Diplomarbeit

From Sketching to BIM

Workflow for the Generation of IFC-based BIM Models from 4D Semantic Sketches

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Abstract

The conceptual design stage lacks eligible design methods for the generation of BIM models. The benefits of analogue techniques to solve complex architectural design tasks are quickly outspent, causing designers to either use a farrago of digital tools that rely on error-prone data exchanges, or push early designs into a rigid and heavy BIM workspace before undergoing optimisation based design space exploration. As advances in Artificial Intelligence are increasingly being used for BIM's big data challenges, this thesis presents a seamless workflow based on a small scope of IFC definitions for the generation of conceptual BIM models from 4D semantic sketches, using a machine learning based pipeline. The workflow offers a user-friendly architectural design perspective and facilitates to preserve information in building models more reliably throughout the entire life cycle of a project.

Kurzfassung

Die verfügbaren Methoden zur Entwicklung von BIM Modellen können den Ansprüchen in frühen Entwurfsphasen nicht genügen. Die steigende Komplexität architektonischer Projekte lässt analoge Techniken schnell an ihre Grenzen stoßen und zwingt Architekten und Ingenieure sich einem Durcheinander digitaler Softwarelösungen zu bedienen, die keine passenden Schnittstellen bereitstellen um erarbeitete Ergebnisse vollumfänglich zu teilen. Alternativ werden Entwürfe viel zu früh in ein unflexibles BIM Modell gemeiselt und damit tiefergehende Optimierungsansätze außer Acht gelassen. Der Einsatz künstlicher Intelligenz kann dabei helfen, weitverbreitete Entwurfsmethoden neu zu denken – auch im Kontext von BIM. Im Rahmen dieser Arbeit wird ein nahtloser und benutzerfreundlicher Workflow untersucht, der 4D semantische Zeichnungen als Ausgangspunkt zur Generierung von konzeptionellen IFC basierten BIM Modellen verwendet. Überbrückt werden die verschiedenen Methoden mithilfe einer Machine Learning Pipeline, die das Festschreiben frühester digitaler Informationen über den gesamten Lebenszyklus eines BIM Modells hinweg ermöglicht.

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Abbreviations

AEC	Architecture, Engineering & Construction
AI	Artificial Intelligence
AR	Augmented Reality
BIM	Building Information Modelling
Brep	Boundary Representation
CAD	Computer-Aided Design
CAAD	Computer-Aided Architectural Design
CSG	Constructive Solid Geometry
GUI	Graphical User Interface
GUID	Globally Unique Identifier
HCI	Human-Computer Interaction
IFC	Industry Foundation Classes
IPD	Integrated Project Delivery
ML	Machine Learning
MVD	Model View Definition
NURBS	Non-Uniform Rational B-Splines
SP	Sub-Project

VR	**Virtual Reality**
2D	**two-dimensional**
3D	**three-dimensional**
4D	**four-dimensional (3D + Time)**

Preface

While paying a visit to the yearly student works exhibition of TU Vienna's Institute of Architectural Design, I came across a text written by Austrian architecture journalist Isabella Marboe (2022) as part of the exhibition's sub-theme *Alternative Practice*. Marboe begins stating that the epoch of the grandmasters best architecture is coming to an end, which puts interdisciplinary teams based on cooperation, communication, and integration in charge of solving increasingly complex design tasks. She proceeds…

> "Tools are also changing the practice. BIM (Building Information Modelling), at one end of the scale, converges information from all stakeholders in a single synchronized file – aiming for efficiency. At the other end: The revival of freehand sketching, hands-on and do-it-yourself, open source, autonomy, daring shortcomings, utmost identification with one's self-made object – aiming for dialogue."

The pioneering practice on that scale is recognized to the Canadian architectural grandmaster Frank O. Gehry. The *El Peix d'Or* (engl. golden Fish) pavilion in Barcelona was seized by the firm to execute a workflow based on a digital, three-dimensional (3D) building model to design and construct the ambitious freeform structure (Dickinson, 2011). The firm achieved this milestone in 1992 by using analogue and digital techniques in a fruitful way to form a watertight design process. Although it was by no means seamless: Gehry's paper sketches (Figure 1, Gehry Partners, LLP) were used by model makers as a reference to create physical models, which were then used by 3D scanning experts to create digital copies, which were then

Figure 1 **Freehand Sketch of the El Peix Pavilion Design**

used hand in hand with the analogue models to further refine the conceptual design, until more detailed design work was executed on the digital model only.

Yet, it demonstrates the ambiguous nature of freehand sketching and how it can be utilized as a starting point in design. In this thesis, the potentials of connecting the practices of sketching and modelling are explored. Except that two-dimensional (2D) analogue sketching is exchanged for 3D digital sketching to sketch building models, or in other words create *model sketches*.

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1 Introduction

Initial analytic and exploratory design steps predominantly shape the direction and outcome of a project. During this stage, most of the information about a project is gathered, aiming to clarify the client's requirements and facilitate progress in design conceptualization and ideation. This is conceived as an iterative process (Figure 2, cf. Jones, 1963), during which designers use abstraction to parse complexity. As the simplified problems grow in volume and concreteness over time, the design process becomes more interactive and interrelated, which not only makes it difficult to compartmentalize the design process in general (Brown et al., 1995), but drastically decreases the influence a designer can have on a project.

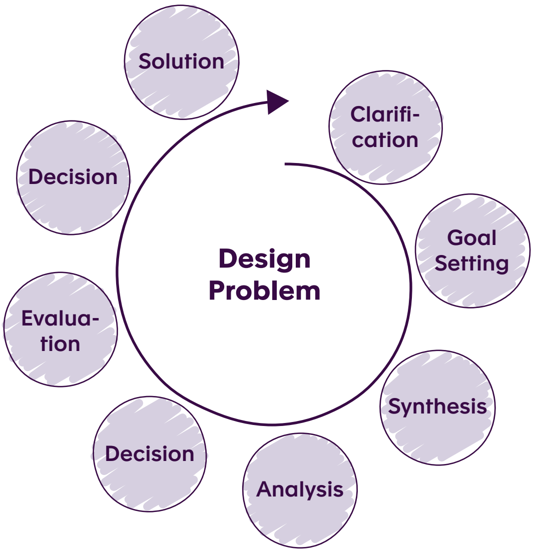


Figure 2 **Iterative Design Process**

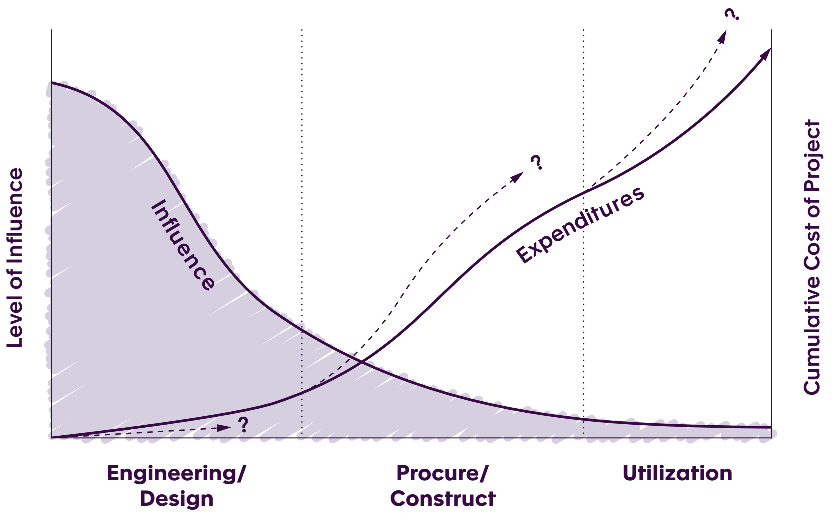


Figure 3 **Paulson's Curve**

The Paulson's Curve shows the level of influence an architectural designer can have on the cumulative costs of a project during its life cycle (Figure 3, cf. Paulson, 1976). Paulson states that all subsequent design decisions have a diminishing influence and are generally more costly to implement, thus construction knowledge should be injected earlier in the design process (Davis, 2013). In addition, shared interests and strategies among multidisciplinary team members are conventionally identified in an ad hoc process, which often leads to inconsistencies and conflicts (Fruchter, 1999).

Although systematic approaches have been identified long ago to make the design process more public, hence fostering contribution of different disciplines to solve design problems (Jones, 1966), actors in the AEC industry just got together in the early 2000's to ideate new ways of implementing methodical strategies such as the Integrated Project Delivery (IPD), which aims to shift intuitive encounters to systematic interactions based on protocols and rigid methodologies (Leon and Laing, 2013), and optimize efficiency throughout the entire project life cycle (Glick and Guggemos, 2009).

On the one hand, BIM methodology can effectively support the collaborative design process, increase productivity and assure reliability of information throughout the entire design, construction, and maintenance process. During the conceptual design stage, that may involve any information about the site, the user's needs, conceptual space allocation plans and geometric or non-geometric dependencies (Mondino, 2021). Early BIM-enabled designs can be readily shared among all stakeholders to exchange and discuss ideas, and first attempts to estimate costs or execute optimization workflows are within the architect's and engineer's grasp.

1.1 Why BIM Workflows Are Disruptive

On the other hand, BIM technology predisposes design tools that focus on the generation of highly detailed building models but exclude such needed for inspirational or abstracted preliminaries (Jabi and Chatzivasileiadi, 2021). This gap in the design process hinders communication of design ideas between stakeholders, disrupts the transfer of model data, and requires laborious redrafting of conceptual designs whenever model data is exchanged among architectural designers based on error-prone briefings. Moreover, these disrupted workflows pose a particular risk of prematurely locking a design into a rigid BIM model before undergoing optimisation based design space exploration.

To address this issue, recent computational design paradigms focused on algorithmic, generative and parametric design strategies within BIM workspaces (Abrishami et al., 2015). They offer a rapid iteration of alternative designs by dissolving design intentions into an array of geometry, composition and algorithmic thought – an approach that requires designers to understand the logic syntax of these systems (Aish, 2005). And although parametric models facilitate comprehensive design changes even in advanced stages, the involved constraints reduce flexibility in early stages of design, and an illusory opportunity to model now and design later is prevalent (Burry and Burry, 2008), giving rise to the question, whether such design strategies can be used to initiate the design process.

1.2 How Sketching Can Help

Another highly iterative approach is obtained from freehand sketching, capable of providing the necessary creative freedom with regard to intuitive early design space exploration. Sketches can cope with complex or missing information by building an abstract narrative that is progressively enriched. The act of sketching also promotes a strong connection between the designer and the design sketch, resulting in higher quality solution findings during initial stages of design (Schütze et al., 2003). Still, architectural practices have reservations about the implementation of digital sketching, fearing the generated data could not be fed into their systems (Dzurilla and Achten, 2022). This concern may soon become obsolete, considering the vast progression of computational technology, in both ways of how humans interact with the computer and Artificial Intelligence (AI) processes design data to bridge different mediums. This advance can further be used to tie intuitive freehand sketching to modelling environments based on the open and vendor-neutral Industry Foundation Classes (IFC), which is widely used for the exchange of information in architecture, engineering, and construction (AEC) disciplines (BuildingSmart International, n.d.).
The conducted research however could not identify existing solutions that make use of 3D freehand sketching for the creation of BIM models. So far, the novel design method is limited to the purpose of recording purely graphical design intentions, which is particularly problematic in the context of an otherwise semantically rich profession of architecture.

1.3 Aim

The aim of this thesis is to present a user-friendly workflow that connects earliest stages of design with BIM methodology by pursuing a seamless transfer of design data acquired through intuitive digital sketching. The workflow intends to approach the beneficial application of BIM in the conceptual design stage, while sustaining maximum creative freedom.

Therefore, a set of criteria must be identified for the graphical and non-graphical description of conceptual IFC models that are aimed for generation on the journey from sketching to BIM. The proposed workflow is demonstrated on a reproduced model sketch of the 1929 Barcelona Pavilion, a modernist classic in architecture.

2 Literature Review

Previous research indicates that there are many challenges to make BIM fit for the conceptual design stage. Its 3D design space is advantageous, but the added complexity and increased attention to building specifications burden the conceptual design development (Flanagan, 2018). This three-part background chapter tries to elaborate on the respective reasons that led to this circumstance. The first two parts cover the origins, current challenges in conceptual design and promising outlooks of BIM. The third part aims to connect it to the use of intuition in the digital design process, which involves a systematic literature review of digital sketching applications. Each part is rounded off with a concluding statement, which can be considered the conductive motives of this research.

2.1 Approaching Conceptual BIM

Due to the lack of eligible design methods for the generation of conceptual BIM models, architectural designers still use analogue and digital techniques to create preliminary designs based purely on geometry. However, given the semantically rich domain of architecture, the benefits of such platforms are quickly outspent. Those methods originated from the "pre-BIM era" (Flanagan, 2018), a time when the architectural plan constituted the most suitable way of capturing design intentions on the basis of multi view drawings, that inevitably required interpretation to derive all 3D shapes and details of a building design (Babalola and Eastman, 2001). The contents usually spread across multiple drawing sheets, overlay systems of different disciplines and use a high level of symbolic representations. To decode the presentational and semantic information, the interpreter had to internalize a vast expertise in the past. This skill repealed with the uptake of object-oriented digital workflows, which was fundamental to the formation of BIM as it is used nowadays. By providing the 3D model at hand, a suitable environment for structuring and reviewing design data can be obtained, which puts behind the cumbersome search for object-unrelated and stacked semantic information in multi view drawings for both humans and computer systems.

2.1.1 Object-based Computer-Aided Design

Among the first example of this paradigm shift and Computer-Aided Design (CAD) tools in general is *Sketchpad*. Developed by Sutherland (1963) within his doctoral thesis, it pioneered the integration of computers in the design process. Capable of creating 2D sketches, using a traceable light-pen to mark points on a monitor screen which could be connected linearly or circularly, the tool formed separate objects that were readily transformable. Hence, it was one of the first approaches to object-oriented design, a method that was adopted to 3D modelling software solutions about a decade later and allowed users of Computer-Aided Architectural Design (CAAD) to constitute building models from geometric primitives and instances. The technology for the description and generation of geometric shapes constantly improved, and designers were eventually presented intricate modelling methods (Figure 4, cf. Ching and Juroszek, 2019) that express geometry as explicit outcomes of a number of parameters, making modification of models significantly easier (Davis, 2013). However, increased fragmentation within the AEC industry was reported by Howard et al. (1989), referring to pioneers of CAD and CAE (Computer-Aided Engi-

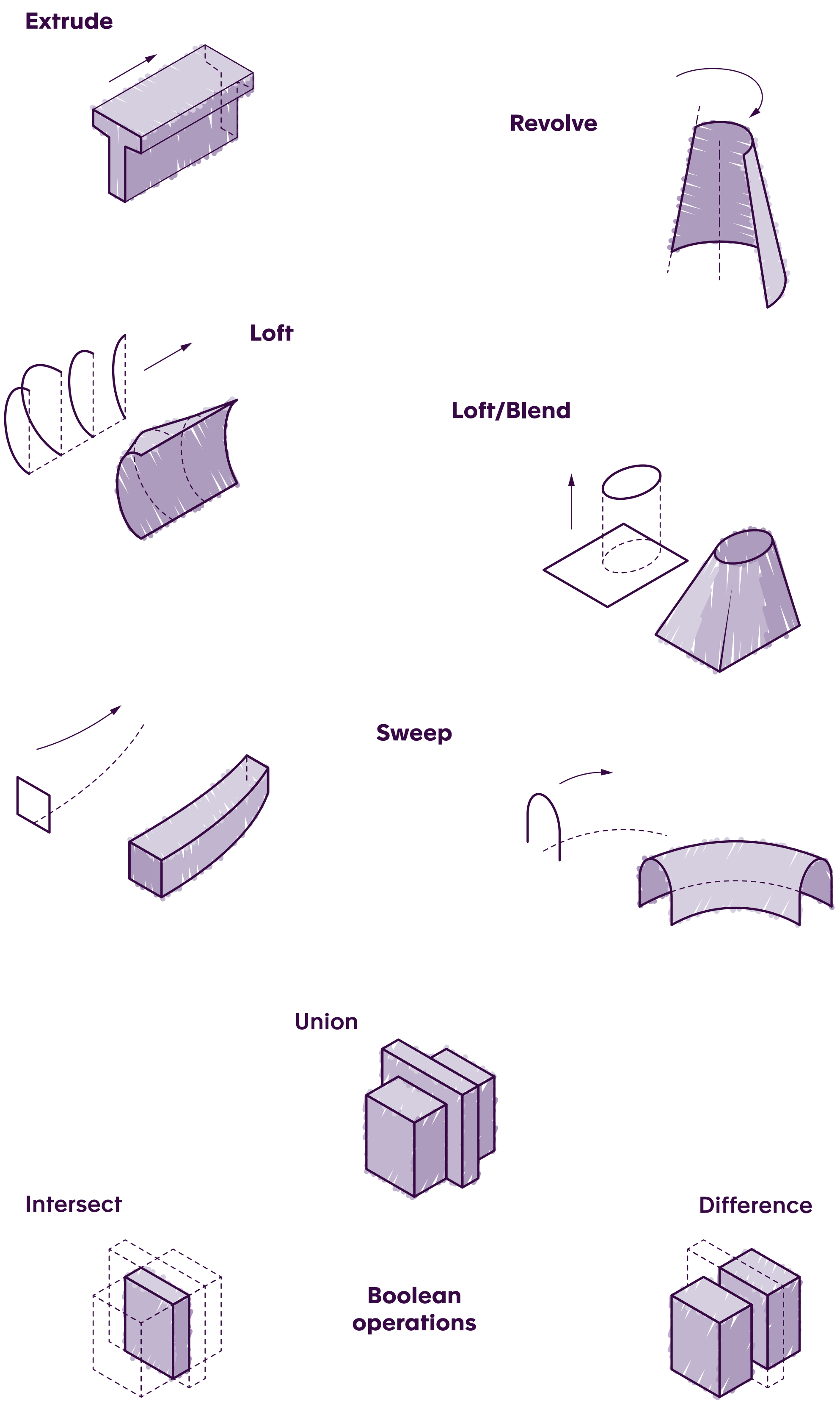


Figure 4 **Digital Modelling Methods**

neering) as "local islands of automation". To support an integrated planning and construction process, Aish (1986) promoted the use of *a) intelligent components, b) relational data base management of non-graphic attribute data, c) model to model links, and d) 2D links* – a development that fundamentally changed how information in building models is handled. This evolution was similarly anticipated by Eastman's (1975) Building Description System (BDS) proposal, that would facilitate the "recording of design decisions" to directly input sketch solutions into the computer.

2.1.2 Building Information Modelling

Effective collaborative design in AEC projects is highly dependant on the deployment of Information and Communication Technology (ICT) nowadays (Leon and Laing, 2013). The advent of BIM has been instrumental in driving this progress by offering a digital, interdisciplinary information management that fosters cooperative and resilient communication (Mondino, 2021).
BIM is now widely used in various AEC sectors (National Building Specification, 2020), ought to become the new digital planning philosophy once the workflows, technologies, and mindsets behind BIM methodology have been adopted (Westphal and Herrmann, 2017). The National Institute of Building Sciences (n.d.) defines BIM as...

> "...a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle; defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder."

In practice, BIM's digital representations comprise the use of intelligent 3D models, that are generated within or in close relationship to authoring platforms and contain building elements' precise geometries, relationships, quantities, properties, material inventories, spatial and geographic information, as well as scheduling and operational features. The operational layers in BIM are referred to as dimensions and start from *3D* modelling, *4D* scheduling, *5D* estimating, *6D* sustainability and *7D* facility management, going up to as far as *10D* in recent models. BIM contains this information in an object-oriented and dynamic environment, in which geometric components are contextually related based on parameters and rules. Hence, Eastman et al. (2011) suggested that BIM models have "behaviour", meaning they can easily be updated by changing the necessary parameters, either in terms of geometric shape generation, relationships or properties. Rich and interoperable building models allow for rigorous analysis, quick simulations and benchmarking performance, improving the quality of the design and inducing innovative solutions (Azhar, 2011). The integration of various tools for streamlining workflows and use of automation techniques is among the key benefits of applying BIM, overall reducing errors and

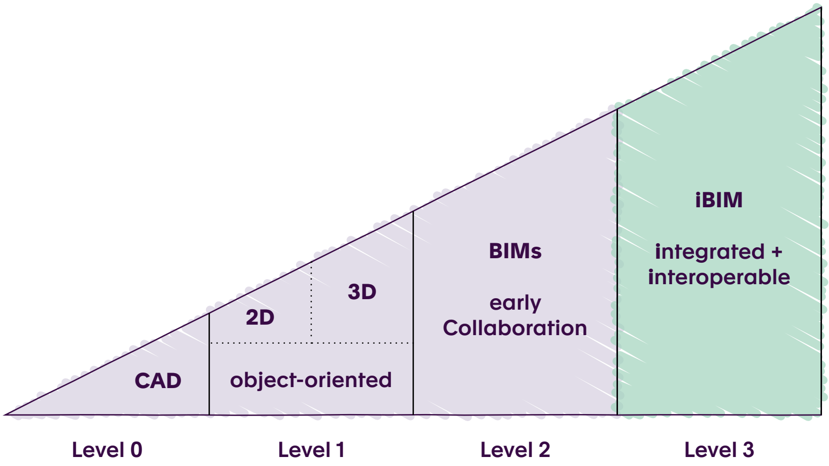


Figure 5 **BIM Maturity Levels**

increasing productivity by enhanced visualization, coordination, estimation, simulation and life cycle analysis.

BIM unfolds towards these benefits in progressive stages, which are commonly described as *Maturity Levels* (Figure 5, cf. Bew and Richards, 2011). At *Level 1* and *2*, architectural designers commit to the building design in partial models, which is then communicated through exchange formats. This is either carried out in closed BIM environments in case all stakeholders use the same vendor-specific authoring platform, or within open BIM ecosystems, which rely on the exchange of information between different platforms provided by vendor-neutral standards such as the IFC schema. According to BIM *Level 3*, this will eventually become a cloud based process using IFC at its core, enabling real-time collaboration and coordination within a shared centralized digital model.

