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THE ROLE OF COMPUTATIONAL DESIGN IN BIM

VLOGA RAČUNSKO PODPRTEGA NAČRTOVANJA BIM



European Master in
Building Information Modelling

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ERRATA

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BIBLIOGRAFSKO – DOKUMENTACIJSKA STRAN IN IZVLEČEK**UDK: 004.2:69.01(4)(043.3)****Avtor: Greta Rossi****Mentor: doc. dr. Matevž Dolenc****Naslov: Vloga računsko podprtega načrtovanja BIM****Tip dokumenta: Magistrsko delo****Obseg in oprema: 93 str., 77 sl., 6 pregl.****Ključne besede: BIM, računsko podprto načrtovanje, Dynamo, Revit, industrija prefabriciranih elementov, upravljanje podatkov, izvedbeni procesi, BIM objekt****Izveček:**

Glavni cilj naloge je oceniti vlogo računsko podprtega načrtovanja BIM. Z vse širšo uporabo načrtovanja BIM ter s ciljem učinkovitega prilagajanja na nove in pogosto spreminjajoče se zahteve pri načrtovanju oz. izvedbi gradbenih projektov so se razvila nova programska orodja za upravljanje s podatki, kot je na primer Dynamo. S ciljem predstaviti vlogo in primernost uporabe takšnih sodobnih programskih orodij v BIM procesih je v nalogi je predstavljena študija uporabe računsko podprtega načrtovanja.

V prvem delu naloge so predstavljene teoretične osnove računsko podprtega načrtovanja BIM, katerega uporaba je v drugem delu prikazana na primeru uporabe v fazi gradnje. Tretji del naloge prikazuje uporabo računsko podprtega načrtovanja v industriji prefabriciranih elementov s posebnim poudarkom na različnih metodah, ki lahko izboljšajo prenos podatkov in s tem poenostavijo delotoke od naročila do končnega izdelka. V zadnjem delu naloge je predstavljen praktičen primer uporabe računsko podprtega načrtovanja, ki prikazuje uporabnost razvitih komponent v okolju Dynamo.

Nova programska orodja, ki omogočajo računsko podprto načrtovanje, kot je npr. Dynamo, odpirajo nove možnosti dela z geometrijskimi in ne-geometrijskimi informacijami digitalnega modela BIM. V nalogi je poudarek predvsem na upravljanju in delu z ne-geometrijskimi informacijami.

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BIBLIOGRAPHIC– DOCUMENTALISTIC INFORMATION AND ABSTRACT**UDC: 004.2:69.01(4)(043.3)****Author: Greta Rossi****Supervisor: Assist. Prof. Matevž Dolenc, PhD.****Title: The role of Computational Design in BIM****Document type: Master thesis****Scope and tools: : 93 p., 77 fig., 6 tab.****Keywords: BIM, Computational Design, Dynamo, Revit, Prefabrication Industry, data management, implementation processes, BIM objects****Abstract:**

The thesis addresses the role of computational design in BIM. The large use of BIM and the desire to respond more effectively to the construction requirements have diffuse new data management tools, such as Dynamo. In order to evaluate the role of such data management tools in modern BIM workflows the thesis study different applications of computational design.

The thesis is organised in sections. The first section provides a theoretical overview of computational design and the second section illustrates its applications during the construction process phase. The third part focuses on the prefabrication industry and how new technologies can be beneficial to improve companies workflows. The final section illustrates a case study for the application of computational strategies to highlight the usefulness of a library of scripts, which have been developed to automatise repetitive procedures during construction processes.

The application of visual programming into BIM tools gives new possibilities to create, manage and check geometrical and non-geometrical information in the digital model. The application phase of the thesis is focused on the management of non-geometrical information.

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1 INTRODUCTION

This research has intended to study applications of Computational Design to improve specific BIM workflows. The emergence of Building Information Modelling (BIM) and its latest development to become a dominant method for construction process during the lifecycle of a building has consequences on how to manage the information. With BIM, all data has a direct or indirect relationship to each other, creating a database which represents a digital copy of a project. Regardless, the design process and the insertion of information with BIM tools are still broadly hand-operated. The desire to respond to the clients effectively and to optimise the design and construction workflows have generated new data management tools. Therefore, several graphical programming tools for design have arisen.

