations and in what format they share information?
2. What data do engineers need to start developing their 3D models/drawings/analyses in final design phases?
3. How are they handling existing data and how and in what extent do they incorporate them into their design?
4. What kind of strategy can link preliminary and final design interfaces?

5. How can this strategy be developed and implemented in projects' processes?
6. How can the proposed strategy be tested and validated?

1.5 Research Scope

ABT bv, which is part of Oosterhoff Group provides the context for this research. ABT bv is a leading multidisciplinary engineering firm that offers a wide set of services in terms of designing, engineering and building aspects. Since the scope of the provided services covers projects of any scale for various phases of the lifecycle, i.e., from initial design stages up to implementation operations, multiple engineers with versatile expertise are engaged in the process. However, project members that operate in the early phases also encounter the shortcomings that are mentioned in chapter 1.2.

Therefore, the objective of this research is aligned with the integrated design ambitions of ABT bv regarding information management. The vision of the company is illustrated in Figure 2.

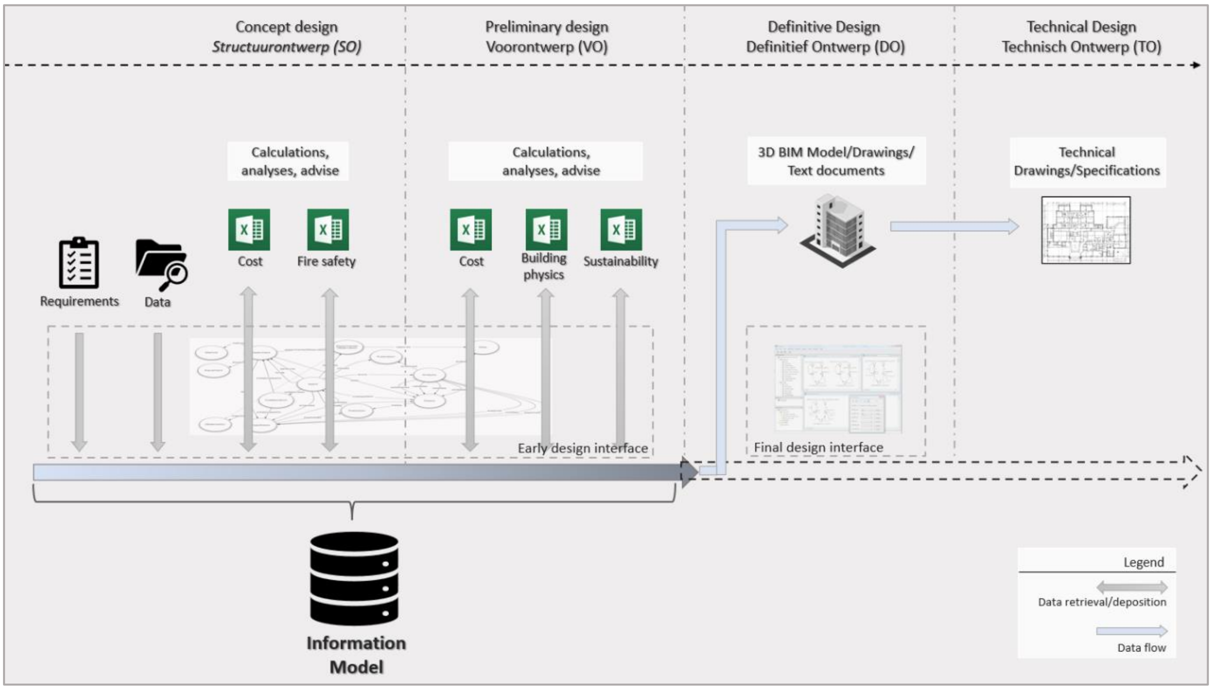

Figure 2: ABT's vision: BIM even without a 3D in preliminary design stages

The vision is to build and use a centralized information model in the initial phase, even if the 3D model is not yet evolved. In this way, specialists that are involved during these phases will retrieve and share data using this model as the main data source. Moreover, it will be stable across the whole building lifecycle, thus when engineers initiate the final design then this data source will be able to be incorporated.

This research focuses on the early phases of a project which include the Concept Design *Structuurontwerp (SO)* and the Preliminary Design *Voorontwerp (VO).* The inclusion of these two design stages sufficiently covers the part of the lifecycle where the roots of the main problem statement are traced. Moreover, in order to provide the context for exploring the transition from early to later design stages, part of the initiation of the final design is included. This consists of the Definitive Design *Definitief Ontwerp* (DO) and Technical Design *Technisch Ontwerp* (TO). Figure 3, graphically represents the scope of this research.

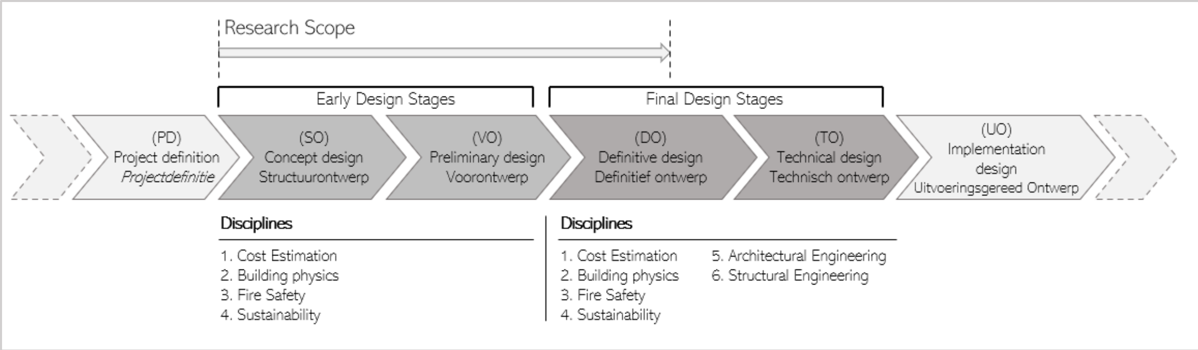

Figure 3: Research scope

Throughout these design phases, project teams are composed of several specialists and engineers, depending on the size and the demands of each project. However, in order to keep this research within a feasible scope, but at the same time capture a significant part of building data, specific domains of ABT that participate in these phases are taken into consideration. Thus, the disciplines to be considered deal with the following tasks:

1. Cost estimation
2. Building physics
3. Sustainability assessment
4. Fire safety
5. Architectural Engineering
6. Structural Engineering

This selection is sufficiently representative for researching information flows in typical projects, since the activities of these domains constitute a significant part of the Dutch Standard Job Description (DNR-STB 2014). The disciplines of cost estimation, building physics, sustainability assessment and fire safety are involved in various phases of a project's lifecycle, from very early (SO) up to Definitive design (DO) or even Technical (TO) design stages. Since the field Building Physics encompasses a wide spectrum of activities, this research includes the undertaking of energy calculations, BENG calculations and daylighting and ventilation reports. The same occurs with sustainability field so the activities to be included are drawing up sustainability concepts, calculating building materials impact and amount of PVs needed.

On the other hand, architect and structural engineers are actively engaged in the final design (DO) and (TO) phases. Moreover, in earlier phases structural engineers create high level designs and architect engineers are only consulting. A notable point of attention is the relation of the architectural engineering department of ABT with the project's external architect. The main two scenarios during the design and engineering process are: First, the architect does both architectural design and engineering, thus ABT architectural department has no role. Secondly, the architect undertakes only architectural design, therefore ABT is assigned with the architectural engineering. This research, will take into consideration the second scenario.

The six above mentioned domains are involved in large-scale fully multi-disciplinary projects, with high budget and long duration, like office buildings, residential towers or other multifunctional buildings. Additionally, there is also a significant amount of smaller-scale projects with a relatively short time span, approximately of 2-3 months where less specializations are involved. These can be small housing buildings, kiosks or retail/commercial buildings.

What is important is that all these domains may operate independently for specific tasks, for example executing only building physics operations, or fire safety advise and collaborating with external parties, or they can be part of ABT integrated teams. However, this research will address the case where they operate as members of integrated project teams, all employed by ABT. Therefore, it will be considered that they work in the same projects where they interact between each other, by communicating, collaborating and exchanging inputs and outputs on a regular basis. As such, they share a mutual understanding of the different phases of a project together with its scope, needs and characteristics.

2. LITERATURE STUDY

2.1 LITERATURE REVIEW

This part of the report is expected to provide the theoretical background of the research with regards to the aforementioned problem context. This step is going to explore the current situation in the field of data management during the early design stages, from both an academic and corporate perspective and identify possible research gaps. The main keywords that will guide the literature search are: Building Information Modelling (BIM), Early Design Stages, Collaboration, Centralized Information, Data Structuring, Interoperability, Semantic Modelling, Ontologies.

2.1.1 Building Information Modelling (BIM)

According to Charles Eastman, ''Building Information Modelling (BIM) is a digital representation of the building process to facilitate exchange and interoperability of information in a digital format". Within literature several definitions of BIM have been established given different perspectives of application in construction industry, where it can be either described as a design tool, an information tool or a process management tool. Nevertheless, the main characteristic of BIM is the generation of centralized digital information and graphically represented 3D model for the entire lifecycle of a built facility. This model can be shared among all stakeholders, thus improving communication and collaboration. Given that, it is regarded as new lifecycle data management paradigm.

Building Information Modelling can be named as one of the most significant efforts in recent years regarding information management in construction industry (Eastman, et al., 2011). BIM environments allow to semantically describe any kind of information about the building in one 3D model, so that it can be better represented and more easily exchanged than in the case of traditional computer-aided design (CAD) tools (Pauwels & Terkaj, 2016). BIM-based workflows involve consistent model-based communication between all stakeholders and across the entire lifecycle of a facility. For the data exchange and the coordination of the model-based workflows, digital technologies such as model servers, databases or project platforms are employed in a comprehensive manner (Borrmann, et al., 2015).

In its current form, BIM process begins with obtaining and collecting information as well as requirements regarding the project. Such data are normally available in many different forms: like model sketches, spreadsheets or pdf. In the subsequent phase, a 3D model is designed according to the requirements specified in the initiation of the project, using BIM authoring tools (Revit, ArchiCAD, Tekla, etc.). It starts with entering basic and generic information on the elements. Consequently, as the project progresses and depending on the requirements, designers further enhance the models with relevant information (Fugas, 2020). Afterwards, the 3D model becomes the centralized information source that is later shared among stakeholders, leveraging the main benefits as stated above.

Several researchers explored the opportunities of applying BIM during the early phases of a project lifecycle. (Çavuşoğlu, 2015) investigated how it can help engineers in the early stages of architectural design, most particularly in decision making processes. BIM has the ability to store, inference and analyze the data related to the building serves as a modeling and decision support environment for designers in the start of a project. In addition to its decision support capabilities, it offers a real time object oriented modeling environment where all the design model parametrically connected to each other with all numeric and non numeric inputs. Aligned with this direction, (Choi, et al., 2015) developed a BIM-based Quantity Take-Off (QTO) system for schematic estimations in the early design stages. The QTO process is comprised of four steps: BIM modelling, physical quality verification, property verification and quantity take-off. So, it is seen that the initial point and the base of this procedure, also in this case is the development of a 3D BIM model in the beginning of the process.

However, although BIM is an entire lifecycle approach paradigm, it can be observed that its main benefits are only evident after the initiation of the geometric modeling. By now, BIM as a method has established itself globally in the construction industry, making the industry shift significantly towards full digitization. Yet, it still suffers from the diversity of (custom) data structures and use of unstructured data in documents (Rasmussen, et al., 2020), which is even more evident in earlier stages of a project. This creates semantic interoperability issues that have been shown to be a major barrier for the seamless transfer of information between various stakeholders and phases of the lifecycle (Belsky, 2021), (Costin & Eastman, 2019). Semantic interoperability denotes the capability for computers to parse and interpret the wide range of meanings of data as it was intended in the processes (Sheth, 1999).

Consequently, there is an emergent need for a standardized approach on structuring information that needs to be scalable and also compatible between different design stages. A common current approach for domain-wide interoperability is the use of information exchanges. Information exchange is the use of domain-approved data representations, definitions, rules, requirements, and processes for the transmission of data, which involves the process of sending data from a source format (or schema) and transforming it into another source format (Costin & Eastman, 2019).

2.1.2 Industry Foundation Classes (IFC)

The IFC standard, developed by buildingSMART, alleviates issues related to exchange of BIM data and enables multiple BIM platforms to interact in an interoperable way (Atazadeh, et al., 2016). This standard, aims at supporting these activities by providing a central "conceptual data schema and an exchange file format for BIM data" (Liebich, et al., 2013). In general, IFC is a standardized, digital description of the built environment, including buildings and civil infrastructure. It is an open, international standard (ISO 16739-1:2018), meant to be vendor-neutral, or agnostic, and usable across a wide range of hardware devices, software platforms, and interfaces for many different use cases (Building Smart, 2020). Furthermore, it is a commonly used collaboration format in BIM based projects. It supports a wide range of geometric representations as well as rich semantic information. IFC files contain data about building objects and connections between those objects.

The IFC standard schema is modular and includes four main layers (Building Smart, 2020) (Chen, et al., 2018) (Atazadeh, et al., 2016):

(1) ***Resource layer:*** it comprises basic entities referenced in other layers. Examples are measurement units, such as time, date, length, area and volume

(2) ***Core layer:*** it consists of 'IfcKernel' subschema and three core extension subschemas, namely product, process and control extension. 'IfcKernel' contains the most abstract 'IfcRoot' entity which is specialized into three fundamental and abstract entities:

- *Object classes* (ifcObjectDefinition): this entity identifies an IFC object, its ownership, and functional units.
- *Relation classes* (ifcRelationship): this entity defines the multiple relations between object classes and their functional units.

- *Property classes* (ifcPropertyDefinitions): this entity describes functional units through a set of attributes.

(3) ***Interoperability layer:*** this specifies subschemas which contain those IFC entities shared and used across multiple AEC domains. For example, 'IfcSharedBldgElements' subschema includes entities for the shared building elements, such as walls and doors.

(4) ***Domain layer:*** this layer defines the most specific subschemas for each AEC domain.

As in any object-oriented data model, inheritance hierarchy defines specialization and generalization relationships and therefore which attributes of which classes can be inherited by other classes. The inheritance hierarchy follows a semantic approach: the meaning of objects is the basis for modeling inheritance relationships (Borrmann, et al., 2015). Figure 4 illustrates the inheritance hierarchy of relationship classes whilst Figure 5 introduces the most important entities of the IFC inheritance hierarchy.

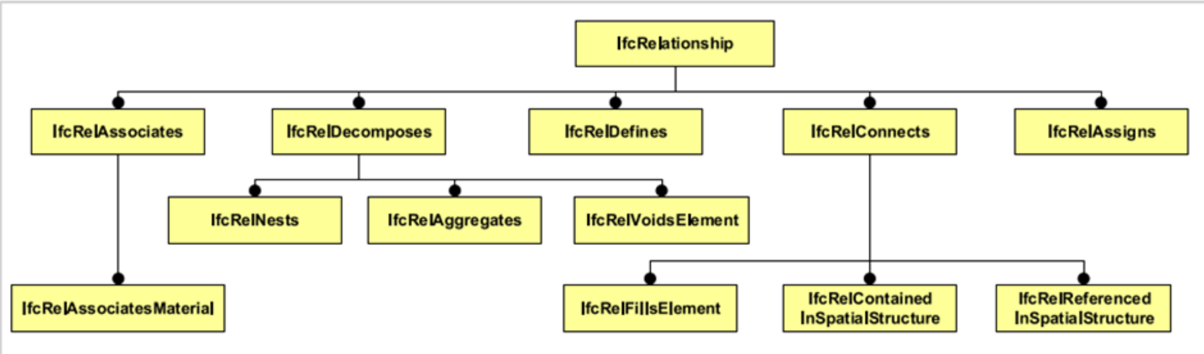

Figure 4: Inheritance hierarchy of relationship classes (Borrmann, et al., 2015)

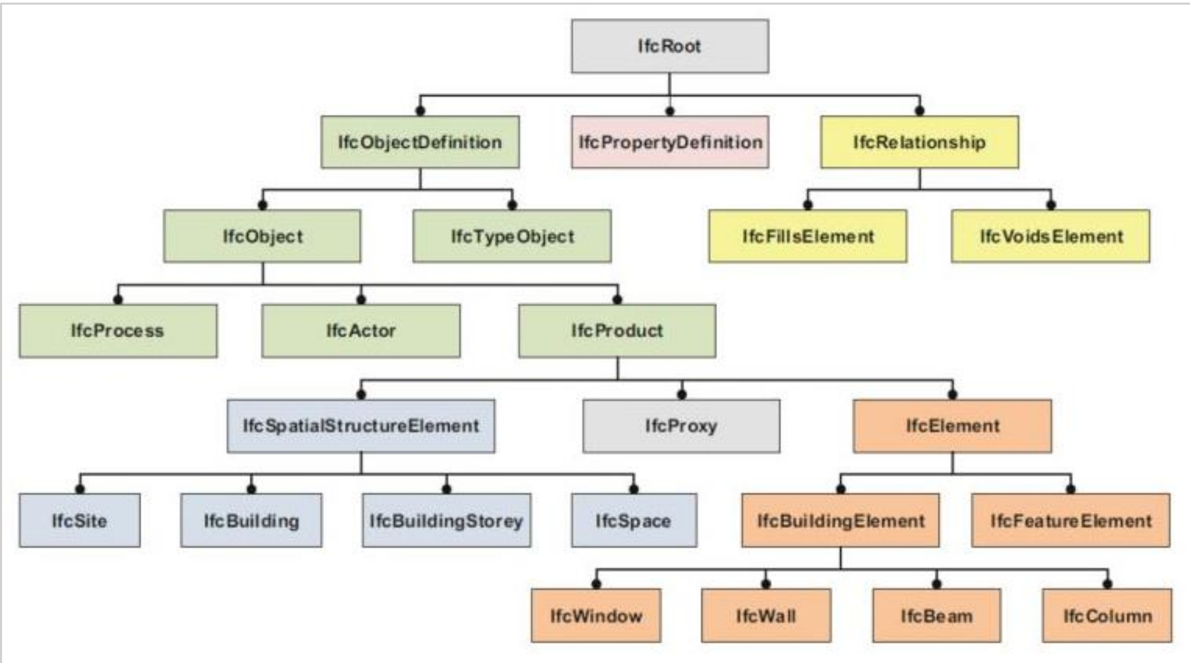

Figure 5: IFC inheritance hierarchy (Borrmann, et al., 2015)

Figure 6 provides an overview of the conceptual data model of IFC. The relationship between entities and attributes of entities is regarded as semantic information for data mapping. Data with blue color (Spatial Entities) are not physically attached to any geometry of the model, data with red are attached to physical objects in the model (components/elements), while spaces can be assigned to zones and components to systems. Data with grey are generated from the attributes of entities.

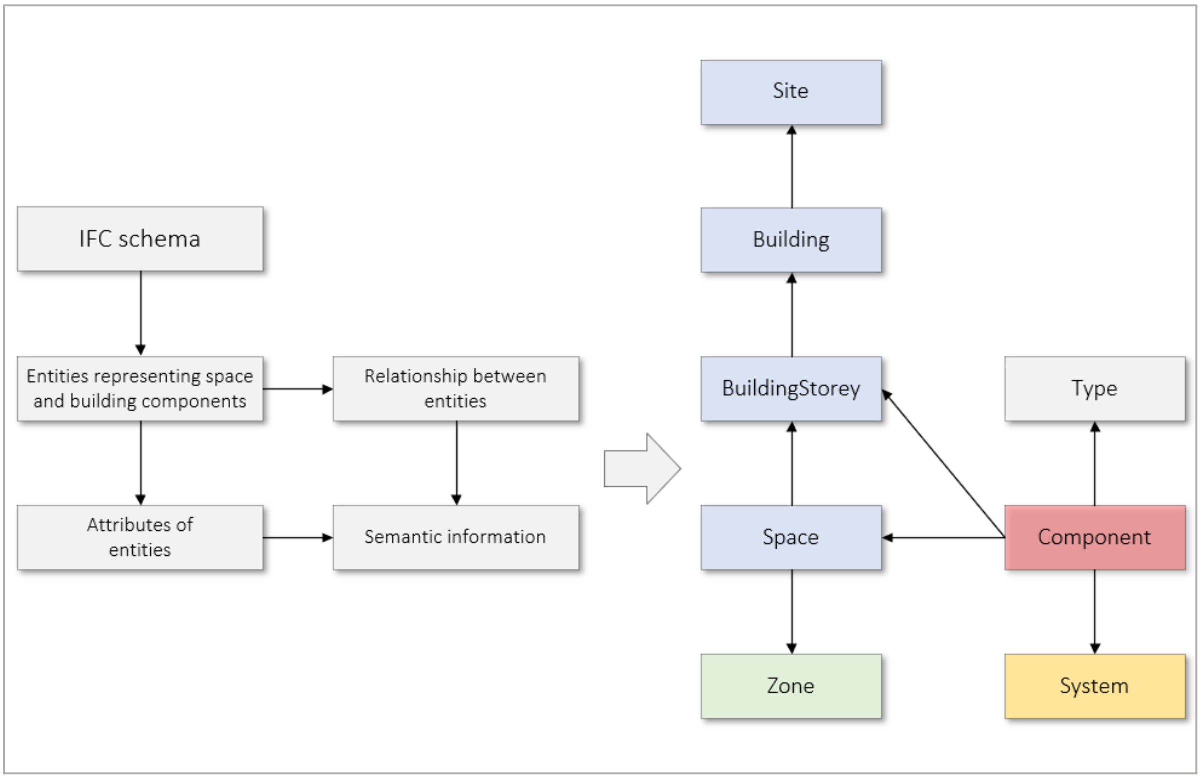

Figure 6: IFC conceptual data schema

The main entities of IFC are classified into two main groups and are hereby presented (Atazadeh, et al., 2016).

- **Spatial entities**

A spatial element *(ifcSpatialElement)* is the generalization of all spatial elements that might be used to define a spatial structure or to define spatial zones. Spatial structures can be defined in a non-hierarchical or hierarchical way.

A hierarchical spatial structure element is the IfcSpatialStructureElement. This is a superclass for the elements site *(ifcSite)*, building *(ifcBuilding)*, storey *(ifcBuildingStorey)* and space *(ifcSpace)*.

Spatial zones *(IfcSpatialZone)* are non-hierarchical and potentially overlapping decompositions of the project under some functional consideration, i.e. to represent a thermal zone, a lighting zone, a usable area zone.

- **Physical entities**

A physical element *(ifcElement)* is the abstract superclass for entities modelling physically existent objects. The relevant physical objects are building elements (IfcBuildingElement) and distribution elements (IfcDistributionElement). Building elements define the architectural structure of the buildings like walls, columns etc., while distribution elements represent different types of utility networks inside as well as around the building.

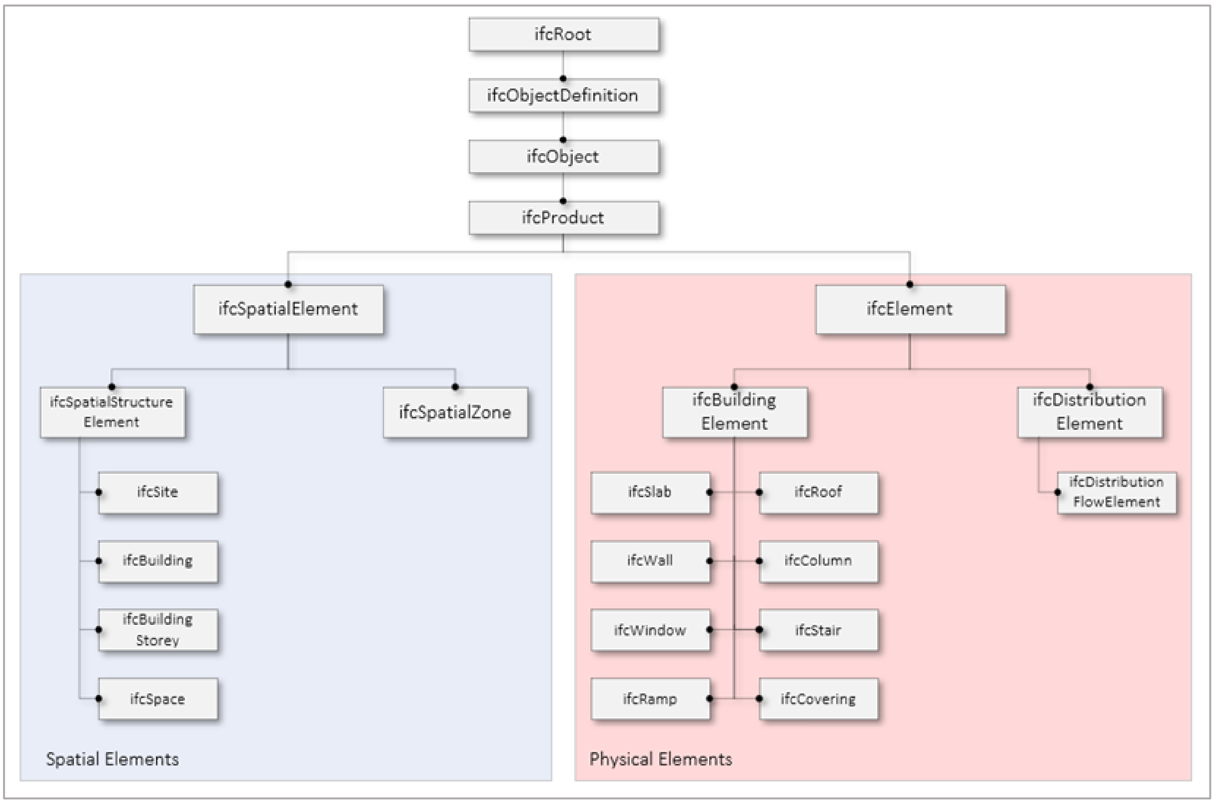

Figure 7: Relevant spatial and physical elements in IFC schema

ifcJSON

IFC specification has been encoded in ifcXML format by buildingSMART to support XML-based data transmission. However, due to the inadequacies of XML, JSON has been widely used in Web applications lately, specifically in Asynchronous JavaScript and XML (AJAX) Web services (Afsari, et al., 2017). JSON is easy for computers to parse and generate and its syntax is also human readable. Moreover, it uses a text format that is independent of the language so its format is different from XML format that has closed tags (Wang, 2011).

Additionally, several studies have shown that JSON has been successful to replace XML as data exchange format in Web services, since its data format supports high scalability and it creates more compact models than XML (Peng, et al., 2011), (Gerhart, et al., 2015). Given that, the IFC schema was translated into JSON in order to leverage the main benefits of this format. All the necessary principles like objects, entities, relationships, values, attributes and property sets are included in this schema. Figure 8 illustrates an example of a door object in JSON.

```
"type" : "IfcDoor",
"globalId" : "157c866c-9c08-4348-a0ed-4d57cd66c9e2",
"name" : "A common door",
"description" : "Description of a standard door",
"overallHeight" : 1.4,
"overallWidth" : 0.7,
"predefinedType" : "GATE"
```

Figure 8: ifcDoor entity in JSON format

ifcOWL

Although information exchange standards have been beneficial within a distinct and well-defined domain, information exchanges across domains require an additional level of significant coordination between them (Costin, 2016). Although these standards enhance interoperability within the construction industry, there are many emergent requirements when developing an interdisciplinary exchange standards. According to (Venugopal, et al., 2015) the IFC data model contains many inconsistencies and ambiguities that may inhibit successful information exchanges. Therefore, an ontological approach is suggested to represent IFC hierarchy and outline the foundation for the development and implementation of a new integrated framework that is expected to define a clearer and more formal structure for IFC.

ifcOWL provides a Web Ontology Language (OWL) representation of the Industry Foundation Classes (IFC) schema. Using the ifcOWL ontology, one can represent building data using state of the art web technologies (semantic web and linked data technologies) (Pauwels & Terkaj, 2016). IFC data thus becomes available in directed labelled graphs (RDF). This graph model and the underlying web technology stack allows building data to be easily linked to material data, GIS data, product manufacturer data, sensor data, classification schemas, social data, and so forth. The result is a web of linked building data that brings major opportunities for data management and exchange in the construction industry and beyond (Building Smart, 2020).

2.1.3 Semantic representation of data

According to (Santos, et al., 2017) semantic web technologies are among the more recent research topics that are gaining momentum in the field of Building Information Modeling BIM. The limitations of BIM regarding the complete and integrated management support for building data, which are distributed across different sources and often need to be combined for the purpose of several analyses, stimulated the use of Semantic Web (Patsias, 2019).

Semantic Web is a network of connected data that are machine accessible and processable (Allemang & Hendler, 2011). It can be seen as a graph in which each node is an instance that is pointing to other nodes. Therefore, a semantic definition of a construction project enables project participants to represent their information in a graph structure and easily combine and connect their information about the project (Niknam & Karshenas, 2014). Given that, it provides a common framework that allows data to be shared and reused across applications, enterprise and community boundaries.

Semantic Web uses formal ontologies to define concepts (classes) and the relationships between concepts (W3C, 2015). RDF/OWL languages are used for creating ontologies and knowledge bases (Antoniou & van Harmelen, 2004). Resource Description Framework (RDF) allows expressing the relationships between things by standardizing on a flexible, triple-based format and then providing a vocabulary which can be used to say a thing. Web Ontology Language (OWL) is similar however it provides a wider vocabulary, is more rigid and allows using data models to support many different kinds of reasoning tasks (Cambridge Semantics, 2019).

Ontologies

Studies and applications of ontology technology in BIM have gained wide attention lately. The ontology-based knowledge representation method allows integration and sharing of existing knowledge across different domains as well as intelligent reasoning of tacit knowledge via concept classification, semantic description, and logic reasoning (Chen & Luo, 2016). Ontologies are explicit formal specifications of the concepts in a domain and relations among them and they are used to create domain knowledge bases (Niknam & Karshenas, 2017). The use of such technologies is encouraged by a number of factors. They offer a common terminology for domain representation and use formal semantics; they provide inference capabilities for consistency checking; they are suitable for integrating heterogeneous data from multiple sources and they facilitate interoperability with other applications (Kontopoulos, et al., 2016). Current applications of ontology technology in BIM are mainly focused on BIM data processing, heterogeneous data integration, and semantic reasoning.

Existing ontologies in AEC sector

Niknam and Karshenas highlighted the importance of developing shared ontologies. In their paper Niknam & Karshenas (2013) they present an approach for achieving semantic interoperability among heterogeneous information applications used in the building construction industry. The approach is based on a shared building ontology that models the element types and element relationships in buildings. Various domain applications that must interoperate should be built on top of the shared building ontology. In the above architecture, each knowledge domain has its own ontology that is built on top of the shared building ontology. The shared ontology contains the primitives of the building domain. It forms a sort of minimal skeleton of shared knowledge between the different domains (Niknam & Karshenas, 2013).