2.1.3 Obstacles of Conceptual BIM

BIM is capable of assisting the collaborative design process effectively, though there are several reasons why its benefits are still not fully transferable to the conceptual design stage. First and foremost, BIM tools provide object-based parametric modelling features. The sophistication of these tools varies in the way objects can be generated, customized, updated and handled in large numbers, and what types of surfaces they utilize (Eastman et al., 2011). While BIM platforms continue to improve the accountable technology, they cannot defy the ongoing standardization of the AEC industry. This constraint unmasks in the generation of model components and results in a blandness of designs (Flanagan, 2018).

Furthermore, BIM nowadays negates the symbolic planar design composition and with it, the advantages of architects' centuries old handwriting (Flanagan, 2018). That is, for example, the effort required to generate simplified symbolic views compared to complex 3D building models, drawing attention to small but important features of a building, or use of symbolic representations and annotations to display unknown components, e.g., from external suppliers (Aish, 1986). Depending on the scale of the architectural plan, implicit statements were made about the elaboration of the represented design (Abualdenien et al., 2021). The flexible understanding of geometry on the basis of vague graphical information in rough small-scale drawings is hard to achieve within a BIM model.

The bias to detail in BIM and forcing overcommitment to particulars is also due to users' tendency of interpreting CAD models as more predetermined and rigid compared to sketches (Woodbury and Burrow, 2006). And yet, despite the initial focus on highly detailed building models, BIM systems are adept at placing and aggregating objects but fail to connect these components in terms of adjacency, access, and circulation, therefore unable to react to spatial changes (Jabi and Chatzivasileiadi, 2021). Last but not least, optimization based exploration in the conceptual design stage requires a strategic balance, involving three major aspects according to Lin et al. (2021):

- **Efficiency**: Rapid design changes require real-time feedback.
- **Accuracy:** Only evaluable analysis results help to identify the correct optimization direction.
- **Usability**: Analysis needs to be accessible to non-experts, as designers and users are often on their own in early design stages.

To satisfy these needs, the technology for optimization-based design exploration would have to converge into a single integration platform with the ability "to shift early design workflows from a linear process (concept – modelling - materialization) to a process of immediate feedback" (Reisinger et al., 2022).

2.1.4 Conclusion

Recorded design intentions can be thoroughly structured and reviewed in object-oriented BIM workspaces. The generation of such objects however lacks creative freedom, quick and flexible externalization of design proposals, and systems in line with the demands of the conceptual design stage for simulation and analysis objectives, leading to less well-informed decision making.

2.2 Prospect of Intelligent BIM

Despite the many challenges BIM faces and persists to face, the opportunities that go along with the digitization of the building and construction industry are immense. Tech innovations such as AI, Augmented and Virtual Reality (AR & VR), robotics, and digital fabrication are on the doorstep of the architectural profession (Mondino, 2021). Particularly game-changing for the architectural designer is the integration of AI technologies in the design process which challenge the user-machine relationship that was considered a prerequisite condition since the development of CAD (Ross, 1960), as AI is capable of performing computational tasks that previously relied on human intelligence.

Sacks et al. (2020) see BIM models “ideally suited to manipulation” by AI strategies. In the broad field of machine learning (ML) applications, a subset of AI, Zabin et al. (2022) describe intelligent BIM “as an intuitive system that is able to consume and process big data produced by BIM [...] to perform data-driven decision-making processes such as classify, automate, or predict to make informed decisions”. To date, AI assisted BIM workflows mainly utilize computer vision, rule-inferencing, ML, and case-based reasoning to offer smart extraction and manipulation of building data for design and planning processes, or delivering information from BIM to the construction site and vice versa (Sacks et al., 2020).

In planning and design stages, AI applications can offer design support and automation, generative design and design review technology, as well as performance simulation and engineering analysis. This affects the conceptual design stage greatly. New tools can provide automated recognition and functional classification of objects within preliminary building models (Qiu et al., 2021 and Collins et al., 2021), reconstruction of 3D geometry from single view perspectives (Tono and Fischer, 2022) or from multi view drawings (Babalola and Eastman, 2001), capable of saving countless hours of manual work.

The uptake of such new innovations in practice is significantly hindered by the heterogeneous landscape of planning and design software in CAAD, which has led most of the applications to use the IFC schema due to its flexibility and richness (Zabin et al., 2022). It is the most expressive vendor-neutral description of the built environment and provides the ISO standard for data sharing in the AEC industry.

2.2.1 IFC Schema

The purpose of the IFC standard is to facilitate seamless communication and exchange of data across discipline-specific platforms that are used to design, construct, and operate facilities (Khemlani, 2004). It uses the ISO-STEP (Standard for the exchange of product model data) EXPRESS language and organizes types, entities, rules and functions within two structures. One structure is used internally to organize the schema itself within four conceptual layers:

- **Domain Layer**: Things specific to one discipline
- **Shared Layer**: Things common to many disciplines
- **Core Layer**: Most basic things in AEC
- **Resource Layer**: Generic things not specific to AEC

The second structure is used to schematize actual design data contained in building models. Any item inside the Core Layer and above is hierarchically derived from $^{\text{Ifc}}$Root and further specified depending on the entity. Every item therefore has its own instance of $^{\text{Ifc}}$Root, where it is assigned a Globally Unique Identifier (GUID). The GUID stays unchanged throughout the entire life cycle of each item to identify and reference it to contextual information in a building model.
Figure 6 illustrates the hierarchical derivation of an $^{\text{Ifc}}$Wall. Its second highest hierarchical order is constituted by the

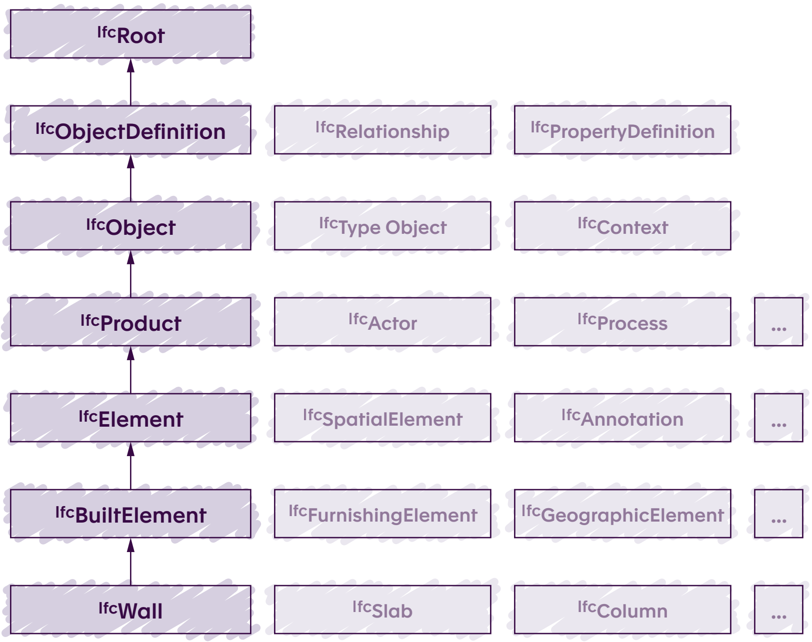


Figure 6 **Hierarchy of an IfcWall**

IfcObjectDefinition, which is the supertype for any physically existing, tangible, or conceptual item. An objectified item may form one or more relationships with other items. These definitions are provided by the supertype IfcRelationship. Lastly, IfcPropertyDefinition defines templates to describe a property set, quantity set or any individual property of an object, enabling the extensibility of the schema.

2.2.2 Model Resources

Resources, among 2D and 3D geometry, text, or material definitions, do not constitute independent entities derived from IfcRoot, but need to form links to the corresponding item either by simple references or specific relationships. The shape representation of an IfcWall for example is referenced to its attributes at the level of IfcProduct. It allows for multiple shape representations of that wall, e.g., for varying Level of Geometry (LOG).

Geometry in return is constructed from the most basic representation items: Among points, curves, surfaces (face-, shell-, or tessellation-based) and advanced surfaces (NURBS). They constitute two formal geometric body representation types in IFC: The *SurfaceModel*, consisting of faces, shells, or tessellated mesh but unsuitable for model analysis and simulation, for which reason the *SolidModel* is commonly used to represent an object's physical shape as a collection of surfaces and volumes. It includes three shape representation methods: Boundary Representation (Brep), Swept-Solid and Constructive Solid Geometry (CSG).

Brep is mainly used for complex shapes and allows for a high level of precision. The method represents an element precisely by its boundaries, where surfaces, curves, and points form connections. The design steps involved in the creation of such geometries are not recoverable, thus Brep is considered an explicit shape representation method, whereas SweptSolid and CSG geometry contains implicit parameters that allow for the reconstruction of the constituting parts of such geometries (Borrmann und Berkhahn, 2021).

SweptSolid is based on extrusion operations which are defined by an extrusion profile, depth, and direction. In IFC it is used to describe the cross section or perimeter, height and orientation of a building element. CSG involves the generation of shape representations based on Boolean operations, which were initially based on primitive geometric shapes only. The method has been adopted by IFC to describe voiding or clipping entities based on subtraction operations, e.g., recesses, doors, and windows defined by the IfcOpeningElement, which allows to shift and manipulate such elements in more flexible ways.

2.2.3 Parametric Object Geometry

Parametric geometry generation relies strictly on the implicit description of geometry to embed parameters, dependencies and constraints that can quickly change the model geometry (Borrmann und Berkhahn, 2021).

However, the intricate nature of parametric geometry makes its interoperable exchange between different BIM systems a challenging task. It led to a rather narrow scope of parametric object definitions that are supported by IFC. To stick to the IfcWall example, Figure 7 demonstrates the geometric description of three types of walls based on freeform and polygonal, sloped, or vertical shape representations. All three occurrences allow for different levels of parametrization. Freeform and polygonal occurrences can only be represented using Brep geometry which makes further manipulation of such elements difficult. On the contrary, sloped and vertical walls based on straight or curved wall paths are represented using SweptSolid geometry, but only the latter also allows for geometric representations of material layers. Such instances were considered the *StandardCase* for parametric descriptions of walls until IFC4, which applies for all building elements in a similar way. In recent versions this term has been deprecated, yet the narrow descriptive repertory remains.

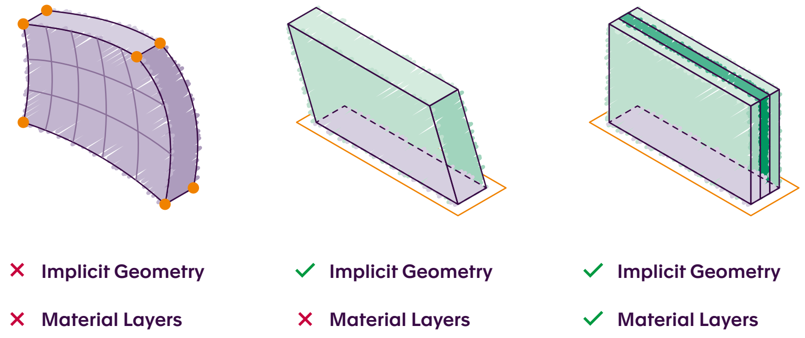


Figure 7 **Level of Parametrization of IfcWall Instances**

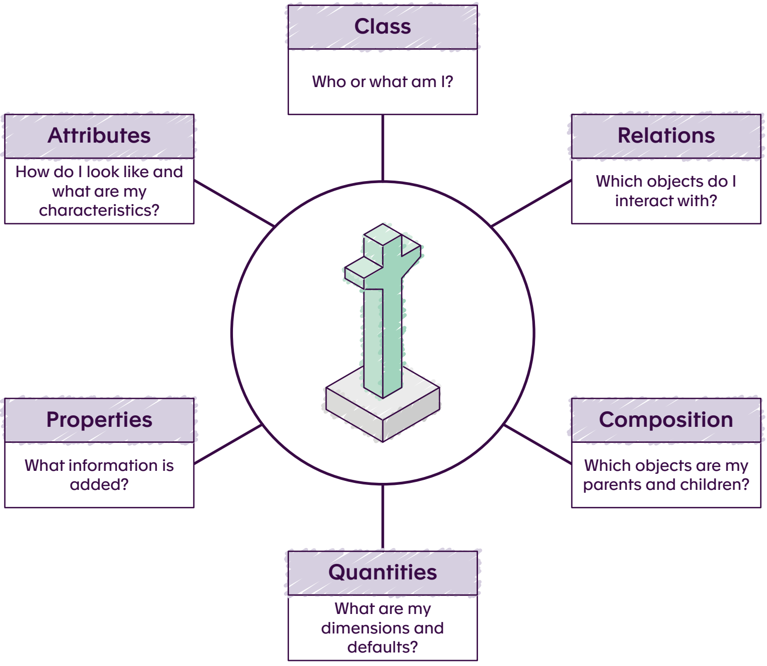


Figure 8 **The BIM Object**

2.2.4 Semantics in BIM

IFC describes objects along with detailed physical and functional characteristics that are needed for downstream applications (Figure 8, cf. Allplan GmbH, 2016). In BIM terminology, this is described as an object's Level of Information (LOI). Closely related to geometry is the quantity set, which contains exact numerical information about important quantities of an object's physical occurrence. Other additional and non-graphical data is given in the property set or by individual properties, which include specifications such as load-bearing properties of building elements, user accessibility of spaces or fire safety information of doors. Any entity in IFC is also equipped with a predefined list of attributes, which is specific to an entity type and enables referencing. To capture the full extent of material, functional, topologic and geometric information, IFC deploys relationships to describe the logical connections among model components and resources. This includes concepts such as the description of element connectivity, the containment of elements in a spatial structure or the association of objects with material definitions.

However, BIM software has its difficulties with providing uniform semantic information. Hence, Belsky et al. (2016) suggested the *semantic enrichment* of building models. This includes the use of AI strategies for recognition and inference mechanisms which also consider material or mechanical features, functional classification and relationships based on the topology and aggregation of objects. The approach enables the solidification of explicit and implicit information contained in IFC models to create meaningful building models, and solve interoperability issues (Sacks et al., 2020).

2.2.5 Conclusion

The development of IFC has shown that the schema expands in breadth rather than depth, aiming to integrate as many AEC disciplines as possible. That is reflected in the narrow scope of parametric definitions that can currently be used for model data exchange. Nevertheless, the abundance and feasibility of IFC particularly in combination with AI strategies can offer a plentiful of novel benefits.

2.3 Intuition and Computers

Tools, machines, buildings, and computers are just primary examples of man-made systems that Simon (1996) refers to as *artificial*. They are shaped by goal driven decision mechanisms set out to satisfy the creator's intentions. While it usually represents a peripatetic logical analysis of information, intuition can stimulate the creator into making quick decisions. Simon describes intuition as a process of pattern recognition arising from past knowledge and memory that one acquires by understanding and learning. In architecture, most of this information is stored in a designer's database of reference works, material inventories, building codes and so on, according to Simon. During the design process, sketches and other architectural drawings externalize these memory structures, guiding designers to use a more profound pool of memories during the next task to further develop the partial design (Akin, 1989). These moments would be seen as "the sudden flashes of "intuition" that sometimes allow the expert to arrive immediately at the answer that the novice can find (if at all) only after protracted search" (Simon, 1996).

Connected to sketching, Ching and Juroszek (2019) refer to it as *speculative drawing*. If pursued across multiple attempts, it avoids the inhibiting nature of more careful sketching, "which often leads to premature closure of the design process" and potentially forces designers to hesitate and disrupt thinking about the problem.

> "To speculate is to engage in thought or reflection. In design, we speculate about the future. As we think about what might be possible in the future, drawing gives material existence to our conceptions so that they can be seen, assessed, and acted upon. The drawing out of these ideas, whether executed quickly or slowly, roughly or carefully, is necessarily speculative in nature. We can never determine beforehand precisely what the final

> outcome will be. The developing image on paper gradually takes on a life of its own and guides the exploration of a concept as it circulates between mind and paper." (Ching and Juroszek, 2019)

2.3.1 Designing with or without Constraints

The computers that have been assembled, and the tools that have been programmed to aid the design process are not (yet) able to procreate human intuition (Watanabe, 2014). Instead, constraints are used as a driver for computational design space exploration, above all within parametric architecture (Kilian, 2006). They can be of various nature, such as material, functional, topologic or geometric constraints. The computationally uncovered states of explicit dependencies are then captured and stored for the designer to interact with. The externalization of constraints is critical to this process and relies on the acquired expertise of the designer. While the number of iterated design solutions within the sets of rules is enormous, it is in question whether the flexibility of these systems is able to withstand the rapid changes during conceptualization, which led Burry and Burry (2008) to suggest its use after conceptual ideas have been developed.

The technology and flexibility of parametric models certainly improved over the past years, so did the integration of such methods in BIM workspaces, among others provided by Autodesk's *Dynamo* or Archicad's *Param-O*. Known as *visual programming*, a type of parametric modelling interface, the uptake of such methods in BIM workflows is suggested to close the conceptual blind spot of BIM (Mondino, 2021). While parametric and algorithmic architecture enable to go beyond what can be drawn by hand, the sophisticated logic behind these geometries must be claimed in very small doses so that designers – if they are not programmers – can cope with it (Aish, 2005).

Extracting images to create architectural form is ultimately about freeing the unconscious from constraints for Japanese architect Watanabe (2014). He refers to it as a virtual world without limitation, where one would then come up with new constraints like playing a game within a set of rules, and where everything is about having fun. In this game, brain and hands, feelings and lines are directly connected. It is the singularity of the line, its momentum, that a sketch stroke inherits and which puts it ahead of what computer graphics can produce. For Watanabe, "a freehand sketch using nothing more than pen and paper has the power to transcend a multitude of analyses and debates [...]"; however, it may not be architectural design itself, but rather the source of it.

2.3.2 Human-Computer Interaction

A similar ambiguity of a real and virtual realm in architecture was conceived by Tschumi within his *paperless studios* that investigated the use of computers for the development of conceptual designs (Bredella, 2014). One specific focus of the design studios was to develop interfaces "where digital and analogue aspects became interwoven". They would acknowledge the computer as an integral part of the design process rather than an autonomous system. In the end, the use of these exploratory open design environments became particularly known for an aesthetic erected from geometric forms.

Nowadays, nascent practical implementation of AR, VR, or Tangible User Interfaces (TUI) has already proved its effectiveness for enhanced Human-Computer Interaction (HCI). Designers can simulate the sensual experience of visual, haptic, hearing and other interactions, determining the specific needs of end-users (Hua and Qiu, 2008), making HCI technology an effective medium in Human-Centred Design (HCD). Similarly, freehand sketching is adept at generating quick variants based on 2D or 3D visual representations which helps to involve any participants in the early phases of the design process more effectively.

However, sketching requires a precise physiological hand-eye coordination, which cannot be sufficiently supported by traditional mouse and keyboard systems. Though, Dickinson predicted in 2011 that sketching will at some point be digitized to such an extent, that the flaws of using computers will no longer be present. Today, new digital design methods highly rely on the capabilities of computational technology and enable the integration of sketching by either scanning and importing hand-made sketches, progressing to user-friendly stylus and tablet technology in 2D and 3D digital environments, e.g., to generate early design mock-ups and models within sculpture-like interfaces, or using AR systems for combining sketching with real-time environmental information (Abrishami et al., 2015).

2.3.3 Digital Sketching Tools

In theory, the review of digital sketching tools could begin with Sutherland's (1963) *Sketchpad*. It was run on a TX-2 computer system, which was developed by MIT Lincoln Laboratory, and is known for its contribution to AI and HCI.

However, it was eventually stripped of its light-pen in 1975 (Youngman, n.d.) and no such user-friendly Graphical User Interface (GUI) appeared for a long time after. In the early 2000's the development of digital sketching applications picked up momentum along with advancements in computer graphics. An example is *SketchBook*, which was released for use with pressure-sensitive drawing tablets in 2004. The tool was acquired by Autodesk in 2005, but again divested in 2021.

The review of digital sketching applications within this thesis primarily aims to identify tools that are connected to BIM and therefore related to the AEC industry. However, similar approaches that originated in other industries are also included due to their innovative use of AI and HCI.

In the field of AEC, such tools comprise the use of 2D perspective building sketches for 3D shape generation (Chen and Lin, 2019, Olsen et al., 2011) or the creation of realistic 2,5D models using a 3D element and texture database (Chen et al., 2008). Digital 3D freeform roof-like structures are generated from 2D axonometric sketches by *Sketch2PQ* (Deng et al., 2022). The tool uses a deep neural network to infer planar quadrilateral meshes. *BuildingSketch* proposes an approach for the generation of intuitive 3D building models within a VR environment, allowing users to sketch 3D strokes (Liu et al., 2021).

While there are only a few sketching tools specifically designed for use in the AEC industry, similar proposals have been conducted for a broader use in digital design such as the VR-based sketching tool *Multiplanes*, using planar parent surfaces for the projection of beautified sketch strokes (Barrera Machuca et al., 2017). Planar and curved canvases for projection of 2D strokes via tablet input combined with mid-air 3D strokes are used by *SymbiosisSketch* (Arora et al., 2018). *Cassie* allows users to sketch 3D strokes in VR and reconstructs parenting surfaces for further projecting of sketch strokes (Yu et al., 2021). A multi-view system for 3D sketches is proposed by *DreamSketch*, exploring solutions through generative design technology (Kazi et al., 2017). *Free2CAD* suggests parsing 2D freehand sketches into CAD commands using deep learning techniques (Li et al., 2022).

Surprisingly, the only tool that was discovered to combined intuitive sketching and BIM is a commercial application named *spaces* (Cerulean Labs Limited, n.d.). On a stylus and tablet based split screen interface users can create 2D sketches of buildings footprints from ground view, which are then extruded to 3D models. Currently, it uses graphically represented space volumes to erect a building mass model, which can be added façades and columns. The tool also supports an export option to IFC.