This research has investigated the graphical programming tool Dynamo for Autodesk Revit. Dynamo is used to automate some steps and has the potential to be widely adopted by users without textual programming skills. Dynamo has proven to be a suitable tool to approach BIM design workflow, reducing labour time, increasing quality assurance, and supporting the interoperability of software. Especially inside structured Companies, where BIM is already implemented in the day-to-day workflow, the use of Dynamo exhibits its effectiveness to automate repetitive tasks. Companies are always looking for possibilities to simplify, optimise and improve their processes. They want to reduce, especially labour-intensive tasks. The application of visual programming into BIM tools like Revit gives new possibilities to create, manage and check geometrical and no-geometrical information in the digital model.

The research is structured in these phases:

- a general study about computational design meaning, Dynamo tool and its advantages and limitations.
- examination of Computational Design application in the construction phases, investigating the literature.
- focus on the production prefabrication industry and how new technologies development can be beneficial to companies.
- examination of the case study and application of computational design strategies in order to improve data management.

The case study has been provided by TRIMO company, a Slovenian production company for envelope components. The thesis has focused on the prefabrication industry and how new technologies development can be beneficial to companies.

An overview of norms and standards necessary to regulate the digital flow of information has been given. It also has examined new technologies in the manufacturing industry, focusing on the production

of prefabricated elements, which have been improved thanks to computational design strategies within BIM tools and workflows.

The thesis has analysed the design phase, giving a process implementation based on BIM and computational design to manage the large amount of information that the engineer's team should provide to the production team during a standard process. The company's processes have been established for many years, and the BIM transition is still not considered. A drastic shift to BIM is even perceived as unnecessary. The results of the research shall reveal the potential of Dynamo demonstrating the utility of a scripts library that can automatise repetitive and manual procedure and improve workflow. The BIM model had been created with Autodesk Revit and had been enriched of information with Dynamo scripts.

2 COMPUTATIONAL DESIGN: THE CORE CONCEPTS

2.1 What is Computational Design?

What is design?

Cerebral and physical are the two components of the design process. The research led by Paul Jeffries (2016) looks at this split within the design process and explains it interestingly. The mental work goes into a design, generating ideas, understanding specifications, thinking and discussion obstacles and deciding on the fundamental principles that go into the formation of “the design”. However, it cannot be just an ephemeral idea. Designers also want to experiment with ideas and transfer them to clients and colleagues. For doing this, calculation, write documents, product documents and models are performed. During the design, there is a continuous interaction between the mental and the physical sides. The process is continuously examined, evaluate, tested and refined, in order to find the final and best solution.