Furthermore, Niknam & Karshenas, (2017) defined a BIM shared ontology referred to as BIMSO that includes all elements in the UNIFORMAT II classification system. The study also presented a building design ontology referred to as BIMDO that extends BIMSO and defines design properties for building elements. BIMSO and BIMDO ontologies were used to create a BIM knowledge base for a 3-storey building project. The BIM knowledge base along with a schedule and a cost knowledge bases were used to demonstrate the effectiveness of the shared ontology approach in enabling a single search interface across the AEC-FM domain. SWRL rules or SPARQL queries are used to integrate data from different domains (Niknam & Karshenas, 2017).

(Pauwels & Roxin, 2016) stated that ifcOWL remains close to the original IFC schema as available in EXPRESS language. Given that, the current ifcOWL ontology does not really simplify handling IFC models, as it does not deliver the highly demanded simpler models to AEC practitioners. As such, there is an emergent need of developing simpler and more agile RDF graphs. SimpleBIM ontology developed by (Pauwels & Roxin, 2016) post process ifcOWL and aims at defining simplified RDF graphs for presenting building information. Moreover, ifcWOD (Farias, et al., 2015) elaborates an adaption of the IFC model into OWL by proposing simple entities, relationships, properties and attributes defined by the IFC standard.

(Rasmussen, et al., 2017) insisted that ontologies such as BIMSO and ifcOWL could be considered ontologies specific to the building domain, but they cover a wider domain as they point to ontologies outside the building as well (units, geometry, location etc.). In this way they violate the principle to keep schemas light for easy reuse leading to limited use within the AEC industry. Therefore, the Building Topology Ontology (BOT) for easy reuse across the considered domain is developed. It is a simple ontology only defining the core topology of a building including the physical and conceptual objects and their relationships. The final version of BOT has 7 classes, 14 object properties and geometrical data relationships. It has also three main classes: bot:Zone, bot:Element, and bot:Interface. A bot:Zone is a part of the world that has a 3D spatial extent, A bot:Element is a constituent of a construction entity with a characteristic technical function, form or position and bot:Interface is a part of the world that is common to some specific zones and elements, and at the boundary of at least one of them (Rasmussen, et al., 2020).

What can be inferred is that ontologies are a useful tool that allows integration and representation of building information stemming from heterogeneous sources. Thus, it can be considered as complementary to Building Information Modelling practices, focusing on organizing and sharing the 'semantics' of a building and not only on the display of its geometric aspects (Pauwels, et al., 2017).

2.1.4 Open-source Common Data Environments

Speckle

This chapter introduces Speckle, a distributed Common Data Environment (CDE) and open-source data platform for Architecture, Engineering and Construction (AEC), differentiating from other web-based interoperability platforms. Speckle does not enforce a predefined topology of communication patterns, but rather allows for the emergence (and analysis) of meaningful data-driven dialogue amongst the stakeholders involved in the design process. Furthermore, it offers an infrastructure for end-users to define their own, domain, company, or even project-specific object models. Via its Admin web app, it also offers full control to data authors on how accessible their information is and with whom. Thus it is similar to existing CDE as it provides a single source of information used to collect, manage and disseminate documentation, the graphical model and non-graphical data for the whole project team (Poinet, et al., 2020).

Speckle's technology stack consists of the same components of the Semantic Web stack, however the main difference lies in the technical implementation of these components. Figure 9 and Figure 10 present a comparison between Speckle and Semantic Web framework.

Components	Identifiers	Syntax	Data interchange	Taxonomies (schemas)	Querying	Trust/auth
Semantic web	URI/URL	XML (RDF/XML) JSON-LD	RDF	RDF-S	SPARQL	–
Speckle	URI/URL (hashes)	JSON	Speckle object	Speckle schemas	MongoDB queries	Passport. js

Figure 9: Speckle and Semantic Web Technology stack (Poinet, et al., 2020)

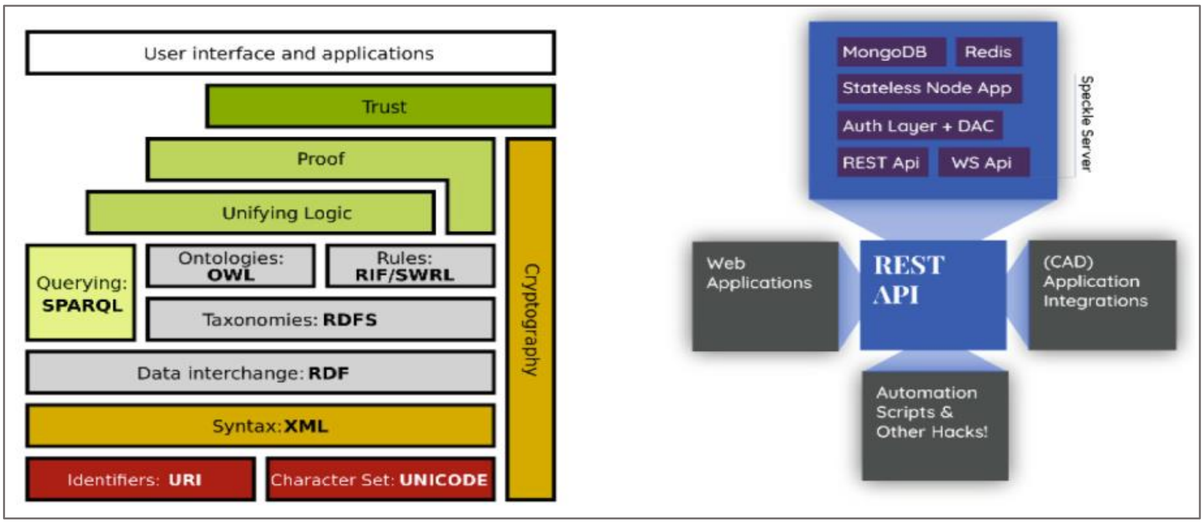

Figure 10: Speckle and Semantic Web Technology stack

What can be initially be observed is that both frameworks make use of Uniform Resource Identifiers (URIs) and Uniform Resource Locators (URLs) to identify and access unique resources. Moreover, while Semantic Web uses the Resource Description Framework (RDF), speckle its own data interchange model and related taxonomy: the SpeckleObject, a simple base class that adds a set of simple properties related to authorization and commenting to all applicable resources. Finally, because Speckle does not use RDF data models and employs MongoDB to store data, it uses the query language developed specifically for MongoDB, as well as query-to-mongo, a Node.js package to convert query parameters into a mongo query criteria and options (Poinet, et al., 2020).

2.1.5 Other existing tools in data sharing

In the recent years, there have been some efforts in developing BIM software that facilitate the generation of information databases in the models. These software have a Data Driven Design orientation, which is an increasingly popular approach to creating a standardized system for recording information to geometric models. In this way, the design process is based on a central database, which is able collect as many requirements and information as possible and then synchronize and map selected data with the model (Lozinski, 2020).

dRofus is a planning, data management and BIM collaboration tool that provides all stakeholders with extensive workflow support and access to building information throughout the building lifecycle. The key features of this tool enable a data centric approach for creating and planning building data, capture client requirements, provide a workflow support for architects and integrate program data with design for validation of building requirements (dRofus, 2019).

Moreover, Bimeye is a cloud based BIM data management aiming to improve the speed and quality of a construction project from the initial idea up to the handover to the facility management. Bimeye provides a common data environment where all project information can be managed in a model centric way. The main principles of this tool is sharing information to every stakeholder, collaboration and interaction of all participants and enrichment of the model with different data such as scheduling, costs maintenance all in one place related directly to the building elements (Bimeye, 2019).

Another software dedicated to information structuring is CodeBook, which provides a narrative of the project life cycle, from inception through design, tender and construction to occupation by the facility users. Two distinctive features of CodeBook are i) Room Data Collector (RDC) and ii) Project Room Data (PRD). RDC is an interface to the central CodeBook project database that can be used to allow any stake holders of the project to view or optionally modify or comment upon the project data. PRD allows all those involved in design, construction and operation of complex buildings to work with coordinated data, produce schedules, graphical views, room data sheets (RDS) and BIM ready outputs. The database will be used for estimating and tendering purposes and during construction for recording compliance and ff+e asset data, with all the captured data available for the purposes of facilities management (CodeBook, 2021).

Overall, despite of the discrete differences between these software some common features can be highlighted. These include the capture and management of clients' initial requirements, the development of room sheets that include information about area, functions etc. Moreover, they enable bi-directional links with 3D models for data synchronization. Hence, an important aspect is the presence of a 3D model of the built facility.

2.2 LITERATURE GAP

BIM advocates seamless exchange and interoperability of information in a digital format among various stakeholders throughout the entire lifecycle. Nonetheless, several studies indicated that BIM workflows still face the shortcoming of semantic interoperability due the existence of several data structures and unstructured data in documents (Farghaly, et al., 2019) (Rasmussen, et al., 2020) (Costin & Eastman, 2019). For that reason, exchange standards, such as the IFC were introduced to overcome these barriers. Yet, they lack formal rigidness to unambiguously capture the full semantics needed for seamless and reliable information exchanges (Belsky, 2021). Furthermore, open source tools for data exchange such as Speckle were introduced. Speckle allows the communication of data with data streams, however these are custom metadata for objects. As such, they are abstract and additional interpretation is needed. So, it can be acknowledged that it focuses more on communicating data rather than defining them.

In addition, the literature search identified several ontologies that intend to reach semantic interoperability and enable data integration across different disciplines in the AEC industry. These lightweight and easy to use ontologies seem to have a promising potential with regards to data sharing, however it is evident they lack an orientation towards the early design phases. Consequently, in order to address the needs of early design information management and take full advantage of these technologies, it is essential to strive towards defining an ontology that covers that needs and implement it alongside BIM. In this way, it will be possible to assist information integration and reuse by reaching semantic interoperability in early phases and later on it will be possible to hand this information to later phases.

3. RESEARCH METHODOLOGY

3.1 RESEARCH DESIGN

This part of the report defines a methodology to answer the main research question. The focus of the research is solution oriented. Given that, the objective is to design a framework that will eventually address the main issue of problem statement. For that purpose, the research follows a sequence of phases where corresponding questions are addressed. Figure 11, provides an overview of the steps and actions that serve this purpose.

The preparatory phase, which serves as research input, addresses the issues of data management in BIM workflows over projects' early phases and captures the company's problem and vision within that context. Additionally, a literature review explores topics relevant to the problem statement and identifies possible gaps. Phase 1, initially explores the existing practices during these stages and then evaluates the deficiencies of the current processes. Phase 2 first introduces a new process model and conceptually defines a data structure and a workflow in order to materialize the proposed process model. Afterwards, in phase 3 the findings of the previous step are implemented in a case project and a working prototype is developed, whereas in phase 4 the outcomes are eventually validated.

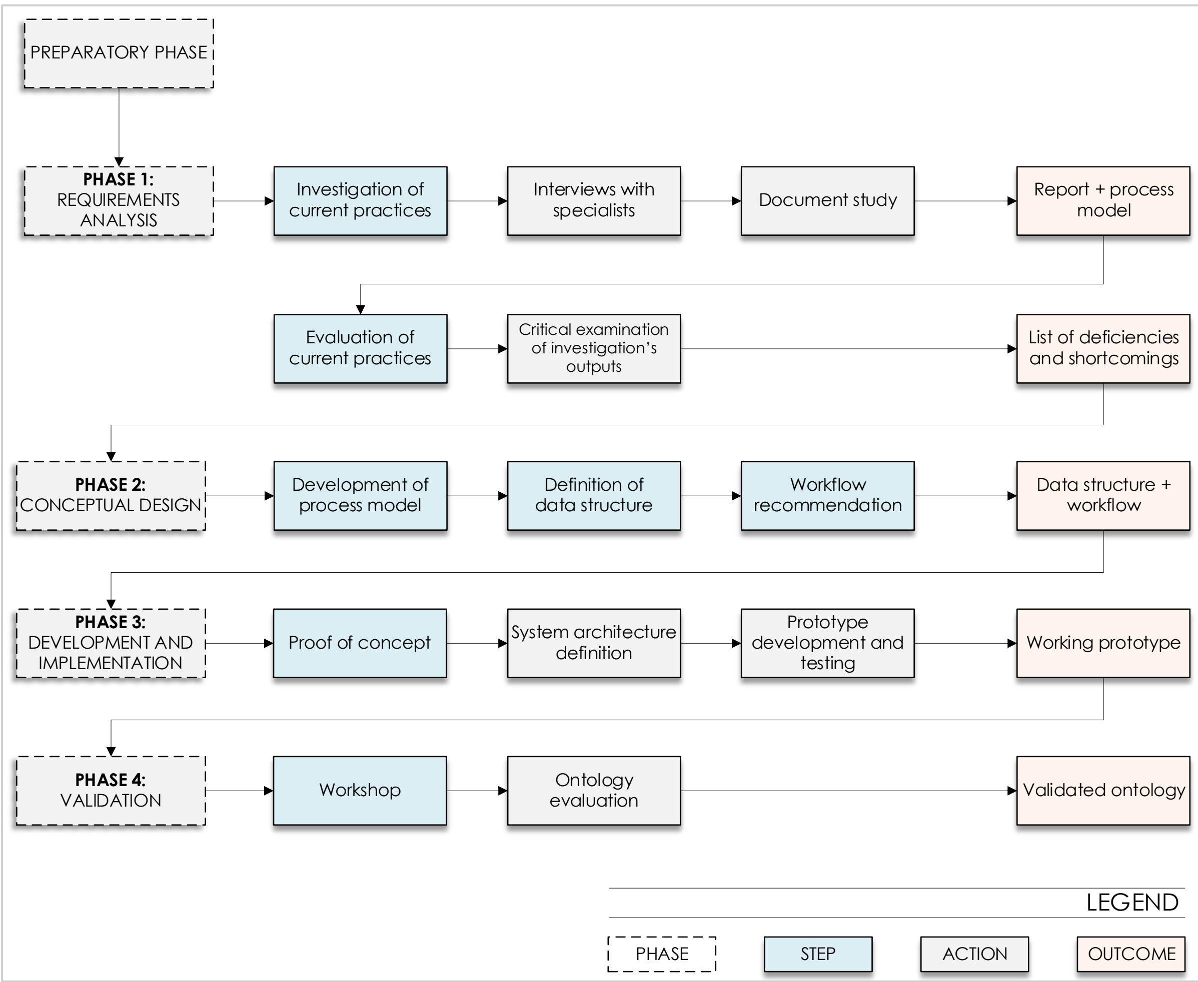

Figure 11: Research design

3.1.1 Phase 1 – Requirements analysis

Investigation of current practices

In this step, the current practices in terms of structuring and using data in the Early (SO/VO) and start of Final (DO) stages of a project were investigated. The main aim was understanding how specialists are dealing with data in these design phases, how they make their interpretations and assumptions on a design and in what extent they collaborate and exchange information.

For that purpose, eight semi-structured in-person interviews were held with ABT's specialists that are involved in these stages. More specifically, two Building Physicists provided insights about the operations with regards to ventilation, daylighting, acoustics and energy calculation analyses *(building physics report)*, a third Building Physicist described the procedure of drawing up sustainability concepts and advise, a Senior Cost Manager was asked about a typical cost calculation process and a Fire Safety Specialist provided an overview of the fire safety analysis procedure. Moreover, two Architectural and a Structural modeler/engineer provided an overview of the role and characteristics of the Architectural and Structural departments.

In order to achieve the objective of this step, the intended questions were categorized in distinct groups, as seen in the scheme of Figure 12.

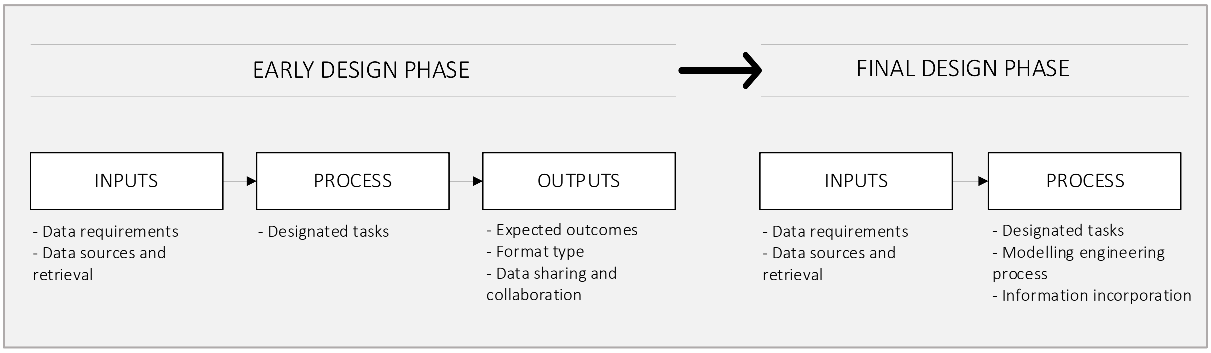

Figure 12: Structure of interviews' questions, including relevant categories

For the early phases, the interview's questions firstly focused on the scope and the type of tasks that are required, how specialists initiate their work, what are the information requirements to do so and which are their data sources. Finally, it was explored what outcomes are produced, in what kind of format and how and where they are eventually shared. As far as the final design is concerned, the questions focused on what information is needed, how it is handled during the initiation of the process and up to what extent information from preceding phases is incorporated into the design. All sessions were concluded with questions focused on the personal reflection and thoughts of the interviewees. The full lists of questions that were asked are presented in Appendix A.

In addition, relevant corporate reports, working files, spreadsheets and other calculation files of the above mentioned disciplines were explored in order to support the documentation and gain credible information with regards to current practices.

For the analysis of the interviews' data an inductive approach was employed. Given that, the analysis started with a set of observations on the insights provided by the interviewees and then common patterns were identified, concerning the different above-mentioned aspects. Therefore, starting from individual process models of each discipline and taking into account the complete set of observations and identified patterns, this step ended up with a general process model for each design stage, presenting in graphic format the sequence of activities of the examined specializations coupled with corresponding information flows. Moreover, concise reports were composed describing the whole process and containing the disciplines involved, their data requirements and the format of their inputs and the outputs that they produce.

Evaluation of existing practices

Having thoroughly investigated the early and final design stages, this step aimed at assessing the current processes from the perspective of data structuring and handling. By critically examining the findings of the previous steps and taking into consideration the personal reflection and opinion of the interviewees as well, the main deficiencies of the current situation were identified. Hence, this step ended up with a report listing and describing these deficiencies together with two illustrations with their position in the current processes.

3.1.2 Phase 2 – Conceptual design

At this phase, a new process model was initially synthesized aiming at overcoming the shortcomings that were identified in the previous chapter. In order to materialize the proposed process model, a structure that responds to the information needs of early and start of final design stages was required. This structure, should also provide compatibility between these two phases. Therefore, a ''reverse engineering'' approach was employed. As such, the aim was that the proposed data model of the early design phases should follow exactly the same structure as in the final phases, with the only difference that it excludes the 3D details. That, would ensure that information is seamlessly integrated into the final stages, since essentially the same structure is used. Thus, this procedure consisted of 3 main steps:

(a) Select a common data structure: based on a second round of literature search, an existing data standard that is employed in the final design phases and is also available in BIM, was selected and therefore reused as basis for the subsequent steps.

(b) Identify what piece of information needs elicited from phase 1 is already covered and what is currently missing.

(c) Define the final data structure by enriching the current one with additional concepts that are required in order to address the needs of early and start of final design stages.

Furthermore, a workflow was also introduced describing how professionals can actually use and work around this data structure. The very first step consisted of the definition of use cases, which are short descriptions of a feature told from the perspective of the person who desires the new capability, usually a user or customer of the system (Cohn, 2018). They also present the specific goals [what] from the perspective of an individual actor [who]. In this case, use cases describe the actions that specialists take while interacting with the proposed data structure.

3.1.3 Phase 3 – Development and implementation

This phase intended to develop a tool that will help materialize the proposed data structure and workflow and implement it in a case study. For this purpose, a proof of concept approach was followed. A Proof of Concept (POC) is a small exercise to test a design idea or assumption. The main purpose is to demonstrate its main functionality, including its general design or specific features and to verify that can be achieved in development (Singaram & Jain, 2018).

This proof of concept consisted of two distinctive parts; the system architecture definition and the prototype development. The system architecture conceptually defined the fundamental constituents of the proposed tool, their connections and relationships as well as the main characteristics of its function (Jaakkola & Thalheim, 2011).

The prototype development concerned the implementation of the system architecture and the creation of a working interactive model, demonstrating how it can actually work. The initial point was the formulation of use cases in order to have a general explanation about the prototype features from the perspective of the user. In the conceptual phase of this research, 3 initial use cases with regards to the main workflow were established, so this step took over and split them into smaller ones in order to gain more detailed insights on the development requirements. Then, the main constituents of the prototype were described in detail. Eventually, a case study project provided the context for the implementation and testing of the prototype in real practice.

3.1.4 Phase 4 – Validation

Validity and reliability are two essential aspects when it comes to determining the quality of a research (Alvin, 2021). In order to evaluate the outcomes of this study a validation strategy was required. Based on the problem statement and research objective, the validation focused on two directions.

As far as the first direction is concerned, the proposed ontology together with the workflow around it were evaluated. For that purpose, a human-based method was selected, in which according to (Lozano-Tello & Gomez-Perez, 2004) the evaluation is done by humans who try to assess how well the ontology meets a set of predefined criteria, standards or requirements. In this case, the criteria that were formulated in order to assess the findings via human expertise are consistency, completeness, rework elimination, scalability, applicability and efficiency.

Consistency indicates whether all disciplines use the same measurement of variables throughout the datasets without having discrepancies over the same data. Completeness assesses whether the information needs of relevant domains are sufficiently covered. Rework elimination indicates whether redundant take-offs for the same data by multiple specialists are reduced. Scalability assesses to what extent the proposed ontology can be used by other specialists of early design phase that are not included in the scope and effectively cover their own needs. Applicability, indicates how easily professionals can use the ontology whereas the last criterion of efficiency addresses the overall efficiency that it bring to professionals' work processes in terms of collecting and managing information.

The second direction intended to evaluate whether the proposed solution facilitates the smooth flow of information from one phase to the other. Consequently, the two evaluation criteria in this case are integration and applicability. Integration indicates the extent that generated information can be incorporated in final design processes and applicability how easily modelers can transfer information from one phase to the other.

For executing the validation, a workshop was organized with 4 professionals that operate in the early design and one in the final design and their expertise corresponds in one of the disciplines that are included in the scope of the research. The workshop was divided in two distinctive rounds. During the first round, the new ontology together with the main idea and functionality of the prototype were presented to the participants. Then, the working prototype was implemented in the study case project. The aim was to provide a demonstration of how the workflow can be applied in practice. Two specialists were actively engaged and used the prototype while the remaining participants were able to spectate and observe how it works. The first round of the workshop concluded with participants receiving and filling a questionnaire in order to evaluate the proposal, according to the criteria that were established before. In order to measure them a 1-5 scale was employed, where the lowest score (1) meant that the criterion is met in a poor level while the highest (5) that the criterion is fully met. The questionnaire can be found in Appendix F. Alongside with the questionnaire the participants provided additional remarks concerning drawbacks, limitations and further improvements on the proposal. In the second round of the workshop, the generated data model together with the workflow of transferring information to final design were presented to a BIM-modeler, who consequently filled a questionnaire as well.

4. REQUIREMENTS ANALYSIS

4.1 INVESTIGATION OF CURRENT PRACTICES

4.1.1 Early design phase

This part of the report presents the outcomes of the investigation of existing practices concerning data handling during the early design stages of a project. Five ABT's specialists that are engaged in these phases were interviewed and relevant working files/documents were explored.

Process model

The existing process model of early design phases as emerged from the exploration of that stage is represented in Figure 13. This image illustrates a representative workflow example of the disciplines that are included in the scope of this research.

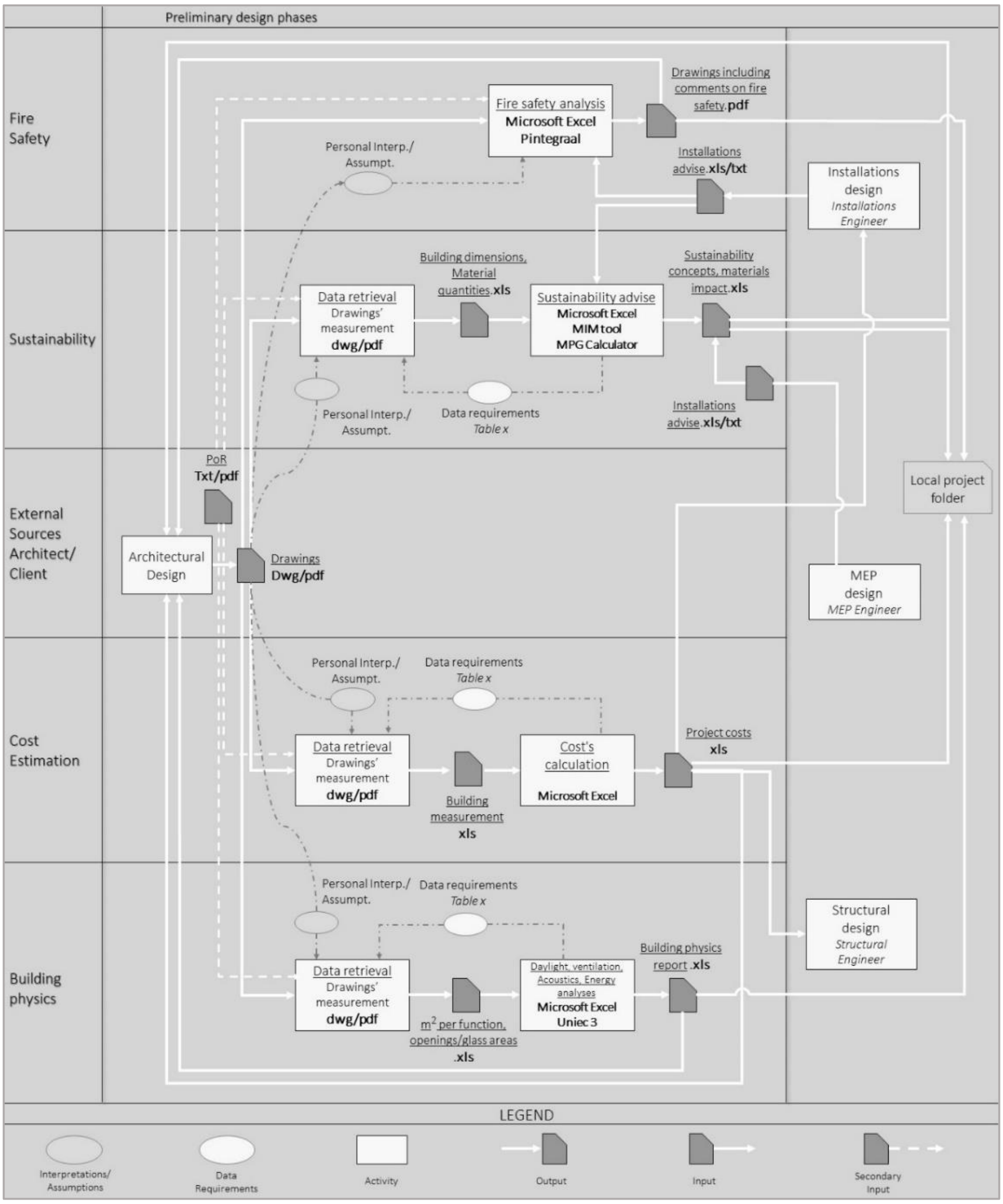

Figure 13: Preliminary design stages process model

A typical process initiates when the architect of the project shares his output with the team, which is usually 2D drawings in pdf or dwg format or sketches/visualizations of a built facility. The 2D drawings consists of the global indication of the layout, elevations and sections in either 1:200 or 1:100 scale presenting the preliminary architectural appearance of the building. Information on the initial selection of materials is also incorporated. Additionally, sketches in 1:200 or 1:100 scale and render visualizations may also be included, as it is optional at this point. Moreover, the drawings consist of the conceptual landscape design and/or the urban development position of the location and the connections to the immediate and wider environment.

This output constitutes the primary source of information for team's specialists. Additionally, the Program of Requirements (PoR), is a source of information as well. PoR is a document that comprises a list of requirements and objectives that a project has to comply with. This document is created by the client and the project initiative and concerns the urban planning, landscape and architectural integration, usage activities, functional and environment performance of a built facility.

When the drawings are shared, a data take-off process follows where each specialist extracts all the information needed for his/her operations. This take-off process, is usually manual by measuring drawings on the pdfs. Here, the data that are retrieved are based on the information requirements of each discipline which are presented later in this chapter. Furthermore, this process depends on the personal interpretation of the design by each specialist and the assumptions that he does when certain information is not included in the drawings.

As soon as the take-off process is completed, the data are placed in spreadsheets and later on are manually transferred in order to be used as input for the different calculations and analyses. However, the retrieved information is temporarily gathered in spontaneous Excel files on the individual working space of each specialist, until it's transferred to the final software. Hence, it is not saved in a centralized database for future use by other project members.

Afterwards, the outputs of different tasks, which are usually excel or pdf files, are shared and used as inputs for other team members or they are communicated to the architect. For example, the product of a cost expert can be used as input by structural or installations engineers or forwarded back to the architect and is sent directly by e-mail. Finally, the products of the above mentioned operations are usually stored in local project folders.

Inputs and outputs of early design phase

Hereby the information that specialists need for the execution of their analyses and calculations together with their outputs are presented. For cost estimation, the NEN 2699 norm is used to determine which building characteristics are required. This norm includes definitions and standardized structure and classification of all building associated costs. Concerning the building physics domain, the information requirements refer to three categories; building's geometry, functionality and usage of different areas/zones and attributes of building components. The sustainability discipline needs information regarding the building's dimensions, the type and characteristics of the installations as well as the used materials. Finally, the fire safety specialization needs information that is graphically expressed like floor plans with the overall building layout, the location of stairs and windows and also insights on the proposed materials. On the left part of Figure 14, the aggregated data needs can be seen, where a color coding represents which domains use certain data. Accordingly, the right side corresponds to the outputs of each operation. Appendix B consists of tables with a more detailed presentation of these inputs and outputs per domain.