2.3.4 Conclusion

The use of intuition is vital for earliest design space exploration – a characteristic that computers have not yet been able to take over from humans. Intuitive and user-friendly interfaces in CAD were initially off to a good start, but 1970's mouse and keyboard technology hindered an advanced HCI until recently. Today, a handful of digital sketching applications have made it to the AEC industry; however, only one tool could be identified that connects to BIM methodology by generating 3D building models from 2D sketch input.

3 Methodology

Creating conceptual BIM models from freehand sketching is an ambitious task. Hence, the presented workflow involves sophisticated technology that was previously developed as part of the funded research project *SFB: Advanced Computational Design* (Wimmer et al., 2022); sub-project SP2 *Integrating AEC domain knowledge*. It consists of two major components that I have to acknowledge to the responsible masterminds and respected colleges: *MR.Sketch* (Kovács et al., 2022), developed by Balint Istvan Kovács. It is a digital sketching tool that is used within this thesis to create model sketches. Secondly, an ML based pipeline titled *Strokes2BIM* (Rasoulzadeh et al., 2023), developed by Shervin Rasoulzadeh. The system is capable of recovering information that is contained in model sketches to generate IFC model data.

When this particular research started, the existing workflows dealt with geometric features only, which excluded BIM methodology as an opportunity to embed meaningful information in building models. Therefore, a literature review was conducted to explore the current state of the art, thoroughly analyse the IFC schema, and develop an associated model sketching approach. The results have been collected in a BIM handbook (9.1 Appendix) that comprises a set of recommended IFC definitions for the description of conceptual BIM models at its core. This domain-specific knowledge was then provided for implementation in the responsible technical constituents of the workflow (Figure 9). To test the contents of the handbook and its ability for the description of conceptual BIM models, the workflow is demonstrated within a Proof of Concept on the basis of a reproduced model sketch of the 1929 Barcelona Pavilion. The obtained IFC model is then examined in an IFC model viewing application to validate the complete and seamless transfer of data.

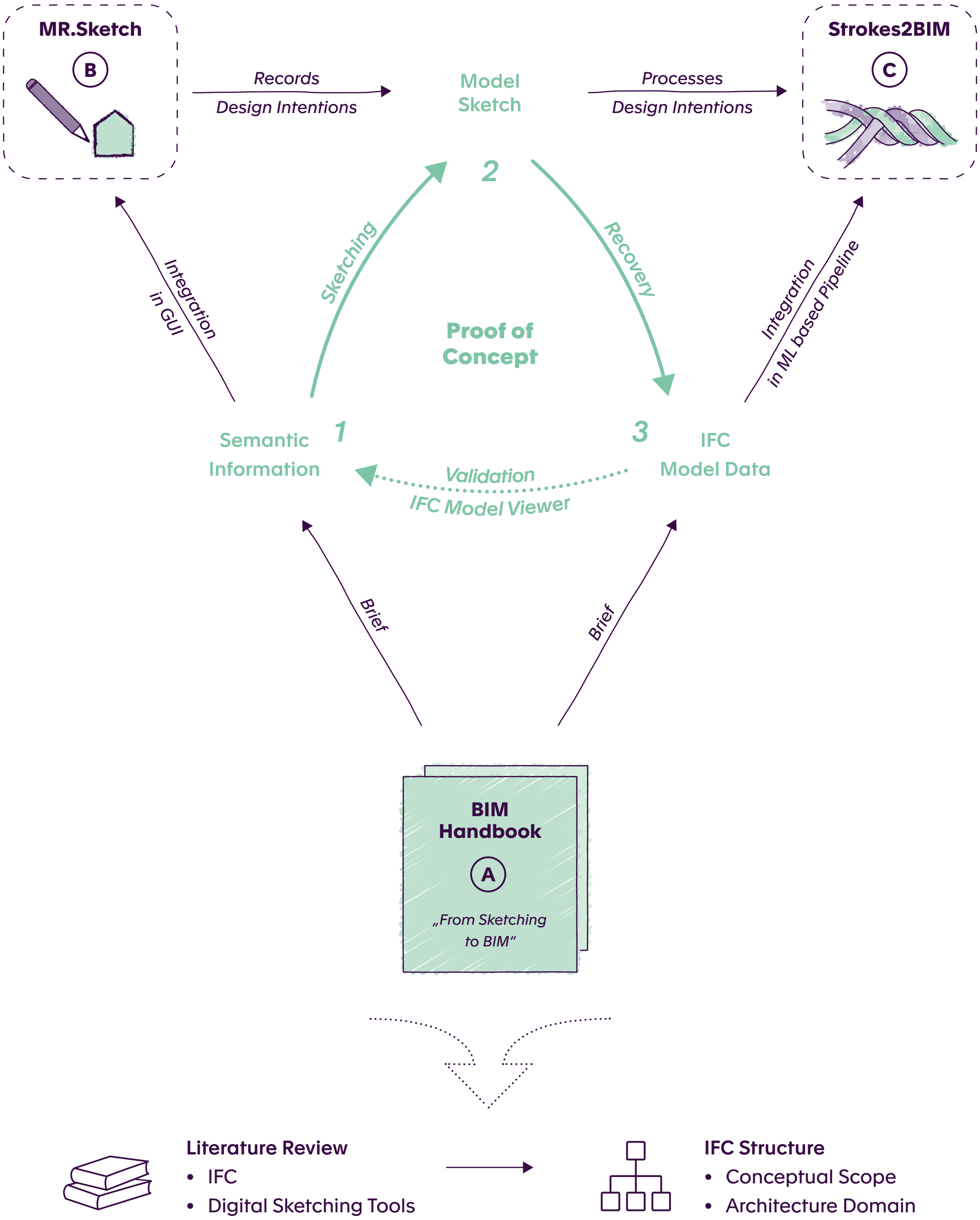


Figure 9 **Framework of the Workflow**

3.1 MR.Sketch

The deployed 4D semantic sketching application *MR.Sketch* sits at the centre of a novel design and integration platform that pursues “a bi-directional data exchange for real time feedback and design optimization of sketches” (Reisinger et al., 2022). The tool itself primarily aims to combine Mixed Reality (MR) and 3D sketching in an intuitive setup, although the mere virtual space is used within this thesis for the creation of model sketches in a stylus and tablet based platform.

The brief of the BIM handbook intended the uptake of additional non-graphical semantic information in the sketching process, which led to the development of a GUI panel that allows designers to assign such semantic information to sketch strokes after they have been created. Since the type of semantic information labels may vary from sketch to sketch, the developer provided a text file that is linked to the GUI of the semantic panel and thus can be adjusted accordingly. The clarification of semantic information in the model sketch, model sketching, and the association of sketch strokes with semantic information constitute the manually performed part of the semi-automated workflow.

3.2 Strokes2BIM

Strokes2BIM is a subsequent version of the *Strokes2Surface* ML based pipeline, which is responsible for an automated geometry reconstruction of 4D semantic sketches by recovering implicit geometric features contained in model sketches for the generation of surface mesh geometry. The existing workflows therefore already coped with the required data structures that are needed for a seamless handover between the sketching application and the ML based pipeline. The arrangements also include a certain set of instructions for sketching models, which had to be partly adopted to support the object-oriented workflow of BIM along with the suggested set of IFC definitions, which is why it was extended by its developer side-by-side with the BIM handbook of this thesis for the generation of IFC models. The specific programming for the translation of sketched model data to IFC data was aided by the IFC documentation, as well as the open-source IFC database *IfcOpenShell* (v.0.7.0), providing developer packages based on the *Python* programming language, on which the ML models are based.

4 From Sketching to BIM

Whenever a project transitions from one designer or design platform to another, the risk of losing or relinquishing information is at its highest, causing cumbersome reproduction of design proposals. This is further compounded by an increasing specialization within the AEC industry that comes along with a growing need to communicate and perform multiple project functions simultaneously, which requires BIM as the technical constituent to provide the reliability of design data (Glick and Guggemos, 2009). The overall aim of this workflow is therefore to provide a seamless data transfer from earliest stages of design to make the design process more efficient and resilient.

With the presented background in mind, the initial measure towards this goal is the utilization of the IFC schema to produce an output that is consistent with the many powerful BIM gateways. Among the most important challenges in the conceptual design stage is the exchange of ideas to engage all stakeholder in the design process. There are plenty of free IFC model viewers such as *Solibri*, *OpenIFCViewer*, or *BIMcollab Zoom* that offer powerful visualizing techniques for the review of designs, e.g., navigating through 3D space, browsing the spatial structure and object explorer, or generating floor plans and sections using the 3D model at hand. They also provide an overview of non-graphical information such as material definitions or quantities of building elements which puts them ahead of other CAD exchange formats.

The second challenge is to extract information from IFC models to perform informed decision making, analyses and simulations. This task is also covered by some IFC model viewers and includes model checking operations such as collision or building code checks. It may also involve the querying of

IFC data to retrieve implicit and explicit information that is visually comprehensive for fabricators (Wülfing et al., 2014) or semantic enrichment tasks to create more meaningful and interoperable building models (Belsky et al., 2016), enabling novel space syntax simulations (Ismail et al., 2018, Langenhahn et al., 2013, Shin and Lee, 2019).

The last and most complex challenge is to directly manipulate IFC models within authoring platforms in follow-up design stages. It allows for the creation of conceptual BIM models in earliest stages of design that can be readily extended and enriched later on. The task of exchanging such editable models is handled by Model View Definitions (MVD) in IFC. Among them is the *Design Transfer View* that has been available since IFC4 for the purpose of "inserting, deleting, moving, and modifying physical building elements and spaces, within the limited scope of parametric exchange" (Graphisoft, n.d.).

4.1 4D Semantic Sketches

To arrive at the IFC model that can be filled with complexity, this workflow makes use of semantic sketching as it inherits a considerate level of abstraction that is necessary to postpone detailing until more advanced stages (Leon and Laing, 2013). Sketches are subject to individual interpretation by forming an associative bridge between the artist and the observer. On the contrary, BIM is highly standardized and negates ambiguity in any shape or form. Within this field of tension, synergies that evolve from the combination of freehand sketching and BIM are explored within this workflow to ease the modelling process and strengthen

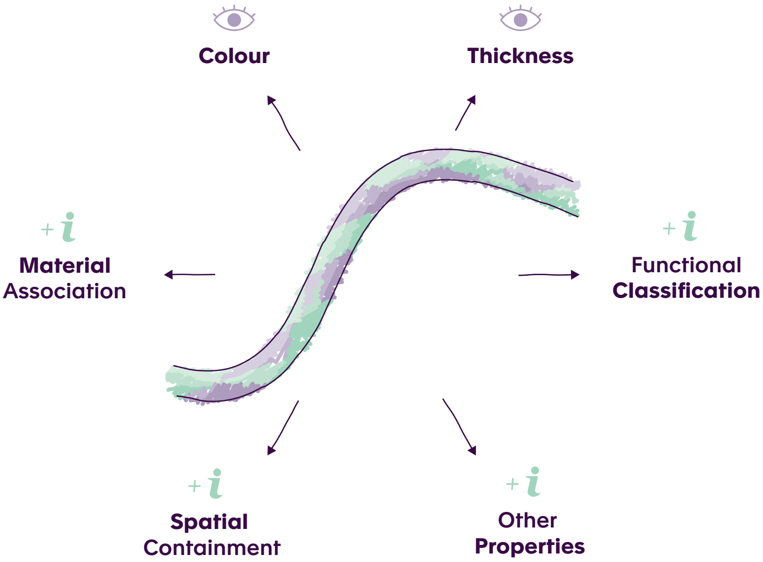


Figure 10 **The BIM Sketch Stroke**

designers' conceptual awareness by promoting an environment that demands only little attention to detail.

The IFC schema offers a plentiful of shared building elements that account for the description of building structures; however, to meet the profile of expectations during earliest design, a fraction is enough to create conceptual BIM models. For this workflow, the following set of components has been defined: walls and columns constitute the vertical elements, slabs and beams the horizontal ones, ramps connect the different levels vertically, and roofs provide the top closure of buildings. Furthermore, windows and doors are represented by plain openings in elements.

To complete the conceptual, single-layer BIM model, building components feature functional classifications, associations with materials, and a localization in a project's spatial structure. To capture this information, AI strategies are deployed for the recovery of explicit and implicit design intentions in model sketches.

The understanding of sketching must be fundamentally altered for this matter. Conventionally, sketches are composed of individual sketch strokes, whose geometric information is visually conveyed by their thickness and colour. Aside from those two graphical parameters, a far greater set of information values must be integrated to capture the semantics akin to a BIM model. Hence, additional semantic information is assigned to sketch strokes by the designer during sketching within this workflow (Figure 10).

To eventually pass information from the level of strokes down to the BIM object, the model sketch must be interpreted, which is within the purview of AI technology. The involved manual steps together with the automated recovery of information in model sketches make this workflow semi-automated. While the approach enables the manifestation of both rich graphical and non-graphical data, it is not possible to manually determine information in a model sketch at the level of objects. This includes parenting/child or other relationships between objects. Hence, the upper limit of manually definable information extends to the need for AI strategies to solidify further information that can only be implicitly represented in model sketches.

To automatically recover graphical and non-graphical information contained in model sketches, rich four-dimensional (4D) information must be captured from a sketch strokes generation, such as the stylus-related speed (time dimension), geometry itself (space dimensions) and geometry-related properties. Geometry-related properties are calculated causal connections between geometric quantities, e.g., the ratio of stroke length to the bounding box of the stroke.

4.2 Stages of the Workflow

The workflow includes three essential stages (Figure 11), of which the first stage is undertaken within the 4D semantic Sketching Application *MR.Sketch* (Kovács et al., 2022). Stage two and three are covered by the ML based pipeline *Strokes2BIM* (Rasoulzadeh et al., 2023). The approach is structured as follows:

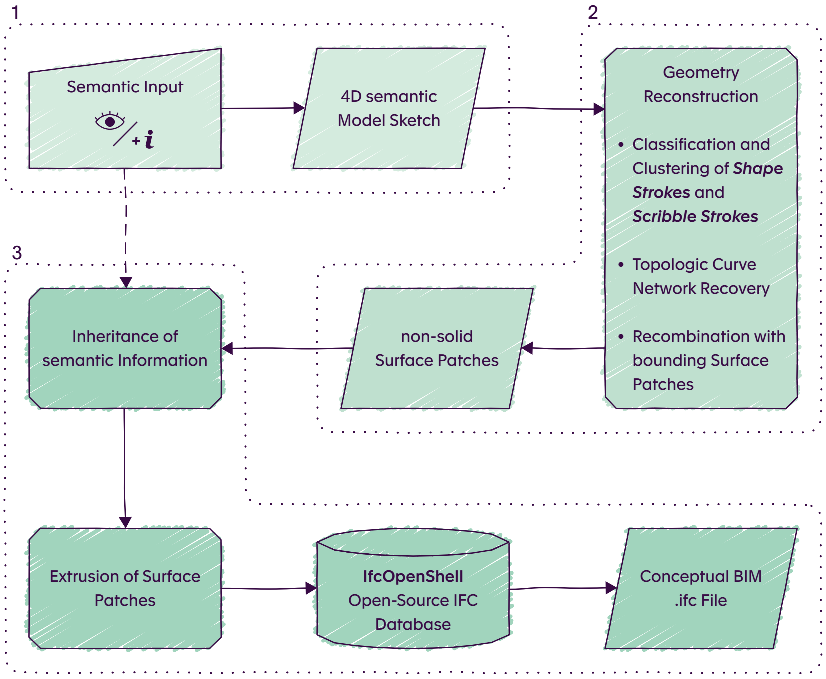


Figure 11 **Essential Steps of the Workflow**

1. **Model Sketching**: Creating model sketches from 4D semantic sketch strokes with additional semantic information.
2. **Geometry Reconstruction**: Processing sketch strokes geometry, geometry-related and stylus-related properties within the ML based pipeline.
3. **IFC Model Generation**: Inheritance of graphical and additional semantic information from the model sketch to reconstructed geometry.

At the end of each stage, a specific data output can be obtained. The first stage produces a model sketch that is constituted from 4D semantic sketch strokes and can be offhand reviewed in third-party applications. The second stage outputs tessellated mesh geometry that was reconstructed based on geometric features only. The final output after stage three holds the conceptual BIM model, which inherited all semantic information from the preliminary model sketch.

4.3 Model Sketching

The first technological challenge is to provide designers' access to 3D space for a complete exploitation of geometric shapes and forms. This is enabled within the 4D semantic sketching application by making use of freely transformable 3D canvases, which can be loaded from preset geometric shapes or external sources and utilised one at a time. The built-in system currently provides planes, cubes, cylinders and spheres. The canvases are represented by a mapped grid, onto which the sketch strokes are projected via stylus input (Figure 12). The faces of an object can be sketched either from a single canvas or aggregated from several canvases. When composed of several canvases, the *Snap Canvas* operation comes in particularly handy. Planar canvases can be snapped to existing strokes either by one, two or three points to aid the positioning of canvases in 3D space. In the *Ateliers Panel*, the designer can define the properties of a stroke that are to be inherited, such as thickness, colour, and additional semantic information. Reference to the dimensions of space for generation of true-to-sale sketches is given by a 1-meter

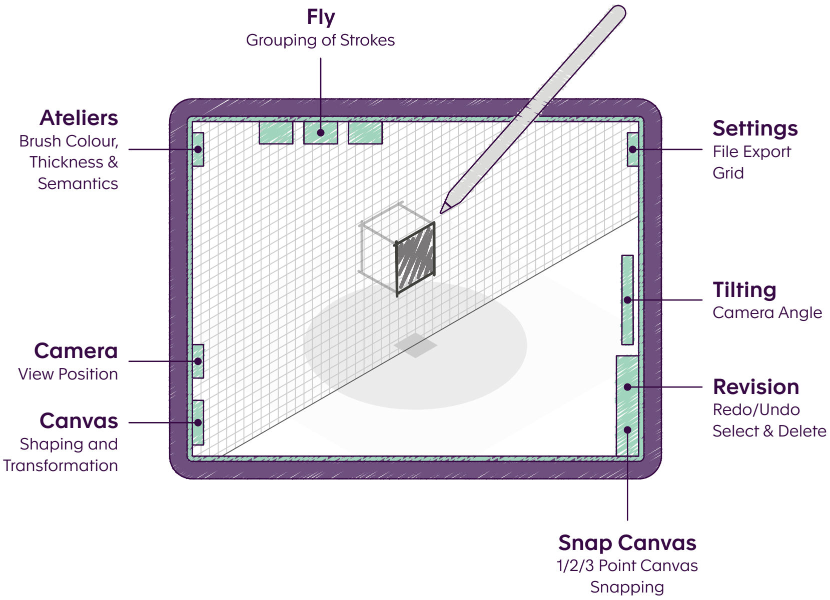


Figure 12 **MR.Sketch Interface**

square plane at the centre of the coordinate system which can be backed by a 1-meter 3D construction grid.

In preparation for stage two of the workflow, the act of model sketching must be tied to a certain set of sketching techniques which was developed by my college Shervin Rasoulzadeh. Those have been designed to ease the sketching process, and once made familiar with, enhance the acquisition of intuitive digital model sketching.

The first guideline rests on the deeply natural habit of perceiving objects' shapes, which also constitutes the key build-up for the reconstruction of geometry by the *Strokes-2BIM* ML based pipeline. That is because the human eye relies on the delineation of the object from its surroundings to perceive it, a process that is aided by the cognation of objects' edges and boundaries (Ching and Juroszek, 2019). It affects the visual perception, imagination, and expression of sketched shapes and increases the likelihood that an architectural designer would start composing an element by its boundaries instead of a filling or would complement its boundaries at some point even without previously given instructions. Accordingly, there are two advised types of sketch strokes in a model sketch:

- **Shape Strokes**: Outline the boundaries of an object, specifically the edges that separate its faces.
- **Scribble Strokes**: Mark the enclosed areas that form the faces of an object.

The second guideline, and most beneficial convergence of sketching 3D models, applies to the quick generation of building components in shape of non-solid surfaces. They receive their physical solidness during the third stage of this workflow depending on the constituent strokes thickness, while inherently maintaining visual feedback of solidness during sketching. The preference over solid sketching was confirmed by the BIM handbook, as it is within the nature of most building elements that they can be sufficiently represented by a non-solid shape. This implies planar elements, e.g., walls,

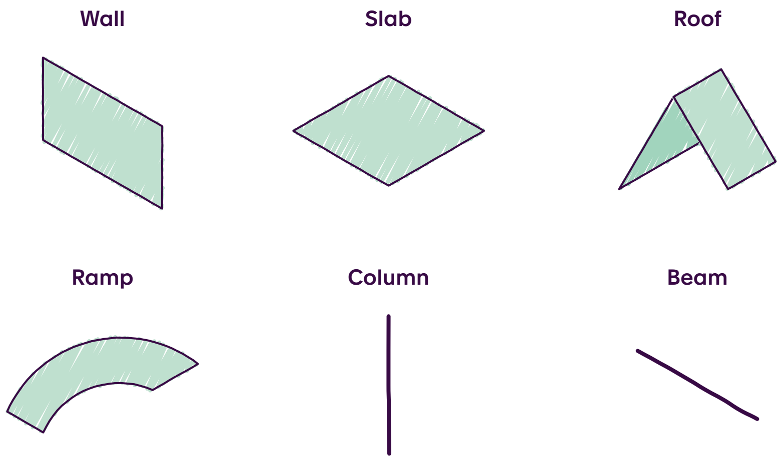


Figure 13 **Exemplary Non-solid Building Elements**

slabs, ramps, roofs, represented by single faces and linear elements, e.g., columns and beams, likely represented by a single sketch stroke (Figure 13). It also remains a technicality since the model sketch needs to be segmented at some point to form separate BIM objects. Therefore, and regardless of an element's intended solid or non-solid shape, the cohesive model sketch is currently disintegrated into single non-solid surface patches at the end of stage two.