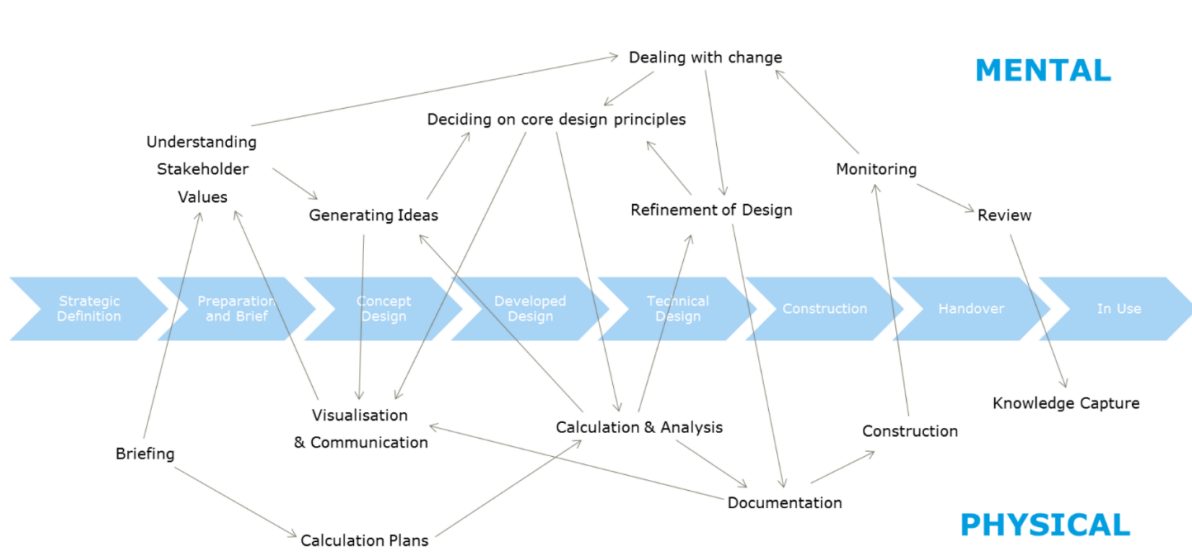


Figure 1 - Diagram of the activities involved in the design process (Jeffries, 2016)

Recently, the computer has been adopted as a production method. Drawings and engineering calculation are performed using the software like CAD (Computer-aided-Design) or software for analysis and calculations. The innovations introduced with the technologies, generally, allow the transition from the term “physical” to “virtual”, in the first aspect of the design process. These changes have made it possible to make the design process more efficient, but they have not changed the process itself. It describes the first transition into the virtual world, but in this first approach to technology, the computer has merely replaced paper, and computing power has been ignored. The computer can play an essential role in the mental aspect if designers describe the relationships that drive the design in a form that is understandable to computers, for example, the algorithms.

It can become not only a data container but also a data generator that generates the design representation from the rules set by the designer. This switch is what distinguishes Computational Design from the traditional use of a computer.

Computation is a term always confused with computerisation. The computation is the process of calculating using math or logic. Enter, process or store data information in the computer are computerisation procedures. The computational approach allows to realised data from an initial abstraction and to express these data in the form of codes, containing values and action. The data in a computational field are processing algorithmically. An algorithm is a set of procedures consisting of a finite number of rules, which define a solution for a given problem. The programming languages allow executing the algorithms through a computing procedure.

In terms of design, computation is the processing of information and interactions between elements, that are part of the specific designing environment. The design generates results that are realized by processing the internal and external features of the project. The result is an object with variable parameters and constraints that are set during the processing phase. The Computational design allows us to explore the many variations that are possible within specific design concepts. Now the computer and software are more available, and the opportunities have exploded. The enormous possibilities contribute to making the formulation of architecture a deeper interaction of material parts, social engagement, shaping form, space and structure.

2.2 Algorithms and Parametrization

Computational design is based on algorithms.

What is an algorithm?

“An algorithm is a finite sequence of explicit, elementary instructions described in an exact, complete yet general manner.”(Menges & Ahlquist, 2011, p. 11)

Algorithms can solve computational problems like generating and manipulating entities, such as geometric forms, design variables, lists of numeric or alphabetical data, mathematical expressions and logic operations. This method allows the designers to control the design and boundary conditions, to enhance their capabilities and to create more suitable solutions. Nevertheless, the quality of the final result depends on the designer’s coding, interpretation and manipulation skills. Even using powerful computers of today, a defective algorithm will produce inadequate or erroneous results. A well-defined algorithm, with the support of multicore computers, will solve the problem faster, more efficiently and produce the correct answer.

Parametric design is a subcategory of algorithmic design and is based on algorithmic principles. Different than the algorithmic design, the parametric system is based on the parameters manipulation principles: the creation of editable parameters in order to offer multiple numbers of possibilities in the design phase, this manipulation allow the achievement of the optimal design solution.

The research conducts by Aish et al. (2005) claims that the principles of the parametric approach allow the designers to investigate infinite possibilities for the design: it enables to investigate the options and improve the design during the entire process. This approach is considered a wider tool for the exploration in architecture. The Aviva Stadium in Dublin (Shepherd, 2011), Ireland is a football stadium designed by Populous architectural firm and engineered by Huro Happold Company. They have used the parametric approach to support the design phase. During the design process, the architects have dealt with the shape and the cladding system, and the engineers drove the structural part. The competition rules have required specific architectural shape and dimension. A single parametric model has been shared between the architectural and engineering offices, which allowed the optimised design of form, structure and facade.