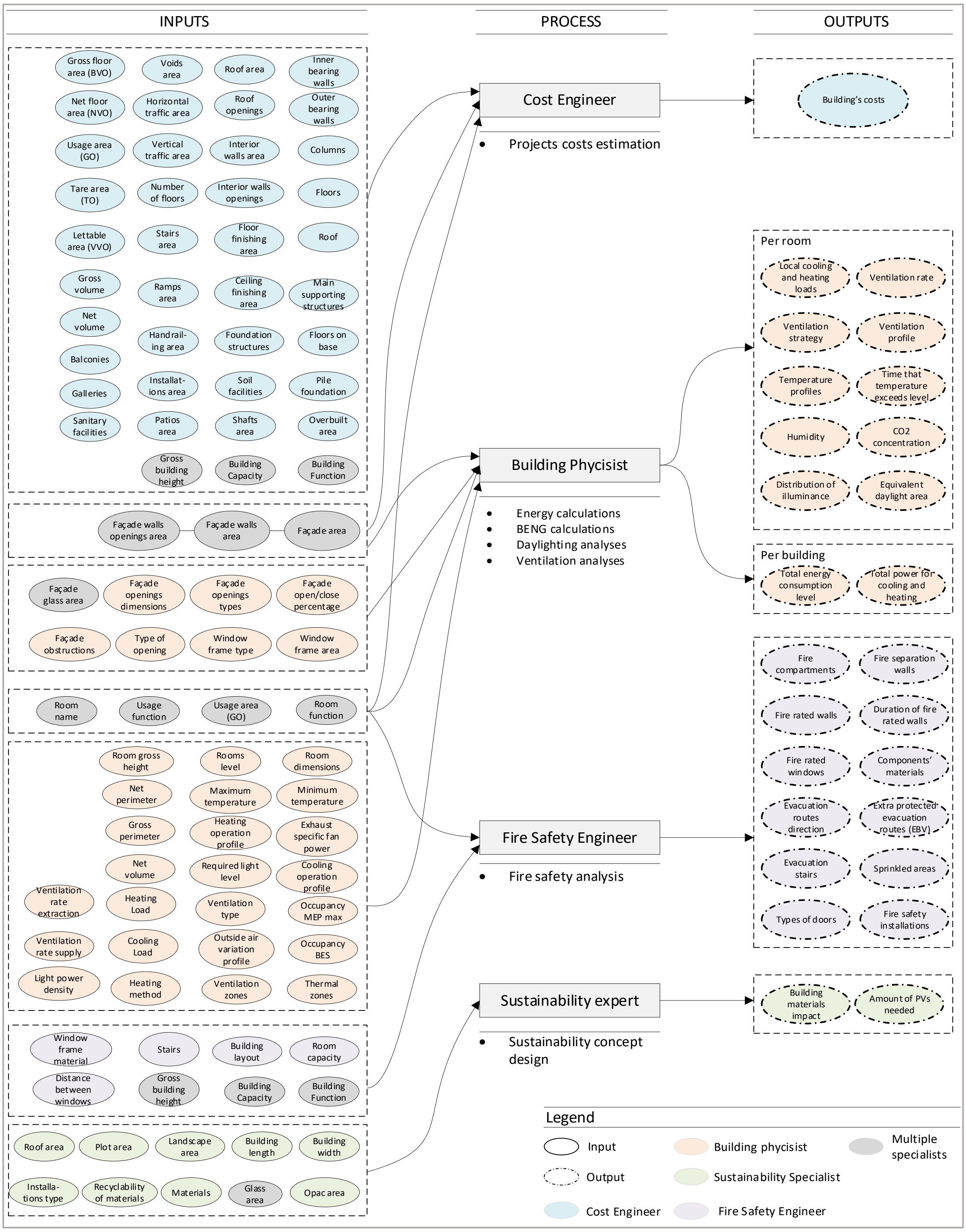

Figure 14: Summarized inputs and outputs of early design phase

4.1.2 Final design phase

This chapter presents the outcomes of the exploration of the current practices with regards to data handling during the initiation of the final design stages. For that purpose eight ABT's specialists and engineers that are involved at that design phase were interviewed and relevant working files/documents were investigated.

Process model

The current process model of the initiation of Definitive Design (DO) phase as emerged from the investigation of that stage, is illustrated in Figure 15. The differences with the early design phases process are highlighted with light blue color and they refer to the engagement of the architectural and structural engineering departments and the development of the 3D BIM model, which also serves as an additional source of information for specialists.

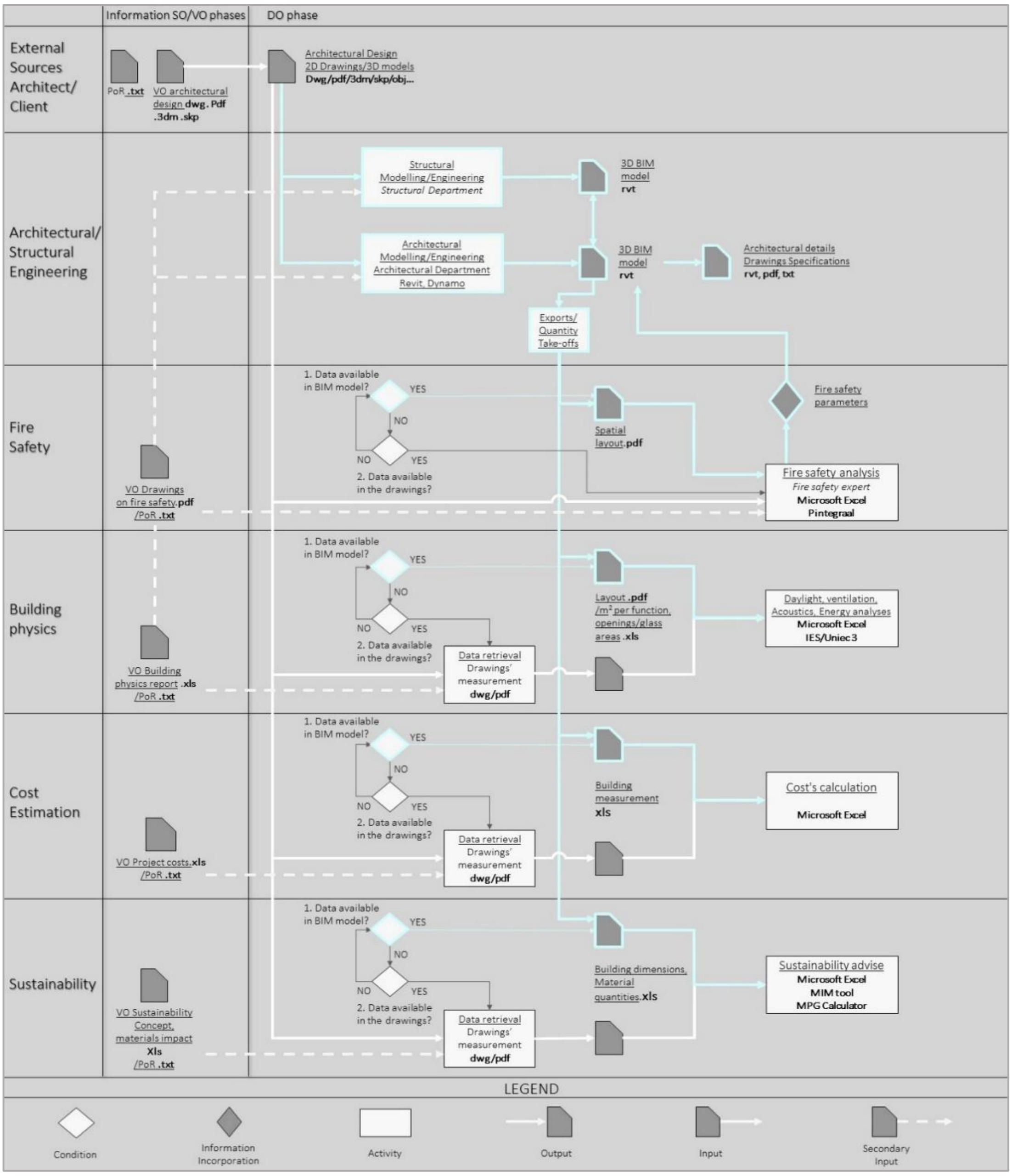

Figure 15: Final design (DO) phase process model

The DO stage initiates when the external architect shares his work ABT team members, which is the primary source of information. Moreover, the outputs of the VO phase, like fire safety and building physics requirements and parameters are also used as input for specialists and the architectural and structural departments.

As soon as the required information is received, structural engineers start by creating a concept structural design. Afterwards, based on this concept design the structural model is being developed and elaborated. On the other hand, the architectural engineering department starts its activities based on the drawings of external architects. The process initiates by incorporating geometrical information in the models. Then, ABT's architect engineers use information from the Program of Requirements, the specialists' outputs from preceding phases and the internal knowledge of ABT to perform technical elaboration of the design.

During that stage, engineers start enriching their models with additional information like rooms, functions or characteristics related to acoustic parameters, fire safety specifications and materials as part of the engineering process. They usually receive pdfs with drawings or excel and text files and they manually adding the parameters to certain elements of the models. However, in some projects specialists are given access to work directly inside the 3D model and add parameters and outputs of their work.

As far as the specializations of cost estimation, building physics, sustainability and fire safety are concerned, their sequence of activities remain the same as described in chapter 4.1. However, a differentiation lies on the fact that the 3D BIM model, developed by the architectural and structural departments is also a source of information. Therefore, when a 3D model is available, specialists can automatically extract data for their calculations and analyses.

Inputs of final design phase

The information that is required for the initiation of the final design phase is presented below. The input needs of the disciplines that were investigated during the early phases remain the same. The architectural and structural engineering departments initially require information with regards to the geometry and shape of a building, for the development of their 3D models and the investigation of clashes and design problems. Furthermore, architect engineers need additional information concerning building physics, environmental and functional performance, constructability and maintainability aspects, regulations or specifications from the Program of Requirements.

Figure 16, illustrates the aggregated inputs of final design, where Appendix C contains a more detailed description of these data. Part of this information can already be traced in the outputs of the previous design phase and is graphically represented with dashed-line oval shapes. Nevertheless, there is also a piece of information that is not produced at all during earlier stages and is required for the work of architects. This is highlighted with yellow-lined oval shapes.

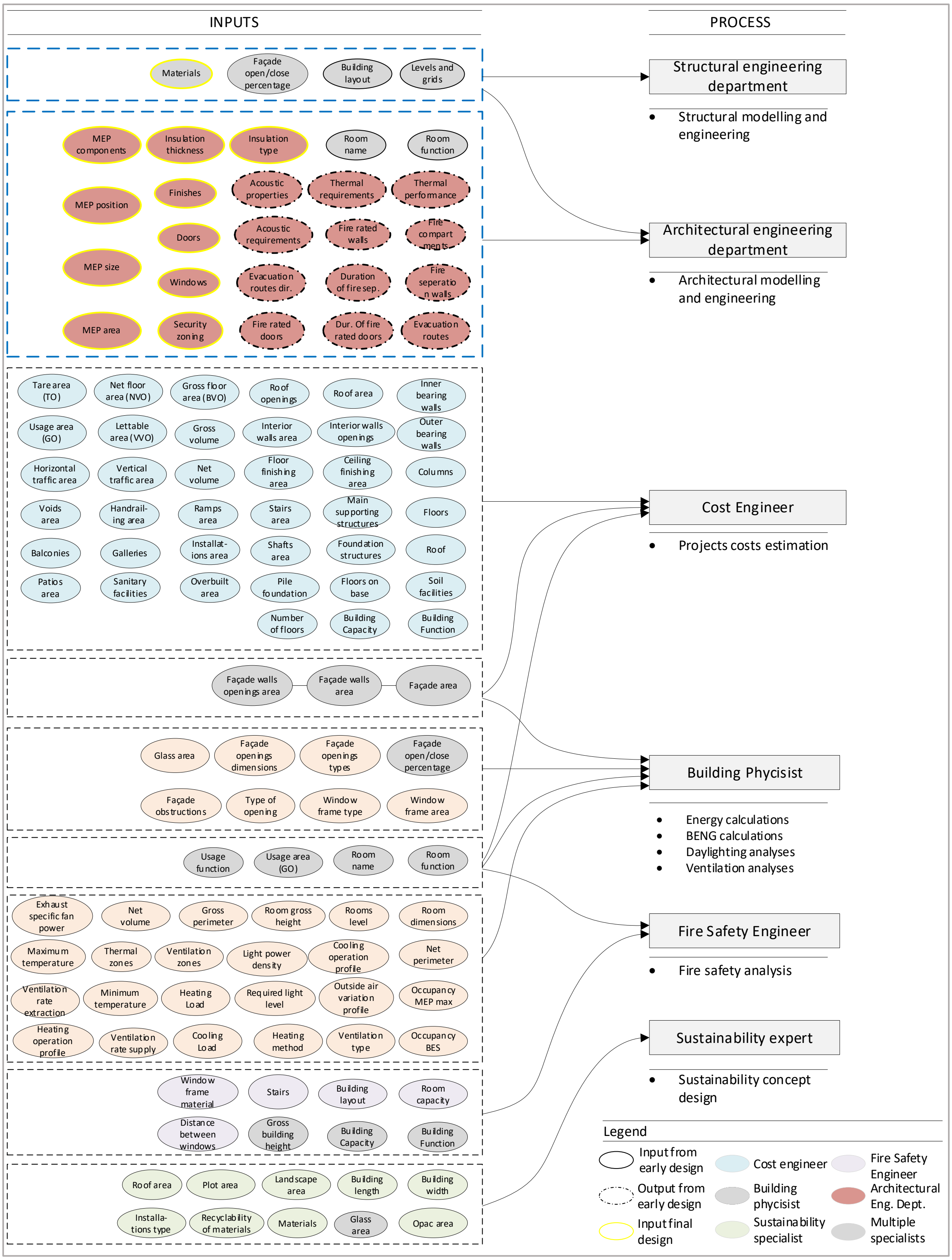

Figure 16: Summarized inputs of final design phase

4.2 EVALUATION OF CURRENT PRACTICES

Further to the thorough investigation of current practices in terms of structuring and using data in the early and final design stages, the main deficiencies and challenges of the existing process are hereby presented. In order to do so, the process models that derived from the exploration of these phases were evaluated and the areas that shortcomings lie were highlighted and further analyzed.

4.2.1 Deficiencies of current early design process

As far as the early design stages are concerned, the main problems relate to data retrieval process, structure of the collected data, and structure of the final outputs. Figure 17 illustrates these points of attention by highlighting them with distinct colors.

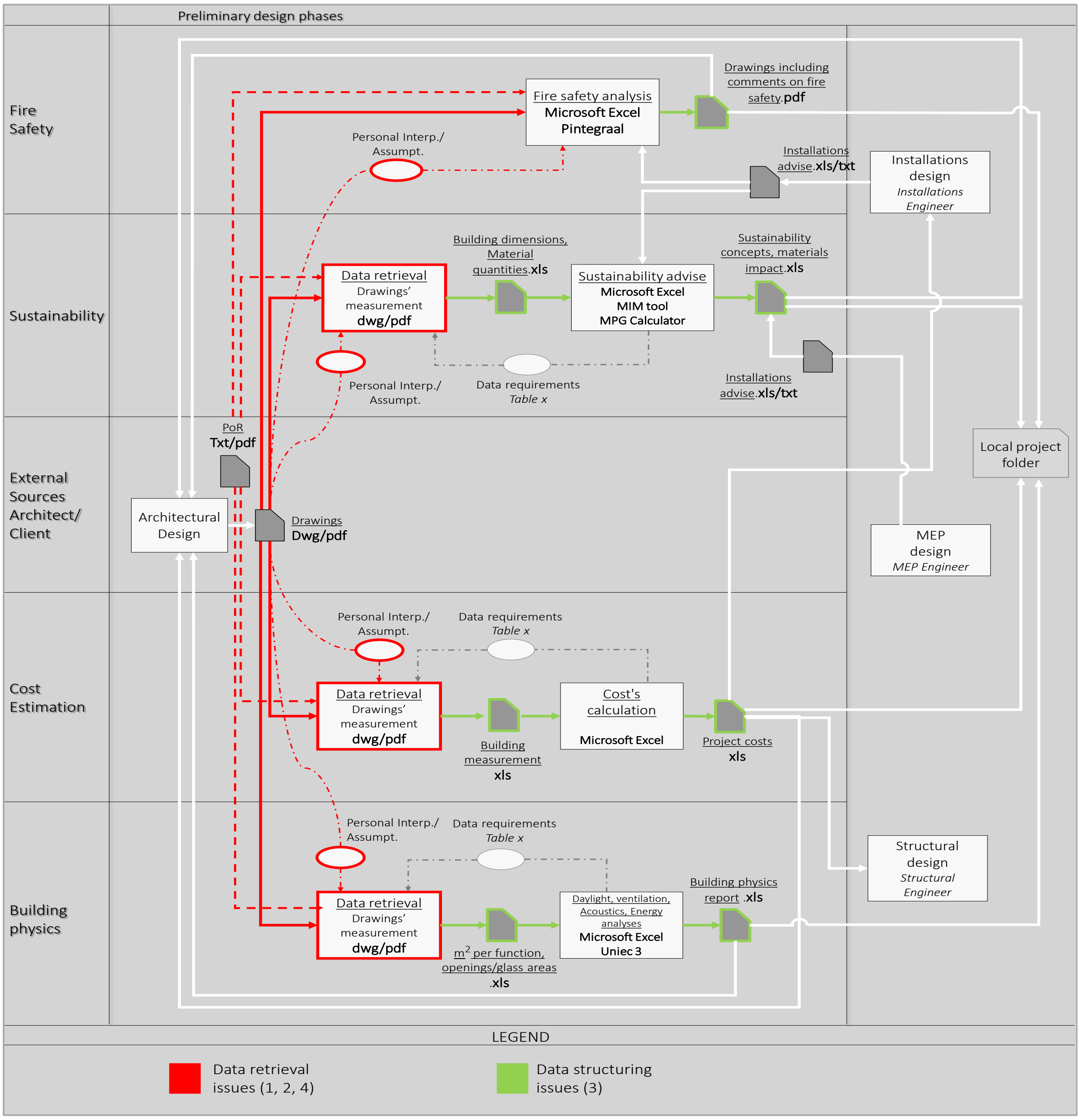

Figure 17: Early design process deficiencies

Lack of collaborative practices

The principal issue is associated with the lack of collaborative practices among integrated project members. What seems to be challenging and problematic for specialists is that there are lots of iterations and rework, from the perspective that each discipline does the same operation in order to retrieve necessary data. Thus, every specialist spends a significant amount of time for an operation that ideally could be only done once.

Time consuming and inaccurate data retrieval approach

The second issue concerns the manual data retrieval approach that is usually followed. This method, requires significant amount of time since the entire design data have to be measured from pdf files. Furthermore, apart from being notably time-consuming, this approach is not accurate at all since errors can be easily made due to loose and imprecise snap and reference points. Moreover, the drawings are plotted in different scales so there is always the hazard that calculations are made on different or false scales. This matter, is even more evident when there is time pressure to give feedback about specific reports and calculations that later on affect other disciplines.

Structuring issue

A notable deficiency of the existing process during the preliminary design phases, concerns data structuring of both inputs as soon as the take off process is completed and outputs of specialists analyses. What can be observed here is that all retrieved information is gathered in temporary Excel files on each specialist's working platform, until it is transferred to the designated software for specific analyses and calculations. Moreover, their outputs are also stored in isolated working files in various format types.

Data consistency issues

Another notable shortcoming relates to inconsistencies when it comes to using certain building data. Given the fact that multiple specialists have to collect all necessary data that are needed for their designated tasks on their own, they tend to interpret the design and make specific assumptions when needed based on their experience and expertise, without aligning it with other project members. This is even more evident when certain constituents of a design are not explicitly defined by the architect (i.e. functions of areas, materials used, type of windows etc). Therefore, that leads to occasions where specialists use different values for the same design data, therefore resulting in data inconsistency issues. However, what is equally leading to the use of inconsistent data, is the fact that specialists in certain cases are not using the same version of the design, because of the existence of multiple information sources.

4.2.2 Deficiencies of interface between early and final design phases

As far as the transition from the one design phase to the other, an important issue is traced on the interface between them. The main limitation here lies on the fact that the information that is generated in the early design stages is saved on format types that are not interoperable with final design stages. Therefore, when engineers start their work in later stages it is not possible to integrate this information into the design (i.e. importing it into Revit).

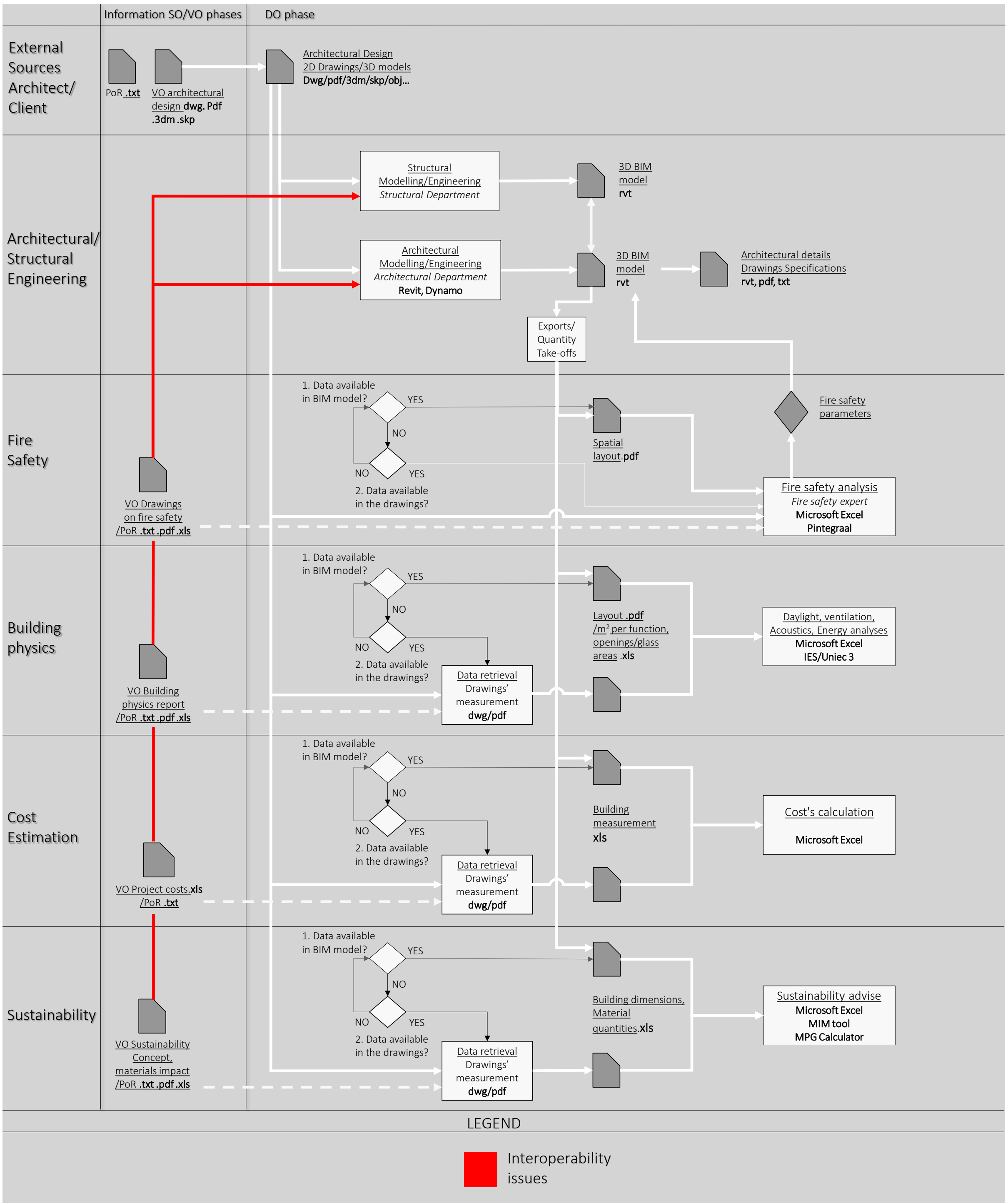

Figure 18: Early and final design interface deficiencies

5. CONCEPTUAL DESIGN

5.1 NEW PROCESS MODEL

Taking into consideration the findings above there is an emergent need of defining a new process model that will mitigate or overcome these barriers. This research introduces a new process for preliminary and start of final design stages with regards to information handling, which is illustrated in Figure 19.

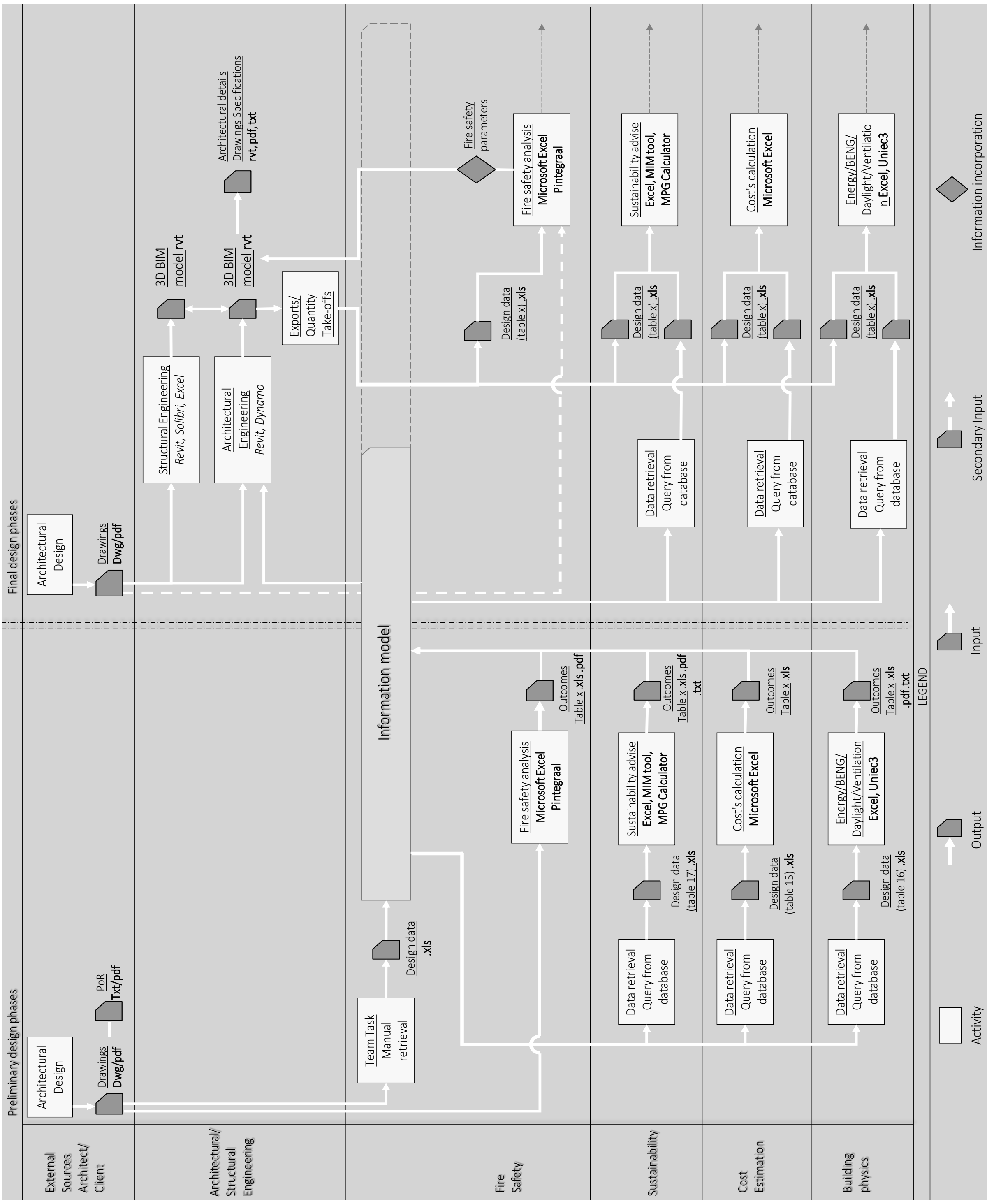

Figure 19: Proposed process model

The core idea is the establishment of a centralized information model which serves as the main information source for the activities of specialists during the early design stages. The very first step consists of the data take-off from the Program of Requirements or from 2D drawings and the deposition of data in the model, which is a manual process. In this case this is a collective task, which implies that there is a shared responsibility among the members of an integrated team for extracting data and filling this database. When certain data are available in the model, specialists can make queries and retrieve them automatically for executing their operations.

Moreover, while switching from the VO to the DO phase, this information model will also act as the principal data source for specialists and the architectural/structural engineering departments and provide them with information from the preceding phase. This will enable a smooth and consistent data flow from the earlier towards the final phases while minimizing the information loss.

Here, it has to be mentioned that during the DO stage there are lots of iterations in the design and engineering process, so depending on the requirements of each project multiple loops with information exchange may take place. However, since the scope of the research covers only the initiation of the DO phase these loops are not depicted in the process model. Throughout this chapter, more detailed insights on the requirements, characteristics, and function of the new workflow will be thoroughly presented.

5.1.1 Process model requirements

Having previously designed a novel process model to address the issues of chapter 4.2, there are some emergent requirements, which can be perceived as pieces of a wider puzzle that have to be put together. These requirements relate to both information structuring aspects and workflow related issues.

1. Inclusion of aggregated data set

The information model that constitutes the core of the new process in order to serve its purpose, it has to contain all data that specialists and engineers require for their designated tasks in early design phases as well as during the initiation of the final phases.

2. Systematic data structure

Moreover, it is essential to provide users with a common language when it comes to data interpretation, so they can share a mutual understanding. Thus, it is necessary to establish a structure to define and describe data in a systematic way.

3. Interoperability with final design phases

What is also necessary, is that the data structure of early phases should be interoperable with the final design phases. In this way, it is ensured that information that is generated in the SO and VO stages can be integrated into the design of engineers in final phases and therefore reused.

4. Flexibility of adding data without a predefined sequence

From the investigation of the SO and VO design stages, it is acknowledged that especially during the very early phases, the availability of information is rather incidental. That means that based on the provided sources there is not a standard piece of information available, so some data might be or not be available depending on the development of the design. At the same time, during the early stages there is not a standard process with sequence of actions by different people. This is determined by the objectives of each project. As such, the new workflow should give specialists the flexibility of adding any kind of data at a time without requiring a strict sequence and dependency of data that are stored.

5. Visual feedback on what is already recorded

Finally, it is necessary that specialists are able to identify what information is already recorded and have a visual feedback on the correspondence between the entities that are filled in the database and the actual design. So for example, when somebody creates Space1 entity, another project member to be able to identify in the design which space is actually Space1.

5.2 DATA STRUCTURE

5.2.1 Selection of a common data structure: *Industry Foundation Classes (IFC)*

According to the literature search, since the IFC format is considered a major data exchange schema standard for BIM (Building Smart, 2020) and comprises a comprehensive set of entities for managing spatial and semantic information about building elements as well as modelling spatial relationships between these elements (Daum & Borrmann, 2014), this research suggests that IFC data format can be used as basis and be extended in accordance with the research's information needs that were acquired in previous chapters, in order to fulfill the first two functional requirements as stated above.

Moreover, another essential aspect that justifies this selection, is that structuring information of early design phases in IFC based format provides interoperability with the final design stages. Hence, when project members like architect engineers start their work in these phases, they are able to open and integrate these data in their platforms (i.e. Revit, ArchiCAD etc.) and use them as a basis for their operations later on (process requirement 3).