4.4 Geometry Reconstruction

In stage two, the ML based pipeline *Strokes2BIM* is fed the geometry, geometry-related and stylus-related properties of a model sketch's constituent 4D sketch strokes. The responsible ML models have been trained to reconstruct geometry based on geometric features only and regardless of other semantic information. The first part of the pipeline carries out three major tasks: The classification of *Shape Strokes* and *Scribble Strokes*, which is enabled by the rich 4D information that was captured during the generation of the model sketch. The two stroke types show notable differences, e.g., in the speed of their generation, or in the ratio of

stroke length to the bounding box. The first ML model then aims to cluster all *Shape Strokes* into separate groups that are intended to form single edges. Likewise, the second ML model aims to cluster all *Scribble Strokes* into separate groups that are intended to form single faces.
Lastly, the results of these two clustering models are combined to recover the curve network and the bounding surface patches of the model sketch. Subsequently, the constituted surfaces are separated from each other to form single non-solid surface patches as mentioned before.

4.5 IFC Model Generation

During stage three, the semantic information is transferred from the model sketch to the reconstructed geometry. Since *Shape Strokes* are partly shared by elements where they connect, reconstructed surface patches will inherit only any other property from the constituent *Scribble Strokes*. If the value of a property is not coherent within a set of sketch strokes, it is determined by calculating the average or by selecting the majority value, depending on the specific property. Among those values is the thickness parameter, which is used as an extrusion variable to retrieve the solid shape of the non-solid surface patches. As mentioned before, geometry is output as tessellated surface mesh; however, as a result of the extrusion performed on the non-solid surface patches, volumetric mesh with actual quantities in shape of *Solid-Model* Brep geometry is generated. As recommended by the BIM handbook, the extrusion should be performed in both directions of the normal vector equally. Yet, the procedure is not ideal, as elements consequentially overlap each other where they form connections, which causes slight deviations from the exact quantities in a model.
Now that the processing of the model sketch is complete, the model geometry and semantic information is described as specified by the IFC schema. In line with the pursued contents of the BIM handbook of this the-

sis, the following IFC definitions are included for the description of reconstructed model sketches:

- IfcWall, IfcColumn, IfcSlab, IfcBeam, IfcRamp and IfcRoof
- IfcFurnishingElement for (built-in) furniture items
- IfcGeographicElement for landscaping and surroundings
- IfcOpeningElement for representation of openings in elements
- IfcMaterial and IfcPresentationStyle for associating elements with materials and colour styles
- Subtypes of IfcSpatialStructureElement for containment of elements in a spatial hierarchy

Unlike the other building element definitions, IfcRoof itself does not have a shape representation but is a composition of building elements according to the IFC schema. An IfcRoof within a model sketch is expected to form an element composition from occurrences of IfcSlab, which is processed automatically during IFC model generation. To retrieve surface geometries based on NURBS-based Brep, a manually executed operation using external software tools can be used, but at this stage it does not support for a seamless BIM workflow.

5 Proof of Concept

Modernist architects understood uniting rationalism and simplicity to create fascinating building structures and spaces. The use of a few distinct building elements, materials, and textures makes designs from that era a good fit to put the proposed workflow to the test. The reproduced model sketch and its ability to represent architecture can then be related to existing design drawings and the completed building structure. For this use case, the *Barcelona Pavilion* (Figure 14, Mies van der Rohe Foundation) by Mies van der Rohe and Lilly Reich was chosen. The reconstructed 1929 *Expo* pavilion is open to visitors on the original site, but can also be experienced online within a virtual tour by the Mies van der Rohe Foundation.

Figure 14 **Interior View of the Barcelona Pavilion**

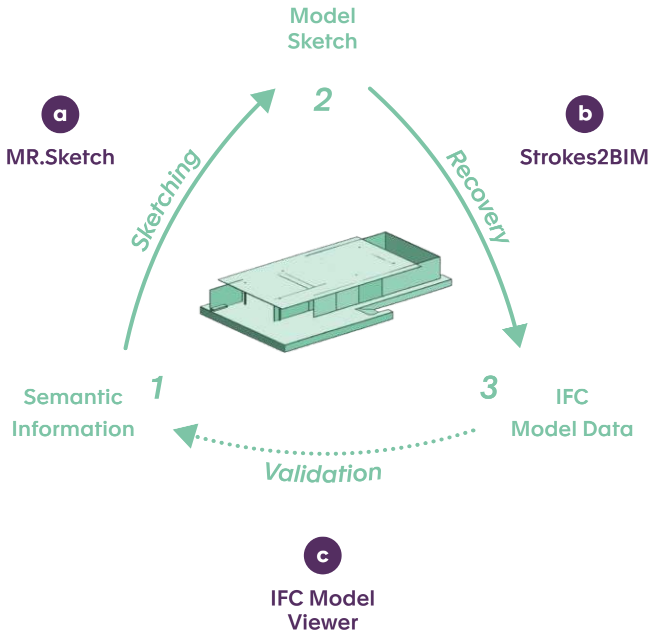


Figure 15 **Involved Tools and Stages**

Firstly, the semantic information for model sketching needed to be clarified (Figure 15). As it is a replica of an existing building, the initial task was to align with its main characteristics. The pavilion is constructed from rich materials that significantly contribute to its appearance. Hence, the approximate colour value of each surface was determined in the model sketch and constitutes the first of two graphical semantic information of *Scribble Strokes*. To represent the different element thicknesses, the brush size of sketch strokes increases progressively, from smaller values for more delicate elements, to larger values for solid components. Components are also associated with respective materials of glass, steel, and concrete. The latter is assigned to solidly appearing components such as the pavilion's roof – which is actually also part of the steel skeleton structure but hidden from view and therefore abstracted in the model sketch. Consequently, the functional classes of building elements comprise walls, columns, and single occurrences of slab, roof and ramp. There is no additional semantic information added regarding the spatial hierarchy, this will be complemented during the automated IFC model generation at the level of the spatial structure element IfcBuilding.

5.1 Sketching Process

The model sketch was approached by specifying three stroke thicknesses depending on the construction method of elements for the inference of their solid shapes from non-solid shape representations:

- Brush Size 0.1: Cruciform Steel Columns
- Brush Size 0.2: Glass Panels
- Brush Size 0.5: "Solid" Concrete Elements

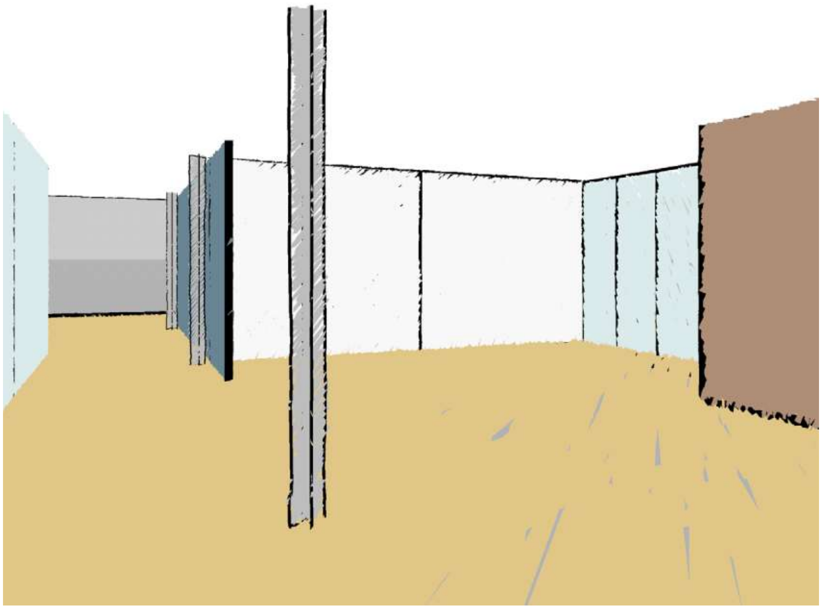


Figure 16 **Sketched Interior**

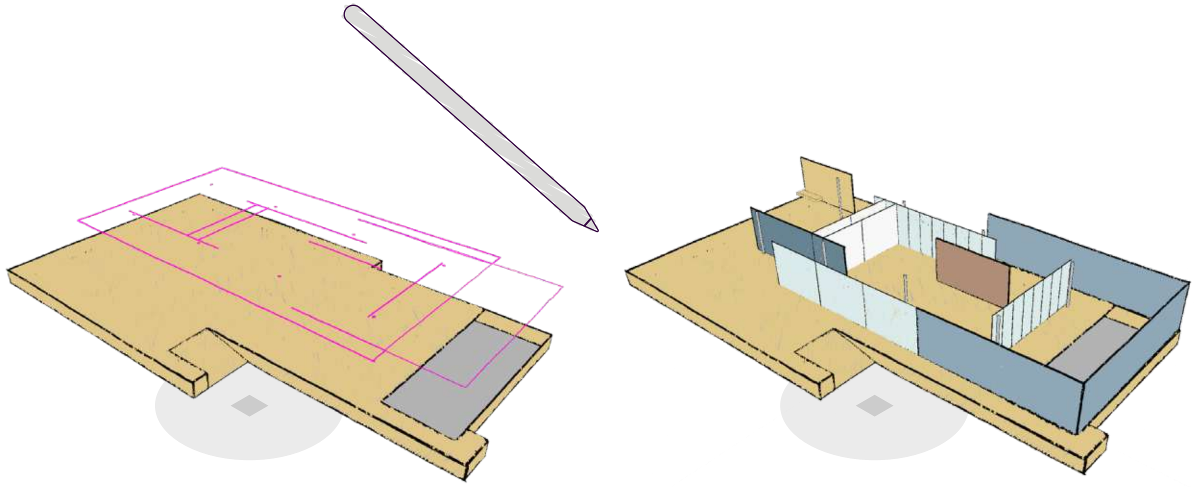


Figure 17 **Sketching Process**

The visual representation of the different thicknesses can be examined in Figure 16. Even though every building element is represented by a non-solid shape, a sense of three-dimensionality is generated. This effect is also due to the delineation of *Shape Strokes*, which are kept in black, whereas the colouring of *Scribble Strokes* depends on the surface features of each element.

Overall, additional semantic information was added to the constituent sketch strokes of each intended element after it was created. For this purpose, I used the *Fly Panel*, which lets one group strokes within three layers. I renamed them in the following order: *a) Unclassified, b) Classified,* and *c) Reference*. Sketched strokes are by default assigned to the first layer. Whenever an element was complete, all strokes within the layer could be selected at once, assigned the functional class and material, and afterwards moved to the *Classified* layer. This method allowed me to keep an overview during the creation of the model sketch, which was initially started from the bottom up. As it turned out, the alignment of the pavilion structure along a 1-meter grid is a welcome side effect to determine the placement and scale of building elements with the help of the sketching tool's integrated 3D grid. This way the perimeter of the building platform could be easily outlined, which was then constructed from lateral walls, a slab on top and the ramp that leads to the main access of the building.

To easily infer the positioning of elements on the ground floor level, a planar canvas was positioned at the roof level to outline the floor plan using purple reference strokes (Figure 17). The canvases could then easily be snapped to those reference strokes, which allowed for a precise but efficient act of sketching. Nevertheless, the exactness of the model sketch certainly overshoots the requirements during the conceptual design stage which is due to its presentational character. The whole process could be repeated by empathizing less strongly on the precision and density of *Scribble Strokes*. This also accounts for the glazed panels, since the sketching application does not support transparency. Less densely scribbled surfaces could for instance evoke a visual representation of such transparent glazed panels for now.

5.2 Solidification of Information

The complete model sketch was then fed into the ML based pipeline, which could resolve the many retraced Shape Strokes that came into existence because I unnecessarily sketched duplicate boundaries even though they were intended to form a single one. This task was part of the first stage of the pipeline: The clustering of *Shape Strokes* into separate groups to identify the curve network. As mentioned before, this procedure was also repeated on the *Scribble Strokes* to reconstruct the bounding surface patches of the curve network (Figure 18), followed by the inheritance of semantic information, the extrusion of non-solid patches, and the generation of IFC data.

When my college Shervin, who developed and operates *Strokes2BIM*, first exported the IFC model, no suitable IFC model viewer was discovered that could represent

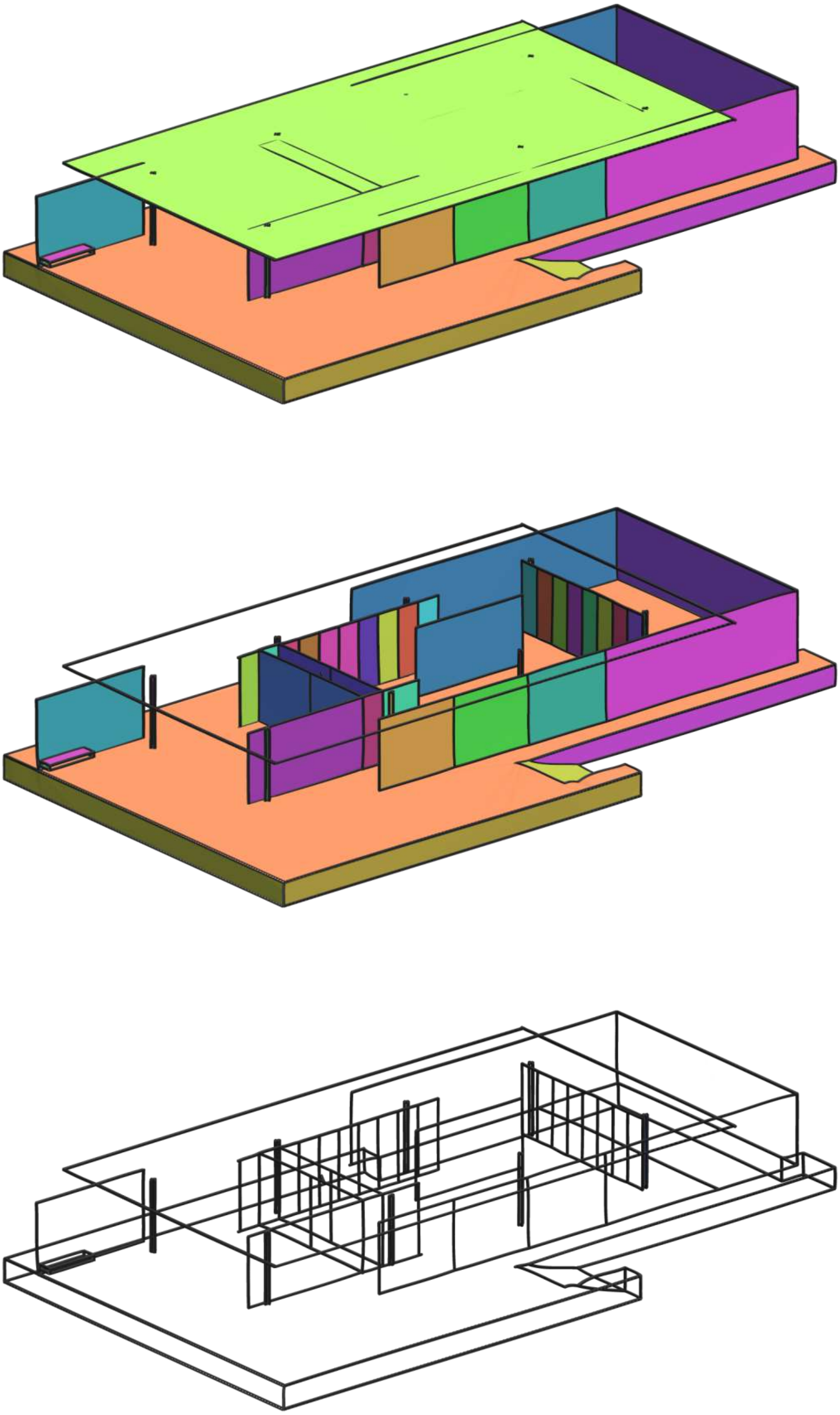


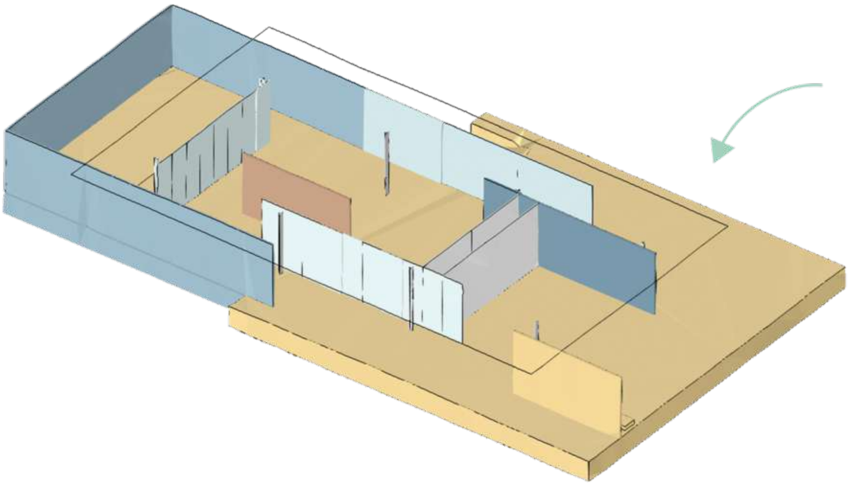
Figure 18 **Curve Network and Surface Patches**

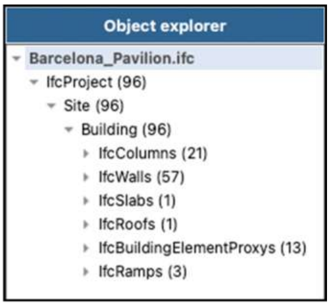
the boundaries of objects properly. He therefore added the curve network of the model sketch to the IFC model as instances of IfcPolyline. Even though these lines are only partly visible as they are not getting extruded along with the surface patches, readability of the geometry enhances greatly. The only tool that was capable of showing the model geometry together with these curves was OpenIFCViewer (Open Design Alliance, n.d.).

Figure 19 shows the IFC model as perceived within the IFC model viewer along with the automatically generated spatial structure. The object explorer suggests that additional components have been generated during geometry reconstruction and element segmentation. These geometries are usually very small and derive from single misinterpreted sketch strokes. Yet overall, the model geometry seems complete at a large-scale. Elements have been recovered as they were intended, and adjacent elements did not mistakenly form topologic connections, which is particularly remarkable in such areas where columns are located very close to a wall.

Nevertheless, some small-scale mistakes can be identified, among topologic connections that could not be recovered for two boundary cycles in the curve network that were meant to form the seating bench in the rear, which is why they lack their closed faces. The cut-out of the atrium in the roof in between the opal glass panels could also not be generated, and the pipeline encountered difficulties with the topologic recovery of the cruciform columns, as only two out of eight could be reconstructed properly (Figure 20).

The correct inheritance of graphical and non-graphical semantic information to any recoverable non-solid model patch in the model sketch can be confirmed within the IFC model viewer. This includes the surface colouring, functional classification, material properties of the constituent *Scribble Strokes*, as well as the thickness variables that led to the correct extrusion of building elements. Due to the complete solidification of information and minor use of stroke beautification, the reconstructed IFC model closely resembles its preliminary model sketch (Figure 21). Imper-





Object explorer

- Barcelona_Pavilion.ifc
  - IfcProject (96)
    - Site (96)
      - Building (96)
        - IfcColumns (21)
        - IfcWalls (57)
        - IfcSlabs (1)
        - IfcRoofs (1)
        - IfcBuildingElementProxys (13)
        - IfcRamps (3)

Figure 19 **IFC Model (Hidden Roof)**

fect shapes and connections of model components add detail and liveliness to an otherwise basic model, which helps to visualize its premature development. This is also due to the precise nature of Brep geometry, as it is adept at capturing the smallest inaccuracies that derive from free-hand sketching, while providing physically accurate shape representations that derive from the extrusion of non-solid model patches. Since the *SolidModel* can be applied for the