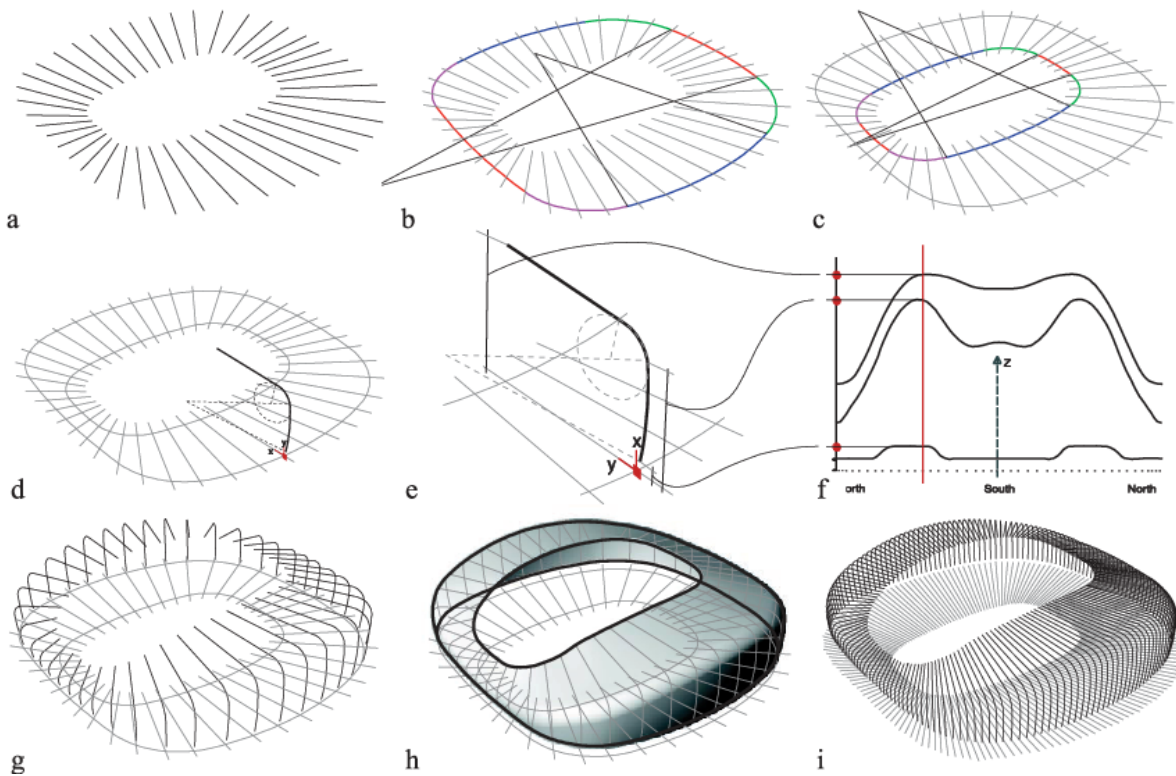


Figure 2 - Computation process for the designing of the Aviva Stadium



Figure 3 - The Aviva Stadium in Dublin

The parametric model developed by the architects was the starting point of the structural model. In a first design meeting, the building envelope was separated at the point where the structure meets the cladding system. It was decided that the architects would be responsible for defining all elements outside this point, including the panels and structural support for the façade. In contrast, the structural team would be responsible for defining the structural support elements within this dividing line. Therefore, the architects developed the model to determine the doubly-curved skin, and the engineers develop the structural model to define the facade and roof structure. The parametric model has been supported by analysis tools and enabling quick analytical feedback to the geometry. The sharing of the parametric model across the other design members and the full integration of the engineering analysis applications could realize the benefits of a parametric approach, in terms of allowing changes to spread through the teams. The parametric software was extended where necessary to integrate with structural analysis and to automate fabrication. At the time of the design (2010), parametric modelling was not spread, and access was restricted to a group of experts. Both the architectural and engineering teams assigned the task of parametric modelling to individual specialists, which meant that the entire design had to go through these people before it appeared in more conventional forms such as 3D CAD or Finite Element Analysis models.