5.2.2 IFC entities relevant to research's needs

Hereby, the IFC schema is explored to identify what piece of information from chapter 4 is already covered. An overview can be seen in Table 22 of appendix D. However, currently IFC does not fully address i) the needs of specialists during the early design phases, ii) part of the information that is needed during the initiation of final design nor iii) part of the early phase's outputs that are used as inputs in the start of final design.

Initially, although IFC schema contains the concept of predefined building systems such as the ''OUTERSHELL'' for facades and zones like ''FIRESAFETY'' for fire compartments, the process of defining them is very rigid. As such, in order to create these systems, all the elements that aggregate them must be defined first. More specifically, in order to capture information concerning the façade for example, all ifcWall entities have to be created and then set the property IsExternal = ''true''. The same thing applies to fire compartmentation, MEP systems, thermal and security zones. However, this process is not useful at all when specialists want to express initial information for that kind of systems as a whole in early stages where information about sub-elements that compose them are not available.

Moreover, as seen in Figure 20, specific concepts and attributes that are necessary during these phases are not included at all. These have to do with general building characteristics, specific measurements according to NEN 2580 norm, the total surface of traffic areas, building physics characteristics and specifications and MEP components.

Therefore, the subsequent part suggests the introduction of additional concepts and property sets, in order to sufficiently cover the information requirements of these phases.

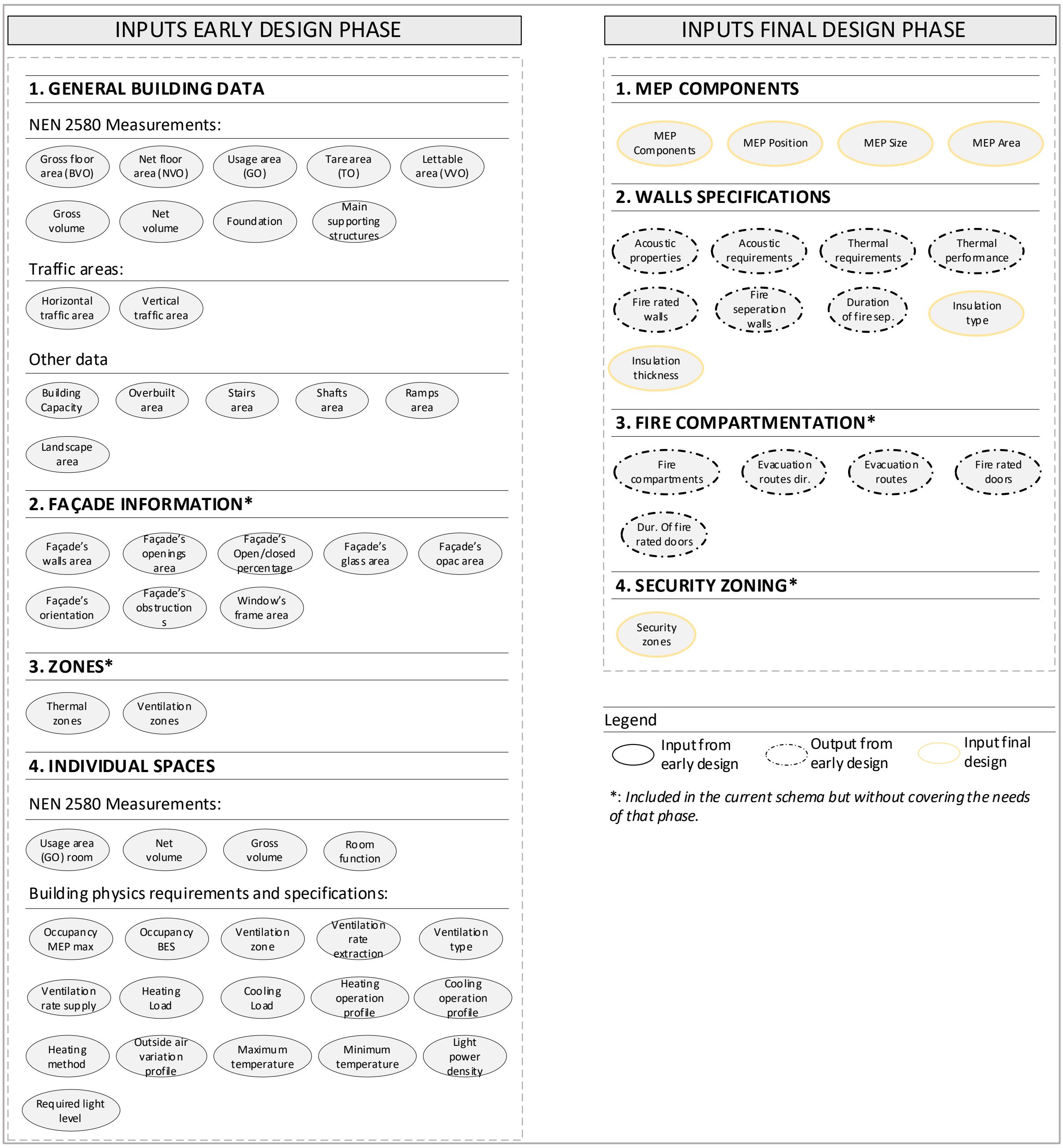

Figure 20: Information that is not covered by the existing IFC schema

5.2.3 Data structure definition

In this step, the development of the proposed data structure is presented. In order to define information with regards to the entities and their relationships, there is the need of an ontological application, which allows the publication of IFC-based objects as directed labelled graphs, represented using the Resource Description Framework (RDF) (Building Smart, 2020). This research's structure is based on ifcOWL ontology whereas red colored boxes demonstrate the proposed new additions.

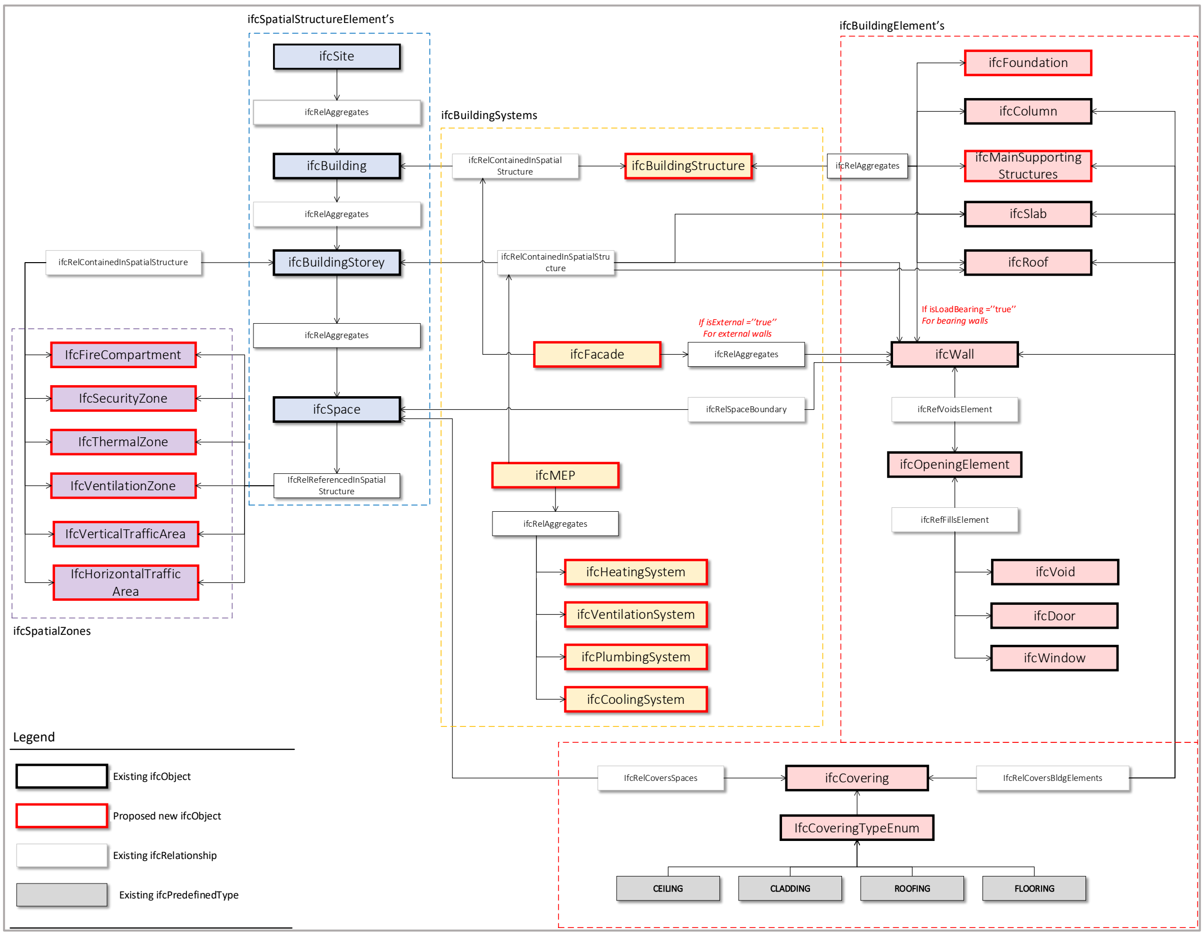

Figure 21: Enriched ontology for early design phases

As shown in Figure 21, the existing ontology is initially complemented by introducing new concepts that represent building systems and zones. These are the building systems *ifcFacade, ifcBuildingStructure* and *ifcMEP* and six spatial systems; *ifcFireCompartment*, *ifcSecurityArea*, *ifcThermalZone*, *ifcVentilationZone*, *ifcHorizontalTrafficArea* and *ifcVerticalTrafficArea.* The introduction of these concepts overcomes the barriers that stem from the strict way that ifc is built up and allows the representation of information about these systems even before defining all objects that compose them. For example, having information on the percentage of open/closed area and the acoustic requirements of the north façade of a building, before capturing all external walls of the building, or defining a ventilation zones before talking about specific spaces.

Furthermore, two more entities; *ifcFoundation* and *ifcMainSupportingStructure* are also added to the current schema. In addition to these extensions, new properties and property sets are also utilized to include data from Figure 20 and are discussed later on this chapter. All new additions throughout the document are highlighted with red color. The rest entities and relationships already exist and therefore reused. Each component of the ontology is briefly explained below.

Spatial structured elements

Initially, the data model starts with spatial elements (highlighted with blue dashed box) which are structured in a hierarchical manner. As such, first the *ifcSite* entity is modeled, which is composed by *ifcBuilding* entities, which in turn is composed by one or more *ifcBuildingStorey*, which again consists of one or more *ifcSpace*. In order to related these entities the *ifcRelAggregates* relationship is utilized.

New spatial elements
Moreover, new additional spatial elements; *ifcFireCompartment*, *ifcSecurityArea*, *ifcThermalZone, ifcVentilationZone, ifcSecurityZone, ifcHorizontalTrafficArea* and *ifcVerticalTrafficArea* are integrated into the structure. These elements represent wider zones under some functional consideration. They are contained in one building storey using the *ifcRelContainedInSpatialStructure* relationship and have a set of predefined properties which are later presented. Moreover, one or more spaces can be referenced in these elements using the *IfcRelReferencedInSpatialStructure* relationship.

New building systems
Three new main concepts as building systems are utilized. *ifcFacade* captures each building's façades as independent components. It is linked to *ifcBuilding* using the relationship *IfcRelContainedInSpatialStructure.* It also consists of property sets that contain general information like id and orientation, basic physical measurements and building physics requirements and specifications, which are presented later. In addition, the *ifcBuildingStructure* entity represents the building's skeleton and is also linked to *ifcBuilding.* Finally, the *ifcMEP* is a generalization of the HVAC system of the building. Each one of the systems namely *ifcHeatingSystem, ifcVentilationSystem, ifcCoolingSystem* and *ifcPlumbingSystem* include other components such as pipes, ducts etc.

Building elements
On the other hand, building elements are highlighted with red dashed box. *ifcSlab*, *ifcRoof* and *ifcWall* elements, using the *IfcRelContainedInSpatialStructure* relationship are associated with one ifcBuildingStorey. These three entities might also contain openings, like doors, windows or plain voids for walls or just voids for roofs and slabs. As such, in order to capture this aspect, the *ifcOpeningElement* entity is connected with these elements using the *ifcRefVoidsElement* capturing the opening in general. Then, the *ifcRefFillsElement* relationship connects the ifcOpeningElement with *ifcDoor*, *ifcWindow* or *ifcVoid* in order to specify the type of opening. Moreover, *ifcFoundation*, *ifcColumn* and *ifcMainSupportingStructures* together with *ifcRoof*, *ifcSlab* and external *ifcWall* are assigned to *ifcBuildingStructure.*

The *ifcWall* entities that have the *IsExternal* property = ''true'' are also referenced in one *ifcFacade* system using the *ifcRelAggregates* relationship. *ifcWalls* also provide boundary to one or more *ifcSpace* entities (*IfcRelSpaceBoundary* relationship). Furthermore, in order to include information with regards to finishes the *ifcCovering* entity is employed. This entity is assigned to one *ifcSpace* using the relationship *IfcRelCoversSpaces* and to one building element using the relationship *IfcRelCoversBldgElements*.

Materials
As far as the materials are concerned, they are specified using the relationship *IfcRelAssociatesMaterial* linked to a building element. The attribute RelatingMaterial may refers to an object, which can have several subclasses like: ifcMaterialLayerSet, ifcMaterialLayer and IfcMaterial. Figure 22 below illustrates in a graph based format the relationship of all building elements with materials.

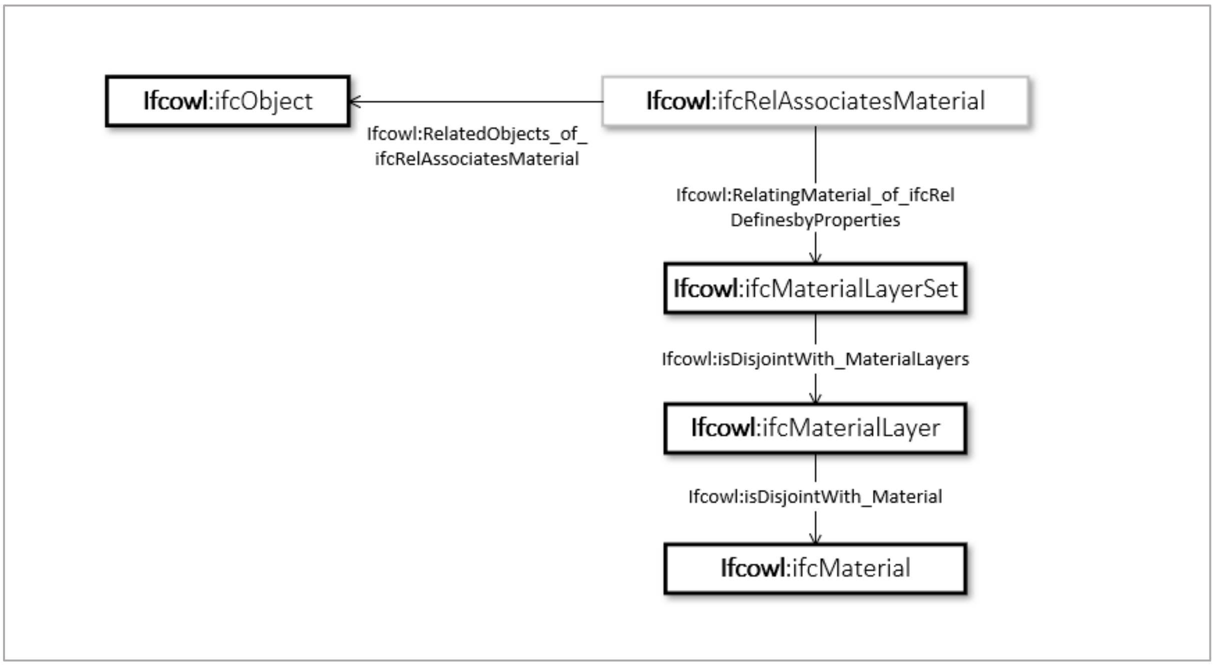

Figure 22: ifcRelationship connecting IfcBuildingElement and IfcMaterial

Property and Quantity Sets

Each ifcObject, both ifcSpatialElement and ifcElement, has specific property and/or quantity sets that define detailed information according to the needs chapter 4. The general approach that is followed related ifcObject classes with ifcPropertySet and ifcQuantitySet classes, using the ifcOWL ontology is illustrated in Figure 23.

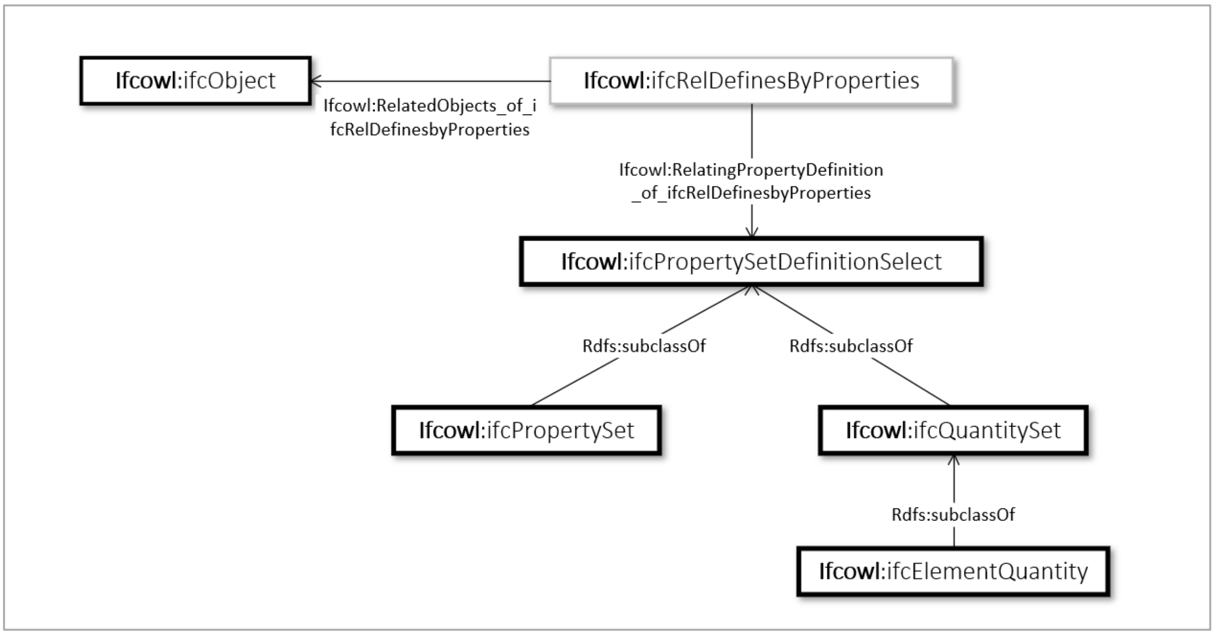

Figure 23: ifcRelationship connecting ifcObject and ifcPropertySet or ifcElementQuantity classes

IFC schema already contains a rich set of properties which are reused, however for information needs that are not included extensions and new property sets and properties are proposed. The new additions are presented in red color. Appendix D contains all ifcObject entities and their respective Property and Quantity Sets. As a general approach, in order to be as simple as possible, the extension of the current IFC schema tries to keep the new properties to minimum while maximizing the usage of existing ones. However, the main aim is to integrate every single data need into the new structure.

5.2.4 Relevance of new concepts throughout the design phases

The main objective of introducing new IFC systems is to respond particularly to the information needs of early design phases. Yet, they are still valuable in a BIM process even later, since specialists keep referring to them for part of their calculations.

Nevertheless, as the design evolves so as its level of detail, they are also decomposed into detailed components in order to support more comprehensive calculations. For example, a facade that is used in early design which is later on decomposed into multiple exterior walls. Therefore, it is inevitable that part of the systems' attributes becomes obsolete or their rough level of detail is no longer useful in later stages. Even so, there is still a significant amount of attributes that are still useful and reused in final phases.

So, the main vision is that these systems are kept and used throughout the lifecycle, but as soon as there are decomposed part of the sub-elements' attributes is automatically inherited from them. Overall, it is expected that this will be the case for the following systems, ifcFireCompartment, ifcSecurityZone, ifcVentilationZone, ifcThermalZone, ifcMEP, ifcFacade and ifcBuildingStructure.

Hereby, the same example with the ifcFacade and ifcWall entities is presented. Tables below contain the attributes of these entities where red colored ones give an indication of attributes that are automatically integrated from façade to walls. Exactly the same approached is followed for the aforementioned building systems.

Table 1: ifcFacade common properties

Pset_FacadeCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier
Orientation	Single value	ifcLabel

Table 2: ifcFacade base quantities

Pset_FacadeBaseQuantities		
PropertyName	**Template**	**Data type**
Length	Single value	IfcIdentifier
Width	Single value	ifcPositiveLengthMeasure
Height	Single value	ifcPositiveLengthMeasure
Gross Area	Single value	IfcAreaMeasure
Total closed area	Single value	IfcAreaMeasure
Total openings area	Single value	IfcAreaMeasure
Open/closed percentage	Single value	IfcAreaMeasure
Total glass area	Single value	IfcAreaMeasure

Table 3: ifcFacade building physics specifications

Pset_FacadeBFISpecifications		
PropertyName	**Template**	**Data type**
AcousticRatingRequirement	Single value	IfcLabel
AcousticRating	Single value	IfcLabel
ThermalTransmittanceRequirement	Single value	IfcThermalTransmittanceMeasure
ThermalTransmittance	Single value	IfcThermalTransmittanceMeasure
FireSeparation	Single value	ifcBoolean

FireRating	Single value	ifcLabel
FireSeparationDuration	Single value	ifcTimeMeasure

Table 4: ifcWall quantities

Qto_WallBaseQuantities		
Name	**Description**	**Type**
Length	Total nominal length of the wall along the wall center line (even if different to the wall path).	Q_LENGTH
Width	Total nominal width (or thickness) of the wall measured perpendicular to the wall path. It should only be provided, if it is constant along the wall path.	Q_LENGTH
Height	Total nominal height of the wall. It should only be provided, if it is constant along the wall path.	Q_LENGTH
NetSideArea	Area of the wall as viewed by an elevation view of the middle plane. It does take into account all wall modifications (such as openings).	Q_AREA
NetFootprintArea	Area of the wall as viewed by a ground floor view, taking all wall modifications (like recesses) into account.	Q_AREA
NetVolume	Volume of the wall, after subtracting the openings and after considering the connection geometry.	Q_VOLUME

Table 5: ifcWall general data

Pset_WallCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier
IsExternal	Single value	ifcBoolean
LoadBearing	Single value	ifcBoolean
Orientation	Single value	ifcLabel

Table 6: ifcWall Building physics specifications

Pset_WallBFISpecifications		
PropertyName	**Template**	**Data type**
Insulation	Single value	IfcLabel
InsulationThickness	Single value	ifcPositiveLengthMeasure
AcousticRatingRequirement	Single value	IfcLabel
AcousticRating	Single value	IfcLabel
ThermalTransmittanceRequirement	Single value	IfcThermalTransmittanceMeasure
ThermalTransmittance	Single value	IfcThermalTransmittanceMeasure
FireSeparation	Single value	ifcBoolean
FireRating	Single value	ifcLabel
FireSeparationDuration	Single value	ifcTimeMeasure

5.2.5 ifcJSON

Moreover, all IFC entities as well as their relationships, properties and property sets are encoded in ifcJSON format. Hereby, two examples are provided. The one captures the relationship between a building storey, a space and a wall object, while the second one defines a wall object and its properties.

```
{
  "type": "IfcBuildingStorey",
  "globalId": "66eaf36c-fab5-4ee5-9d8c-bcaa2f2d7c7d",
  "isDecomposedBy": [
    {
      "type": "IfcRelAggregates",
      "ref": "46f56d4d-c3e6-42a7-913a-23e4e8eae73c"
    }
  ],
  "decomposes": [
    {
      "type": "IfcSpace",
      "globalId": "0ad0aae1-7fbe-4cf0-9c00-621071ee204a"
    }
  ],
  "containsElements": [
    {
      "type": "IfcRelContainedInSpatialStructure",
      "ref": "3af95fed-7542-48e4-8e98-f543d0b5de32"
    },
    {
      "type": "IfcWall",
      "globalId": "e38a0149-dbbb-48be-8b04-1c5bc73ab55e"
    }
  ]
}
```


Figure 24: ifcBuildingStorey, ifcSpace and ifcWall relationships in JSON


```
{
  "type": "IfcWall",
  "globalId": "f92c2898-fd68-44ef-9178-3348e340017b",
  "isDefinedBy": [
    {
      "type": "IfcRelDefinesByProperties",
      "globalId": "d2ecfe17-45be-4b36-959d-1be3ec8193bd",
      "ownerHistory": "6d7919fd-2c83-497b-b21c-d4209e5162bf",
      "relatingPropertyDefinition": {
        "globalId": "486f7679-1a8a-4deb-8798-5a7e0c8c7d51",
        "ownerHistory": "6d7919fd-2c83-497b-b21c-d4209e5162bf",
        "name": "QTO_WallBaseQuantities",
        "hasProperties": [
          {
            "type": "IfcPropertySingleValue",
            "name": "Length",
            "description": "Length",
            "nominalValue": {
              "type": "IfcPositiveLengthMeasure",
              "stringValue": "insert URL"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "Width",
            "description": "Width",
            "nominalValue": {
              "type": "IfcPositiveLengthMeasure",
              "stringValue": "insert URL"
            }
          },
```


Figure 25: ifcWall properties and property sets in JSON

5.3 PROPOSED WORKFLOW

This part of the research introduces a workflow in line with the process model that is defined in chapter 5.1. The main objective is to describe how specialists of early phases can use the proposed data structure in order to meet the research's objectives. Moreover, it is demonstrated how the data generated in early design can be transferred to the final design.

5.3.1 Early design phase workflow

As described in chapter 3.1.2, initially three main use cases are formulated and presented below.

Table 7: Main use cases

• A ***project member*** wants to ***store information*** for an entity ***for the very first time***.
• A ***project member*** wants to ***add further information*** to an ***already recorded entity***.
• A ***project member*** wants to ***reuse information*** already ***recorded by others***.

Moreover, the basic workflow is illustrated in Figure 26, where detailed description and insights about the actions that are taken in each step are presented throughout this chapter. As a general remark, this workflow intends to bring as little as possible obligations for project members. Thus, they can start their processes by collecting information directly for the building components that they require. Additionally, the retrieval process of use case 3 has its own starting point since its start is not depended on the end of the other two use cases.

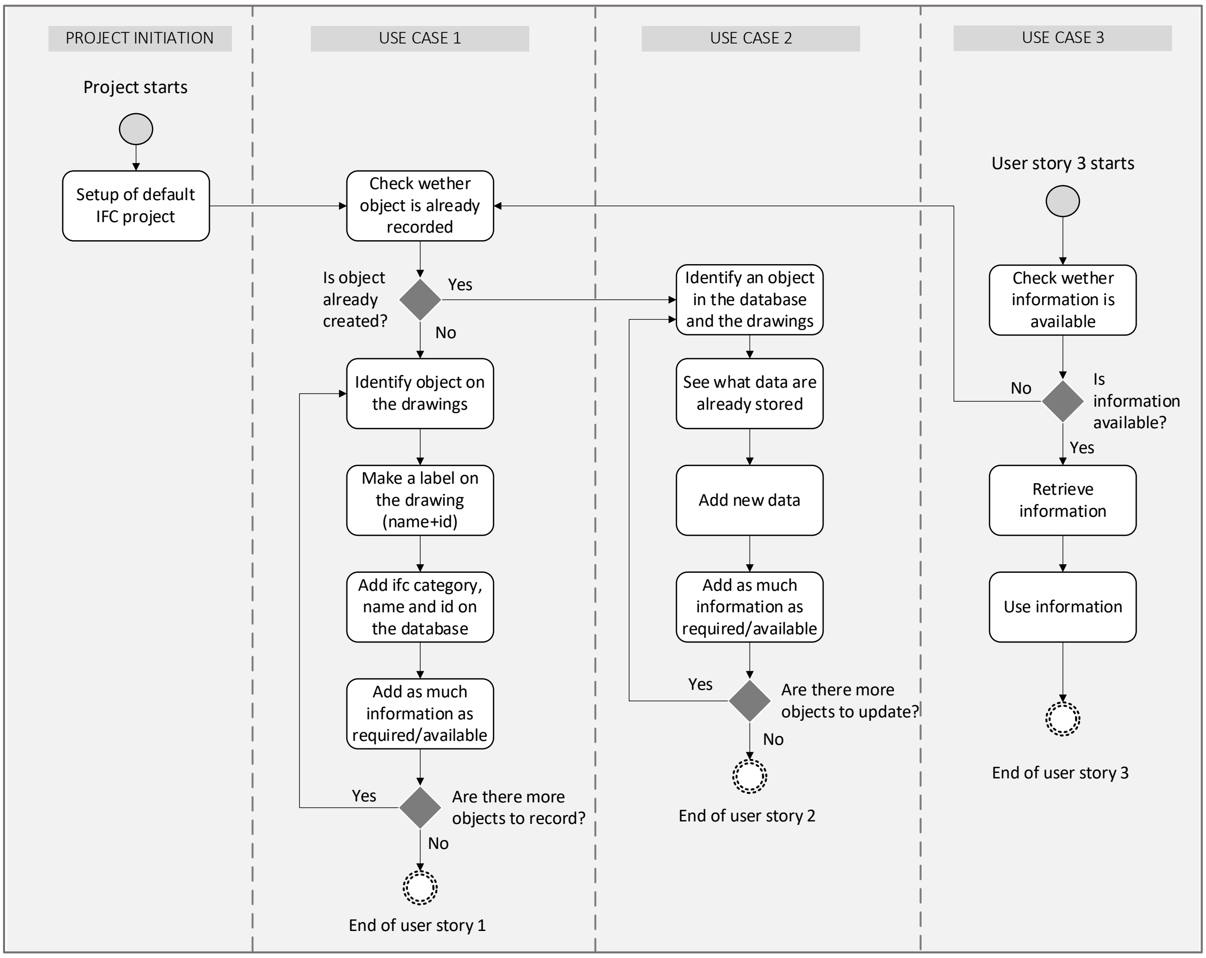

Figure 26: Basic workflow in early design stages

Project initiation

According to chapter 5.2, it is essential that the new workflow provides flexibility in filling the database without a predefined sequence. So every specialist can directly collect and deposit only the information that is relevant to his operation. However, the aim is to balance this requirement with the relationships and dependencies between different entities, as the data structure of Figure 21 suggests.

Hence, it is proposed that every project is initiated with predefined default entities and attributes corresponding to the ifc format, like one default ifcSite, ifcBuilding, ifcBuildingStorey, ifcFacade and so on. But, if it is needed to modify and add new entities on a later time it is possible to do so.

Visual feedback on what is already collected

Moreover, in order to allow specialist to identify and match the entities recorded in the database with the actual objects in the design, this research suggests that one set of drawings is shared and used within the project team. In this set, whenever specialists record new entities, they add labels for these entities in the drawing, using a pdf editor. This label consist of a unique name and id, which is the same as the one filled in the database.