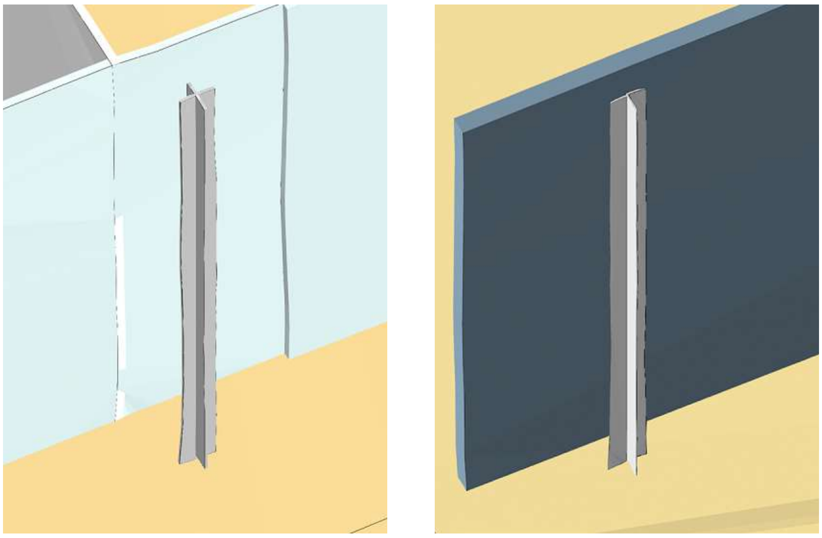


Figure 20 **Varying Reconstruction Outcomes**

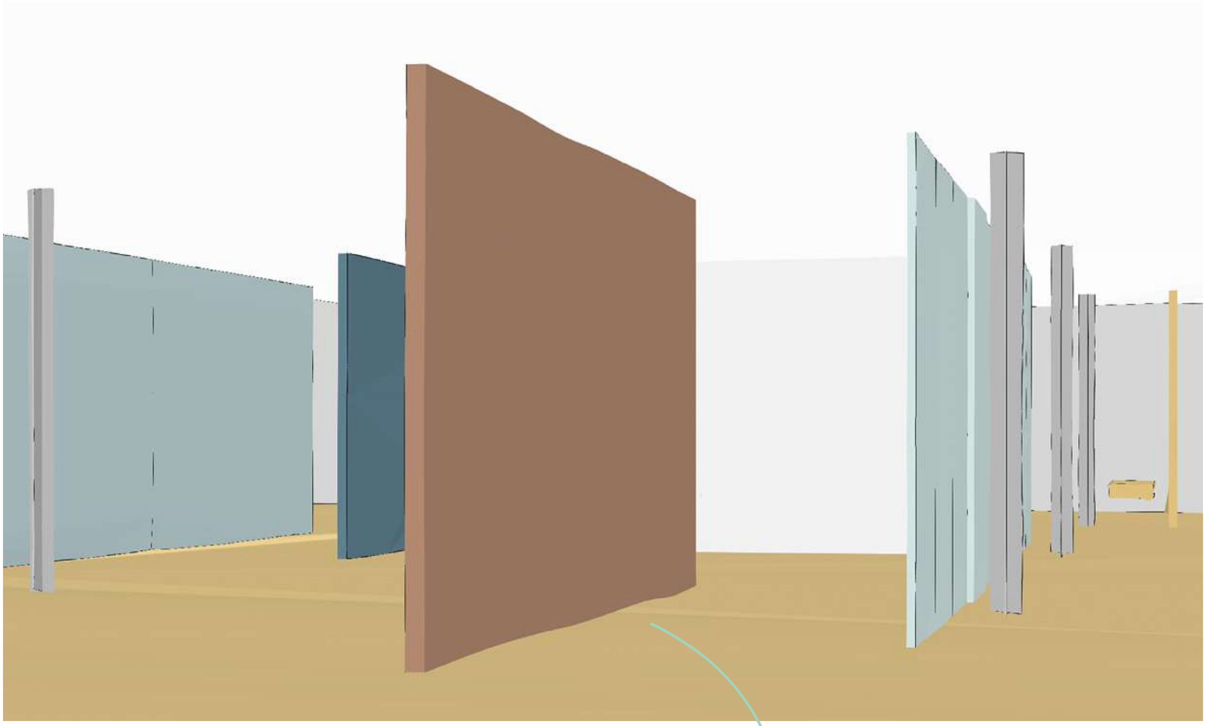
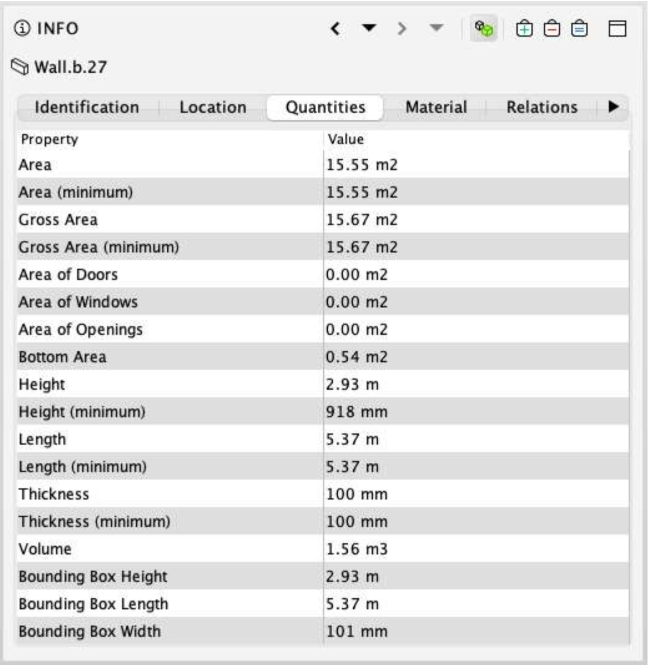


Figure 21 **Reconstructed Interior**



Property	Value
Area	15.55 m2
Area (minimum)	15.55 m2
Gross Area	15.67 m2
Gross Area (minimum)	15.67 m2
Area of Doors	0.00 m2
Area of Windows	0.00 m2
Area of Openings	0.00 m2
Bottom Area	0.54 m2
Height	2.93 m
Height (minimum)	918 mm
Length	5.37 m
Length (minimum)	5.37 m
Thickness	100 mm
Thickness (minimum)	100 mm
Volume	1.56 m3
Bounding Box Height	2.93 m
Bounding Box Length	5.37 m
Bounding Box Width	101 mm

Figure 22 **Quantities of the Red Interior Wall**

description of geometry, IFC model viewers are capable of calculating the model components quantities.

Figure 22 shows the quantities of the red marble wall in the centre of the pavilion. The brush size of 0.1 that was used for the creation of its constituent sketch strokes has been translated into a thickness of 100mm. The overall quantities are yet affected by the incorrect connections and overlaps of volumetric elements, first rough model checks and estimations could however be performed on the IFC model right away, and depending on the MVD, it could be also altered in an authoring platform.

Additional figures and IFC data excerpts are provided within the 9.2 Appendix.

6 Discussion

While the role of geometry certainly remains unchangeably vital in the design process, the presented workflow is part of a new paradigm that aims “to shift design thinking in the early stages from pursuing a fidelity of design form to pursuing a fidelity of design concept […] by supporting the designers’ need for abstraction, awareness and conceptual thinking through the tools of geometry, topology and semantics” (Jabi and Chatzivasileiadi, 2021). BIM can effectively aid this process, but needs to be radically scaled in complexity. Thus, a small set of criteria has been identified for the purpose of describing conceptual IFC models. This allows designers to operate within the versatile BIM landscape while maintaining their creative independence through the use of intuitive digital sketching.

The chosen criteria comprise a handful of IFC definitions that enable the classification of building elements, related openings, furniture and landscaping elements, the association of elements with materials and surface styles, and their containment in a spatial structure. The scope of descriptive definitions could suitably be used within the demonstrated workflow for the creation of the 1929 Barcelona Pavilion model sketch from an architectural point of view. To cover other domains for cross-disciplinary collaboration, the uptake of more specific definitions will become compulsory. However, the methodical approach proofs that information could be seamlessly sustained from sketching to BIM.

The presented workflow can therefore enhance the uptake of methodical strategies such as the IPD by putting behind inefficient and cumbersome intermediate steps in the communication and discussion of ideas among all stakeholders. The presence of experts in the conceptual design stage however is rare, which motivated the funded research project *SFB: Advanced Computational Design* to deploy a novel design and integration platform that provides designers with immediate feedback at an expert level, while their influence on a project is high, hence allowing for much more flexible proposals compared to conventional approaches in design.

6.1 Creating Flexibility

Flexibility – in terms of the adaptability to change – is also created by BIM's efficiency and reduced workload (Davis, 2013), which is neglected for conceptualization due to the absence of eligible design methods. For this reason, sculpt-like digital sketching has been investigated for the creation of BIM-enabled model sketches in this thesis. The approach opens up the three-dimensionality of space for the use of intuitive sketching, where more complex information can be structured and reviewed. This was achieved by transferring the object-oriented methodology of BIM to the level of sketch strokes, where information is contained. The use of novel AI strategies enables to bridge the assigned semantic information across different mediums seamlessly. The semi-automated approach however also comes with a few challenges as it stands currently. First and foremost, additional semantic information in the sketching application can only be assigned in a subsequent process after sketch strokes have been created by selecting the respective strokes and choosing semantic labels from a drop down menu in the GUI. Furthermore, there is currently no feedback available that would facilitate designers to validate this input.

In the Proof of Concept, two additional non-graphical semantic labels have been assigned to the model sketch, and it is important to keep this manual input as low as possible to not overburden the intuitiveness of sketching. This is anyhow necessary, given that sketched model data is limited to physically representable entities and properties allocable to sketch strokes. The interpretation of various relationships that are formed by objects such as the IFC concept of element connectivity that provides descriptions for logical and geometrical connections of elements within a building, or non-tangible objects such as the $^{\text{Ifc}}$Space for performing space syntax analysis within IFC models therefore highly relies on the deployed AI strategies.

Consequently, the benefit of model sketching in this thesis is determined by the performance of the *MR.Sketch*'s GUI, the ML based pipeline *Strokes2BIM*, and an approach that fulfils designers' need for abstraction and intuition. Freehand sketching particularly leverages its strengths through the ability to swiftly iterate design steps until a promising result is achieved in "a trial-and-error process" (Ching and Juroszek, 2019). This process can be supported by the chosen sketching technique based on *Shape Strokes* and *Scribble Strokes*. The rough filling of surfaces and the topological recovery of boundaries can assist designers' need to act quickly.

The presented example however was carefully created to fulfil its presentational use case within this thesis based on an existing design, which is why it cannot provide answers regarding the speculative and more iterative nature of freehand sketching. More studies must be conducted under conditions that come close to real life design practice to test the workflow's capabilities of allowing maximum abstraction while delivering satisfactory outputs as needed for earliest design conceptualization.

6.2 Adding Parameters

Flexibility is also created through the use of little involved constraints that facilitate quick design changes. On the journey from intuition to precision however, well-organized parameters are needed to achieve the same flexibility even in more advanced stages of design, during which many interactions and interrelationships are prevalent. BIM is adept at handling complexity by "creating a centralised repository of data that all representations draw upon; change the data once and theoretically everything updates" (Davis, 2013). Therefore, even smallest components are constituted from a wide range of parameters, which collectively form a relational model as a whole. This approach can interfere with creative freedom during conceptualization, as immanent in the IFC schema, providing only a narrow scope of parametric definitions for model geometry. It does not come as surprise that this workflow produces Brep geometry, which allows designers...

> "...to make virtually any form they could conceive. There is no meaning captured beyond solidity; designers are free to make their own associations between the forms represented and the thing being designed." (Woodbury and Burrow, 2006)

To transfer the creative freedom involved in the creation of Brep into more complex contexts, the concept of *semantic enrichment* proposes the use of AI to interpret and supplement information that is contained implicitly in models, which also involves parametric geometry and constraints (Sacks et al., 2018).
I want to elaborate on this by briefly discussing a second workflow that was tested on another model sketch I created within the funded research project. The sketch represents the *BUGA* pavilion by Jan Knippers, a freeform roof structure that is made up of wooden modules. The workflow involved the geometry reconstruction using the *Strokes2Surface* ML based pipeline (SP2), the surface reconstruction from mesh to NURBS

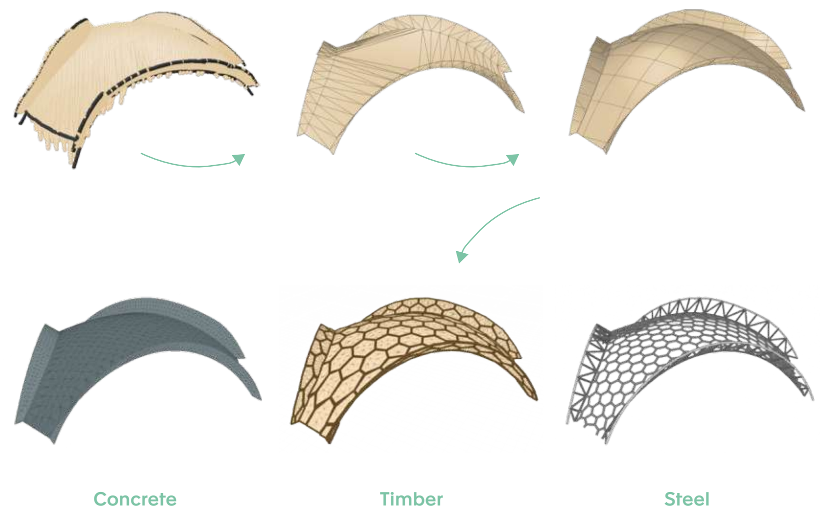


Figure 23 **Enriched Model Sketch**

geometry (SP6) and subsequent panelling of the surface (SP6) in various materialized variants (Figure 23, cf. Daleyev et al., 2023). Each stage of the workflow gradually solidified a new set of parameters that enabled design space exploration through the tools of parametric modelling. The merging of such workflows with the presented workflow of this thesis could be a promising outlook for the iterative development of design. It can further reduce the burden of complexity during earliest conceptualization, and evoke parameters in a circular process of immediate feedback and design space exploration that can lead to new findings, e.g., in terms of materialization, sustainability, or structural properties.

While seamlessly transferred data from semantic sketches to IFC can so far be shared effectively for visualization and nascent model checking, enrichment of semantic data can also enable overcoming interoperability issues of vendor-specific gateways to allow further design development of conceptual BIM models within authoring platforms in more advanced stages. The uptake of actual IFC model editing however will mainly rely on the development and adoption of BIM maturity *Level 3*, which will require further major collective efforts in the AEC industry.

6.3 Outlook

The tendency to cloud based collaboration could be just as well brought to the 4D semantic sketching application, as it would facilitate designers to collectively work together on the same model sketch. From a broader multidisciplinary point of view, the entities of the BIM handbook could be revised and possibly extended to other domains as mentioned before. The process of assigning such additional semantic information to sketch strokes in *MR.Sketch* currently lacks an intuitive GUI, and some way of providing feedback on the non-graphical semantic attributes could be considered. The coupling of the canvas function with generative design methods for the generation of space allocations plans, or with terrain data from geo-referenced sites for the creation of buildings' layouts could support designers effectively, while preserving this information in the IFC model subsequently.

Most of the benefits within this workflow arise from the deployed AI strategies, as they fundamentally enable the extraction of implicit and explicit information contained in sketches. Immanent in any AI strategy, the agenda of items to be improved is endless. However, there are some more pressing issues that await implementation. Among is a solid-checker within the ML based pipeline that recognizes whether the shape representation of an element is intended to be solid or non-solid. Consequently, such detected geometry would not be disintegrated into single surface patches. Among is also the consideration of more than just geometric features for the reconstruction of geometry, which could further improve the precision at which *Strokes2BIM* is able to recover topologic connections without stitching adjacent elements together, or identify elements that are made up of more than just one surface patch. Among is also the refinement of element connectivity in the model. Overall, the rough and imperfect reconstruction of the model sketch can be suitably used to visualize conceptual ideas using Brep geometry. When considering model checking operations or further extension of the IFC model in authoring platforms, well organized geometries become inevitable. This could be aided by the information contained in the model's curve network, as it mostly resolved the connectivity of elements in the process. As a next step, the curves could be further smoothed and connected to other respective surfaces, curves, and points. The topologic connectivity could be preserved to joint extruded non-solid elements together and form connection geometry, which can be formally embedded in the IFC file.

The BIM handbook of this thesis initially included many more parametric IFC definitions, such as the use of Swept-Solid geometry for building elements' shape representations wherever possible, body clipping operations, implementation of the IfcOpeningElement, or the containment of elements in more precise spatial structure hierarchies. This also includes the use of IfcSpace to perform space syntax analysis in the conceptual design stage. Such definitions require significant efforts but would greatly enhance the utility of this workflow in the future.

7 Conclusion

The expansion of BIM methodology towards the conceptual design stage can have a significant impact on the design process, but is undermined by the lack of eligible technology for the preliminary development of highly specified BIM models. Other widely adopted techniques can effectively enhance the design process in early stages, but fail at supporting the semantic richness of architectural practice nowadays. The revival of such techniques within digital platforms can however open up new possibilities for a user-friendly and explorative generation of BIM model resources, particularly in combination with AI.

The proposed semi-automated workflow in this thesis deployed sculpt-like digital sketching for the generation of abstraction-enabled IFC models. In doing so, a set of graphical and non-graphical information was identified for the creation of semantic model sketches. The findings of this thesis were then recommended for implementation in the technical components of the workflow, which led to the development of a new GUI panel in the sketching application *MR.Sketch*, and the extension of an existing ML based pipeline responsible for geometry reconstruction and IFC model generation titled *Strokes2BIM*. The methodical workflow was demonstrated on a model sketch of the 1929 Barcelona Pavilion, which confirmed that information can be seamlessly sustained from sketching to BIM. This enables architectural designers to capture, visualize, and discuss their findings in more efficient and effective ways, or make use of optimization based design automation.

The creation of parametric and semantically rich building models from model sketches will however rely on a significant leap in the deployed technology. This involves both computer graphics and AI systems, and more broadly, the technology of BIM in general with the IFC schema at its base.

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8.1 Table of Figures

8.2 Other References

Alternative Praxis / Alternative Practice

Isabella Marboe

"Die Epoche der großen Meister mit dem genuinen Wissen um die beste Architektur geht zu Ende. Deren einzigartige Handschrift hatte und hat ihren Preis. Genies fordern alles von sich und anderen. Die totale Hingabe an die Architektur und durchgezeichnete Nächte sind dabei ebenso selbstverständlich wie überzogene Budgets.

Es ist die Zeit der Teams. Immer mehr Frauen lehren an Architekturfakultäten und ergreifen den Beruf. Umgangsformen sind wertschätzend, Hierarchien flach. Man setzt auf Kooperation, Kommunikation und Vernetzung. Hochkomplexe Aufgaben und Bauprozesse sind nur interdisziplinär zu schaffen. Große Büros haben mehrere Standorte, Forschungs-, Entwicklungs-, Entwurfs-, Rechts- und Publikations-abteilungen, kleine Büros agieren wendig und flexibel in unterschiedlichen Arbeitsgemeinschaften.

Partizipative Planung heißt auch, die Gestaltungsoberhoheit abzugeben. Das erfordert neue Formen der Entscheidungsfindung. Soziokratie ist eine von vielen Möglichkeiten, konsensuale Lösungen zu erzielen. Kollektive Bauherrschaften bedingen auch neue Finanzierungsmodelle wie Mikro-credite und Crowdfunding.

Auch Werkzeuge verändern die Praxis. An einem Ende der Skala steht BIM - Building Information Modelling. Eine digitale Planungstechnologie, bei der alle Informationen aller Gewerke synchron in einer Datei zusammenlaufen. Es geht um Effizienz. Am anderen Ende: Das Revival der Handskizze, Hands on und Do It Yourself, Open Source, Autonomie, Mut zur Lücke und maximale Identifikation mit dem selbst produzierten Objekt. Es geht um Dialog."

As presented during the Review '22 exhibition of TU Vienna, Institute of Architectural Design.

"The era of the grandmasters with their genuine knowledge of best practice architecture is coming to an end. Their unique handwriting had and still has its price. Geniuses demand everything from themselves and others. Thorough dedication to architecture and sleepless nights are just as common as inflated budgets.

It is the era of teams. More and more women teach at architectural faculties and embrace the profession. Manners are respectful, hierarchies are flat. Emphasis is placed on cooperation, communication, and networking. Highly complex tasks and construction processes can only be achieved through interdisciplinary collaboration. Large offices have multiple locations, research, development, design, legal, and publishing departments, while small offices operate agile and flexible in various consortia.

Participatory planning also means relinquishing design authority. This requires new forms of decision-making. Sociocracy is one of many ways to achieve consensus-based solutions. Collective building ownership also necessitates new financing models such as micro-credits and crowdfunding.

Tools are also changing the practice. BIM, at one end of the scale, converges information from all stakeholders in a single synchronized file – aiming for efficiency. At the other end: The revival of freehand sketching, hands-on and do-it-yourself, open source, autonomy, daring shortcomings, utmost identification with one's self-made object – aiming for dialogue."

Translated into English by Philipp Stauss.

9 Appendix

9.1 BIM Handbook "From Sketching to BIM"

This appendix contains an IFC structure that was chosen for the description of conceptual BIM models within four sections: *9.1.1 IFC Core Data Architecture, 9.1.2 Building Structure Definitions, 9.1.3 Material Definitions, 9.1.4 Spatial Structure Definitions*.

Images and Individual text passages are directly incorporated from the IFC4.3.0.1 documentation (BuildingSmart International, n.d.). The version of the standard is currently under ISO voting. IFC4.3 was released in March 2022.

9.1.1 IFC Core Data Architecture

The IFC Schema defines a structure for organizing data in a way that allows users to store, exchange, and share information. It uses a formal language which is provided in EXPRESS and XML. A naming convention is deployed for all its types, entities, rules and functions which start with the prefix *Ifc* followed by CamelCase wording, e.g., IfcBuildingStorey. The schema architecture consists of four conceptual layers: The **Domain Layer, Shared Layer, Core Layer** and **Resource Layer**.

The **Domain Layer** includes definitions that are specific to an AEC discipline. The multidisciplinary extent of the funded research project *SFB: Advanced Computational Design* can be linked to the *Architecture Domain*, *Structural Analysis Domain*, *Structural Elements Domain,* and *Electrical Domain* (Lighting). Though their contents are too specific for this framework and not further included. This is because most of the architectural entities are found in the **Shared Layer**. It holds the IfcSharedBldgElements, defining subtypes of the IfcBuiltElement, e.g., IfcWall, IfcSlab, IfcRoof, IfcRamp, IfcColumn, IfcBeam.

The schema definition of the IfcBuiltElement itself, as well as the IfcOpeningElement, IfcFurnishingElement and IfcGeographicElement (all inherited from the IfcElement), is found in the **Core Layer**'s Product Extension. It also contains the IfcSpatialStructureElement, which is used to describe the spatial hierarchy of building elements.

Inside the Core Layer the definition for the IfcKernel is provided. It is the underlaying secondary structure of IFC based on a hierarchical family tree. Any type, entity, rule or function in the Core Layer and above is inherited from Root , where it receives a Globally Unique Identifier (GUID).
The lowest layer – **Ressource Layer** – includes all individual schemas containing resource definitions. Those definitions do not include an GUID and shall not be used independently of a definition declared at a higher layer.

The definitions that emanate from IfcRoot split into three subtypes at a first hierarchical level:

Object Definition

Supertype for any physically existing items (e.g., IfcSpace), tangible items (e.g., IfcWall) or conceptual items (e.g., IfcGrid). An IfcObject can be defined by an IfcTypeObject, which is shared among multiple occurrences and then becomes part of the Project Library provided in the IfcContext.

Relationship

Any objectified schema definition may form a Relationship with other definitions. It may use subtypes of Assigns, Associates, Connects, Declares, Decomposes, Assigns, or Defines to form a 1-to-1 or 1-to-many relationship.