2.3 Generative Design

Generative design is an approach that is distinct from other design methods.

“A generative system is a set-up based on abstract definitions of possible design variations capable of displaying or producing design products (or elements of design products). There is, in principle, no reason to restrict this approach to the application of digital tools.” (Fischer, 2001, p. 3)

The generative design approach is articulated in four steps: the identification of start conditions and parameters (inputs), the definition of the generative mechanism (rules, algorithms), the multiple options generation (outputs), and the choice of the best solution. The final result emerges just after the last step.

The research led by Gursel et al. (2012) claims that generative design can be categorised into two classes: linguistic and biological. A linguistic generative system is based on the shape grammar approach, that defines rules to apply to a starter object (shape) in order to modify it and generate a sophisticated design. The rules are generally applied recursively and they combine shape and spatial rules at the same time. The concept of shape grammar was introduced some decades ago and was applied in particular for analysing the structure of well-known architecture. The studies have demonstrated that complex geometries could be generated by a set of rules, starting from a simple geometric shape. The shape grammar has proved to be very helpful for the understanding of cultural heritage and consequently, its preservation. Biological generative design examines the nature and its organism and applies their rules in order to transform architectural form.

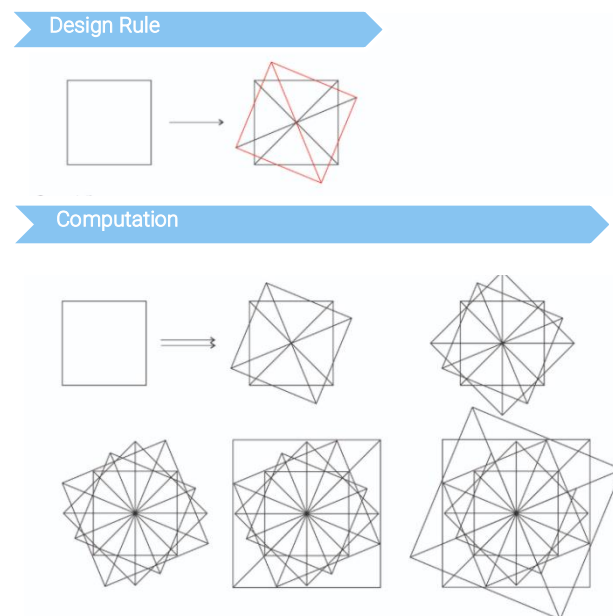


Figure 4 - Example of generative design

2.4 Textual Programming

Nowadays, the use of digital tools is increasing, and it is becoming prevalent hear about algorithmic, parametric and generative design. These approaches have not become famous with the computer advent, but were known from before: many old architectures demonstrate the application of their principles. The advent of the computer allows easier access to these principles. As mentioned before the generative design is an approach using a set of rules to generate a final result. Therefore, the mental process is translated into a formal language readable by a computer. The formal language is called Programming Language (PL). It consists of a set of instructions, algorithmically expressed, that produces output. Most programming languages consist of computers instructions. Interesting research led by Leitao et al. (2018) discussed the generative design and the use of programming language. We can identify two different programming language: textual (TPL) and visual (VPL). The researchers outline the advantages and disadvantages of both of them. In a textual programming language (TPL), a string of numbers and letters are applied to developed instructions. Python is one of the most usually used programming languages today and is a natural language for beginners to learn.

A VPL consists of items to manage, representing the inputs and the outputs. The significant difference between a VPL and a TPL is in the dimensional: TPLs are one-dimensional while VPLs are, at least, bi-dimensional. Although the considerable number of researches analysing VPLs and TPLs, there is no conclusive evidence of their relative benefits. In general, VPLs are more convenient for beginners to learn so that they can become productive more quickly. On the other hand, TPLs are considerably more productive to address complicated problems. The obstacle for designers is the abstract way to write the textual code and to know and understand the specific syntax of the language. Therefore the designers have to familiarise with a completely new field of knowledge.