Use case 1

The first use case addresses the scenario when a specialist is the first person to record and add information for an ifc entity. Hereby, a small example is provided to support the description of this process. In this case it is assumed that a new project starts and a building physicist is asked to analyze the acoustic requirements and performance of the façade first. Figure 27 illustrates an abstract sketch of preliminary design with the façade entity.

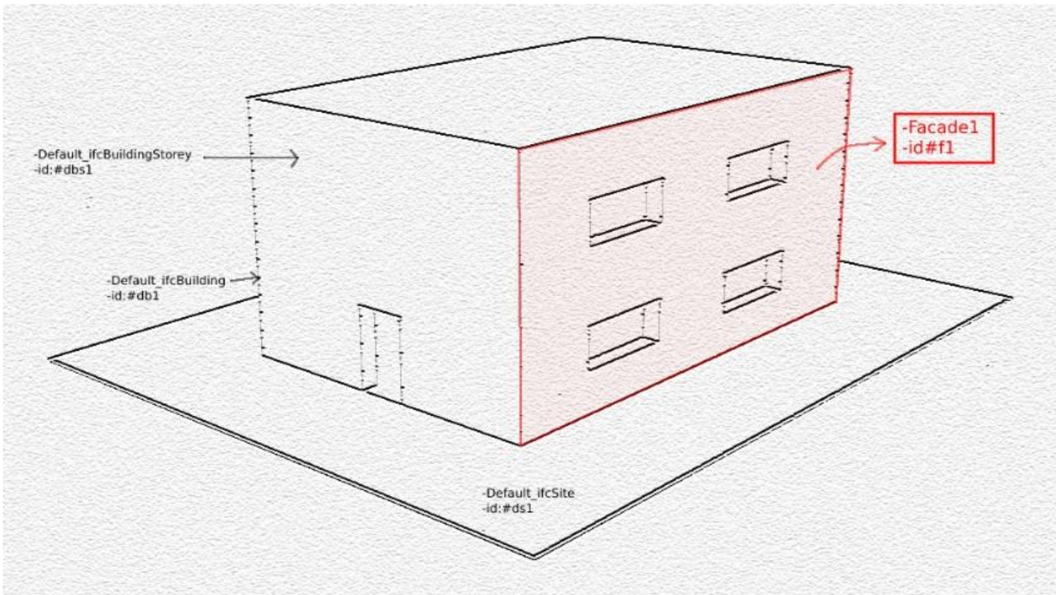

Figure 27: Abstract sketch of preliminary design with highlighted façade entity

Initially the building physicist identifies the façade that needs to be analyzed (which has not been recorded yet) and adds a label on the drawing with name and id. Accordingly, the same data is added to the database and then measurements about the façade are also filled. However, since the complete set of information about the façade is not available, some values are left to default. According to the suggestion earlier, the project already contains a default ifcSite, ifcBuilding, one ifcBuildingStorey etc. So the Façade1 is linked to default ifcBuilding.

Figure 28 and Figure 29 present two snapshots of the IFC at the specific time. In the snapshot, the attributes that are filled together with the values that are left to default can be seen.


```
{
  "name": "Default_Building",
  "type": "IfcBuilding",
  "globalId": "#b_def",
  "isDecomposedBy": [
    {
      "type": "IfcRelAggregates",
      "ref": "46f56d4d-c3e6-42a7-913a-23e4e8eae73c"
    }
  ],
  "decomposes": [
    {
      "name": "Default_BuildingStorey",
      "type": "IfcBuildingStorey",
      "globalId": "#bs_def"
    }
  ],
  "containsElements": [
    {
      "type": "IfcRelContainedInSpatialStructure",
      "ref": "3af95fed-7542-48e4-8e98-f543d0b5de32"
    },
    {
      "name": "Facade1",
      "type": "IfcFacade",
      "globalId": "#f1"
    }
  ]
}
```


Figure 28: Relationships between Facade 1, building and building storey

```
{
  "name": "Facade1",
  "type": "IfcFacade",
  "globalId": "#f1",
  "isDefinedBy": [
    {
      "type": "IfcRelDefinesByProperties",
      "globalId": "d2ecfe17-45be-4b36-959d-1be3ec8193bd",
      "ownerHistory": "6d7919fd-2c83-497b-b21c-d4209e5162bf",
      "relatingPropertyDefinition": {
        "globalId": "486f7679-1a8a-4deb-8798-5a7e0c8c7d51",
        "ownerHistory": "6d7919fd-2c83-497b-b21c-d4209e5162bf",
        "name": "Pset_FacadeBaseQuantities",
        "hasProperties": [
          {
            "type": "IfcPropertySingleValue",
            "name": "Length",
            "description": "Length",
            "nominalValue": {
              "type": "IfcPositiveLengthMeasure",
              "stringValue": "10"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "Width",
            "description": "Width",
            "nominalValue": {
              "type": "IfcPositiveLengthMeasure",
              "stringValue": "default"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "Height",
            "description": "Height",
            "nominalValue": {
              "type": "IfcPositiveLengthMeasure",
              "stringValue": "6"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "GrossSideArea",
            "description": "GrossSideArea",
            "nominalValue": {
              "type": "IfcAreaMeasure",
              "stringValue": "60"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "WallsArea",
            "description": "NetWallsArea",
            "nominalValue": {
              "type": "IfcAreaMeasure",
              "stringValue": "50"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "OpeningsArea",
            "description": "OpeningsArea",
            "nominalValue": {
              "type": "IfcAreaMeasure",
              "stringValue": "default"
```


Figure 29: ifcFacade and facade properties

On a later stage, it is supposed that the building consists of two levels, so one other project member wants to add more detail and decompose the facade into two parts, by recording two new walls, one on each building storey. In order to do so, first he creates two new ifcBuildingStorey entities, and then two ifcWall, Wall 1 and Wall 2, following the sequence of steps of user story 1. Figure 30 presents the sketch design with the entities that are required to analyze. As soon as the new walls are created they automatically inherit part of the façade's attributes, as stipulated in chapter 5.2.3. Moreover, when the two walls are linked with the façade, part of the façade's attributes is automatically updated or filled as the aggregate of the corresponding walls' attributes. These are: i) Gross area, ii) Total closed area, iii) Total openings area, iv) Open closed percentage. The rest façade properties remain the same.

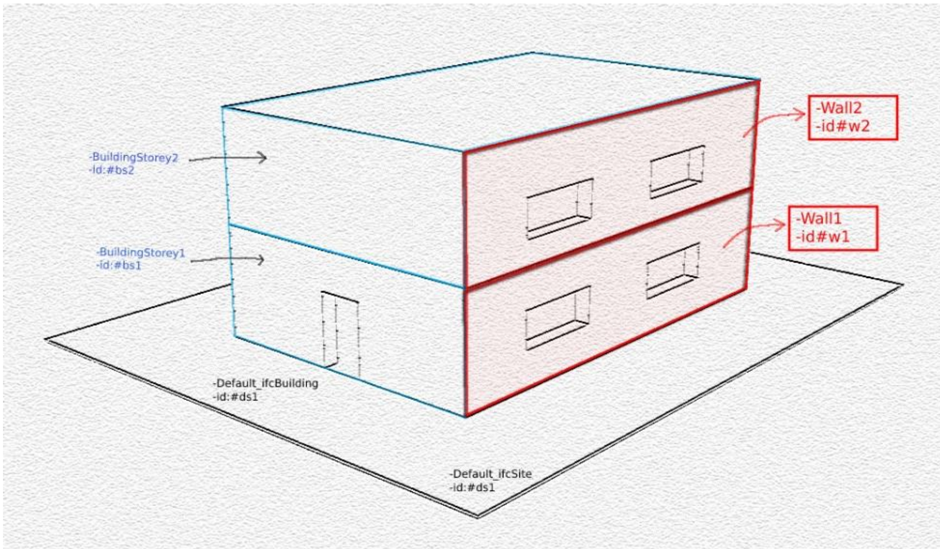

Figure 30: Abstract sketch of preliminary design with highlighted walls and storeys entities

Use case 2

The second use case relates to the scenario when objects have already been recorded and specialists enrich them with additional information or updating existing values. So using the same example, a third project member requires additional unregistered data in order to execute thermal analysis for the façade. As such, first he/she identifies the specific façade in the database and the drawings, sees what information is already available and consequently fills the required information based on the PoR, i.e. façade materials, thickness, thermal requirements. So, these attributes that were previously remained at default value, now are updated to the values based on the take-off of the second specialist. At the same time it is possible to change some existing attributes if there has been any modification in the design.

Use case 3

The third and last use case has to do with the scenario that a specialist only wants to retrieve and use information that is already collected earlier. This procedure is more straightforward and a project member initially checks if the information that he needs is already available. If so, he makes queries, collects it and therefore reuse it. In other case, he just goes back to user story 1 and follows the same steps.

5.3.2 Data incorporation in the final design

As far as the early design data incorporation into the final design is concerned, the main workflow is presented in Figure 31.

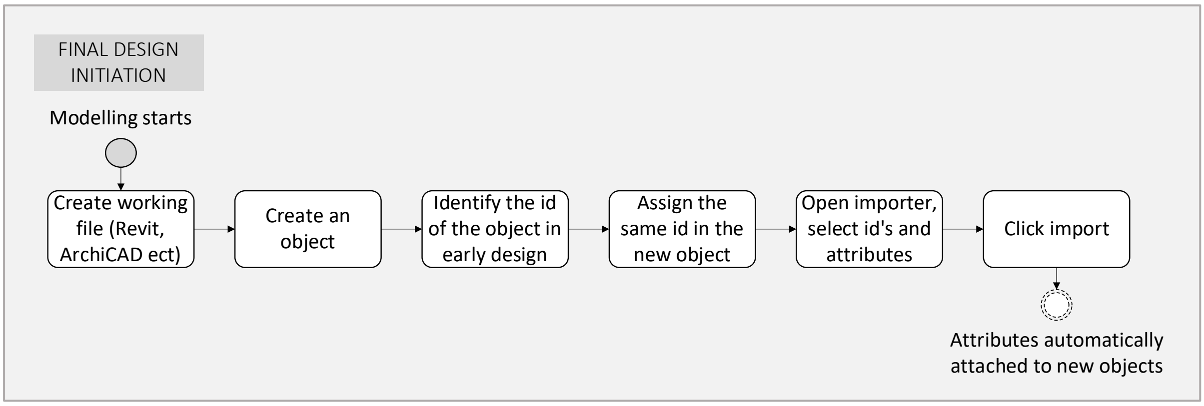

Figure 31: Data incorporation workflow

BIM modelers posses the main role in this transition. The process starts with the creation of objects in the working software (i.e. creating walls in Revit). What is essential, is that the id's of these objects should match the id's of the ifc objects that were created during the previous phase. As such, the modeler gets back to the outputs of early phases and makes sure that the id's between the objects correspond. Afterwards, an add-in application is required to import the attributes of ifc objects into the relevant objects of the final design file. For this research's case, a custom importer shall be developed and used. In this add-in the modeler selects the id's of the objects and the attributes that he wants to transfer. Then, the add-in reads the selected attributes from the ifc model and then automatically attach them to the new objects.

However, a distinction should be made between different piece of information that should or shouldn't be incorporated into the final design. The first group concerns attributes that characterize physical measurements such as length, width, area, height etc. These are generated automatically in final design as soon as an object is created in the 3D model. However, if these attributes are transferred from the early design model to the 3D model, and the values of early design don't match the values of final design, the geometry of the object will be modified. This will consequently cause problems and clashes to the 3D model. So, their transfer from previous phases is not recommended. On the other hand, all the other attributes that are not related to physical measurements shall be transferred from early design model to the 3D model.

6. DEVELOPMENT AND IMPLEMENTATION

Having proposed a new ontology and a workflow for preliminary design stages, it is important to demonstrate whether this proposal is feasible from an implementation standpoint. Therefore, using a Proof of Concept method this chapter aims to develop a prototype tool in order to showcase how the ontology can be applied in a case study. Moreover, for the scope of this research only wall and space entities shall be included in the working prototype.

6.1 System Architecture

The first part of this chapter describes the main system architecture of the proposed tool, which is composed of three fundamental parts. A user interface, an application programming interface (API) and a database, which are illustrated in the global architecture scheme of Figure 32.

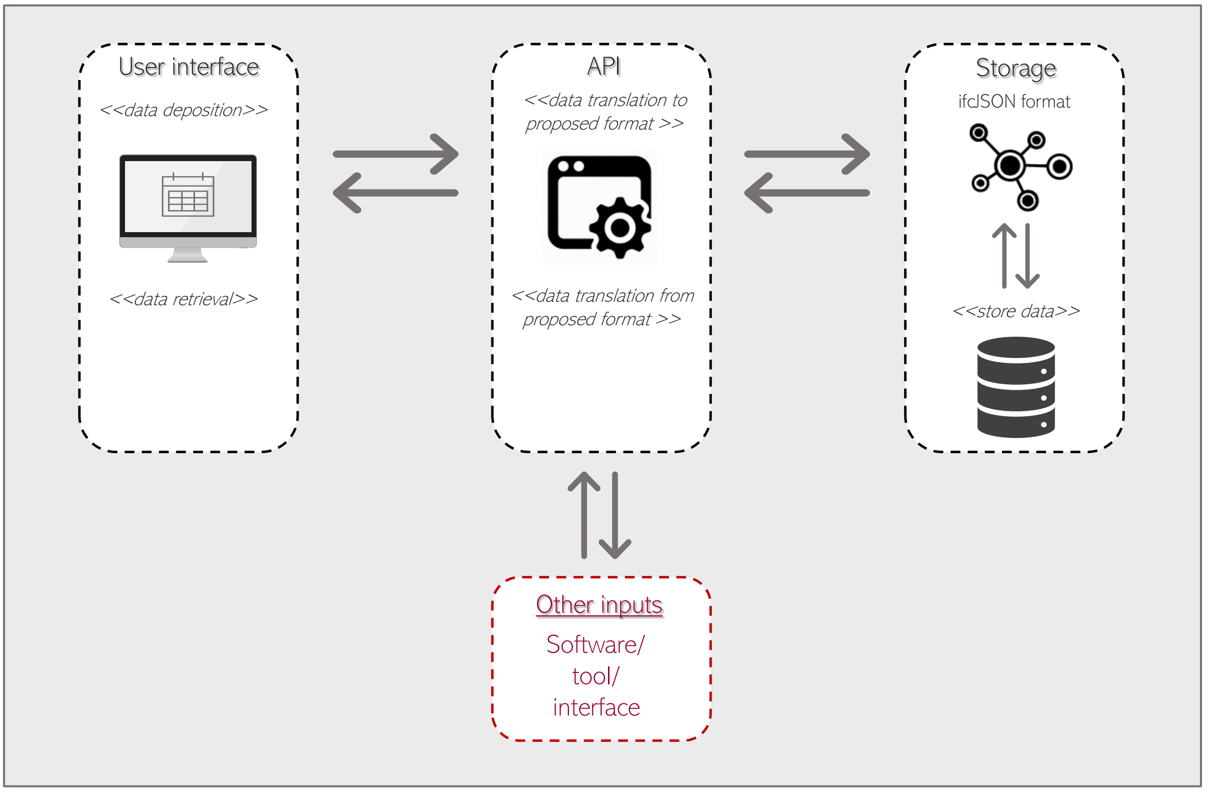

Figure 32: Global architecture scheme

In a nutshell the main idea is, as soon as the manual data take-off is completed, specialists and engineers deposit their data into a front-end (user interface). Then, data will automatically be parsed and translated using an Application Programming Interface (API) into ifcJSON and subsequently stored in this format into a database. On the same line, when specialists need to retrieve data from the database, they use this front-end to make queries from it. Then the API will read the data from the library and return them to the user front end in a easily readable format.

This proof of concept proposes an interface that specialists use to manipulate and add information. However, in a fully developed solution the overall system shall allow the integration of information from other sources, besides the manual take-off. As such, by using different interfaces or software, project members still will be able to covert information to the proposed structure and eventually deposit it in this centralized database.

6.1.1 User and application interface

Hereby a general system activity diagram is presented in Figure 33. As far as the data deposition is concerned, initially the user requests and receives a specific template containing only the datasets that are relevant to his take-off process through the user interface. For example, if a building physicist wants to add information related only to rooms' measurements and properties. The application receives this request and gets back to the user tables with the above mentioned datasets. Then, the user fills the tables with information collected from his/her manual take-off and finally clicks a save button in order to submit it. Then the application parses the data from these tables, converts them to JSON format and eventually exports them to the database where they are stored.

For the process of data retrieval from the data base, the user makes a data retrieval request, selecting again only the templates that he/she is interested in. The application interface receives the request and subsequently processes the request to the database. Afterwards, the database sends back the data that are requested in JSON format. Then the application parses the JSON format data, translates them in an easily readable format and sends them to the user in tables based on the templates that were initially requested.

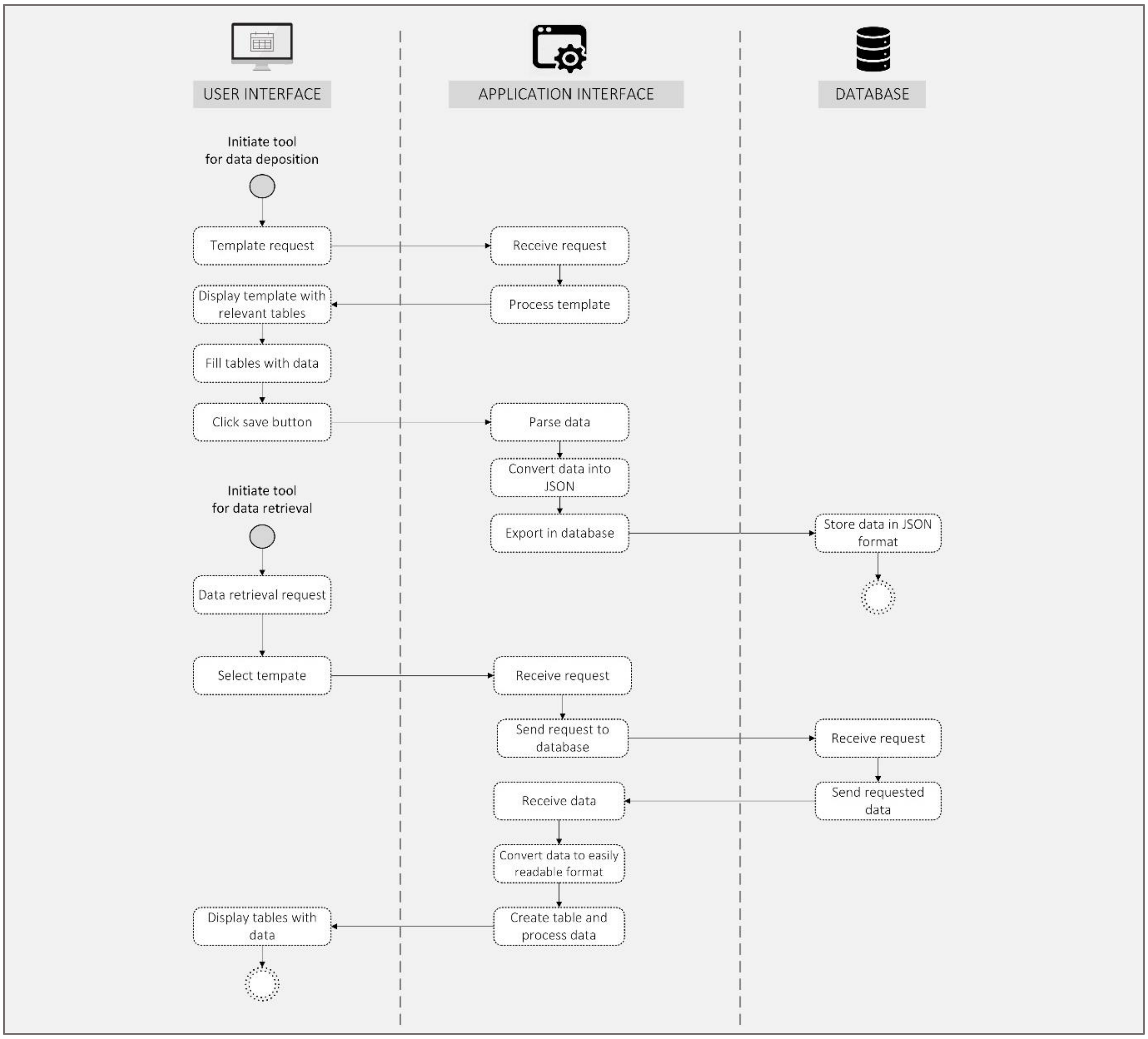

Figure 33: General system activity diagram

6.1.2 Storage provider

As far as the storage of data is concerned, a storage provider that supports JSON is required. As such, this proof of concept suggests that a NoSQL Document Database is utilized for that purpose. NoSQL technology stores information in JSON documents instead of columns and rows used by relational databases (Couchbase, 2021). Two main advantages of this choice can be acknowledged. The first is the flexible schemas that allow adding new fields, removing existing fields or changing the field values to a new type. This is particularly important since it supports cases where the main data structure is modified in order to capture additional building information. The second is the fast and easy queries of data (Schaefer, 2017).

6.2 PROTOTYPE DEVELOPMENT

This part of the research provides insights with regards to the development of the working prototype. In line with the findings of the previous step, this part intends to shape the user and application interface. In addition, it describes how data are converted into ifcJSON format and subsequently stored. Accordingly, the reverse process of translation of ifcJSON data and their display in the user interface in an easily readable format is described. For this proof of concept only two datasets, related to wall and space entities are taken into consideration.

The starting point consists of the definition of use cases. In chapter 5.3 three general use cases (epics) have been already formulated, which are hereby broken-down into smaller ones presenting more detailed actions.

Table 8: Use case 1

1. A ***project member*** wants to ***store information*** for an entity ***for the very first time***.	
•	1a. **Project member 1** wants to ***store data related to wall*** entities ***for the very first time***.
✓	Project member 1 creates wall objects.
✓	Project member 1 adds wall quantities and properties.
✓	Project member 1 saves to database.
•	1b. ***Project member 1*** wants to ***store data related to space*** entities ***for the very first time.***
✓	Project member 1 creates space objects.
✓	Project member 1 adds space measurements and properties.
✓	Project member 1 saves to database.

Table 9: Use case 2

3. A ***project member*** wants to ***add further information*** to an ***already recorded entity***.	
•	3a. ***Project member 2*** wants to ***store additional information related to wall entities***.
✓	Find what walls information is already available in the database
✓	Add walls information that is not yet stored
✓	Save to database
•	3b. ***Project member 2*** wants to ***store additional information related to space entities***.
✓	Find what space information is already available in the database
✓	Add space information that is not yet stored
✓	Save to database

Table 10: Use case 3

2. A ***project member*** wants to ***reuse information*** already ***recorded by others***.
• 2a. ***Project member 3*** wants to ***make queries and automatically retrieve data*** for ***building's walls and spaces***
✓ Find available wall measurements and properties
✓ Find available space properties

6.2.1 User interface

The initial point for shaping the working prototype is the establishment of the user and application layout. The front-end that shall be used for this system is Microsoft Excel. The purpose of this selection is to allow specialists depositing their data collected from a manual take-off, as well as retrieving data necessary for their calculations and analyses, that are already stored in the database. Excel is a widely adopted software by professionals for managing and processing building data. Therefore, the choice of this software can provide project members an easy access to the database.

6.2.2 Application interface

According to the global architecture scheme, an intermediate layer is required as a connection between Excel data and the database. Hence, a new Excel add-in is developed that can export data into ifcJSON format and consequently store them in this format, as well as import data from the database and present them in Excel. This add-in is created by ABT's development team.

As such, a new tab ''Add-ins'' can be found containing three main buttons namely; i) Create template, ii) Import from database and iii) Export to database.

Figure 34: New Add-in tab

The first button 'Create template'' creates two sheets that correspond to templates designated for depositing data; one for wall and another one for space objects. These are the main templates which consists of columns with name, id and all properties of the objects. To create a new object, i.e. a new wall, this can be easily done in the first column where the user shall give the name of the object and an id in the second. For exporting reasons, in the first row from cells C3 and onwards the property display format is the following ''Property/relationship/data type''. The following image presents the main template for depositing data.

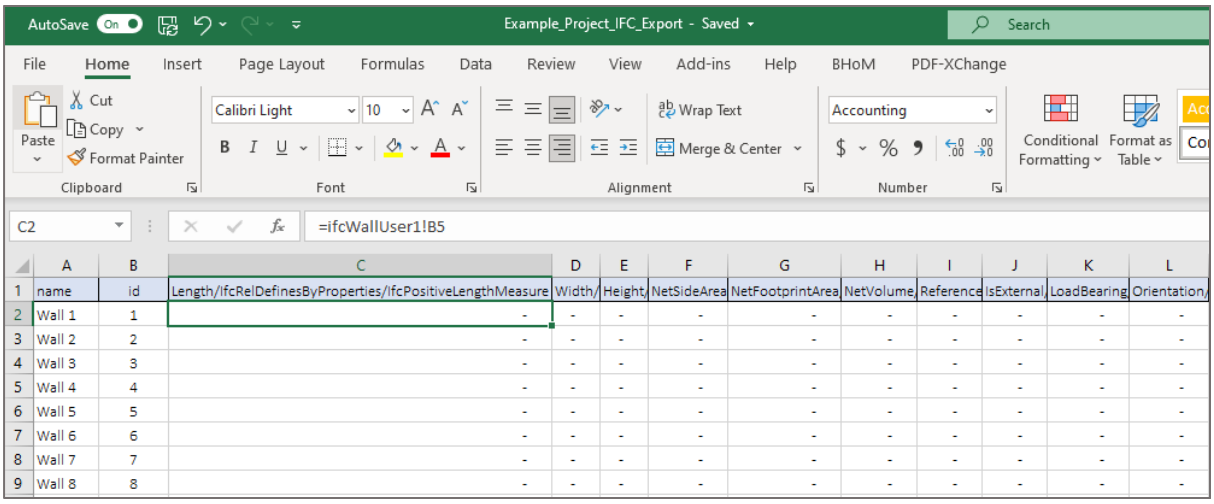

Figure 35: Data deposition main template

However, given the fact that this might be confusing for the end users and also in order to provide them specialized templates where they can manage only the data that they actually need, two pairs of secondary templates, connected to the main one are proposed. This allow specialists to customize the sets of data that they would like to deposit, without having to go through the entire dataset, which in large and multidisciplinary projects might be long. In other words, in the whole range of information each user can have his own perspective on what information he wishes to see.

So, all cells in the secondary sheets are linked to the main template. Hence, when specialists deposit data into their templates, data are automatically transferred into the main one. Eventually, when end users have filled their data, they click ''Export to database'' and data are stored in the end database. The two different templates are shown in the following illustrations. What should be mentioned here is that for the development of this prototype, the secondary sheets are created manually, however in a fully developed proposal these sheets would appear automatically when inserting a new template.

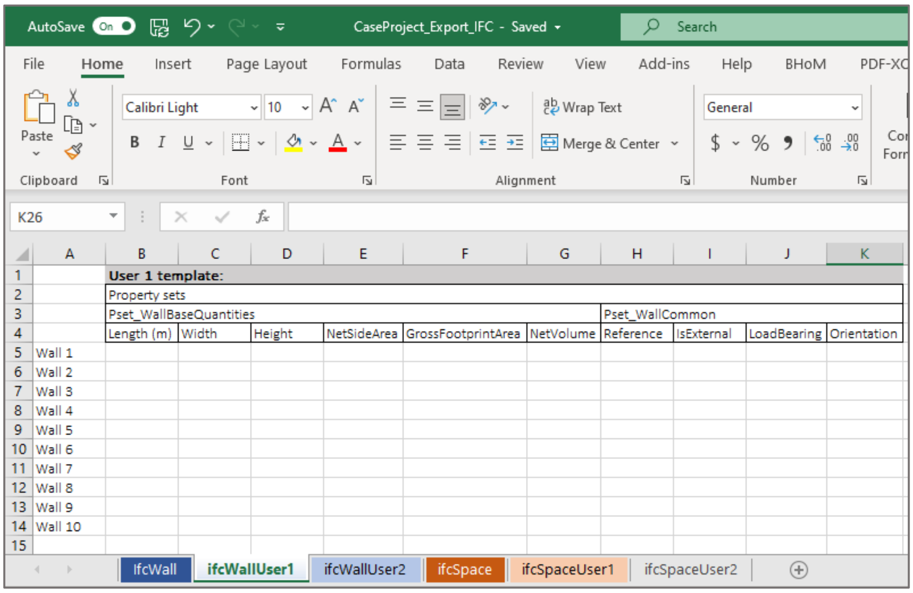

Figure 36: User 1 template

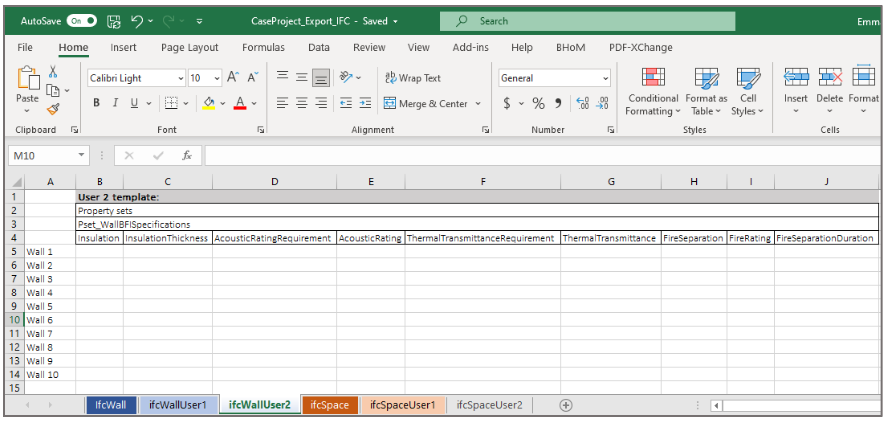

Figure 37: User 2 template

Accordingly, for the retrieval of data, the end user should click the button ''Import from database''. Then, three sheets are shown on the interface as well, one principal and two specialized ones. So, according to his needs, every specialist can overlook the entire dataset or customize and see the data of his preference.