Property Definition

Defines the generalization of any characteristic or set of characteristics for an actual IfcObject or IfcTypeObject. The property definition provides templates for property sets or individual properties which are then included in the project library. Templates enable extensibility of the schema by creating user defined properties specific to a building information model.

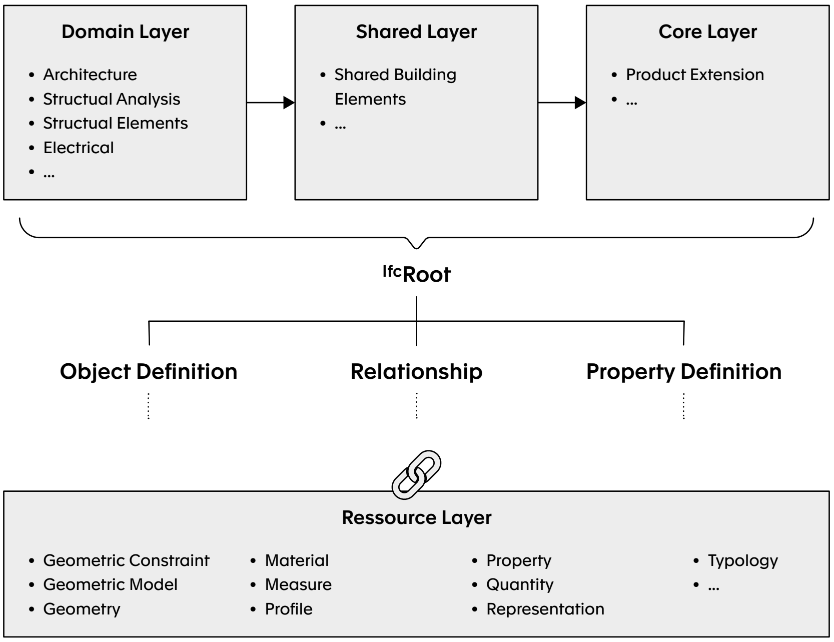


Figure i **Schema of the IfcKernel** (Personal Interpretation)

An IfcPropertyTemplate or IfcPropertySetTemplate may be used for occurrences of IfcPropertySet (Pset_) or of IfcQuantitySet (Qto_) or of individual properties. An Object may have a *Pset_ [...]Common* or *Qto_[...]BaseQuantities* defined with lists characteristics common to all occurrences of this entity.

9.1.2 Building Structure Definitions

The aim of this workflow is to produce single-layer solid building elements that do not exceed this completeness during the conceptual design stage, e.g., by enabling generation of more than one material layer for building elements. This handbook proposes the use of six building element entities to create building models at the level of completeness expected in the conceptional design stage:

- IfcWall
- IfcSlab
- IfcRoof

- IfcRamp
- IfcColumn
- IfcBeam

Other building elements are for the time being not fundamental to the perception of architectural space by generating a more precise representation and therefore can be introduced at a later stage, e.g.:

- IfcDoor and IfcWindow → Abstracted as voided openings (9.1.2.2)
- IfcStair → Abstracted as ramps

This consideration is based on the geometric complexity of a sketched element (effort invested by the designer) and the complexity of its parametric representation in IFC (effort invested by the developer) while providing a sufficient visual representation during the design development.

The use of the IfcFurnishingElement (9.1.2.5) and IfcGeographicElement (9.1.2.6) in addition to the built elements is recommended.

9.1.2.1 Shape Representations

While it is possible to describe a building model just logically in IFC, tangible building components usually have one or more shape representations. The ultimate goal of this framework is provide these within the given variety of parametric definitions and concepts. Shape representations are referenced by the use of IfcProductDefinitionShape and IfcShapeRepresentation to built elements. In IFC basic representation types are used for the description of geometric data, among:

- Points
- Curves
- Surfaces (face-, shell-, or tessellation-based)

- Advanced Surfaces (NURBS)
- ...

They constitute the *SurfaceModel*, or physically accurate representations of surfaces and respective volumes within the *SolidModel* representation, among:

Boundary Representation (Brep)

Used for complex shapes based on simple surfaces. It allows for a high level of precision by representing an element precisely by its boundaries, where surfaces, curves, and points form connections.

Advanced Brep

Used for complex shapes as stated above, but based on NURBS surfaces.

SweptSolid

Based on extrusion operations which are defined by an extrusion profile , depth, and direction. The extrusion can also be tapered. The method is used for standard parametric geometry definitions of building elements. However, IFC does not generate SweptSolid geometry other than from footprint profiles, which limits the use of SweptSolid geometry significantly.

Constructive Solid Geometry (CSG)

Involves the generation of shape representations defined by basic shapes that an object occupies, and combined though Boolean operations. The method has been adopted by IFC to describe opening elements, e.g., recesses and windows, or body clipping occurrences based on subtraction operations

9.1.2.2 Element Voiding

Elements may have openings (geometric voids) defined, which can be a partial recess or extend to the full depth. These ppenings may optionally be filled by another element such as a door or window. This is described by the IfcOpeningElement and the IfcRelFillsElement if the void is filled by an element.

There are two types of voiding elements:

- Thickness of the voiding element is equal or greater than the thickness of the voided element, which is an *Opening*.
- Thickness of the voiding element is smaller than the thickness of the voided element, which is a *Recess*.

If the shape representation of the voided element is provided as a *SolidModel*, CSG operations are used to achieve the desired representations. If it is provided as *SurfaceModel*, no additional operations are required. The opening or recess is then just referenced to the shape representation of the voided Element.

Even though this framework proposes no geometric representation of an IfcWindow or IfcDoor, this information is needed for analysing spatial relationships. Therefore it is recommended to determine whether an Opening Element can be used as a passage to another space and by whom it can be accessed. A Door may then have properties defined that define the accessibility of connected spaces for different user groups.

The opening element should not be contained in a spatial structure.

9.1.2.3 Body Clipping

Built elements should preferably be represented with their gross geometry, allowing for quick design changes of openings, or other desired shapes that are formed from substraction operations. That applies for an element that is clipped by another element, e.g., a wall clipped by a roof, or if the targeted shape can not be generated from a parametric representation. These operations then include half space solids using CSG. A half space solid is defined by a plane and a bounding solid on one side of the plane

9.1.2.4 Element Connectivity

Built elements may participate in various connectivity relationships with other objects. They can be hierarchically to describe element compositions (parenting-child elements), or topologic connections in a building structure. Building components are then connected via the RelatingElement

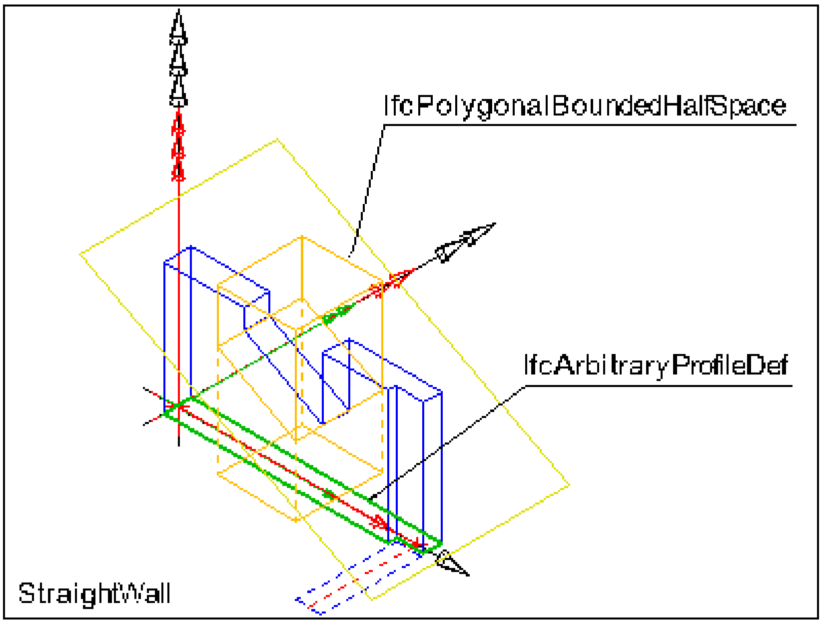


Figure ii Body Clipping Operation

and the RelatedElement using the IfcRelConnectsElements. It may provide a connection geometry for the RelatingElement (mandatory) and the RelatedElement (optionally), or just describe the connection logically, which requires the receiving application to generate the connection geometry.

Axis Geometry

A fundamental topological concept is the connectivity of objects which are based on paths. This applies to built elements that are represented as SweptSolid geometry. The IfcRelConnectsPathElements relationship connects the axis of two objects.

9.1.2.5 Furnishing Element

The use of furniture in the conceptual design stage aids the designer to evaluate functionality and dimensions of a space, and to explore the aesthetic relationship with the building structure. A furnishing element is either...

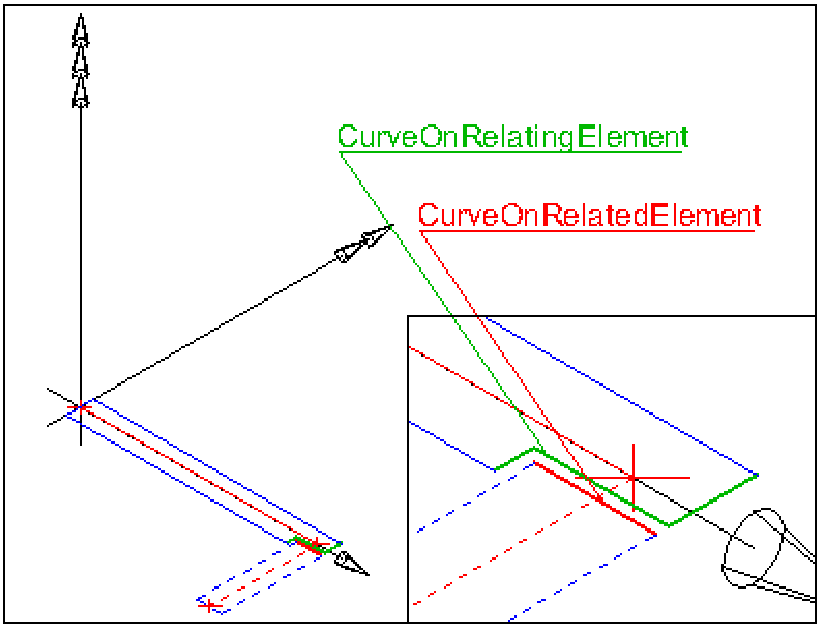


Figure iii **Path Connection Geometry**

- Pre-manufactured and assembled on-site, or
- Manufactured on-site, e.g., built in furniture

Built-in furniture should use IfcRelConnectsElements to connect to a built element.

The Furnishing Element should be contained in a Building Storey or Space.

9.1.2.6 Geographic Element

The geographic surroundings of a building influence the design on multiple levels and account for accessibility, orientation and layout as well as light and ventilation studies.

This entity includes landscape elements, e.g., trees or terrain. It is labelled as one of the four element types:

- Point features such as seating, bus shelters, signage, trees
- Linear features such as parking bays
- Area features such as ponds, lakes, woods and forests
- Drainage such as catchment, reserver or outfall

The Geographic Element should be contained in the IfcSite spatial structure element.

9.1.3 Material Definitions

In IFC there is two ways to represent materiality of an element:

- by assigning an IfcMaterial that the element is made of
- by using IfcPresentationStyle

An IfcMaterial itself can have an IfcPresentationStyle defined in order to represent a material colour, texture or pattern.

Furthermore a material is defined by physical properties that are important for model analysis.
In situations where the designer chooses varying styles for a sketched element, e.g., for colour scheme or representations of coverings it is important to support such styles in the workflow.

An IfcPresentationStyle assigned directly to the shape representation has priority over an IfcPresentationStyle of a Material. The use of materials within the workflow can be approached as follows:

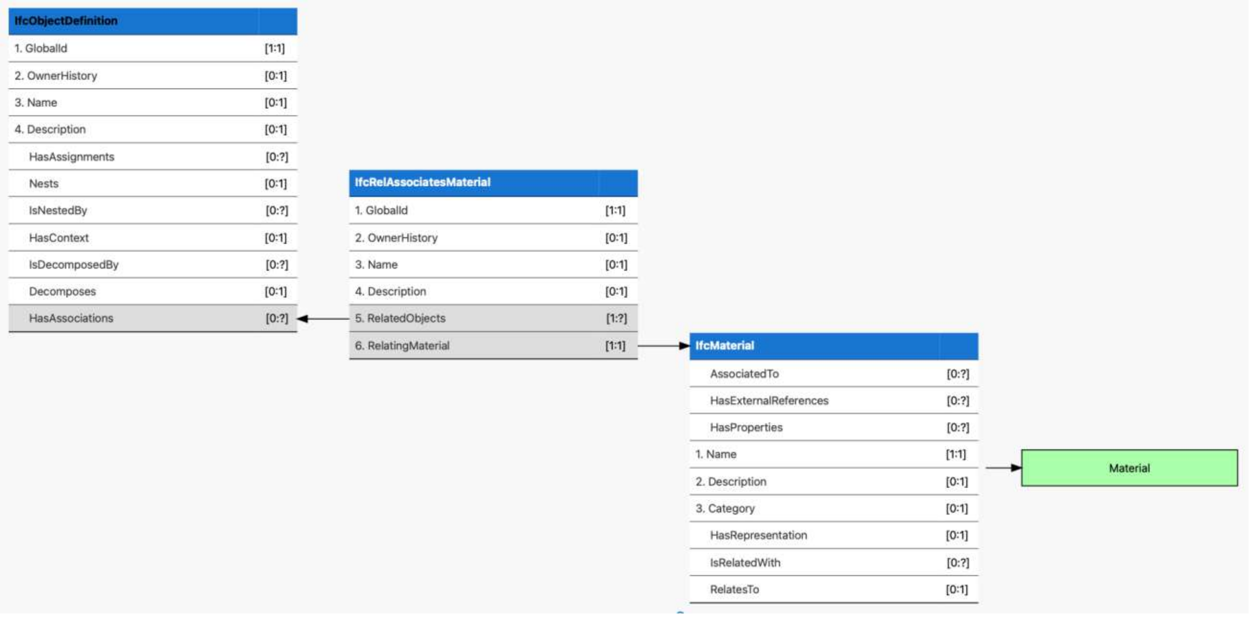
- An IfcMaterial may be directly associated with a colour or overrides this attribute. The Presentation Style of all surfaces is then provided within the IfcMaterial. It does not allow individually styled surfaces of an element.
- An IfcMaterial does not provide any IfcPresentationStyle. This information is assigned directly to the shape representation based on the colouring of each geometry surface.

9.1.3.1 Material Association

This framework uses single-layer elements made of a single Material as expected at the conceptual design stage.
Subtypes of an IfcElement, e.g., IfcBuiltElement or IfcFurnishingElement use IfcRelAssociatesMaterial to assign material information by the inverse relation *HasAssociations* attribute at the object definition level.

An IfcMaterial may carry the following information:

- Material properties
- Material classification and material library reference
- Material presentation in shape models (e.g., by color, hatching, rendering)
- Relation to the ingredients of a material composite



IfcObjectDefinition	
1. GlobalId	[1:1]
2. OwnerHistory	[0:1]
3. Name	[0:1]
4. Description	[0:1]
HasAssignments	[0:?]
Nests	[0:1]
IsNestedBy	[0:?]
HasContext	[0:1]
IsDecomposedBy	[0:?]
Decomposes	[0:1]
HasAssociations	[0:?]

IfcRelAssociatesMaterial	
1. GlobalId	[1:1]
2. OwnerHistory	[0:1]
3. Name	[0:1]
4. Description	[0:1]
5. RelatedObjects	[1:?]
6. RelatingMaterial	[1:1]

IfcMaterial	
AssociatedTo	[0:?]
HasExternalReferences	[0:?]
HasProperties	[0:?]
1. Name	[1:1]
2. Description	[0:1]
3. Category	[0:1]
HasRepresentation	[0:1]
IsRelatedWith	[0:?]
RelatesTo	[0:1]

Figure iv **Inheritance of an IfcMaterial**

In more advanced design stages parametric element instances commonly use a *Material Layer Set* for walls and slabs, and a *Material Profile Set* for columns and beams to associate materials. Representations of *Material Layer Set* or *Material Profile Set* are also associable for every other (non-parametric) instance of elements but without generating a geometric shape representation.

Elements made of more than one item, e.g., a window splits into a frame and glazing use *Material Constituent Set* to associate materials.

9.1.3.2 Presentation Styles

Defines styles for geometric representations of items. This could be styles for curves, surfaces, areas and text based on colour, hatching, rendering, and text fonts. This concept is assigned by using an IfcStyledItem.

The styles are defined by length measures of type *Model* or *Draughting*. Model measure is scale dependent, meaning it is always the same length in model space. Draughting measure is scale independent, meaning it is always the same length when plotted on paper for example. There are four different types of presentation styles:

- IfcFillAreaStyle defines hatching or tiling of an area or surface.
- IfcSurfaceStyle defines rendering properties like diffuse, specular or transmission.
- IfcCurveStyle defines colour, font and width of geometric curves.
- IfcTextStyle defines colour and font characteristics of text.

For the purposes of this framework sketched elements should be coloured by a Surface Style if not assigned to a Material

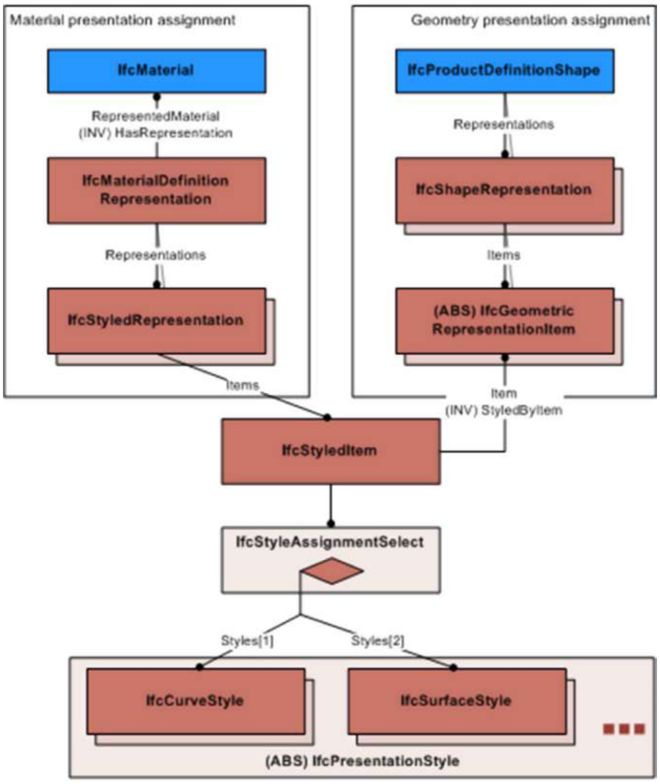


Figure v **Styled Item**

and/or using different styles for its surfaces. It is possible to define separate styles for the two sides of a single face. The attribute *Surface Side* should then be used within the IfcSurfaceStyle. In this case, the side with the surface normal is refereed to as the positive side and the opposite side therefore is called the negative side.

9.1.4 Spatial Structure Definitions

Setting up a spatial structure is important during any architectural design task. It breaks the complexity of a building into smaller zones and determines the spatial containment of its elements.

An element can be contained in either an IfcSpatialStructureElement, or in an element composition with the composed element being contained in the spatial structure in return. Furthermore, it can be part of an IfcSpatialZone, which is a non-hierarchical grouping of mostly functional character, e.g., thermal zones.

The hierarchical spatial structure in IFC is derived from the IfcProject and *Aggregates* to the following spatial structure elements in order:

- IfcSite
- IfcFacility, e.g., IfcBuilding
- IfcFacilityPart, e.g., IfcBuildingStorey
- IfcSpace

While these are valid containers for building elements, the default container is usually IfcBuildingStorey. An Element uses IfcRelContainedInSpatialStructure to form the containment in an IfcSpatialStructureElement.

An element can also be referenced to a Spatial Structure Element without being contained, which is used for elements

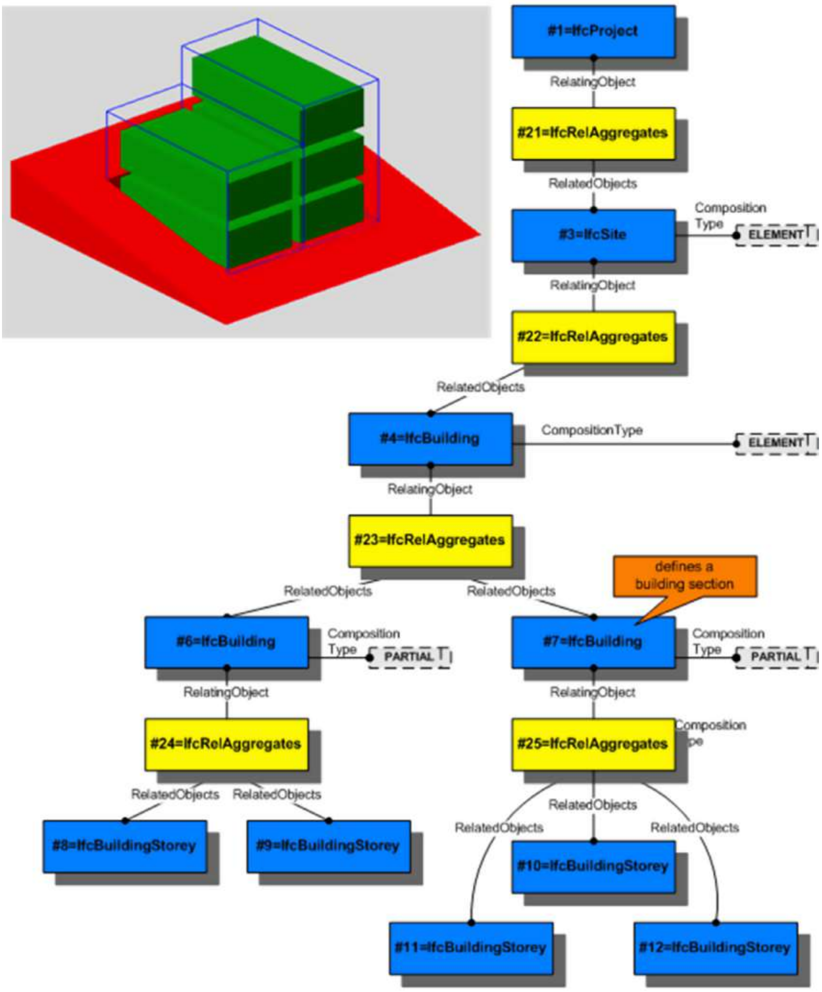


Figure vi **Styled Item**

that origin in another storey but go across multiple levels, e.g., a lift shaft. In this case, IfcRelReferencedInSpatialStructure is used.