2.5 Analysis and Optimization

The optimisation is considered a technique of Generative Design. Generative Design Primer (“Generative Design Primer”) presents to the argument. It is essentially a mathematical problem that involves creating design options that are oriented towards the results during their creation. It is about maximising or minimising a mathematical function to achieve the best possible solution for a problem. Optimisation problems occur in all possible areas, from aerospace engineering to architectural design, but regardless of the domain, every optimisation problem has three characteristics: an objective function, constraints, data.

An objective function has outputs that are wanted to maximise or minimise. The final result is what is consider the best solution: it can be imagined as the goal of a generative design. In generative design workflow, it is possible have multiple goals, that have to work together in order to optimise the entire

design. Therefore, The optimisation is more about finding the best compromise between these objectives, rather than finding the best solution. For example, a problem could be having to design a façade shaded by vertical brise-soleil. The aim is finding the best solution in terms of costs and energy saving. Therefore, the designers want to obtain the maximum number of shading panels, that protect the glass window from irradiation, respecting requirement budget.

A constraint is a requirement that a solution to an optimisation problem must meet. In the example of shading façade, the constraint may be the dimension of the façade. Constraints provide a model with its realism; they guarantee a realistic solution or values that the user knows are decisive to the design brief. If a model is unconstrained, it is expected to return absurd and unrealistic results that are not of any practical use. Constraints are necessary as they guarantee that a generative design algorithm outputs something realistic and reasonable.

Data is the fundamental essence to feed into an optimisation model, the inputs and outputs that the objective function and constraints act upon. In the design example mentioned, data could be the density or price of construction materials. The optimisation model takes all this data and works to maximise or minimise values as specified.

The optimisation allows to analyse and compare the design solutions and choose the best one. It bridges the gap between architectural work and engineering work, and the new conceptual design becomes a part of the digital building model. With an iterative workflow by using algorithms, the significant decisions are made very early, based on the given constraints and inputs. The effort to make decisions at an early phase of design can save much money.

3 FUNDAMENTALS OF VISUAL PROGRAMMING LANGUAGES: DYNAMO

3.1 Visual Programming principles

Frequently, designing requests to define relations between the parts of a project. These relationships follow a workflow carrying on from an idea to a result by a set of rules. The algorithms defines the actions consisting in input, processing and output. Programming is based on this workflow and permits us to formalise the algorithms.

Dynamo Primer (“<https://primer.dynamobim.org/>”), in which are collecting much information about the use of Dynamo and the Computational Design in general, provides an exciting way to explain an algorithm: through an origami crane. The process starts with a paper (input) and following a series of steps (processing actions) it gives the result: a crane (output). The algorithm can be defined as the abstract set of steps, representable in a couple of ways: textually or graphically.