6.2.3 Data parsing and processing

The main idea for processing data is hereby briefly presented. Initially, raw data in Excel are reformed into an intermediate class structure and then from this structure into the proposed ifcJSON format. The reason that the intermediate format is utilized is that it operates as a translation class thus simplifying the conversion to ifcJSON. In this intermediate format, each ifc object has a specific name, id and list of parameters as seen in the images below. The application code of this Add-in operates the translations between these data formats and the export to ifcJSON. Figure 38 and Figure 39 show an example of this class structure for a wall entity.

```
public class IfcWall
{
    public string name { get; set; }
    public int id { get; set; }
    public string IfcName = "IfcWall";
    public List<ifcParameter> parameters = new List<ifcParameter>();
```

Figure 38: ifcWall in intermediate format

```
public class ifcParameter
{
    public string propertySet { get; set; }
    public string propertyName { get; set; }
    public string propertyValue{ get; set; }
    public string propertyvalueType { get; set; }
    public string originalName { get; set; }
```

Figure 39: ifcWall parameters in intermediate format

6.2.4 Database

In the description of the system architecture in chapter 6.1 it is stipulated that a NoSQL Document Database is utilized. However, due to time constraints the development and implementation of such a database in the working prototype is not possible. Given that, as an alternative option a text (.txt) file storage of ifc objects in JSON format is employed. Although it does not have the same capabilities as a NoSQL database, it can still support the primal aim of this prototype, which is a simple and practical demonstration of how it can work. Hereby, a screenshot of the final export and storage of walls in ifcJSON format is presented in Figure 40.


```
[
  {
    "name": "Wall 1",
    "type": "IfcWall",
    "globalId": "w1",
    "isDefinedBy": [
      {
        "type": "IfcRelDefinesByProperties",
        "globalId": "e920ce28-43ac-46f2-84a6-7d2b157f4cbd",
        "ownerHistory": null,
        "relatingPropertyDefinition": {
          "globalId": "ae3fd3fd-1b36-4f17-b015-506a007ac1b7",
          "ownerHistory": null,
          "name": "IfcRelDefinesByProperties",
          "hasProperties": [
            {
              "type": "IfcPropertySingleValue",
              "name": "Length",
              "description": "Length",
              "nominalValue": {
                "stringValue": "5",
                "type": "IfcPositiveLengthMeasure",
                "value": "5"
              }
            },
            {
              "type": "IfcPropertySingleValue",
              "name": "Width",
              "description": "Width",
              "nominalValue": {
                "stringValue": "5",
                "type": "IfcPositiveLengthMeasure",
                "value": "5"
              }
            },
            {
              "type": "IfcPropertySingleValue",
              "name": "Height",
              "description": "Height",
              "nominalValue": {
                "stringValue": "5",
                "type": "IfcPositiveLengthMeasure",
                "value": "5"
```


Figure 40: Screenshot of this proof of concept database

6.3 CASE STUDY IMPLEMENTATION

The developed prototype is applied and tested through a study case project. The goal is to provide a demonstration of how it can be applied in real practice. The selected project is the educational building Eben-Haezer in Boskoop, The Netherlands. It is a single-floor building with overall dimensions 26,78m x 11,26m x 4,48m. It consists of two main teaching rooms, an office space, a technical and two sanitary rooms and a corridor with two enclosed porches. What is important to mention here is that the design that was used for this case corresponded to the Preliminary Design Voorontwerp (VO) stage, which is aligned with the main focus of this research. The available information sources were 2D drawings and they are contained in Appendix E section of the report.

The application and testing of the developed tool is executed by two specialists, a cost engineer and a building physicist where it is assumed that they need to perform their typical analyses during the VO phase, building cost estimation and ventilation/daylight/thermal calculations respectively. The process starts with the cost engineer intending to collect information for walls and spaces that are relevant to his/her analyses. First, he/she identifies in the 2D drawings all walls and spaces and then adds labels with names and id's, as seen in Figure 41.

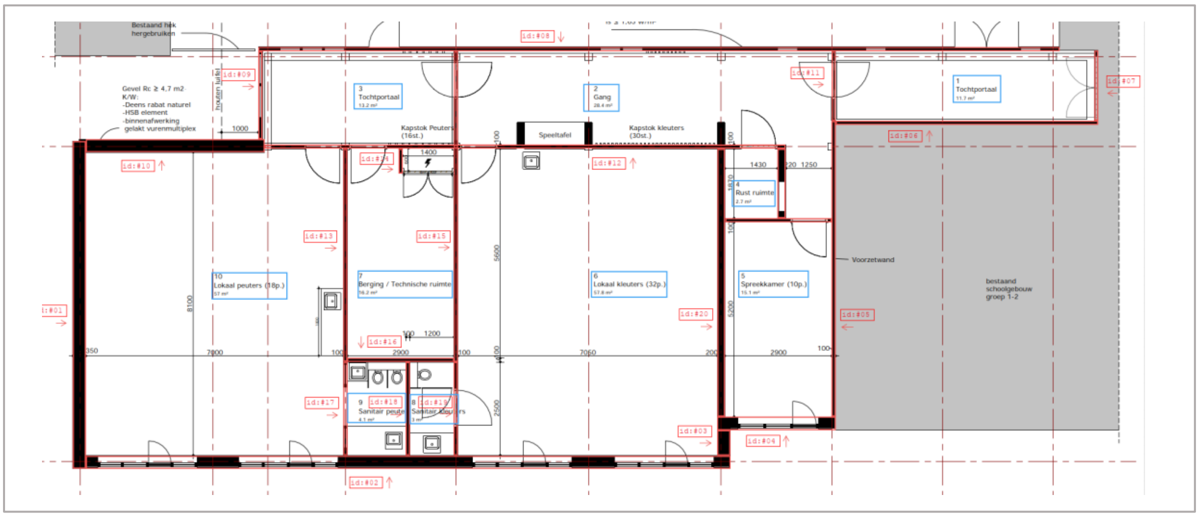

Figure 41: Case study drawing (plan) with labels

Then, he/she opens Microsoft Excel, goes to the tab ''ifcWallCostEst'' fills the needed attributes and consequently clicks ''Export To Database'' in order to save them. The same procedure is followed for spaces in tab ''ifcSpaceCostEst''. Figure 42 and Figure 43 illustrate two screenshots of the tabs ''ifcWallCostEst'' and ''ifcSpaceCostEst'' filled with data.

Afterwards, the building physicist wants to add more information that is needed for his/her discipline. Thus, first he/she opens Microsoft Excel and clicks ''Import From Database'' in order to see what information is already recorded before. Then, opens the tabs ''ifcWallBFI'' and ''ifcSpaceBFI'', fills additional data and finally clicks ''Export To Database''. During the process, the building physicist used the same pdf with labels that the cost engineer created in order to identify the objects recorded in the database and the drawings. In the last step, it is supposed that the cost estimator needs to retrieve all the information that was recorded in this study case. Therefore, he/she opens Excel clicks ''Import From Database'' and then receives the tabs with all data related to walls and spaces. As far as the exported data into JSON are concerned, Figure 44 illustrates a screenshot of the database including a certain building's space.

	Cost est template:									
	Property sets									
	Pset_WallBaseQuantities						Pset_WallCommon			
	Length (m)	Width	Height	NetSideArea	GrossFootprintArea	NetVolume	Reference	IsExternal	LoadBearing	Orientation
Wall 1	8.70	0.35	3.89	33.84	3.04	11.73	NLRS_21.10_WA_HSB	TRUE	FALSE	west
Wall 2	17.50	0.35	4.48	43.81	2.65	15.33	NLRS_21.10_WA_HSB	TRUE	FALSE	south
Wall 3	0.73	0.35	4.48	1.98	0.22	0.56	NLRS_21.10_WA_HSB	TRUE	FALSE	east
Wall 4	3.20	0.35	3.22	5.38	0.96	1.61	NLRS_21.10_WA_HSB	TRUE	FALSE	south
Wall 5	8.00	0.10	3.22	25.75	0.80	2.57	NLRS_21.10_WA_HSB	TRUE	FALSE	east
Wall 6	7.03	0.10	3.22	22.63	0.70	2.26	NLRS_21.10_WA_HSB	TRUE	FALSE	south
Wall 7	2.19	0.10	3.22	2.79	0.22	0.28	NLRS_21.10_WA_HSB	TRUE	FALSE	east
Wall 8	21.74	0.10	3.22	41.65	1.12	4.17	NLRS_21.10_WA_HSB	TRUE	FALSE	north
Wall 9	2.40	0.10	3.22	1.62	0.24	0.16	NLRS_21.10_WA_HSB	TRUE	FALSE	west
Wall 10	7.25	0.30	4.51	22.36	2.18	6.71	NLRS_21.10_WA_HSB	TRUE	FALSE	north
Wall 11	1.85	0.1	2.89	3.14	0.18	0.31	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 12	13.95	0.1	3.04	22.806	1.395	2.281	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 13	5.69	0.1	2.72	15.47	0.569	1.548	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 14	0.648	0.095	0.895	1.876	0.062	0.178	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 15	8.3	0.1	2.815	17.32	0.83	1.733	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 16	1.9	0.1	3.22	8.42	0.29	0.843	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 17	2.5	0.1	2.72	2.34	0.25	0.234	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 18	2.5	0.1	2.72	7.23	0.25	0.724	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 19	2.5	0.1	2.72	4.35	0.25	0.435	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 20	7.17	0.2	2.72	19.5	1.434	3.9	NLRS_22.13_WA_hsb-	FALSE	FALSE	-
Wall 21	2.9	0.1	3.22	5.95	0.284	0.595	NLRS_22.13_WA_hsb-	FALSE	FALSE	-

Figure 42: Walls' data filled in cost estimation template

	BFI template:									
	Property sets									
	Pset_SpaceCommon									
	Reference	IsExternal	Usage area (	GrossHeight	NetHeight	Length	Width	GrossPerimeter	NetPerimeter	Net Volume
Tochtportaal 1	Abt.001.cr	FALSE	11.70	2.90	2.70	7.02	1.85	17.76	15.16	31.59
Gang	Abt.001.cr	FALSE	28.40	2.90	2.70	10.15	2.50	27.75	24.15	76.68
Tochtportaal 2	Abt.001.cr	FALSE	13.20	2.90	2.70	5.20	2.50	15.38	11.78	35.64
Rust ruimte	Abt.001.of	FALSE	2.67	2.90	2.40	1.87	1.43	6.60	5.70	6.41
Spreekkamer	Abt.001.mf	FALSE	15.10	2.90	2.70	2.90	5.20	16.20	14.70	40.77
Lokaal kleuters	Abt.001.cr	FALSE	57.80	3.55	3.25	7.05	8.20	30.05	26.65	187.85
Berging / Technische ruimte	Abt.001.of	FALSE	16.25	3.55	2.70	2.90	5.60	17.00	16.20	43.88
Sanitair kleuters	Abt.001.co	FALSE	3.00	3.55	2.70	1.20	2.50	7.40	6.50	8.10
Sanitair peuter	Abt.001.co	FALSE	4.10	3.55	2.70	1.65	2.50	8.30	7.40	11.07
Lokaal peuters	Abt.001.co	FALSE	57.00	3.55	3.25	7.00	8.10	30.20	27.70	185.25

Figure 43: Spaces' data filled in cost estimation template

```
{
  "name": "Tochtportaal 1",
  "type": "ifcSpace",
  "globalId": "s1",
  "isDefinedBy": [
    {
      "type": "IfcRelDefinesByProperties",
      "globalId": "cabe4efa-5a29-46fe-911a-f5b83a3c1cba",
      "ownerHistory": null,
      "relatingPropertyDefinition": {
        "globalId": "82369e36-7751-4e58-95d8-999e8328e754",
        "ownerHistory": null,
        "name": "IfcRelDefinesByProperties",
        "hasProperties": [
          {
            "type": "IfcPropertySingleValue",
            "name": "Reference",
            "description": "Reference",
            "nominalValue": {
              "stringValue": "Abt.001.cr",
              "type": "IfcLabel",
              "value": "Abt.001.cr"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "IsExternal",
            "description": "IsExternal",
            "nominalValue": {
              "stringValue": "False",
              "type": "ifcBoolean",
              "value": "False"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "Usage area (GO)",
            "description": "Usage area (GO)",
            "nominalValue": {
              "stringValue": "11.7",
              "type": "ifcAreaMeasure",
              "value": "11.7"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "GrossHeight",
            "description": "GrossHeight",
            "nominalValue": {
              "stringValue": "2.9",
              "type": "ifcPositiveLengthMeasure",
              "value": "2.9"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "NetHeight",
            "description": "NetHeight",
            "nominalValue": {
              "stringValue": "2.7",
              "type": "ifcPositiveLengthMeasure",
              "value": "2.7"
            }
          },
          {
            "type": "IfcPropertySingleValue",
            "name": "Length",
            "description": "Length",
            "nominalValue": {
              "stringValue": "7.02",
```


Figure 44: Exported space data

7. VALIDATION

As described in Chapter 3.1.4 'Phase 4 – Validation' a validation workshop was held in order to evaluate the proposed ontology and workflow. The workshop was executed in two rounds. The first intended to assess the impact of the proposal upon the early design practices. The expert panel consisted of a cost engineer, a building physicist, a sustainability specialist and a fire safety engineer. The proposed ontology as well as the new workflow were presented to participants and the developed prototype was applied in the selected case project. Moreover, additional examples were given on how each discipline can use the ontology, in order to support its comprehension by different backgrounds. The second round focused on the transition towards the final design. Therefore, the information that was generated through the application of the prototype and the workflow of data integration in final phases were presented to an architectural BIM modeler. Both rounds ended with participants evaluating the findings by filling a questionnaire, as seen in Appendix F.

7.1 First round – Impact on early design stage

Concerning the first part of the validation, the criteria that are used to evaluate the contribution of the proposed ontology on early design stage are consistency, completeness, rework elimination, scalability, applicability and efficiency. Table 11 presents the aggregated results of the expert panel questionnaires.

Table 11: Evaluation aggregated results - early phases

Criteria	**Scores (1-5)**				**Average per criterion**
	Domain expertise				
	Building physics	*Sustainability*	*Cost estimation*	*Fire safety*	
Completeness	4.00	5.00	3.00	4.00	4.00
Consistency	5.00	4.00	5.00	3.00	4.25
Rework elimination	5.00	5.00	4.00	4.00	4.50
Scalability	3.00	5.00	3.00	4.00	3.75
Applicability	4.00	5.00	3.00	5.00	4.25
Efficiency	3.00	5.00	4.00	4.00	4.00
Average per discipline	*4.00*	*4.83*	*3.66*	*4.00*	***Overall score:*** **4.12**

As the results indicate, the rework elimination that the proposed ontology and workflow can achieve scored the highest among participants with 4.5/5.0. Nevertheless, consistency in use of data and applicability of the ontology scored very close with 4.25/5.00 respectively. When it comes to completeness in terms of addressing early design information needs and the overall efficiency in the work processes, both criteria received a 4.00/5.00. The scalability of the proposed ontology seems to be the least appreciated criterion with an average of 3.75/5.00 among participants.

Among the disciplines that were involved in the first round of the validation process, the ontology received the higher score from the sustainability expert with an average of 4.83/5.00. The disciplines of building physics and fire safety both evaluated the proposal with an average of 4.00/5.00, whilst the cost engineer evaluated with a 3.66/5.00. Overall, the proposed ontology and workflow were evaluated with an average of 4.12/5.00 concerning their contribution in early design stages.

More specifically, as far as the criterion of completeness is concerned, two out of four participants stated that the ontology covers their early design information needs to a good extent, one claimed that the ontology fully meets his needs while another one insisted that it covers his needs to a fair extent. What was particularly mentioned is that for the building physics department there is still some room for optimization of this criterion regarding detailed measurements that can easily be added as new properties to the existing property sets. Moreover, the fire safety engineer observed that there are parameters (ex. direction of fire rating in a wall or window, fire rating property in part of a wall and not in the entire wall) that still need to be considered. Additionally, the cost engineer claimed that the standards (i.e. NEN2580, NEN2699) that are used for defining building measurements should be clearly specified among the project team.

Concerning the criterion of consistency, the majority of the participants stated that the ontology can significantly contribute towards a consistent use of data which was also highlighted as the major advantage. Moreover, one participant believed that consistency can be achieved in a fair level, since an attention point remains the coordination between the disciplines in the start of the process but also during the iterations.

Regarding the rework elimination criterion, half of the experts claimed that the new workflow is expected to reduce the level of redundant rework to an absolute level, while the rest are confident that unnecessary take-offs will be decreased to a good level. However, this can be achieved as long as there is good and constant communication among project members, and can be optimized if a secondary system of communication and coordination is used together with the tool.

Moving to scalability aspects, it is observed that the proposal scored the lowest rate among the defined criteria. Although some of the participants think that it can be adopted be other disciplines in a good level, the main observation that stems from the real practice, is that it is quite possible that some people will be reluctant in changing the conventional practices.

As far as the applicability is concerned, two out of four participants mentioned that the new ontology and workflow are easy to use in an absolute extent, one believed that it can be applied in a fair level while the last participant stated that it is applicable in a good level. Overall, everyone appreciated the effort that was made in order to structure the proposal in a way that it can be as easy to use as possible. Additionally, the decision to use Microsoft Excel as the user interface of the developed working prototype was a great advantage, since everybody acknowledges that it is a convenient software for managing and manipulating data.

Finally, regarding the overall efficiency that the ontology can bring to their processes, mixed reactions were collected. One respondent claimed that it can definitely improve his efficiency, two of them concluded that it can contribute to a good extent while one participant stated that it can help in a fair level. However, the main claim of two participants is that they could only answer this question as long as it is applied and tested in real practice. Therefore, the outcome is that it seems to be promising but the overall efficiency can only be measured after it is adopted in daily practice.

7.2 Second round - Transition to final design stage

Regarding the second round of the validation, the two evaluation criteria that are employed are integration and applicability. Table 12 presents the evaluation scores by the architectural BIM modeler.

Table 12: Evaluation results - start of final phases

Criteria	**Scores (1-5)**
	Domain expertise
	Architectural BIM modelling
Integration	4.00
Applicability	5.00
	Overall score: 4.50

For the criterion of integration, the BIM modeler evaluated the proposal with a 4.00 out of 5.00. More specifically, he insisted that the way information is structured in early phases can allow its transfer to final design in a good extent. Moreover, the benefit of giving access to specialists for adding specific element related information in the early design model is especially valuable for the integrality of the final design. On the other hand, the applicability of the proposed workflow for transferring data to the final design stage was assessed with a 5.00/5.00. In general, it was acknowledged that the proposed workflow is a good start for creating an automated transition from the earlier to the final design stages of project. Nevertheless, it was pointed out that it is important to consider how this workflow in later stages can be managed and adapted to fit the 3D models in execution.

7.3 Validation conclusion

To summarize, the evaluation results indicate that the ontology scored a fairly good grade in the criteria that were established on both rounds. Moreover, specific observations and remarks were given by the participants which provide the context for further investigation. Consequently, the proposal can be regarded as valid and can successfully contribute towards the fulfillment of the main research objective.

8. DISCUSSION

8.1 RESEARCH CONTRIBUTION

As evidenced in the literature, existing BIM strategies lack an orientation towards the early design phases, whereas their main benefits are mostly exploited in later stages only after the initiation of the geometrical 3D modelling. This is triggered by the fact that existing BIM structures do not fully cover the information needs of specialists during these stages, nor they provide them a common language to exchange information. As far as the scientific contribution of this research is concerned, this study fills this gap by developing a structure that supports information integration by disciplines of early design and a workflow that enables professionals to work together around this structure. More specifically, the proposed ontology emerges from the extension of the current IFC schema, with additional concepts that respond to the needs of early phases. The main novelty is the introduction of generic systems before the entities that compose them (i.e. zones, facades, MEP etc) in order to capture more abstract information. Furthermore, the intention of structuring information in IFC format, has additional value since it's interoperable with final design thus allowing a smooth flow of data into later stages.

8.2 RESULTS INTERPRETATION

The most significant observation is that the outcomes remain close to the primal hypothesis of this research, which is summarized in its title ''BIM without a 3D in early design stages''. The application of the working prototype in real practice revealed that it is possible to create a centralized model in early design, without having any 3D data, which professionals can use in order to store, collect and reuse information. Moreover, the fact that this model can seamlessly integrate early design data and enable them to be passed towards later stages, makes it even more relevant and necessary for an efficient and versatile information management.

Furthermore, it is equally important that a new way of working based on centralized information can actually be accomplished. The evaluation of the proposal by domain experts revealed that it has a promising potential in bringing consistency and efficiency to their practices and concurrently eliminate redundant rework. At the same time, the easy application and agility of the proposed tool is also a great advantage as far as its adoption is concerned. Additionally, a noteworthy observation is that this novel way of working engages disciplines of preliminary design phases in the BIM process, which use to have limited participation in current practices.

8.3 RESEARCH IMPLICATIONS

The intention to use IFC as basis for defining the research's data structure, underlines the possibilities of a wider use of this format in early design phases. It is common practice that IFC is employed in later stages, where it plays an important role in creating and exchanging digital building models. However, while it is structured in a way that it particularly responds to the needs of the respective phases, the findings suggest that IFC with the proposed extensions, can be effectively used even in earlier phases where there is no 3D information. In this direction, IFC can ensure structuring information in an open, well-documented format and ensure vendor-neutrality and sustainable data continuity, eventually leading towards Big Open-BIM (Borrmann, et al., 2015) already from the very early design stages.

Furthermore, the utilization of IFC structure and eventually its translation into a sort of database has the potential to ensure that IFC files can be accessed and edited from other interfaces apart 3D models. At the same time, disciplines that do not have affinity with 3D modelling can still use and modify them. Therefore, this is a valuable conclusion that can have a more universal approach and can work for every organization that aims towards a more versatile and flexible management of IFC files.

8.4 LIMITATIONS AND FUTURE WORK

Further to the discussion of the results, this research possesses some limitations which provide space for further research as well. Initially, although this study is intended to be used for the early design phases of the whole construction sector, the organization that provided the context is an engineering consultancy company. Hence, only aspects that are relevant to engineering consultancy are taken into account. Other stakeholders, for example architects are excluded from the scope. Additionally, due to time constraints only five representative disciplines delivered input for the needs of this research. However, in early stages many more different specializations are engaged. In order to address this limitation, additional research ought to include a wider spectrum of backgrounds and thoroughly investigate multiple stakeholders across various sectors of the industry.

Second, during the validation stage, professionals raised the issue of tracking down design changes and consequently modifications to the information model. During a typical workflow it is indispensable for professionals to be able to identify when a design has been changed and then adjust their analyses accordingly. This is usually addressed by one-to-one communication between project members, which is not always that efficient. For that reason, it is important that future research introduces a version management perspective to the study.

Third, as far as the development and implementation is concerned, the prototype structures information in ifcJSON. So the objective was to demonstrate that data can be saved in an IFC object format definition rather than create a working IFC file. After all, the creation of a valid IFC file requires the definition of the entire hierarchy as presented in chapter 2.1.3 'Industry Foundation Classes (IFC)' and the addition of geometrical information.

Finally, concerning the wider adoption of the proposal, it is designed for being as easy as it can be and close to the existing standard practices of professionals. Nevertheless, it is always possible that people might be reluctant in changing their working routines and use new tools, especially in conceptual design phases. The difficulties in adopting digital innovations are argued to be rooted into the very traditional way of working of the construction industry and its reluctance to change its conventional practices (Oloke, 2021). Consequently, in order to ensure a high adoption rate, professionals need to be convinced about the benefits that it can bring to their processes but also to the overall efficiency of the project team, in order to change their working practices and embrace the new proposal.

8.5 RECOMMENDATIONS FOR A FULLY DEVELOPED TOOL

This part of the research aims to reflect on the adopted approach concerning the prototype development and identify the opportunities for the transition towards a fully developed tool. In order to do so, the prototype is evaluated in terms of the extent that it covers the process model requirements of chapter 5.1.1, and then based on this reflection specific recommendations are drawn up.

Systematic data structure

As far as the data structuring and conversion are concerned, an Excel interface was employed to deposit raw data and an Excel add-in API to convert them into ifcJSON. Therefore, the users would only need to use Excel to fill in information, which can be regarded as an advantage since it is very close to their existing working practices. And then on the background the API would do the conversion to ifcJSON which is the main intention. Therefore, the developed prototype addresses the requirement of structuring and conversion of data.

Inclusion of aggregated data set

Since the prototype took into account only datasets related to space and wall entities, it has to be recognized that the scope of data conversion is rather limited. Therefore, in order to include the aggregated information requirements of early phases in a fully developed proposal, the existing Excel interface should be expanded and be designed in a way that it can facilitate an easy deposition and retrieval of the entire data set of early phases.

Interoperability with final design phases

Concerning the interoperability aspect, structuring information in ifcJSON format allows for semantic interoperability with the final design phases, which is already demonstrated in a conceptual level in chapter 5. However, in its current state the developed prototype is fragmented from later phases since it does not address the transfer of data into the final design model. So it is necessary to find a way to link in a practical way the BIM without a 3D with the 3D BIM model of final design in order to achieve the goal of seamless information flow later on.

Therefore, it is recommended that a custom importer is developed within the 3D modelling authoring software (i.e. Revit, ArchiCAD etc.) that can read and attach data from the model of early design to the 3D of final design. It is essential that this importer has the ability to read and attach data based on a unique ID, in order to match the entities of early model with the actual entities in the 3D model, as stipulated in the workflow of chapter 5.3.2.

Flexibility of adding data without a predefined sequence

Afterwards, the application interface of the developed tool allows specialists to create their custom templates for managing data only for the entities that they want. So currently the requirement of adding data without a predefined sequence is fully met.

Visual feedback on what is already recorded

Moreover, regarding the visual feedback on the correspondence between the entities that are filled in the database and the actual design, the workflow of the current prototype indicates the manual addition of labels with objects' id in a common set of drawings by using a pdf editor. Then, each engineer has to detect where each object is located in the drawing. However, it has to be acknowledged that in a fully developed proposal manually adding and identifying labels for all the objects of the data structure in the drawings would not be convenient.

Given that, it is suggested that a visual platform is developed and integrated into the tool, where the drawings of the design are imported. There, the labels will be added as an additional layers on the drawing, based on the type of the entity and its id on the database. So when, an engineer selects a certain entity on the database (for example a wall), then it will be automatically highlighted in the visual platform. This integrated feature within the tool would efficiently address the requirement for visual correspondence between the database and the design.

Tracking down design changes

Finally, a limitation of the overall research that was identified in the previous chapter is related to the detection of design changes. Therefore, aligned with the intention of applying a version management approach to the research, in further development steps it is recommended that the tool is complemented with a communication feature (version tracker) where every discipline can be up to date with design updates and iterations.

8.6 CONCLUSION

To sum up, this study aimed to introduce a strategy for working around centralized data in preliminary design stages when a 3D model is not yet available, which can later enable a seamless integration of information in final phases. The findings demonstrated that the proposal is a promising start to the direction of centralized information management in the early phases of a project's lifecycle. Consequently, this research can be regarded as an attempt to bridge the gap between BIM and its implementation in early design phases.

REFERENCES

Afsari, K., Eastman, C. & Castro-Lacouture, D., 2017. JavaScript Object Notation (JSON) data serialization for IFC schema in web-based BIM data exchange. *Automation in Construction 77:24-51,* p. DOI: 10.1016/j.autcon.2017.01.011.

Allemang, D. & Hendler, J., 2011. *Semantic Web for the Working Ontologist.* 2nd ed. Waltham: Morgan Kaufmann.

Alvin, N., 2021. *Reliability and Validity.* [Online]
Available at: https://www.researchprospect.com/reliability-and-validity/

Amoah, K. & Nguyen, T. V., 2019. *An Approach to Enhance Interoperability of Building Information Modeling (BIM) and Data Exchange in Integrated Building Design and Analysis.* Banff, Canada, 36th International Symposium on Automation and Robotics in Construction.

Antoniou, G. & van Harmelen, F., 2004. *A Semantic Web Primer.* London, England: The MIT Press.

Aranda, S., Tasbihi, A. & Turner, M., 2015. Interoperability and integration in the construction industry. *CMAA Emerging Technologies Committee.*

Atazadeh, B. et al., 2016. Extending a BIM-based data model to support 3D digital management of complex ownership spaces. *International Journal of Geographical Information Science 31 (3), DOI: 10.1080/13658816.2016.1207775.*

Belsky, M. E., 2021. A framework for leveraging semantic interoperability between BIM applications. In: *ECPPM 2021 – eWork and eBusiness in Architecture, Engineering and Construction.* London: CRC Press.

BHoM, 2021. *The Buildings and Habitats object Model.* [Online]
Available at: https://bhom.xyz/

Bimeye, 2019. *Bimeye. Product and functionality.* [Online]
Available at: https://www.tribia.com/en/bimeye/product

BNA & NLingenieurs, 2014. Standaardtaakbeschrijving DNR-STB 2014, Toelichting.

Bogenstätter, U., 2000. Prediction and optimization of life-cycle costs in early design. *Building Research & Information, 28 (5-6),* pp. 376-386, doi: 10.1080/096132100418528.

Borrmann, A., Beetz, J., Koch, C. & Konig, M., 2015. *Building Information Modelling - Technology Foundations and Industry Practice.* Cham, Switzerland: Springer.

Building Smart, 2020. *Industry Foundation Classes (IFC) - An Introduction.* [Online]
Available at: https://technical.buildingsmart.org/standards/ifc

Building Smart, 2020. *What is ifcOWL?.* [Online]
Available at: https://technical.buildingsmart.org/standards/ifc/ifc-formats/ifcowl/

Cambridge Semantics, 2019. *RDF vs OWL.* [Online]
Available at: https://www.cambridgesemantics.com/blog/semantic-university/learn-owl-rdfs/rdfs-vs-owl/

Çavuşoğlu, Ö. H., 2015. *The Position of BIM Tools in Conceptual Design Phase: Parametric Design and Energy Modeling Capabilities.* Vienna, eCAADe 2015: Real Time - Extending the Reach of Computation, pp. 607-612.

Chen, W., Chen, K. & Cheng, J. C. P., 2018. Towards an Ontology-based Approach for Information Interoperability Between BIM and Facility Management. In: B. D. Ian F. C. Smith, ed. *Advanced Computing*

Strategies for Engineering. Lausanne, Switzerland: 25th EG-ICE International Workshop 2018, pp. 447-469, doi: 10.1007/978-3-319-91638-5_25.

Cheong, M., Li, H. & Scott, D., 2012. Web-based Construction Information Management System. *Australasian Journal of Construction Economics and Building 3(1),* p. doi: 10.5130/ajceb.v3i1.2910.

Choi, J., Kim, H. & Kim, I., 2015. Open BIM-based quantity take-off system for schematic estimation of building frame in early design stage. *Journal of Computational Design and Engineering, 2,* pp. 16-25, doi: 10.1016/j.jcde.2014.11.002.

Choi, J., Lee, S. & Kim, I., 2020. Development of Quality Control Requirements for Improving the Quality of Architectural Design Based on BIM. *Applied Sciences 10(20):7074.*

Chungoora, T., 2018. *Practical Knowledge Modelling: Data, Information and Knowledge.* [Online]
Available at: https://www.udemy.com/practical-knowledge-modelling/

CodeBook, 2021. *CodeBook. Product.* [Online]
Available at: http://codebookinternational.org.uk/

Cohn, M., 2018. *User Stories.* [Online]
Available at: https://www.mountaingoatsoftware.com/agile/user-stories

Costin, A., 2016. A new methodology for interoperability of heterogeneous bridge information models. *Ph.D. dissertation, Georgia Institute of Technology.*

Costin, A. & Eastman, C., 2019. Need for Interoperability to Enable Seamless Information Exchanges in Smart and Sustainable Urban Systems. *Journal of Computing in Civil Engineering 33(3), doi: 10.1061/(ASCE)CP.1943-5487.0000824.*

Couchbase, 2021. *NoSQL Databases. Why successful enterprises rely on NoSQL.* [Online]
Available at: https://www.couchbase.com/resources/why-nosql

Daum, S. & Borrmann, A., 2014. Processing of Topological BIM Queries using Boundary Representation Based Methods. *Advanced Engineering Informatics, 28 (4),* pp. 272–286, doi:10.1016/j.aei.2014.06.001.