The elevation of a spatial structure element can be defined in relation to the local placement of the next higher hierarchical element by using the attribute *PlacementRelTo*. It is also possible to use the absolut placement in the world coordinate system.

9.1.4.1 IfcProject

Basic contextual information is specified within the IfcProject, which is a subtype of IfcContext. It requires the input of units definitions, coordinate system and space dimensions, and level of precision used within the geometric representations. Optionally, a true north indicator and a geospatial reference can be given.

Properties
Project Type
Project Investment Estimate
Funding Source
Return on Investment (ROI)
Net Earned Value
Payback Period

9.1.4.2 IfcSite

An IfcSite may provide georeferenced coordinates by a longitude, latitude and an elevation relative to sea level. This information is used to define the point 0.,0.,0. of the local placement of an IfcSite.

A Project may be located on more than one site. Therefore, it may be decomposed accordingly using *Aggregates*:

- Complex = site complex
- Element = site
- Partial = site section

Properties
Buildable Area
Site Coverage Ratio
Floor Area Ratio
Building Height Limit
Total Area

Quantities

Gross Perimeter

Gross Area

9.1.4.3 IfcBuilding

An IfcBuilding is a subtype of IfcFacility and provides the internal height 0.00 relative to sea level by its local placement. This height is usually defining the floor finish level (FFL) of the ground floor.

A site may include more than one building or segmented parts of it. Therefore, it may be decomposed accordingly using *Aggregates*:

- Complex = building complex
- Element = building
- Partial = building section

Properties

Construction Method

Gross/Net Planned Area

Number Of Storeys

…

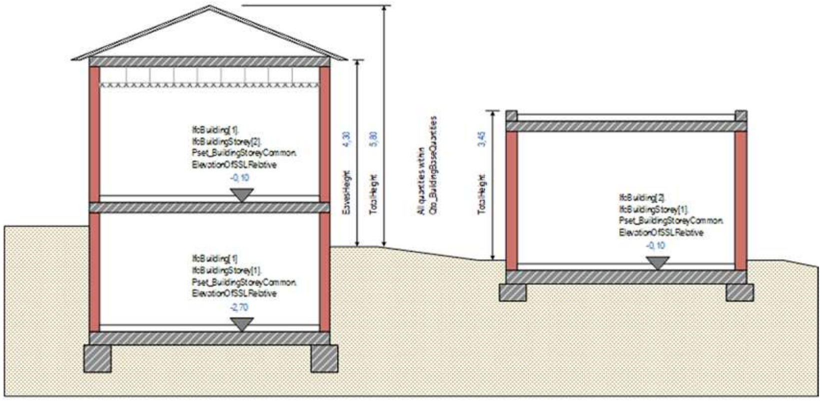


Figure vii **Height Quantities of an IfcBuilding**

Quantities

Height (from top of the roof to terrain)

Eaves Height (from base of the roof to terrain)

Foot Print Area

Gross/Net Floor Area

Gross/Net Volume

9.1.4.4 IfcBuildingStorey

An $^{\text{Ifc}}$BuildingStorey is a subtype of $^{\text{Ifc}}$FacilityPart. The elevation is given in relation to its structural slab level (SSL) and finish floor level (FFL).

A building may include split levels or spatial connections of more than one building storey. Therefore, it may be decomposed accordingly using *Aggregates*:

- Complex = building storey complex
- Element = building storey
- Partial = partial building storey

Properties

Elevation of SSL relative

Elevation of FFL relative

Entrance Level

Above Ground

Gross/Net Planned Area

...

Quantities

Gross/Net Height

Gross Perimeter

Foot Print Area

Gross/Net Floor Area

Floor Area

Gross/Net Volume

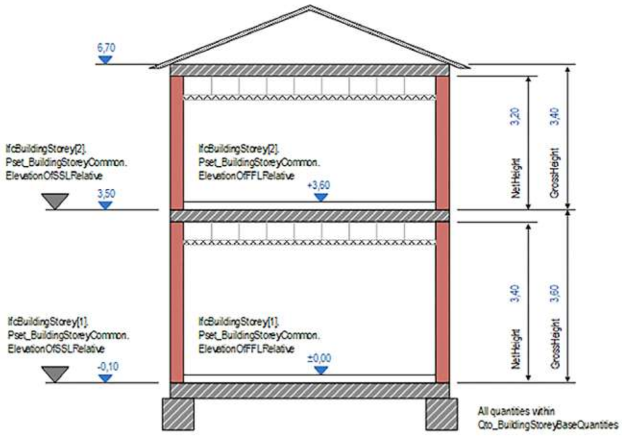


Figure viii **Height Quantities of an IfcBuildingStorey**

In interdisciplinary building modelling it is common to split the storeys of a building at SSL, which was also adopted by IFC by definition. This means that the structural slab as part of the ceiling belongs to the lower storey, while the construction of the finish floor belongs to the upper storey, enabling a precise assignment of elements. This approach requires some kind of foundation level for the lowest slab or other foundations.

If only the FFL is known to determine the elevation of a building storey, e.g., in a single-layer building model, each storey will begin at the FFL level and end at the next higher FFL.

9.1.4.5 IfcSpace

An IfcSpace is an area or volume that has actual or theoretical boundaries and usually relates to a certain function. It has an association with an IfcBuildingStorey, or an IfcSite in case of an exterior space.

A building storey may include segmented parts of an IfcSpace, or multiple instances grouped together. Therefore it may be decomposed accordingly using *Aggregates*:

- Complex = space group
- Element = space
- Partial = partial space

Properties

Is External
Gross/Net Planned Area
Publicly Accessible
Handicap Accessible

Quantities

Height
Finish Ceiling Height
Finish Floor Height
Gross/Net Perimeter
Gross/Net Floor Area
Gross/Net Wall Area
Gross/Net Ceiling Area
Gross/Net Volume

The short name or number of a space is given at the *Name* attribute of IfcRoot, and the full descriptive name is using the *LongName* attribute at IfcSpatialElement level. User defined categories can be defined at IfcSpace using the attribute

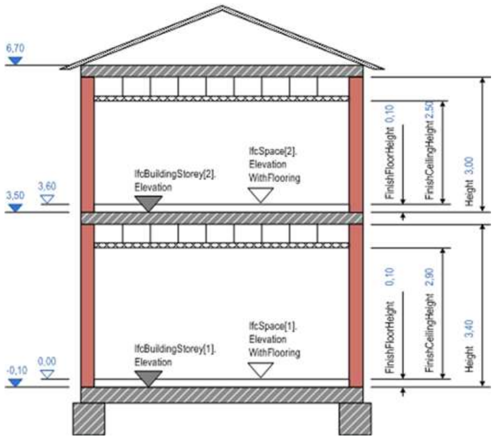


Figure ix **Height Quantities of an IfcSpace**

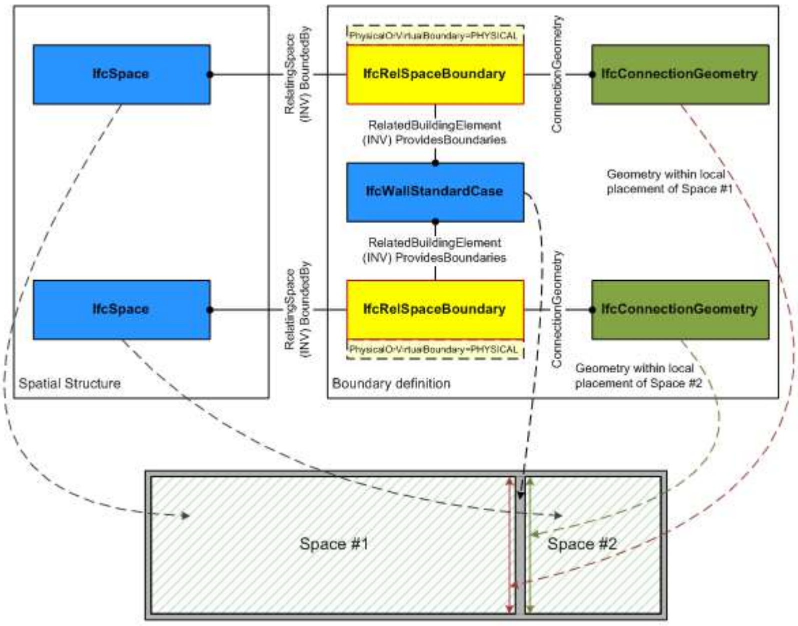


Figure x **Space Boundaries of a Physical IfcElement**

PredefinedType. At the same level, the *BoundedBy* attribute defines physical or virtual boundaries using IfcRelSpaceBoundary. For architectural purposes space boundaries of the first level are required.

A built element or a virtual element is needed to engage as the *RelatedBuildingElement* in this relationship. An opening element can also act as a virtual boundary. A connection geometry may therefore be given as 3D surface geometry for the relating space only. If no geometry is attached, the relationship only exits logically. The *InternalOrExternalBoundary* attribute defines whether a space boundary is adjacent to exterior space.

9.2 Additional Material (PoC)

This appendix contains additional figures and IFC data excerpts of the Proof of Concept (PoC) within three sections: ***9.2.1 Model Sketch, 9.2.2 Geometry Reconstruction, 9.2.3 IFC Model*****.**