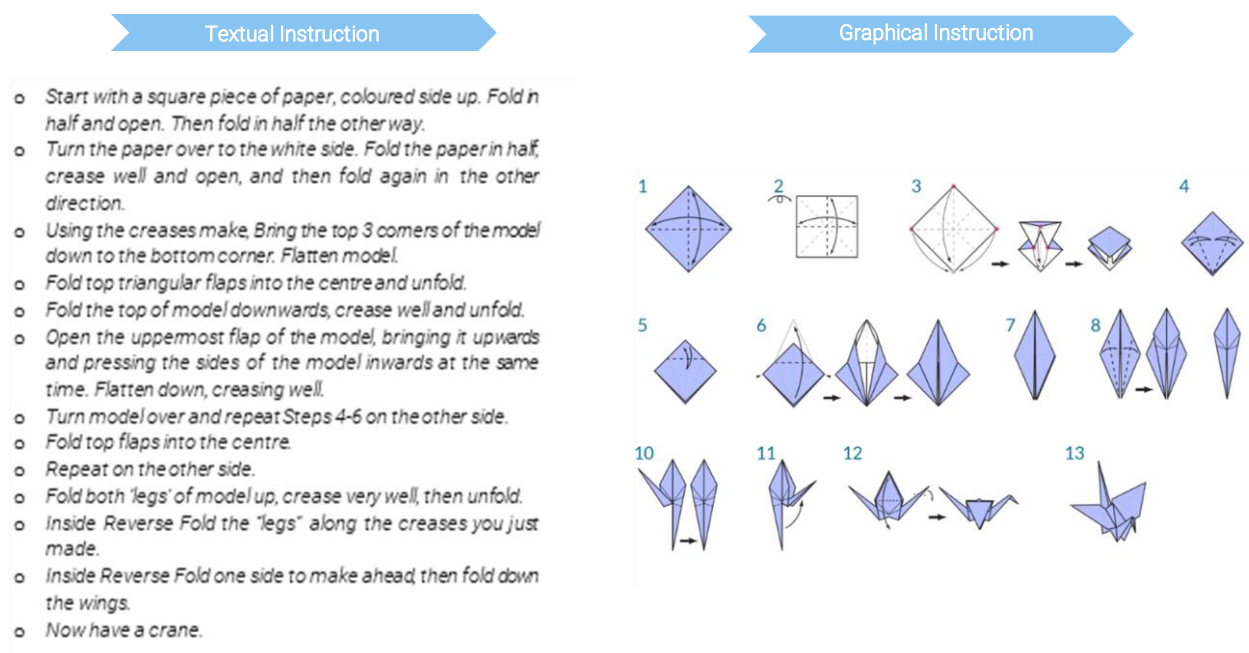


Figure 5 – Graphical and textual Instruction (“<https://primer.dynamobim.org/>,” n.d.)

The Process of the Visual Programming is essentially the same as Textual Programming. The difference is in the use of a visual interface that allows a more manageable approach, easily attainable also for the beginners.

Visual programming is a language that does not need assembling code or experience with a textual programming language (like C# or Python). It uses a visual method: users can connect nodes of pre-defined functionality that constitute scripts to achieve complex goals. This approach is more natural to learn and makes tasks accessible to everyone. These tools are becoming commonplace in many organisations, especially as they move away from traditional CAD (Computer-Aided Design) tools accelerates.

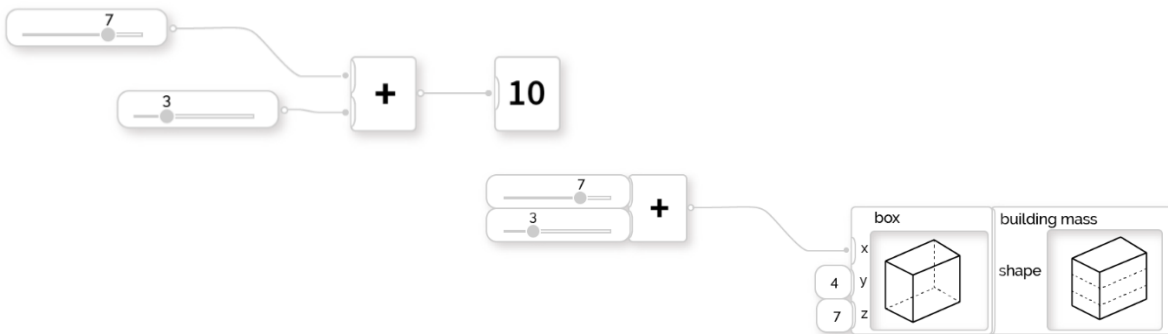


Figure 6 - The nodes of a VPL([“https://primer.dynamobim.org/”](https://primer.dynamobim.org/))

Dynamo and Grasshopper are two examples of a visual programming language. In this section, I will go deep in Dynamo tools because it is more recommended for BIM workflows. Indeed, Dynamo is a tools running on Revit.