Dejaco, M. C. et al., 2020. Building and District Data Organization to Improve Facility and Property Management. *Digital Transformation of the Design, Construction and Management Processes of the Built Environment,* pp. 255-265, doi: 10.1007/978-3-030-33570-0_23.

Deng, X., Chang, T.-Y. P. & Lai, H., 2019. BIM-Based Platform for Collaborative Building Design and Project Management. *Journal of Computing in Civil Engineering.*

DesigningBuildings, 2020. *Design Information.* [Online]
Available at: https://www.designingbuildings.co.uk/wiki/Design_information

dRofus, 2019. *dRofus. Product Overview.* [Online]
Available at: https://www.drofus.com/en/product

Eastman, C. . M. et al., 2011. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors.* 2nd ed. New Jersey: John Wiley And Sons Ltd.

Farghaly, K., Abanda, H., Vidalakis, C. & Wood, G., 2019. *Semantic and syntactic interoperability of BIM and asset management data.* Chania, Crete, Greece, Lean & Computing in Construction Congress (LC3), p. doi: 10.35490/EC3.2019.154.

Farias, T. M., Roxin, A. & Nicolle, C., 2015. *IfcWoD, Semantically Adapting IFC Model Relations into OWL Properties.* Eindhoven, Proceedings of the 32nd CIB W78 Conference on Information Technology in Construction.

Fugas, K., 2020. *Data Driven Design Explained In One Guide.* [Online]
Available at: https://bimcorner.com/data-driven-design-explained-in-one-guide/

Gerhart, M., Bayer, J., Höfner, J. & Boger, M., 2015. Approach to define highly scalable metamodels based on JSON.

Gonçal, C., 2017. Integration of building product data with BIM modelling: a semantic-based product catalogue and rule checking system. p. doi: 10.13140/RG.2.2.11123.63522.

Grilo, A. & Jardim-Gonçalves, R., 2010. Value proposition on interoperability of BIM and collaborative working environments. *Automation In Construction, 19(5), 522-530, https://doi.org/10.1016/j.autcon.2009.11.003.*

Jaakkola, H. & Thalheim, B., 2011. *Architecture-driven modelling methodologies.* Jyväskylä, Finland, 20th European-Japanese Conference on Information Modelling and Knowledge Bases (EJC 2010), p. p98.

Kang, T.-W. & Choi, H.-S., 2015. BIM perspective definition metadata for interworking facility management data. *Advanced Engineering Informatics, vol. 29, issue 4,* pp. 958-970, doi: 10.1016/j.aei.2015.09.004.

Kolltveit, B. J. & Grønhaug, K., 2004. The importance of the early phase: the case of construction and building projects. *International Journal of Project Management, 22,* pp. 545-551, doi: 10.1016/j.ijproman.2004.03.002.

Kontopoulos, E., Martinopoulos, G., Lazarou, D. & Bassiliades, N., 2016. An ontology-based decision support tool for optimizing domestic solar hot water system selection. *Journal of Cleaner Production, vol.112, part 5,* pp. 4636-4646, doi: 10.1016/j.jclepro.2015.08.088.

Lee, D.-G., Park, J.-Y. & Song, S.-H., 2017. BIM-Based Construction Information Management Framework for Site Information Management.

Liebich, T. et al., 2013. *Industry Foundation Classes IFC4 official release.* [Online]
Available at: http://www.buildingsmart-tech.org/ifc/IFC4/final/html/index.htm

Lozano-Tello, A. & Gomez-Perez, A., 2004. ONTOMETRIC: a method to choose the appropriate ontology. *ournal of Database Management 15(2),* pp. 1-18, doi: 10.4018/jdm.2004040101.

Lozinski, I., 2020. *Ultimate BIM software list for BIM Coordinators.* [Online]
Available at: https://bimcorner.com/ultimate-bim-software-list-for-bim-coordinators/

Mayouf, M. et al., 2019. BIM Role within the Conceptual Design Phase: A Case Study of a UK. *International Journal of Architecture, Engineering and Construction, 8(1).*

Morales, G. G. & Orrell, T., 2018. Interoperability: A practitioner's guide to joining-up data in the development sector.

Niknam, M. & Karshenas, S., 2013. *Ontology-Based Building Information Modeling.* Los Angeles, ASCE International Workshop on Computing in Civil Engineering, p. 476–483. doi: 10.1061/9780784413029.060.

Niknam, M. & Karshenas, S., 2014. *A Social Networking Website for AEC Projects.* Florida, United States, Computing in Civil and Building Engineering, pp. 2208-2215, doi: 10.1061/9780784413616.274.

Niknam, M. & Karshenas, S., 2017. A shared ontology approach to semantic representation of BIM data.

Oloke, D., 2021. Deployment of Building Information Modelling (BIM) for Energy Efficiency in the UK. In: *Collaboration and Integration in Construction, Engineering, Management and Technology.* London: Cham Springer, pp. 559-564.

Patsias, D., 2019. *Addressing the limited adoption of Semantic Web for data integration in AEC industry: Exploration of an RDF-based approach depending on available ontologies and literals matching,* Enschede: University of Twente.

Pauwels, P. & Roxin, A., 2016. *SimpleBIM: From full ifcOWL graphs to simplified building graphs.* Limasol, ECPPM 2016 (11 European Conference on Product and Process Modelling).

Pauwels, P. & Terkaj, W., 2016. EXPRESS to OWL for construction industry: Towards a recommendable and usable ifcOWL ontology. *Automation in Construction, 63,* pp. 100-133, doi: 10.1016/j.autcon.2015.12.003.

Pauwels, P., Zhang, S. & Lee, Y. C., 2017. Semantic web technologies in AEC industry: A literature overview. *Automation in Construction, Volume 73,* pp. 145-165, doi: 10.1016/j.autcon.2016.10.003.

PCSG, 2020. *Data in the construction industry.* [Online]
Available at: https://www.designingbuildings.co.uk/wiki/Data_in_the_construction_industry

Peng, D., Cao, L. & Xu, W., 2011. Using JSON for Data Exchanging in Web Service Applications. *Journal of Computational Information Systems, 7 (16),* pp. 5883-5890.

Penttila, H., 2007. Early Architectural Design and BIM. *Computer-Aided Architectural Design Futures (CAADFutures).*

PerformanceNetwork, 2021. *BHoM: Buildings and Habitats object Model.* [Online]
Available at: https://www.performance.network/courses/bhom-buildings-and-habitats-object-model

Poinet, P., Stefanescu, D. A. & Papadonikolaki, E., 2020. *Collaborative Workflows and Version Control Through Open-Source and Distributed Common Data Environment.* Sao Paulo, 18th International Conference on Computing in Civil and Building Engineering (ICCCBE), pp. doi: 10.1007/978-3-030-51295-8_18.

Poirier, E. A., Forgues, D. & Staub-French, S., 2014. *Dimensions of Interoperability in the AEC Industry.* s.l., Construction Research Congress.

Protégé, 2017. *Protégé Product.* [Online]
Available at: https://protege.stanford.edu/products.php

Rasmussen, M. H., Lefrançois, M., Schneider , G. F. & Pauwels, P., 2020. BOT: The building topology ontology of the W3C linked building data group. *Semantic Web, vol 12,* pp. doi: 10.3233/SW-200385.

Rasmussen, M. H., Pauwels, P., Karlshøj, J. & Hviid, C. A., 2017. *Proposing a Central AEC Ontology That Allows for Domain Specific Extensions.* Heraklion, Greece, s.n., pp. 237-244.

Rasmussen, M. H. et al., 2017. *Recent changes in the Building Topology Ontology.* Dijon, France, 5th International Workshop on Linked Data in Architecture and Construction, p. doi: 10.13140/RG.2.2.32365.28647.

RIBA, 2020. *Plan of Work 2020, Overview,* 66 Portland Place, London, W1B 1AD.: RIBA.

Rice, T., 2020. *Dealing with Data in the Construction Industry.* [Online]
Available at: https://www.constructormagazine.com/dealing-with-data-in-the-construction-industry/

Santos, R., Grilo, A. & Costa, A. A., 2017. Bibliometric analysis and review of Building Information Modelling literature published between 2005 and 2015. *Automation in Construction, doi: 10.1016/j.autcon.2017.03.005.*

Schaefer, L., 2017. *What is NoSQL?.* [Online]
Available at: https://www.mongodb.com/nosql-explained

Sheth, A. P., 1999. Changing Focus on Interoperability in Information Systems:From System, Syntax, Structure to Semantics. In: *Interoperating Geographic Information Systems.* Boston: Springer, pp. 5-29.

Singaram, M. & Jain, P., 2018. *What is the Difference between Proof of Concept and Prototype.* [Online] Available at: https://www.entrepreneur.com/article/307454

Steiner, C. M. & Albert, D., 2017. Validating domain ontologies: A methodology exemplified for concept maps. *Cogent Education, 4:1, 1263006,* p. doi: 10.1080/2331186X.2016.1263006.

Sulankivi, K., 2004. Benefits of centralized digital information management in multipartner projects. *Journal of Information Technology in Construction ITcon, Vol. 9,* pp. 35-63.

Timita, M., 2017. *Racing towards a data-centric business model.* [Online] Available at: https://www.ice.org.uk/news-and-insight/the-civil-engineer/august-2017/racing-towards-a-data-centric-business-model

Uschold, M. & Gruninger, M., 1996. Ontologies: Principles, Methods and Applications. *Knowledge Engineering Review 11(2).*

Venugopal, M., Eastman, C. & Teizer, J., 2015. An ontology-based analysis of the industry foundation class schema for building information model exchanges. *Advanced Engineering Informatics 29(4),* p. doi: 10.1016/j.aei.2015.09.006.

W3C, 2015. *Ontologies.* [Online] Available at: https://www.w3.org/standards/semanticweb/ontology

Wang, G., 2011. *Improving Data Transmission in Web Applications via the Translation between XML and JSON.* Qingdao, China, 2011 Third International Conference on Communications and Mobile Computing, pp. 18-20.

APPENDIX A – INTERVIEWS QUESTIONS

Table 13: Interview guide - Early design phases

Focus of questions	Interview questions
Recording consent	1. Before we start, for the needs of the results' analysis, I would like to record this interview. Is this ok for you? *The recordings will be transcribed by me personally and erased once the transcriptions are checked for accuracy. Neither your name nor any other identifying information (such as your voice or picture) will be used in presentations or in written products resulting from the study.*
Scope and function	2a. Can you tell me what kind of projects you are involved in?
	3a. What is the design phase that you are engaged?
	4a. With regards to the SO/VO phases, can you describe me what are your tasks, responsibilities and outcomes in these projects?
Data requirements	5b. Moving on to the data requirements issue, what piece of information about the building facility do you need to execute your work?
	6b. What is the format of the data you need? *(i.e. dwg, pdf, xls)*
	7b. How do your information requirements change depending on the design phase you are involved in? (*if you participate in more than one)
	8b. In addition, depending on the design phase, what kind of information do you usually miss and in what extent does this occur?
Software type	9c. Could you tell me what tools/software you use?
	10c. What are the data formats that are supported by these software?
Data retrieval	11d. During the initiation of a typical task, can you explain me what are your main data sources? And who is the provider of these sources?
	12d. Moreover, can you describe how you extract data from these data sources?
	13d. Further to the extraction of data, what are the main challenges and what are the barriers you have to overcome?
	14d. In what extent do you face interoperability issues and how do you overcome them in your daily work?
Design interpretation and assumptions	15e. Can you explain me how you interpret a design based on the information you posses, and how and in what extent do you align your personal interpretation with your team members one?
	16e. Can you tell me what kind of assumptions do you usually face in a typical project?
	17e. What are the factors that drive your assumptions?
Data sharing and collaboration	18f. Does your output serve as input for your team members?
	19f. Can you describe how, where and in what format you share your outputs?
	20f. Can you tell me in what extent you exchange data with your team members?
Discussion and conclusions	21g. Moving to the last part of the interview, could you reflect on the main issues and challenges that you face in this process?
	22g. Additionally, based on your experience and expertise what do you think should be done in order to overcome these barriers?
	23g. Can you think of any representative example projects that I can extract information from, for the topics that were addressed?
	24g. Finally, would like to add anything else before we end this session?

Table 14: Interview guide - Final design phases

Focus of questions	Interview questions
Recording consent	1. Before we start, for the needs of the results' analysis, I would like to record this interview. Is this ok for you? *The recordings will be transcribed by me personally and erased once the transcriptions are checked for accuracy. Neither your name nor any other identifying information (such as your voice or picture) will be used in presentations or in written products resulting from the study.*
Scope and function	2. Can you tell me what kind of projects you are involved in? 3. Could you describe me what are your tasks, responsibilities and products in these projects? And what software do you use?
Data requirements	4. Moving on to the data requirements issue, what piece of information about the building facility do you need to start your work? 5. What is the format of the data you need? *(i.e. dwg, pdf, xls)* 6. In addition, what kind of information do you usually miss and in what extent does this occur?
Data retrieval	7. During the initiation of the modelling/engineering process, can you explain me what are your main data sources? And who is the provider of these sources? 8. Moreover, can you describe how you extract data from these data sources? 9. Further to the extraction of data, what are the main challenges and what are the barriers you have to overcome? 10. In what extent do you face interoperability issues and how do you overcome them in your daily work?
Modelling/engineering procedure and information incorporation	11. What kind of information from preceding phases (VO) is available at the start of the modelling/engineering process? 12. What information and how do you embody it into your calculations/designs/3D models? 13. Could you describe me in short the sequence of steps in your engineering/modelling process? **(for architectural/structural department)* 14. Do the information requirements of other specialists affect your modelling process? **(for architectural/structural department)* 15. Is there any specific piece of information that has to be modelled first? **(for architectural/structural department)*
Discussion and conclusions	16. Moving to the last part of the interview, could you reflect on the main issues and challenges that you face in this process? 17. Additionally, based on your experience and expertise what do you think should be done in order to overcome these barriers? 18. Can you think of any representative example projects that I can extract information from, for the topics that were addressed? 19. Finally, would like to add anything else before we end this session?

APPENDIX B – EARLY DESIGN PHASE INPUTS-OUTPUTS

Table 15: Cost estimation discipline information requirements

DATA	ADDITIONAL INFO	UNIT	SOURCE	TAKE-OFF
GENERAL				
Function	Per building	type	PoR	Auto
Levels (floors)	Per Building	num	Design docs/PoR	Manual/Auto
Capacity	Users (per building)	num.	PoR	Auto
Rooms		name	Design docs/PoR	Manual/Auto
Gross height	Per building	m	Design docs/PoR	Manual/Auto
Gross height	Per floor	m	Design docs/Assmpt.	Manual/Oth.par
Gross floor area (BVO)	NEN 2580	m^2	Design docs/PoR	Manual/Auto
Net floor area (NVO)	NEN 2580	m^2	Design docs/Assmpt.	Manual/Oth.par
Usage area (GO)	NEN 2580	m^2	Design docs/Assmpt.	Manual/Oth.par
Tare area (TO)	NEN 2580	m^2	Design docs/Assmpt.	Manual/Oth.par
Lettable floor area (VVO)	NEN 2580	m^2	Design docs/Assmpt.	Manual/Oth.par
Voids and holes		m^2	Design docs/Assmpt.	Manual/Oth.par
Shafts		m^2	Design docs/Assmpt.	Manual/Oth.par
Horizontal traffic area		m^2	Design docs/Assmpt.	Manual/Oth.par
Vertical traffic area		m^2	Design docs/Assmpt.	Manual/Oth.par
Overbuilt area		m^2	Design docs/Assmpt.	Manual/Oth.par
Patios		m^2	Design docs/Assmpt.	Manual/Oth.par
Gross volume	NEN 2580 *(BVO + voids with a surface > 4m² * gross height)*	m^3	Design docs/Assmpt.	Other par. /Oth.par
Net Volume	NEN 2580 *(NVO + voids with a surface > 4m² * net height)*	m^3	Design docs/Assmpt.	Other par. /Oth.par
Installations area		m^2	Design docs/Assmpt.	Manual/Oth.par
Sanitary facilities		m^2	Design docs/Assmpt.	Manual/Oth.par
INDIVIDUAL SPACES				
Room		name	Design docs/PoR	Manual/Auto
Room level		num	Design docs/PoR	Manual/Auto
Room function	Bouwbesluit room type	type	Design docs/PoR	Manual/Auto
Usage function	Bouwbesluit room function	type	Design docs/PoR	Manual/Auto
Usage Area (GO)	Per room	m^2	Design docs/PoR	Manual/Auto
FOUNDATION				
Soil Facilities		m^2	Design docs/Assmpt.	Manual/Oth.par
Floors on base		m^2	Design docs/Assmpt.	Manual/Oth.par
Foundation structures		m^2	Design docs/Assmpt.	Manual/Oth.par
Pile foundations		m^2	Design docs/Assmpt.	Manual/Oth.par
SKELETON				
Inner bearing walls		m^2	Design docs/Assmpt.	Manual/Oth.par
Outer bearing walls		m^2	Design docs/Assmpt.	Manual/Oth.par
Columns		m^2	Design docs/Assmpt.	Manual/Oth.par
Floors		m^2	Design docs/Assmpt.	Manual/Oth.par
Roof		m^2	Design docs/Assmpt.	Manual/Oth.par
Main supporting structures		m^2	Design docs/Assmpt.	Manual/Oth.par

FLOOR FINISHING				
Floor finishing area	(NVO - Vertical traffic areas)	m^2	Design docs/Assmpt.	Oth.par
ROOF FINISHING				
Roof area		m^2	Design docs/Assmpt.	Manual/Oth.par
Roof openings		m^2	Design docs/Assmpt.	Manual/Oth.par
FAÇADE FINISHING				
Exterior/facade walls area		m^2	Design docs/Assmpt.	Manual/Oth.par
Exterior/facade walls openings		m^2	Design docs/Assmpt.	Manual/Oth.par
Exterior/facade walls area incl. variations		m^2	Design docs/Assmpt.	Manual/Oth.par
INTERIOR WALLS FINISHING				
Interior walls area		m^2	Design docs/Assmpt.	Manual/Oth.par
Interior walls openings		m^2	Design docs/Assmpt.	Manual/Oth.par
Interior walls area incl. variations		m^2	Design docs/Assmpt.	Manual/Oth.par
STAIRS AND RAMPS				
Stairs area		m^2	Design docs/Assmpt.	Manual/Oth.par
Ramps area		m^2	Design docs/Assmpt.	Manual/Oth.par
Handrails length		m	Design docs/Assmpt.	Manual/Oth.par
CEILINGS				
Ceiling finishes	(NVO - Vertical traffic areas + overbuilt surface)	m^2	Design docs/Assmpt.	Other par.
NOT INCLUDED IN THE BVO				
Balconies		m^2	Design docs/Assmpt.	Manual/Oth.par
Galleries		m^2	Design docs/Assmpt.	Manual/Oth.par

Table 16: Building physics discipline information requirements

DATA	ADDITIONAL INFO	UNIT	SOURCE	TAKEOFF
Function	Per building	type	PoR	Auto
Rooms		name	Design doc/PoR	Manual/Auto
Room level		num	Design docs	
Room function	Bouwbesluit room type	type	Design doc/PoR	Manual/Auto
Usage function	Bouwbesluit room function	type	Design doc/PoR	Manual/Auto
Room dimensions	Length/width	m	Design doc	Manual
Usage area (GO)	Per room	m^2	Design doc	Manual
Gross height	Per building	m	Design doc/PoR	Manual/Auto
Gross height	Per room	m	Design doc	Manual
Gross perimeter	Per room	m	Design doc	Manual
Net perimeter	Per room	m	Design doc	Manual
Net Volume	Per room	m^3	Design doc	Manual
Occupancy MEP max	Room occupancy peak	num.		
Occupancy BES	Room occupancy BES	num.		
Ventilation zone	Climate zone Per room	type		
Ventilation rate supply	Per room	num.		
Ventilation rate extraction	Per room	num.		
Ventilation type (One-side/cross)	Per room	type		
Exhaust specific fan power	Per room	num.		
Outside air variation profile	Per room	type		

Heating Load	Per room	num.		
Cooling Load	Per room	num.		
Heating method	Per room	type		
Maximum temperature	Per room	num.		
Minimum temperature	Per room	num.		
Heating operation profile	Per room	type		
Cooling operation profile	Per room	type		
Light power density	Per room	num.		
Required light level	Per room	num.		
Facade walls area	Per floor/orientation	m^2	Design doc	Manual
Façade openings types	Per floor/orientation	type	Design doc	Manual
Façade openings dimensions	Per floor/orientation	m	Design doc	Manual
Façade openings area	Per floor/orientation	m^2	Design doc	Manual
Façade open/closed percentage	Per floor/orientation	m^2	Design doc	Manual
Glass area	Per floor/orientation	m^2	Design doc	Manual
Window frames type	Per floor/orientation	type		Manual
Window frames area	Per floor/orientation	m^2	Design doc	Manual
Type of opening (90°/reclined)	Per floor/orientation	type	Design doc	Manual
Façade openings’ obstructions	Per floor/orientation	real	Design doc	Manual
Façade openings’ obstr. dimensions	Per floor/orientation	m	Design doc	Manual

Table 17: Sustainability discipline information requirements

DATA	ADDITIONAL INFO	UNIT	SOURCE	TAKE-OFF
Building length		m	Design docs	Manual
Building width		m	Design docs	Manual
Building height		m	Design docs	Manual
Roof area		m^2	Design docs	Manual
Materials	Per building element	m^3/kg	Design docs	Manual
Recyclability	Per material	%	Int. knowledge/xls	Automatic
Installations type		m	Installations docs	Automatic
Glass areas		m^2	Design docs	Manual
Opac areas		m^2	Design docs	Manual
Plot area		m^2	PoR/Design docs	Auto/Manual
Landscape area		m^2	PoR/Design docs	Auto/Manual

Table 18: Fire safety discipline information requirements

DATA	ADDITIONAL INFO	UNIT	SOURCE	TAKE-OFF
Function	Per building	type	PoR	Auto
Building layout	Included in drawings	dwg/pdf	Design docs	Manual
Gross height	Per building	m	Design docs	Manual
Usage area (GO)	Per room	m^2	Design docs	Manual
Capacity	Users (per building)	num	PoR	Auto
Capacity	Users (per room)	num	PoR	Auto
Stairs	Included in drawings	dwg/pdf	Design docs	Manual
Materials	Per building element	type	Design docs/PoR	Manual/Auto
Distance between windows	Vertical	m	Design docs	Manual
Window frames materials		type	Design docs	Manual

Table 19: Specialists' outcomes and generated information

<table>
<tr><td colspan="4">COST MANAGER</td></tr>
<tr><td><u>OUTCOME</u></td><td><u>INFORMATION</u></td><td><u>TYPE</u></td><td><u>SHARED TO</u></td></tr>
<tr><td>Project's costs spreadsheet</td><td>1. Building costs</td><td>Excel</td><td>1. Architect
2. Structural Eng.
3. Local project folder</td></tr>
<tr><td colspan="4">FIRE SPECIALIST</td></tr>
<tr><td><u>OUTCOME</u></td><td><u>INFORMATION</u></td><td><u>TYPE</u></td><td><u>SHARED TO</u></td></tr>
<tr><td>Drawings with comments/lines</td><td>1. Fire compartments
2. Fire separation walls
3. Fire rated walls
4. Duration of fire rated walls
5. Fire rated windows
6. Components' materials
7. Evacuation routes direction
8. Extra protected evacuation routes (EBV)
9. Evacuation stairs
10. Sprinkled areas
11. Types of doors
12. Fire safety installations</td><td>Pdf</td><td>1. Architect
2. Building physicist
3. Installations eng.
4. Local project folder</td></tr>
<tr><td colspan="4">BUILDING PHISICIST</td></tr>
<tr><td><u>OUTCOME</u></td><td><u>INFORMATION</u></td><td><u>TYPE</u></td><td><u>SHARED TO</u></td></tr>
<tr><td>Energy calculations report</td><td><u>Entire building</u>
1. Total energy consumption level
2. Total power for cooling and heating
<u>Individual rooms</u>
1. Local cooling and heating loads
2. Ventilation rate
3. Temperature profiles
4. Number of hours that temperature goes above a certain level
5. Humidity
6. CO_2 concentration</td><td>Excel</td><td>1. Architect
2. Local project folder</td></tr>
<tr><td>BENG calculations report</td><td>1. Total energy requirement in kWh per m 2 of usable area
2. Total primary fossil energy use, also in kWh per m 2 usable area
3. the total share of renewable energy in percentages
4. the hours that temperature goes above 25C</td><td></td><td></td></tr>
<tr><td>Daylighting analysis report</td><td><u>Individual rooms</u>
1. Distribution of illuminance
2. Equivalent daylight area</td><td></td><td></td></tr>
<tr><td>Ventilation analysis report</td><td>1. Ventilation strategy
2. Ventilation rate
3. Ventilation rate per room
4. Ventilation profile</td><td></td><td></td></tr>
<tr><td colspan="4">SUSTAINABILITY</td></tr>
<tr><td><u>OUTCOME</u></td><td><u>INFORMATION</u></td><td><u>TYPE</u></td><td><u>SHARED TO</u></td></tr>
<tr><td>Sustainability concepts</td><td>1. Building materials impact
2. Amount of PVs needed</td><td>Excel/ Report</td><td>1. Architect
2. Cost manager
3. Local project folder</td></tr>
</table>

APPENDIX C – FINAL DESIGN PHASE INPUTS

Table 20: Architectural engineering information requirements

DATA	ADDITIONAL INFO	UNIT	SOURCE	TAKEOFF
Geometry/layout	Per building	dwg/pdf/3D	Design docs	Auto
Levels and grids	Per building	dwg/pdf/3D	Design docs	Auto
Rooms		name	Design docs/PoR	Auto
Rooms		number	Design docs/PoR	Auto
Functions	Per room	type	Design docs/PoR	Auto
Fire compartments	Per building	room attribute	Fire specialist docs	Auto
Fire rated walls	Per building	name	Fire specialist docs	Auto
Fire separation	Per room bounding element	element attribute	Fire specialist docs	Auto
Duration of fire separation	Per room bounding element	element attribute	Fire specialist docs	Auto
Evacuation route	Per room	room attribute	Fire specialist docs	Auto
Evacuation route direction			Fire specialist docs	Auto
Security zoning	Per building	room attribute	Fire specialist docs	Auto
Fire rated doors		name	Fire specialist docs	Auto
Duration of fire rated doors	Per component	minutes	Fire specialist docs	Auto
Acoustic properties	Per room/walls/doors	value (db)	Building physics docs	Auto
Acoustic requirements	Per room/walls/doors	value (db)	Building physics docs/PoR	Auto
Thermal requirements	Per room/bounding element	Rc (m2K/W)	Building physics docs	Auto
Thermal performance/specifications	Per room/bounding element		Building physics docs/PoR	Auto
Insulation		type	Building physics docs	Auto
Insulation	Thickness	mm	Building physics docs	Auto
Maintainability	Per component	text	Internal knowledge/docs	Auto
Constructability	Per component	text	Internal knowledge/docs	Auto
Availability on market	Per component	text	Internal knowledge/web	Auto
Doors		type	Design docs	Manual
Windows		type	Design docs	Manual
Materials	Per component	type/m^3	Design docs/PoR	Manual/Auto
Finishes	Per room/and-or bounding element	type/m^2	Design docs	Manual
MEP components		type	MEP engineer docs	Auto
MEP components position		dwg/pdf	MEP engineer docs	Auto
MEP components size		m	MEP engineer docs	Auto
MEP components area		m^2	MEP engineer docs	Auto

Table 21: Structural engineering information requirements

DATA	ADDITIONAL INFO	UNIT	SOURCE	TAKE-OFF
Geometry/layout	Per building	dwg/pdf	Design docs	Auto
Levels and grids	Per building	dwg/pdf	Design docs	Auto
Façade openings percentage	Per facade	%	Design docs	Manual
Materials	Per element	type	Design docs/PoR	Manual/auto

APPENDIX D – IFC SCHEMA

Table 22: Research's information needs that included in IFC schema

DATA	IFC ENTITY	PROPERTY SET	PROPERTY
GENERAL INFORMATION			
Function	ifcBuilding	Pset_BuildingCommon	OccupancyType
Number of floors	ifcBuilding	Pset_BuildingCommon	NumberOfStoreys
Gross height	ifcBuilding	Qto_BuildingBaseQuantities	Height
Voids	ifcOpeningElement	Qto_OpeningElementBase Quantities	Area
Balconies	ifcSpace	Pset_SpaceCommon	is External/ NetFloorArea
Galleries	ifcSpace	Pset_SpaceCommon	is External/ NetFloorArea
Patios	ifcSpace	Pset_SpaceCommon	is External/ NetFloorArea
Materials	IfcMaterial	-	-
Finishes	ifcCovering	Qto_CoveringBaseQuantities	NetArea
Doors	ifcDoor	Pset_DoorCommon	Reference
Acoustic requirements	ifcDoor	Pset_DoorCommon	AcousticRating
Acoustic properties	ifcDoor	Pset_DoorCommon	AcousticRating
INDIVIDUAL SPACES			
Rooms	ifcSpace	Pset_SpaceCommon	Reference
Room level	ifcSpace	-	-
Usage function	ifcSpace	Pset_SpaceOccupancy Requirements	OccupancyType
Capacity	ifcSpace	Pset_SpaceOccupancy Requirements	OccupancyNumber
Gross Height	ifcSpace	Qto_SpaceBaseQuantities	Height
Net Height	ifcSpace	Qto_SpaceBaseQuantities	FinishCeilingHeight
Maximum temperature	ifcSpace	Pset_SpaceThermal Requirements	SpaceTemperature Max
Minimum temperature	ifcSpace	Pset_SpaceThermal Requirements	SpaceTemperature Min
FIRE SAFETY			
Fire separation	ifcWall	Pset_WallCommon	FireRating
Evacuation route	ifcSpace	Pset_SpaceFireSafety Requirements	FireExit
FOUNDATION			
Pile foundations	ifcPile	Qto_PileBaseQuantities	GrossSurfaceArea
SKELETON			
Inner bearing walls	ifcWall	Qto_WallBaseQuantities	NetSideArea
Outer bearing walls	ifcWall	Qto_WallBaseQuantities	NetSideArea
Columns	ifcColumn	Qto_ColumnBaseQuantities	CrossSectionArea