9.2.1 Model Sketch

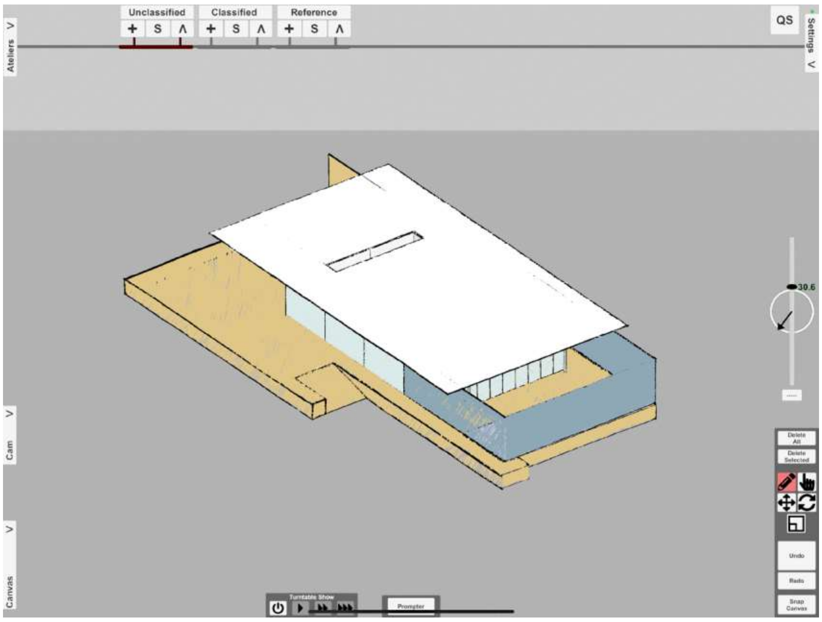


Figure xi Axonometric Projection

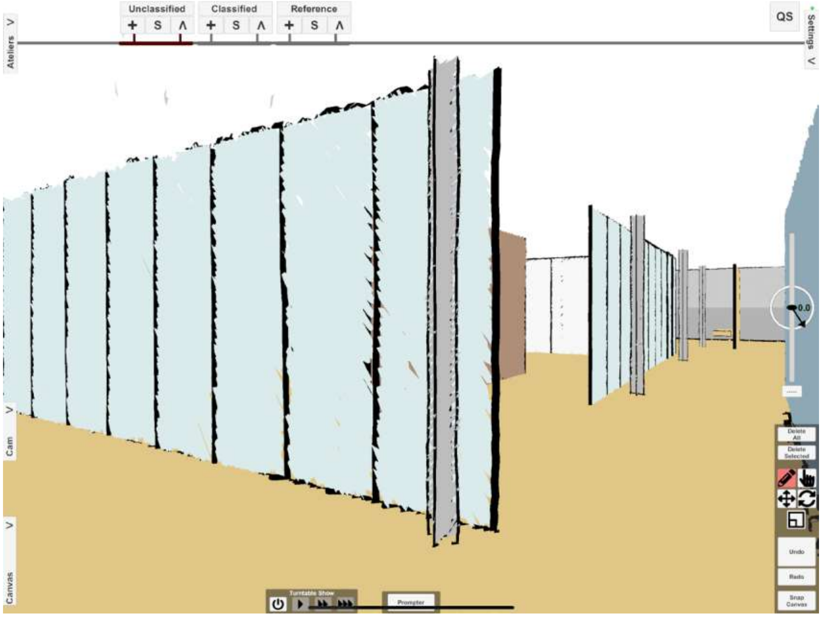


Figure xii Exterior/Interior View

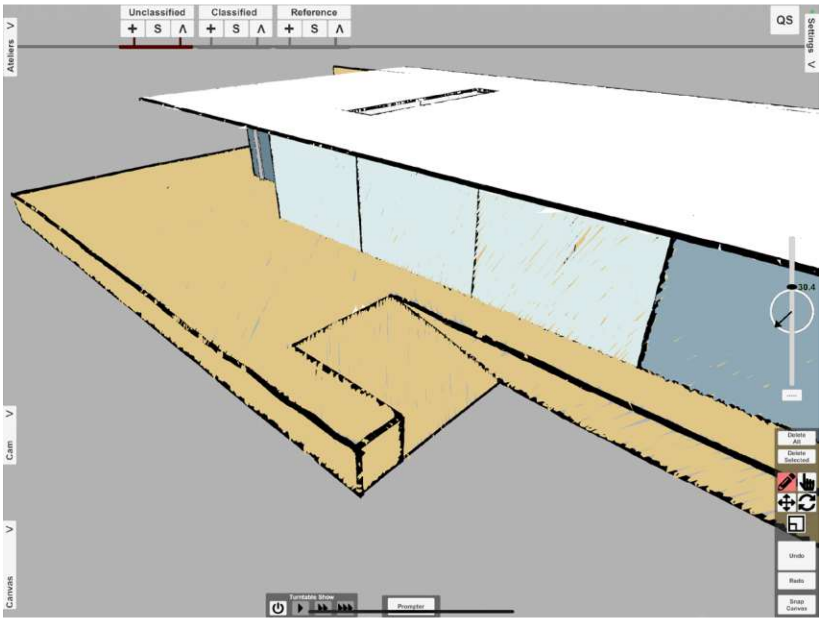


Figure xiii **View of the Ramp**

Figure xiv **View of the Rear**

9.2.2 Geometry Reconstruction

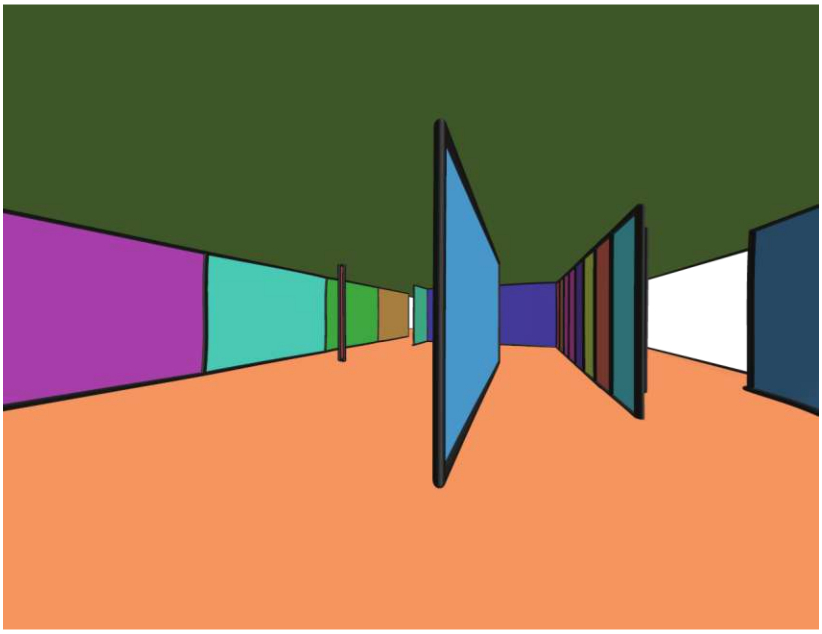


Figure xv **Interior View**

Figure xvi **Exterior/Interior View**

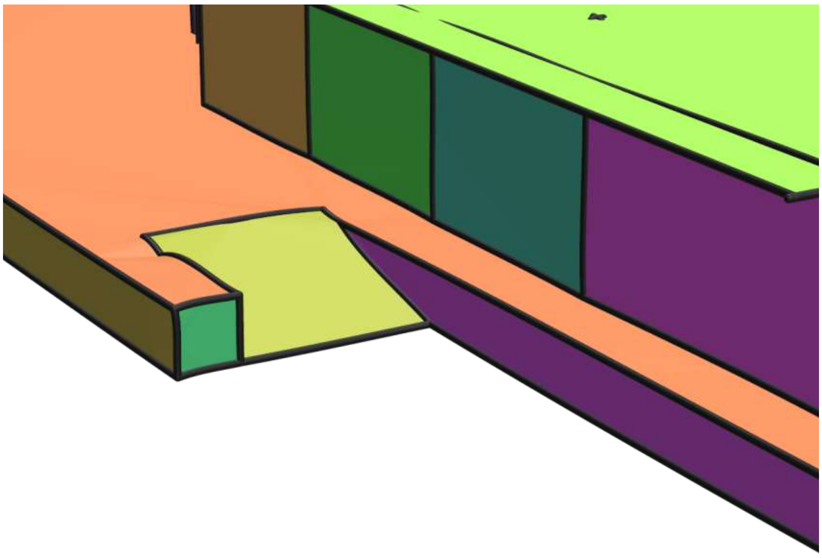


Figure xvii **View of the Ramp**

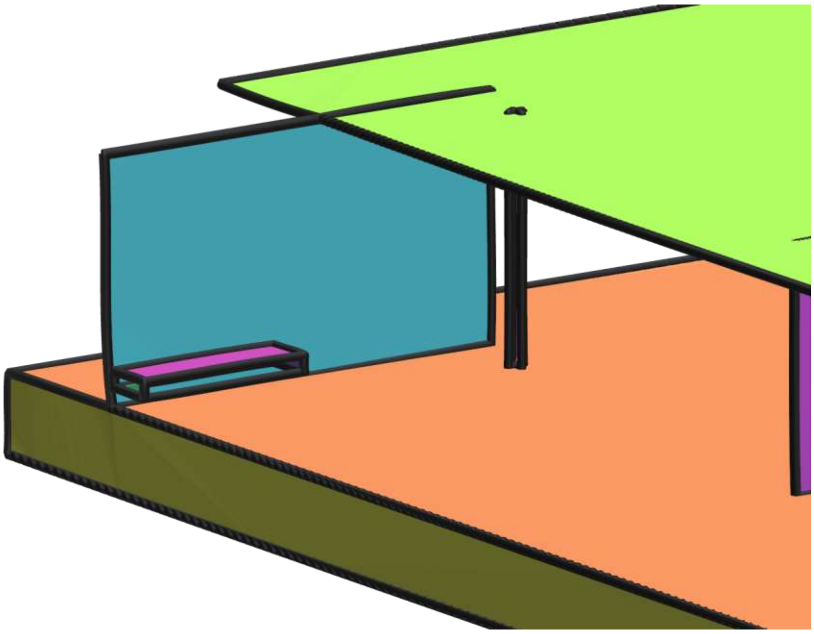


Figure xviii **View of the Rear**

9.2.3 IFC Model

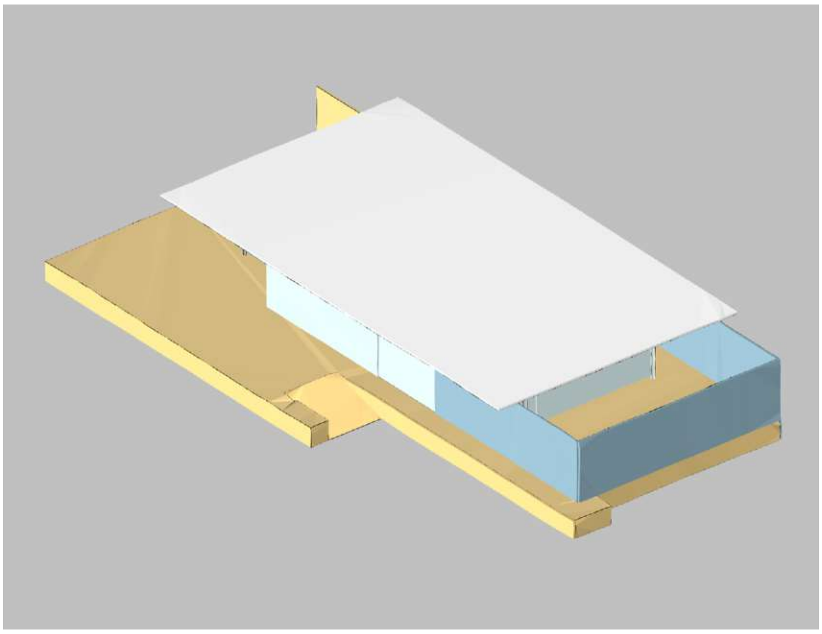


Figure xix Axonometric Projection

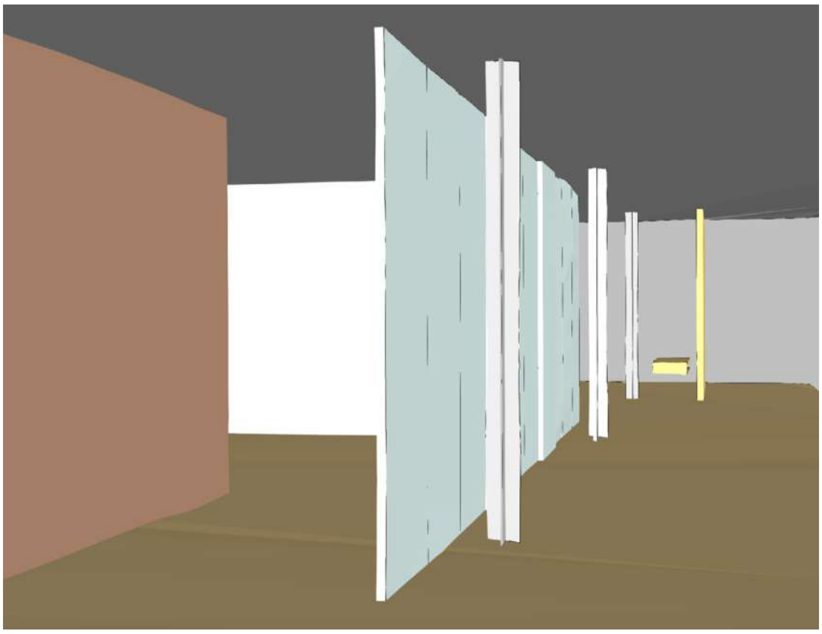


Figure xx Interior View

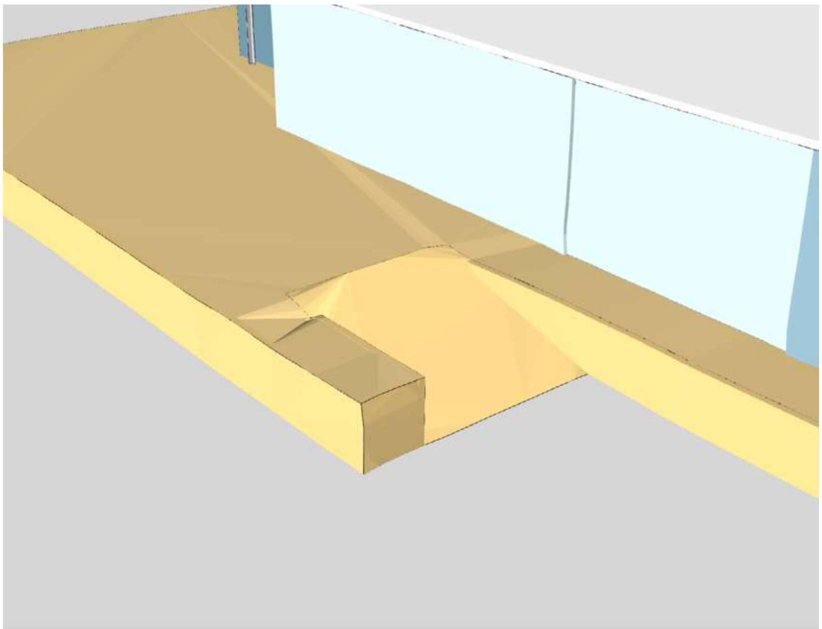


Figure xxi **View of the Ramp**

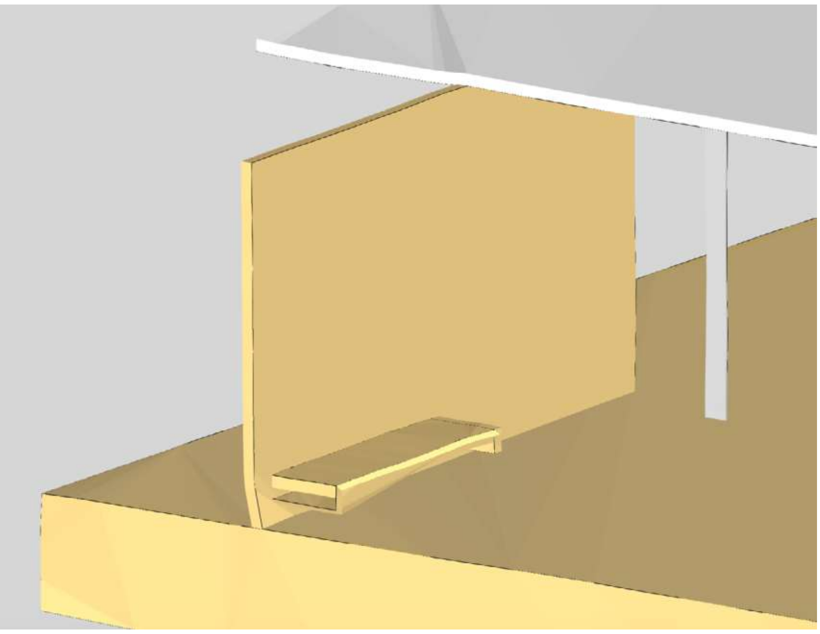


Figure xxii **View of the Rear**

9.2.3.1 First 100 Lines of Code

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HEADER;
FILE_DESCRIPTION((‘ViewDefinition [CoordinationView]’),’2;1’);
FILE_NAME(‘sketches/Barcelona_Pavilion.ifc’,’2023-03-30T17:01:47’,(‘Shervin Rasoulzadeh’),(‘Vienna University of
Technology’),’Strokes2BIM-0.0.1’,’Strokes2BIM-0.0.1’,’’);
FILE_SCHEMA((‘IFC4’));
ENDSEC;
DATA;
#1=IFCPERSON($,$,’Shervin Rasoulzadeh’,$,$,$,$,$);
#2=IFCORGANIZATION($,’Vienna University of Technology’,$,$,$);
#3=IFCPERSONANDORGANIZATION(#1,#2,$);
#4=IFCAPPLICATION(#2,’0.0.1’,’Strokes2BIM-0.0.1’,’’);
#5=IFCOWNERHISTORY(#3,#4,$,.ADDED.,$,#3,#4,1680195707);
#6=IFCDIRECTION((1.,0.,0.));
#7=IFCDIRECTION((0.,0.,1.));
#8=IFCCARTESIANPOINT((0.,0.,0.));
#9=IFCAXIS2PLACEMENT3D(#8,#7,#6);
#10=IFCDIRECTION((0.,1.,0.));
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#12=IFCDIMENSIONALEXPONENTS(0,0,0,0,0,0,0);
#13=IFCSIUNIT(*,.LENGTHUNIT.,$,.METRE.);
#14=IFCSIUNIT(*,.AREAUNIT.,$,.SQUARE_METRE.);
#15=IFCSIUNIT(*,.VOLUMEUNIT.,$,.CUBIC_METRE.);
#16=IFCSIUNIT(*,.PLANEANGLEUNIT.,$,.RADIAN.);
#17=IFCMEASUREWITHUNIT(IFCPLANEANGLEMEASURE(0.017453292519943295),#16);
#18=IFCCONVERSIONBASEDUNIT(#12,.PLANEANGLEUNIT.,’DEGREE’,#17);
#19=IFCUNITASSIGNMENT((#13,#14,#15,#18));
#20=IFCPROJECT(‘0DhEJo6m5Fje79rXznC2BQ’,#5,’’,$,$,$,$,(#11),#19);
#21=IFCCARTESIANPOINT((0.,0.,0.));
#22=IFCDIRECTION((1.,0.,0.));
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#25=IFCLOCALPLACEMENT($,#24);
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#28=IFCDIRECTION((0.,0.,1.));
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#33=IFCRELAGGREGATES(‘2EOU82pnmHxRjgCW5biTEz’,#5,’Site Container’,$,#26,(#32));
#34=IFCRELAGGREGATES(‘2EOUd8pnmHxRjgCW5biTEz’,#5,’Project Container’,$,#20,(#26));
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#36=IFCDIRECTION((0.,0.,1.));
#37=IFCDIRECTION((1.,0.,0.));
#38=IFCAXIS2PLACEMENT3D(#35,#36,#37);
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#42=IFCPOLYLINE((#40,#41));
#43=IFCCOLOURRGB(‘Black’,0.,0.,0.);
#44=IFCCURVESTYLE($,$,$,#43,$);
#45=IFCSTYLEDITEM(#42,(#44),$);
#46=IFCCARTESIANPOINT((-9.00807520738725,2.01785749339552,5.66082963838479));
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9.2.3.2 Last 100 Lines of Code

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#25897=IFCSTYLEDITEM(#25894,(#25896),$);
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#25899=IFCCARTESIANPOINTLIST3D(((4.00469,1.97656,6.01072),(4.05525,1.97747,6.00953),(4.00524,1.92541,6.01089),(4.1058
2,1.97837,6.00833),(4.00578,1.87426,6.01106),(4.15638,1.97928,6.00714),(4.00633,1.82311,6.01124),(4.20694,1.98019,6.00594),(4
.00688,1.77197,6.01141),(4.25751,1.9811,6.00474),(4.00743,1.72082,6.01158),(4.30806,1.98197,6.00355),(4.35865,1.98194,6.00311
),(4.94911,1.65287,6.01789),(4.95016,1.70424,6.01616),(4.40922,1.98188,6.002),(4.45979,1.98182,6.00083),(4.51037,1.98181,6.000
05),(4.56095,1.98182,5.99934),(4.61153,1.9817,5.99901),(4.66212,1.98154,5.99883),(4.7127,1.9812,5.99925),(4.76314,1.97763,5.99
971),(4.95308,1.7555,6.0132),(4.956,1.80677,6.01023),(4.81354,1.97337,6.00012),(4.95892,1.85804,6.00727),(4.86395,1.9691,6.00
053),(4.96184,1.90931,6.00431),(4.91435,1.96484,6.00094),(4.96475,1.96057,6.00135),(4.00816,1.66968,6.01112),(4.00833,1.6185
3,6.01064),(4.94942,1.60144,6.01738),(4.00835,1.56738,6.01017),(4.00837,1.51623,6.0097),(4.94977,1.55001,6.01681),(4.00844,1.4
6508,6.00907),(4.95025,1.49858,6.01603),(4.45546,1.01034,6.00493),(4.95073,1.44715,6.01522),(4.50567,1.00921,6.00504),(4.5
5587,1.00804,6.00514),(4.95118,1.39573,6.01435),(4.95159,1.3443,6.0135),(4.60606,1.00679,6.00525),(4.65627,1.00574,6.00536
),(4.70647,1.00482,6.00547),(4.95177,1.29287,6.01277),(4.95194,1.24144,6.01224),(4.75648,1.00128,6.0078),(4.95281,1.19003,6.013
55),(4.95369,1.13862,6.01488),(4.80644,0.997053,6.01057),(4.8564,0.99283,6.01333),(4.95456,1.08721,6.0162),(4.95544,1.0358
,6.01753),(4.90636,0.988608,6.01609),(4.95632,0.984385,6.01885),(4.00855,1.41394,6.0083),(4.40526,1.01142,6.00482),(4.3550
5,1.01202,6.00472),(4.00872,1.36279,6.00761),(4.00899,1.31165,6.00704),(4.30484,1.01225,6.00461),(4.25465,1.01105,6.00447),(4
.00924,1.2605,6.00644),(4.00836,1.20937,6.00529),(4.20446,1.00981,6.00362),(4.00719,1.15825,6.00402),(4.15426,1.00858,6.00
276),(4.00602,1.10713,6.00274),(4.10407,1.00735,6.00191),(4.00486,1.05601,6.00147),(4.05388,1.00612,6.00105),(4.00369,1.0048
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9,6.00019),(4.00536,1.97546,5.91081),(4.05592,1.97637,5.90962),(4.00591,1.92431,5.91098),(4.10649,1.97727,5.90842),(4.00645
,1.87316,5.91115),(4.15705,1.97818,5.90723),(4.007,1.82201,5.91133),(4.20761,1.97909,5.90603),(4.00754,1.77087,5.9115),(4.25818,1
.98,5.90483),(4.0081,1.71972,5.91167),(4.30873,1.98087,5.90364),(4.35932,1.98084,5.9032),(4.94978,1.65177,5.91798),(4.95083,1
.70314,5.91625),(4.40989,1.98078,5.90209),(4.46046,1.98072,5.90092),(4.51104,1.98071,5.90014),(4.56161,1.98072,5.89943),(4.6
122,1.9806,5.8991),(4.66279,1.98044,5.89892),(4.71337,1.9801,5.89934),(4.76381,1.97653,5.8998),(4.95375,1.7544,5.91329),(4.95
667,1.80567,5.91032),(4.81421,1.97227,5.90021),(4.95959,1.85694,5.90736),(4.86461,1.968,5.90062),(4.96251,1.90821,5.9044),(4
.91502,1.96374,5.90103),(4.96542,1.95947,5.90144),(4.00883,1.66858,5.91121),(4.009,1.61743,5.91073),(4.95009,1.60034,5.91747
),(4.00902,1.56628,5.91026),(4.00904,1.51513,5.90979),(4.95044,1.54891,5.9169),(4.00911,1.46398,5.90916),(4.95092,1.49748,5
.91612),(4.45613,1.00924,5.90502),(4.9514,1.44605,5.91531),(4.50634,1.00811,5.90513),(4.55654,1.00694,5.90523),(4.95185,1.39
463,5.91444),(4.95226,1.3432,5.91359),(4.60673,1.00569,5.90534),(4.65694,1.00464,5.90545),(4.70714,1.00372,5.90556),(4.952
44,1.29177,5.91286),(4.95261,1.24034,5.91233),(4.75715,1.00018,5.90789),(4.95347,1.18893,5.91364),(4.95436,1.13752,5.91497),(4
.80711,0.995956,5.91066),(4.85707,0.991733,5.91342),(4.95522,1.08611,5.91629),(4.95611,1.0347,5.91762),(4.90703,0.987511,5.91
618),(4.95698,0.983288,5.91894),(4.00922,1.41284,5.90839),(4.40593,1.01032,5.90491),(4.35572,1.01092,5.90481),(4.00939,1.36
169,5.9077),(4.00965,1.31055,5.90713),(4.30551,1.01115,5.9047),(4.25532,1.00995,5.90456),(4.00991,1.2594,5.90653),(4.00903,1
.20827,5.90538),(4.20513,1.00871,5.90371),(4.00786,1.15715,5.90411),(4.15493,1.00748,5.90285),(4.00669,1.10603,5.90283),(4.104
74,1.00625,5.902),(4.00553,1.05491,5.90156),(4.05455,1.00502,5.90114),(4.00435,1.00379,5.90028)));
#25900=IFCTRIANGULATEDFACESET(#25899,$,.F.,((1,2,3),(77,78,79),(2,4,3),(78,80,79),(4,5,3),(80,81,79),(4,6,5),(80,82,81),(6,7,5
),(82,83,81),(6,8,7),(82,84,83),(8,9,7),(84,85,83),(8,10,9),(84,86,85),(10,11,9),(86,87,85),(10,12,11),(86,88,87),(12,13,11),(88,89,87),(1
3,14,11),(89,90,87),(13,15,14),(89,91,90),(13,16,15),(89,92,91),(16,17,15),(92,93,91),(17,18,15),(93,94,91),(18,19,15),(94,95,91),(19,20,15
),(95,96,91),(20,21,15),(96,97,91),(21,22,15),(97,98,91),(22,23,15),(98,99,91),(23,24,15),(99,100,91),(23,25,24),(99,101,100),(23,26,2
5),(99,102,101),(26,27,25),(102,103,101),(26,28,27),(102,104,103),(28,29,27),(104,105,103),(28,30,29),(104,106,105),(30,31,29),(106,1
07,105),(14,32,11),(90,108,87),(14,33,32),(90,109,108),(14,34,33),(90,110,109),(34,35,33),(110,111,109),(34,36,35),(110,112,111),(34,37
,36),(110,113,112),(37,38,36),(113,114,112),(37,39,38),(113,115,114),(39,40,38),(115,116,114),(39,41,40),(115,117,116),(41,42,40),(117,118,11
6),(41,43,42),(117,119,118),(41,44,43),(117,120,119),(44,45,43),(120,121,119),(45,46,43),(121,122,119),(45,47,46),(121,123,122),(45,48,47
),(121,124,123),(45,49,48),(121,125,124),(49,50,48),(125,126,124),(50,51,48),(126,127,124),(50,52,51),(126,128,127),(52,53,51),(128,129
,127),(53,54,51),(129,130,127),(53,55,54),(129,131,130),(53,56,55),(129,132,131),(56,57,55),(132,133,131),(57,58,55),(133,134,131),(57,5
9,58),(133,135,134),(40,60,38),(116,136,114),(40,61,60),(116,137,136),(61,62,60),(137,138,136),(62,63,60),(138,139,136),(62,64,63),(13
8,140,139),(62,65,64),(138,141,140),(65,66,64),(141,142,140),(66,67,64),(142,143,140),(66,68,67),(142,144,143),(66,69,68),(142,145,1
44),(69,70,68),(145,146,144),(69,71,70),(145,147,146),(71,72,70),(147,148,146),(71,73,72),(147,149,148),(73,74,72),(149,150,148),(73,75
,74),(149,151,150),(75,76,74),(151,152,150),(1,2,77),(77,2,78),(3,1,79),(79,1,77),(2,4,78),(78,4,80),(5,3,81),(81,3,79),(4,6,80),(80,6,82),(7
,5,83),(83,5,81),(6,8,82),(82,8,84),(9,7,85),(85,7,83),(8,10,84),(84,10,86),(11,9,87),(87,9,85),(10,12,86),(86,12,88),(12,13,88),(88,13,89
),(15,14,91),(91,14,90),(13,16,89),(89,16,92),(16,17,92),(92,17,93),(17,18,93),(93,18,94),(18,19,94),(94,19,95),(19,20,95),(95,20,96),(20
,21,96),(96,21,97),(21,22,97),(97,22,98),(22,23,98),(98,23,99),(24,15,100),(100,15,91),(25,24,101),(101,24,100),(23,26,99),(99,26,102
),(27,25,103),(103,25,101),(26,28,102),(102,28,104),(29,27,105),(105,27,103),(28,30,104),(104,30,106),(30,31,106),(106,31,107),(31,29,1
07),(107,29,105),(32,11,108),(108,11,87),(33,32,109),(109,32,108),(14,34,90),(90,34,110),(35,33,111),(111,33,109),(36,35,112),(112,35,111
),(34,37,110),(110,37,113),(38,36,114),(114,36,112),(37,39,113),(113,39,115),(39,41,115),(115,41,117),(42,40,118),(118,40,116),(43,42,119),(1
19,42,118),(41,44,117),(117,44,120),(44,45,120),(120,45,121),(46,43,122),(122,43,119),(47,46,123),(123,46,122),(48,47,124),(124,47,123
),(45,49,121),(121,49,125),(49,50,125),(125,50,126),(51,48,127),(127,48,124),(50,52,126),(126,52,128),(52,53,128),(128,53,129),(54,51,1
```

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30),(130,51,127),(55,54,131),(131,54,130),(53,56,129),(129,56,132),(56,57,132),(132,57,133),(58,55,134),(134,55,131),(57,59,133),(133,5
9,135),(59,58,135),(135,58,134),(60,38,136),(136,38,114),(40,61,116),(116,61,137),(61,62,137),(137,62,138),(63,60,139),(139,60,136),(64
,63,140),(140,63,139),(62,65,138),(138,65,141),(65,66,141),(141,66,142),(67,64,143),(143,64,140),(68,67,144),(144,67,143),(66,69,142
),(142,69,145),(70,68,146),(146,68,144),(69,71,145),(145,71,147),(72,70,148),(148,70,146),(71,73,147),(147,73,149),(74,72,150),(150,72,1
48),(73,75,149),(149,75,151),(75,76,151),(151,76,152),(76,74,152),(152,74,150)),$);
#25901=IFCCOLOURRGB(‘Green’,0.878431379795074,0.780392169952393,0.537254929542542);
#25902=IFCSURFACESTYLESHADING(#25901,$);
#25903=IFCSURFACESTYLE($,.BOTH.,(#25902));
#25904=IFCSTYLEDITEM(#25900,(#25903),$);
#25905=IFCSHAPEREPRESENTATION(#11,‘Body’,‘Tessellation’,(#25900));
#25906=IFCPRODUCTDEFINITIONSHAPE($,$,(#25898,#25905));
#25907=IFCMATERIAL(‘Concrete’,$,$);
#25908=IFCWALL(‘2FyncwpnmHxRjgCW5biTEz’,#5,‘wall’,‘an-awesome-wall’,$,#25551,#25906,$,$);
#25909=IFCRELASSOCIATESMATERIAL(‘2FynqgpnmHxRjgCW5biTEz’,#5,$,$,(#25908),#25907);
#25910=IFCRELCONTAINEDINSPATIALSTRUCTURE(‘2FynzGpnmHxRjgCW5biTEz’,#5,$,$,(#198,#363,#532,#701,#870,#1039,#
1204,#1367,#1514,#2150,#4273,#4610,#4774,#4938,#5131,#5320,#5954,#7440,#7776,#7968,#8160,#8353,#8545,#8738,#8930
,#9095,#9258,#9426,#9593,#9760,#10315,#10380,#10541,#10686,#10877,#11045,#11212,#11359,#11469,#11757,#11822,#12013,#
12683,#12829,#13021,#13357,#13422,#13583,#13728,#13793,#13954,#14099,#14470,#15067,#15538,#15707,#15876,#16045,#162
13,#16380,#16547,#17101,#17799,#17862,#18022,#18167,#18232,#18393,#18538,#19331,#19445,#19726,#20006,#20764,#20990
,#21184,#21568,#21755,#21945,#22114,#22300,#22487,#22656,#22843,#23012,#23181,#23370,#23539,#23729,#23918,#24087
,#24396,#24941,#25244,#25545,#25908),#32);
ENDSEC;
END-ISO-10303-21;
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