Slabs	ifcSlab	Qto_SlabBaseQuantities	NetArea
Roof	ifcRoof	Qto_RoofBaseQuantities	NetArea
INTERIOR WALL FINISHING			
Interior walls area	ifcWall	Qto_WallBaseQuantities	NetSideArea
Interior walls openings	ifcOpeningElement	Qto_OpeningElementBase Quantities	Area
ROOF FINISHING			
Roof area	ifcRoof	Qto_RoofBaseQuantities	NetArea
Roof openings	ifcOpeningElement	Qto_OpeningElementBase Quantities	Area

Table 23: IfcSite properties

Pset_SiteCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier
TotalArea	Single value	IfcAreaMeasure
BuildableArea	Single value	IfcAreaMeasure
LandscapeArea	Single value	IfcAreaMeasure

Table 24: ifcBuilding quantities

Qto_BuildingBaseQuantities		
Name	**Description**	**Type**
TotalHeight	Gross height, from the top surface of the construction floor, to the top surface of the construction floor or roof above	Q_LENGTH
EavesHeight	Gross height, from the top surface of the construction floor, to the base of roof structure.	Q_LENGTH

Table 25: ifcBuilding general data

Pset_BuildingCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier
BuildingID	Single value	IfcIdentifier
NumberOfStoreys	Single value	IfcInteger
OccupancyType	Single value	IfcLabel
OccupancyNumber	Single value	IfcCountMeasure

Table 26: ifcBuilding measurements

Pset_BuildingMeasurements		
PropertyName	**Template**	**Data type**
GrossFloorArea(GFA)	Single value	IfcAreaMeasure
NetFloorArea (NVO)	Single value	IfcAreaMeasure
UsageArea (GO)	Single value	IfcAreaMeasure
TareArea (TO)	Single value	IfcAreaMeasure
LettableFloorArea (VVO)	Single value	IfcAreaMeasure
OverbuiltArea	Single value	IfcAreaMeasure
Gross volume	Single value	ifcVolumeMeasure
Net volume	Single value	ifcVolumeMeasure

Table 27: ifcBuildingStorey quantities

Qto_BuildingStoreyBaseQuantities		
Name	**Description**	**Type**
GrossHeight	Gross height of this storey, from the top surface of the construction floor, to the top surface of the construction floor or roof above.	Q_LENGTH
NetHeight	Standard net height of this storey, from the top surface of the construction floor, to the bottom surface of the construction floor or roof above.	Q_LENGTH
GrossPerimeter	Perimeter of the outer contour of the building story without taking interior slab openings into account.	Q_LENGTH

Table 28: ifcBuildingStorey general data

Pset_BuildingStoreyCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier

Table 29: ifcSpace general data

Pset_SpaceCommon		
PropertyName	**Template**	**Data type**
Room name	Single value	IfcLabel
Reference	Single value	ifcIdentifier
IsExternal	Single value	ifcBoolean
Usage area (GO)	Single value	ifcAreaMeasure
GrossHeight	Single value	ifcPositiveLengthMeasure
NetHeight	Single value	ifcPositiveLengthMeasure
Length	Single value	ifcPositiveLengthMeasure
Width	Single value	ifcPositiveLengthMeasure
GrossPerimeter	Single value	ifcPositiveLengthMeasure
NetPerimeter	Single value	ifcPositiveLengthMeasure
Net Volume	Single value	ifcVolumeMeasure

Table 30: ifcSpace Occupancy data

Pset_SpaceOccupancyRequirements		
PropertyName	**Template**	**Data type**
Room function *(Type)*	Single value	ifcLabel
OccupancyType *(Usage function)*	Single value	IfcLabel
OccupancyNumber	Single value	IfcCountMeasure
OccupancyNumberPeak	Single value	IfcCountMeasure
OccupancyTimePerDay	Single value	IfcTimeMeasure

Table 31: ifcSpace Fire Safety requirements

Pset_SpaceFireSafetyRequirements		
PropertyName	**Template**	**Data type**
FireCompartment	Single value	ifcBoolean
FireCompartmentationReference	Single value	ifcLabel
FireExit	Single value	ifcBoolean

Extra protected evacuation routes (EBV)	Single value	ifcBoolean
SprinklerProtection	Single value	ifcBoolean
SprinklerSystemType	Single value	ifcLabel
FlammableStorage	Single value	ifcBoolean

Table 32: ifcSpace Security requirements

Pset_SpaceSecurityRequirements		
PropertyName	Template	Data type
SecurityArea	Single value	ifcBoolean
SecurityAreaReference	Single value	ifcLabel

Table 33: ifcSpace BFI requirements

Pset_SpaceBFIRequirements		
PropertyName	Template	Data type
Occupancy MEP max	Single value	IfcCountMeasure
Occupancy BES	Single value	IfcCountMeasure
AcousticLevelRequirement	Single value	ifcLabel
ThermalRequirement	Single value	ifcLabel

Table 34: ifcSpace BFI specifications

Pset_SpaceBFISpecifications		
PropertyName	Template	Data type
AcousticLevel	Single value	ifcLabel
ThermalPerformance	Single value	ifcLabel
SpaceTemperatureMax	Single value	IfcThermodynamicTemperatureMeasure
SpaceTemperatureMin	Single value	IfcThermodynamicTemperatureMeasure
Ventilation zone	Single value	ifcLabel
Ventilation rate supply	Single value	IfcCountMeasure
Ventilation rate extraction	Single value	IfcCountMeasure
Ventilation type (One-side/cross vent.)	Single value	ifcLabel
Exhaust specific fan power	Single value	IfcPowerMeasure
Outside air variation profile	Single value	ifcLabel
Heating Load	Single value	IfcPowerMeasure
Cooling Load	Single value	IfcPowerMeasure
Heating method	Single value	ifcLabel
Heating operation profile	Single value	ifcLabel
Cooling operation profile	Single value	ifcLabel
Light power density	Single value	IfcIlluminanceMeasure
Required light level	Single value	IfcIlluminanceMeasure

Table 35: ifcSpace finishes

Pset_SpaceCoverings		
PropertyName	Property type	Data type
Floor covering	Single value	IfcLabel
Floor covering thickness	Single value	ifcPositiveLengthMeasure
Wall covering	Single value	IfcLabel
Wall covering thickness	Single value	ifcPositiveLengthMeasure
Ceiling covering	Single value	IfcLabel
Ceiling covering thickness	Single value	ifcPositiveLengthMeasure

Concealed flooring	Single value	IfcBoolean
Concealed ceiling	Single value	IfcBoolean

Table 36: ifcSlab general data

Pset_SlabCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	ifcIdentifier
LoadBearing	Single value	ifcBoolean
AcousticRating	Single value	IfcLabel
FireRating	Single value	IfcLabel

Table 37: ifcSlab quantities

Qto_SlabBaseQuantities		
Name	**Description**	**Type**
Width	Nominal width (or thickness) of the slab. Only given, if the slab is prismatic (constant thickness).	Q_LENGTH
Perimeter	Perimeter measured along the outer boundaries of the slab. Only given, if the slab is prismatic (constant thickness)	Q_LENGTH
NetArea	Total area of the extruded area of the slab. Openings and recesses are taken into account by subtraction, projections by addition. Only given, if the slab is prismatic.	Q_AREA

Table 38: ifcVoid general data

Pset_VoidCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	ifcIdentifier
Length	Single value	ifcPositiveLengthMeasure
Width	Single value	ifcPositiveLengthMeasure
Area	Single value	IfcAreaMeasure

Table 39: ifcRoof general data

Pset_RoofCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	ifcIdentifier
LoadBearing	Single value	ifcBoolean
AcousticRating	Single value	IfcLabel
FireRating	Single value	IfcLabel

Table 40: ifcRoof quantities

Qto_RoofBaseQuantities		
Name	**Description**	**Type**
NetArea	Total net area of the outer surface of the roof. It is the sum of all roof slab net areas. Roof openings, like sky windows and other openings and cut-outs are taken into account.	Q_AREA

ProjectedArea	Total gross area of the outer surfaces of the roof, projected to the ground. It is the sum of all projected roof slab gross areas. Roof openings, like sky windows and other openings and cut-outs are not taken into account.	Q_AREA

Table 41: ifcColumn general data

Pset_RoofCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	ifcIdentifier
LoadBearing	Single value	ifcBoolean

Table 42: ifcColumn quantities

Qto_RoofBaseQuantities		
Name	**Description**	**Type**
Length		Q_LENGTH
CrossSectionArea	Total area of the cross section (or profile) of the column.	Q_AREA
OuterSurfaceArea	Total area of the extruded surfaces of the column, normally generated as perimeter * length.	Q_AREA

Table 43: ifcMainSupportingStructure general data

Pset_MainSupportingStructureCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	ifcIdentifier
LoadBearing	Single value	ifcBoolean
TotalArea	Single value	ifcAreaMeasure

Table 44: ifcWall quantities

Qto_WallBaseQuantities		
Name	**Description**	**Type**
Length	Total nominal length of the wall along the wall center line (even if different to the wall path).	Q_LENGTH
Width	Total nominal width (or thickness) of the wall measured perpendicular to the wall path. It should only be provided, if it is constant along the wall path.	Q_LENGTH
Height	Total nominal height of the wall. It should only be provided, if it is constant along the wall path.	Q_LENGTH
NetSideArea	Area of the wall as viewed by an elevation view of the middle plane. It does take into account all wall modifications (such as openings).	Q_AREA
NetFootprintArea	Area of the wall as viewed by a ground floor view, taking all wall modifications (like recesses) into account.	Q_AREA
NetVolume	Volume of the wall, after subtracting the openings and after considering the connection geometry.	Q_VOLUME

Table 45: ifcWall general data

Pset_WallCommon		
PropertyName	**Template**	**Data type**

Reference	Single value	IfcIdentifier
IsExternal	Single value	ifcBoolean
LoadBearing	Single value	ifcBoolean
Orientation	Single value	ifcLabel

Table 46: ifcWall Building physics specifications

Pset_WallBFISpecifications		
PropertyName	**Template**	**Data type**
Insulation	Single value	IfcLabel
InsulationThickness	Single value	ifcPositiveLengthMeasure
AcousticRatingRequirement	Single value	IfcLabel
AcousticRating	Single value	IfcLabel
ThermalTransmittanceRequirement	Single value	IfcThermalTransmittanceMeasure
ThermalTransmittance	Single value	IfcThermalTransmittanceMeasure
FireSeparation	Single value	ifcBoolean
FireRating	Single value	ifcLabel
FireSeparationDuration	Single value	ifcTimeMeasure

Table 47: ifcDoor quantities

Qto_DoorBaseQuantities		
Name	**Description**	**Type**
Width	Total outer width of the door lining. It should only be provided, if it is a rectangular door.	Q_LENGTH
Height	Total outer height of the door lining. It should only be provided, if it is a rectangular door.	Q_LENGTH
Perimeter	Total perimeter of the outer lining of the door.	Q_LENGTH
Area	Total area of the outer lining of the door.	Q_AREA

Table 48: ifcDoor general data

Pset_DoorCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier
IsExternal	Single value	ifcBoolean
SecurityRating	Single value	IfcLabel
AcousticRating	Single value	IfcLabel
ThermalTransmittance	Single value	IfcThermalTransmittanceMeasure
FireSeparation	Single value	ifcBoolean
FireRating	Single value	ifcLabel
FireSeparationDuration	Single value	ifcTimeMeasure
FireExit	Single value	ifcBoolean
SelfClosing	Single value	ifcBoolean

Table 49: ifcWindow quantities

Qto_WindowBaseQuantities		
Name	**Description**	**Type**
Width	Total outer width of the window lining. It should only be provided, if it is a rectangular window.	Q_LENGTH
Height	Total outer height of the window lining. It should only be provided, if it is a rectangular window.	Q_LENGTH
Perimeter	Total perimeter of the outer lining of the window.	Q_LENGTH
Total area	Total area of the outer lining of the window.	

Glazing area	Total glass area of the window.	Q_AREA
Opac area	Total opac area of the window.	Q_AREA
Frame area	Total frame area of the window.	Q_AREA

Table 50: ifcWindow general data

Pset_WindowCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier
IsExternal	Single value	ifcBoolean
GlazingAreaFraction	Single value	IfcLabel
SecurityRating	Single value	IfcLabel
AcousticRating	Single value	IfcLabel
ThermalTransmittance	Single value	IfcThermalTransmittanceMeasure
SelfClosing	Single value	ifcBoolean

Table 51: ifcWindow types

Window types		
Attribute	**Description**	**Type**
PredefinedType	Predefined generic type for a window that is specified in an enumeration. There may be a property set given specifically for the predefined types.	IfcWindowTypeEnum
PartitioningType	Type defining the general layout of the window in terms of the partitioning of panels.	IfcWindowTypePartitioningEnum

Table 52: ifcWindow lining properties

Lining properties		
Attribute	**Description**	**Type**
LiningDepth	Depth of the window lining (dimension measured perpendicular to window elevation plane).	IfcPositiveLengthMeasure
LiningThickness	Thickness of the window lining as explained in the figure above. If LiningThickness value is 0. (zero) it denotes a window without a lining (all other lining parameters shall be set to NIL in this case). If the LiningThickness is NIL it denotes that the value is not available.	IfcNonNegativeLengthMeasure

Table 53: ifcWindow panel properties

Panel properties		
Attribute	**Description**	**Type**
OperationType	Types of window panel operations. Also used to assign standard symbolic presentations according to national building standards.	IfcWindowPanelOperationEnum
PanelPosition	Position of this panel within the overall window style.	IfcWindowPanelPositionEnum
FrameDepth	Depth of panel frame, measured from front face to back face horizontally (i.e. perpendicular to the window (elevation) plane).	IfcPositiveLengthMeasure

FrameThickness	Width of panel frame, measured from inside of panel (at glazing) to outside of panel (at lining), i.e. parallel to the window (elevation) plane.	IfcPositiveLengthMeasure

Table 54: ifcFacade common properties

Pset_FacadeCommon		
PropertyName	**Template**	**Data type**
Reference	Single value	IfcIdentifier
Orientation	Single value	ifcLabel

Table 55: ifcFacade base quantities

Pset_FacadeBaseQuantities		
PropertyName	**Template**	**Data type**
Length	Single value	IfcIdentifier
Width	Single value	ifcPositiveLengthMeasure
Height	Single value	ifcPositiveLengthMeasure
Gross Area	Single value	IfcAreaMeasure
Total closed area	Single value	IfcAreaMeasure
Total openings area	Single value	IfcAreaMeasure
Open/closed percentage	Single value	IfcAreaMeasure
Total glass area	Single value	IfcAreaMeasure

Table 56: ifcFacade BFI specifications

Pset_FacadeBFISpecifications		
PropertyName	**Template**	**Data type**
AcousticRatingRequirement	Single value	IfcLabel
AcousticRating	Single value	IfcLabel
ThermalTransmittanceRequirement	Single value	IfcThermalTransmittanceMeasure
ThermalTransmittance	Single value	IfcThermalTransmittanceMeasure
FireSeparation	Single value	ifcBoolean
FireRating	Single value	ifcLabel
FireSeparationDuration	Single value	ifcTimeMeasure

APPENDIX E – USE CASE PROJECT

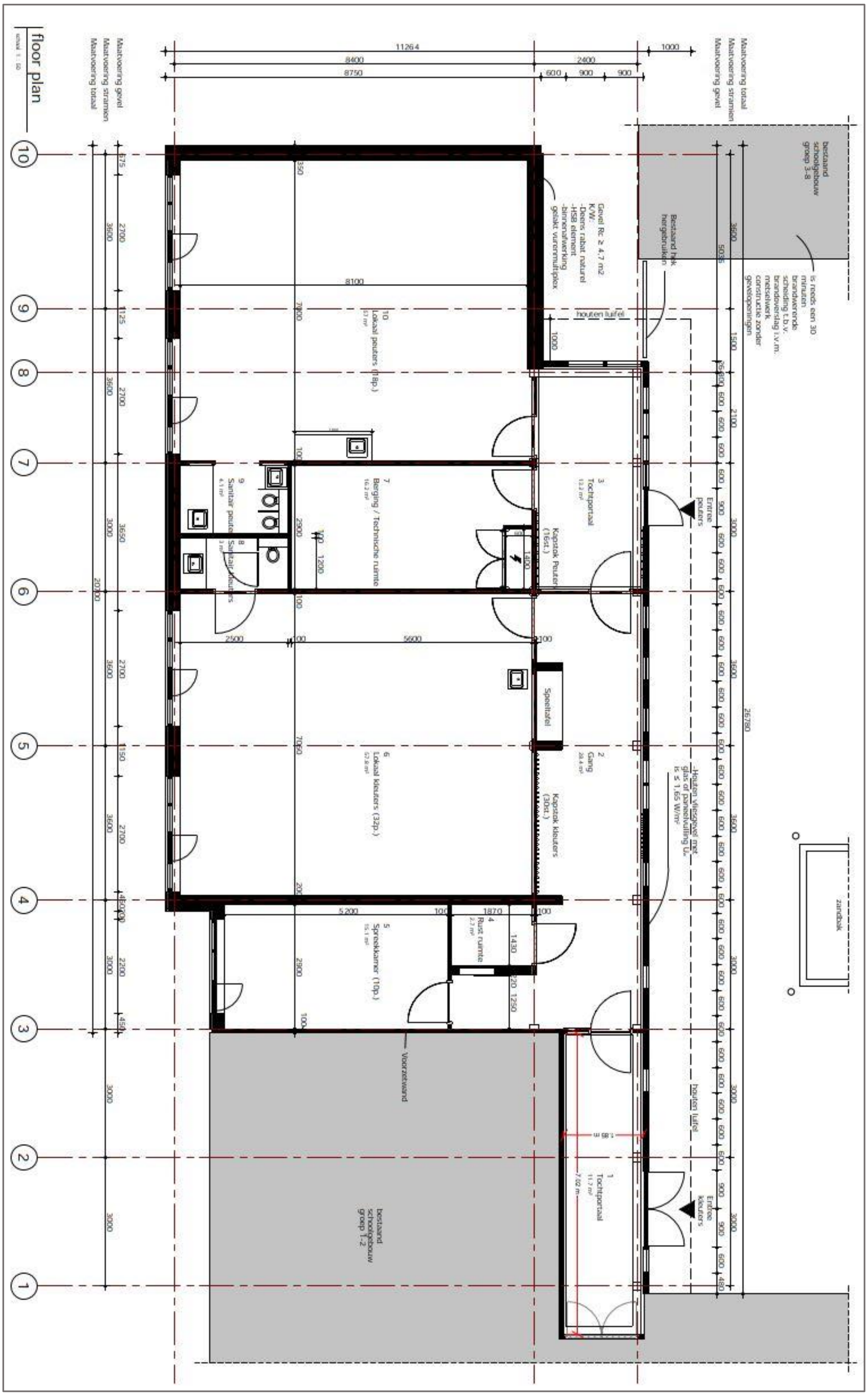

Figure 45: Floor plan

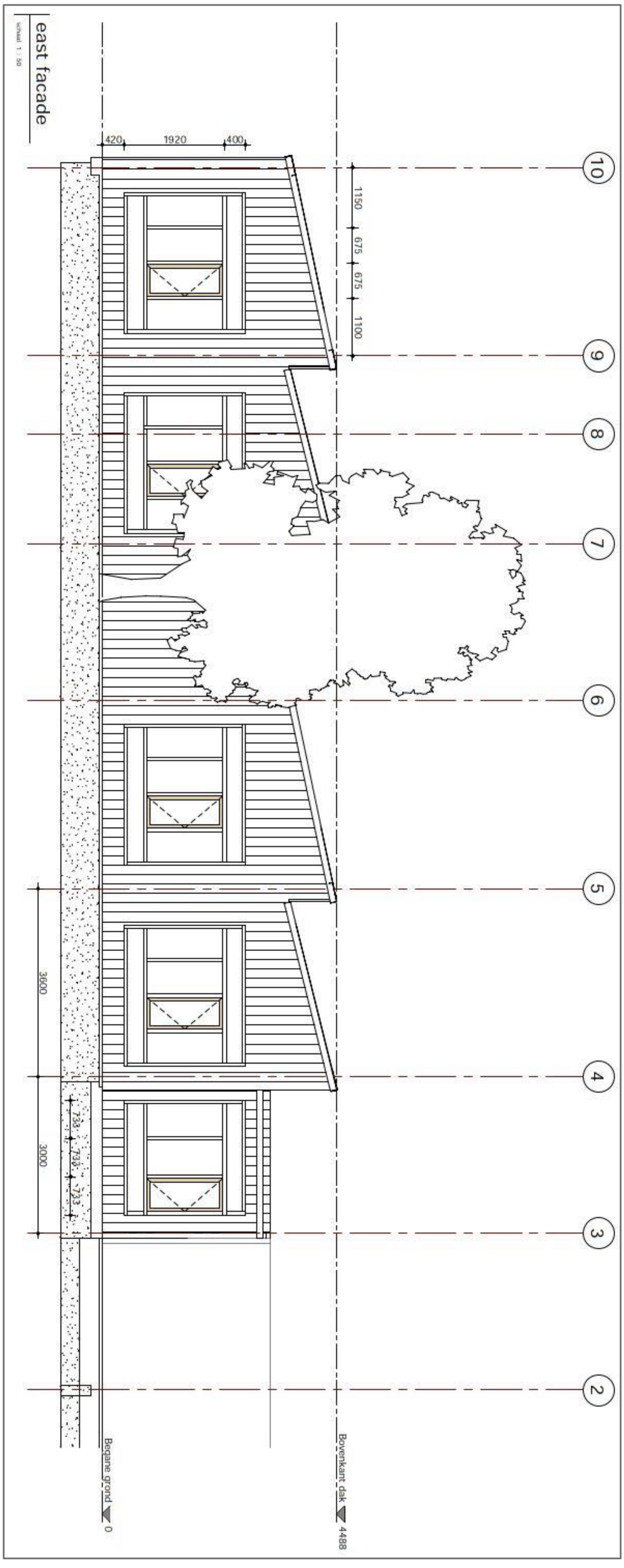

Figure 46: East facade

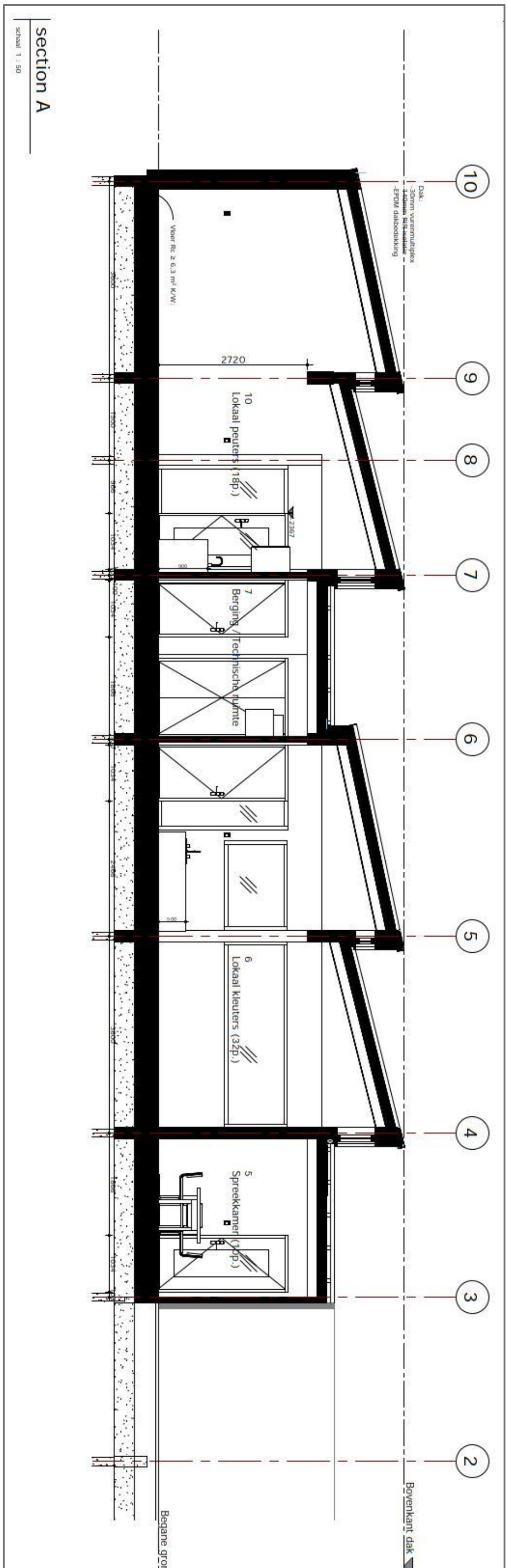

Figure 47: Section A

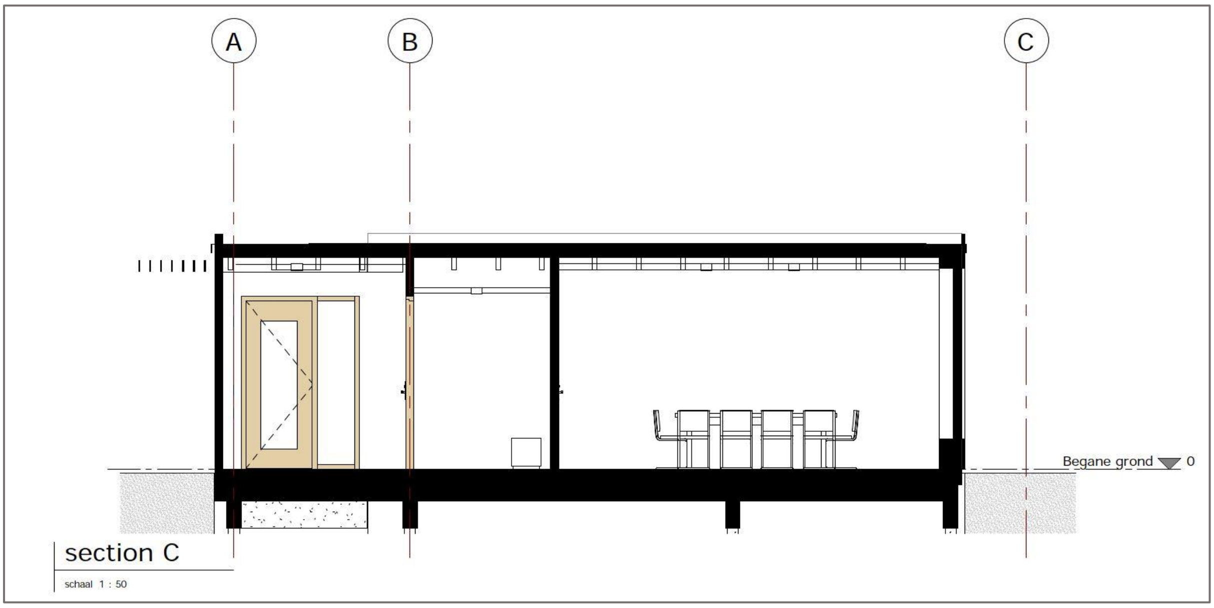

Figure 48: Section C

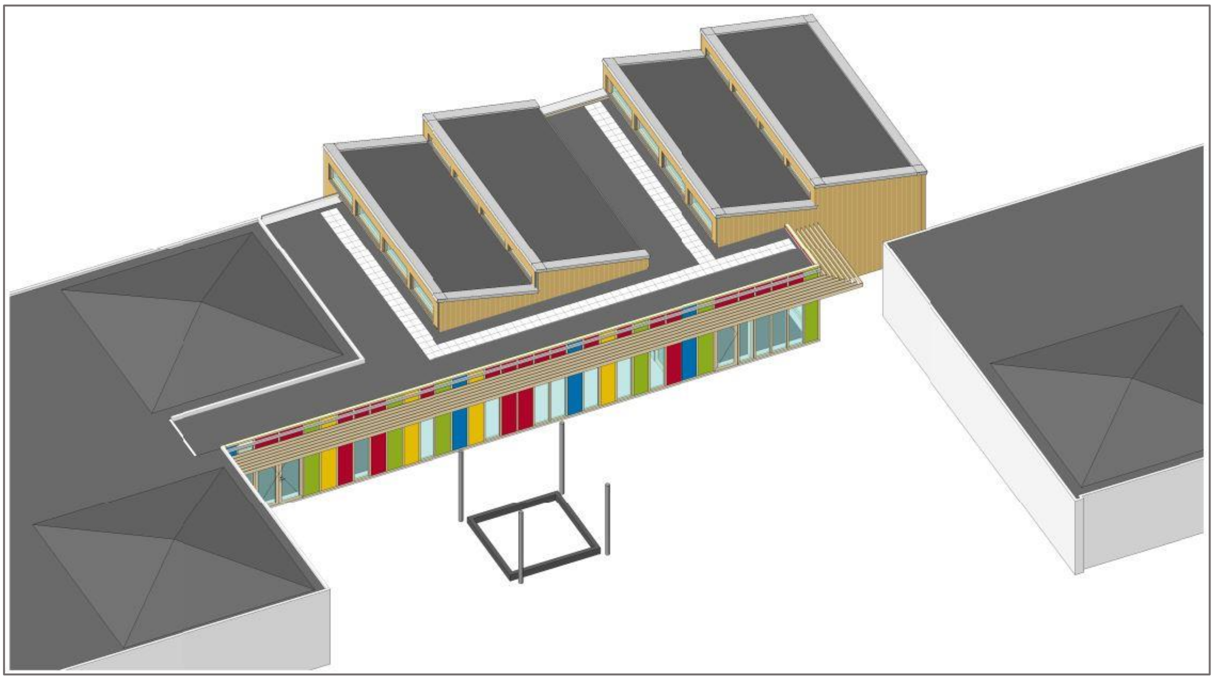

Figure 49: 3D illustration

APPENDIX F – VALIDATION QUESTIONNAIRES

Table 57: Validation form - early design

CRITERIA	SCORE				
	1	2	3	4	5
1. Consistency *All disciplines use the same measurement of variables throughout the datasets without having discrepancies over the same data.*					
<u>Additional remarks:</u>					
2. Completeness *Evaluator's information needs are sufficiently covered.*					
<u>Additional remarks:</u>					
3. Rework elimination *Redundant take-offs for the same data by multiple specialists are reduced.*					
<u>Additional remarks:</u>					
4. Scalability *Extent that the proposed structure can be used by other specialists of early design phase.*					
<u>Additional remarks:</u>					
5. Applicability or ease of use *How easily the evaluator can use the proposed solution.*					
<u>Additional remarks:</u>					
6. Efficiency *Overall efficiency that the proposal brings to evaluator's work process in terms of collecting and managing information.*					
<u>Additional remarks:</u>					

Scale: 1. Poor, 2. Low, 3. Fair, 4. Good, 5. Excellent

Table 58: Validation form - final design

CRITERIA	SCORE				
	1	2	3	4	5
1. Integration *Indicates the extent that generated information can be incorporated in final design.*					
Additional remarks:					
2. Applicability *How easily modelers can transfer information from one phase to the other.*					
Additional remarks:					

Scale: 1. Poor, 2. Low, 3. Fair, 4. Good, 5. Excellent