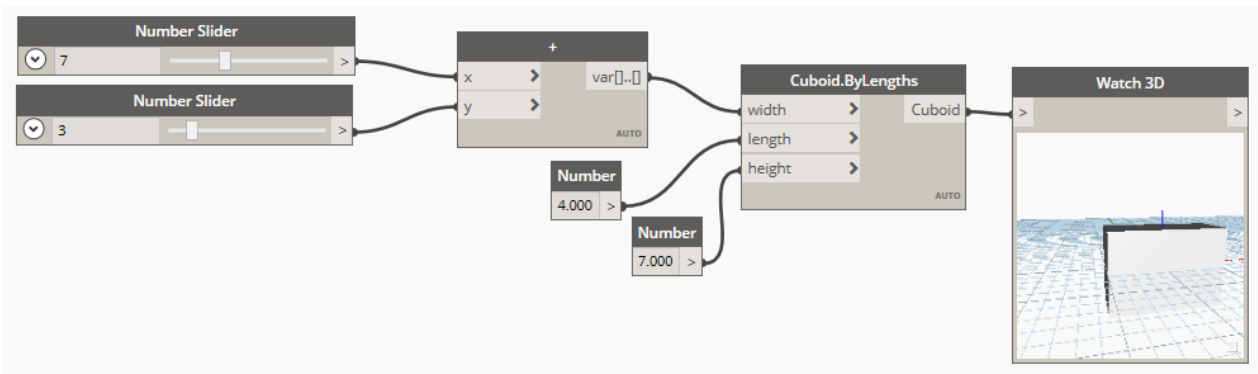


Figure 7 - Script in Dynamo

3.2 The interaction between Visual programming and BIM

BIM (Building Information Modelling) has grown in the AEC industry. The emergence BIM and its recent development to become a mainstream method for the design and analysis of the life cycle construction context has consequences on how to handle the increasing amount of information. With BIM, all data has a direct or indirect relationship to each other, creating a database which represents a digital copy of a project. This database can be visually represented as a digital model, and it has also intelligence and properties embedded in its objects. The high expectations by clients, the complexity of given sites and conditions, and the pressure to optimise the design workflow have resulted in new data management and data manipulation tools. Scripting can be used to create a more intelligent and flexible building information model. In this situation several graphical programming tools for design have emerged to reduce the work, and nearly every BIM authoring tools have today its counterpart for graphical programming. Dynamo is one of those tools and it has been used not just in the early conceptual phase. It is actually used in a considerable portion of the project. The scripts can help automate work in the office to increase efficiency and accuracy, assist in shape generation, analyse BIM files, access Building Data, explore multiple design option.

In addition to time-saving features, Dynamo provides analysis results (e.g. daylighting, thermal comfort, window optimisation). The designer who knows how to use Dynamo is not forced to learn the new software developed every year. His/her only problem is learning how to use Dynamo for his analyses by creating a script and obtaining the results that allow the optimal choice. This allows also to overcome interoperability problems that usually occur with data models exchange.

Generally, the possibilities introduced with the script are many: helps to reduce the struggle in the early design phase, overcome conceptual design and modelling challenges, enhances designers and BIM capabilities.

3.3 Dynamo overview and its possibilities

Dynamo is a graphical programming tools. Above all else, it is a platform, allows designers to explore visual programming, solve problems, and make their tools. Dynamo allows to utilise a visual programming process: connections are established between elements, called nodes, using algorithms which describe the action involved. It is possible to use algorithms for an extended range of applications, from data processing to geometry generation, without writing code. Each node executes code to perform tasks. Nodes have inputs and outputs and are connected by wires. The result is a graphical representation of the actions needed to realise the desired result.

One of the forces of visual programming is the immediate access to nodes contained in the library. Instead of having to remember the exact code for a particular task, Dynamo makes it easy to find the required node in the library. It will be mentioned four ways from which get the benefit for the using of Dynamo:

- Complex geometrical object creation
- Automate repetitive tasks
- Access to building data
- Explore multiple design options
- Test performance

3.3.1 Complex geometrical object creation

The use of Dynamo and mathematical algorithms allow reaching a complex object in architecture. Just think about the complex architecture of the architect Frank Gehry. The figures below show the Walt Disney Concert Hall of Los Angeles in California and the Guggenheim Museum of Bilbao in Spain. Could be impossible to manage this kind of geometry just with the use of AutoCAD.



Figure 8 - Walt Disney Concert Hall of Los Angeles in California, Gehry Architect



Figure 9 - Guggenheim Museum of Bilbao in Spain, Gehry Architect

The Guggenheim Museum Bilbao has been recognised as a pinnacle of technological progress since its October 1997 opening. The use of the modelling software CATIA (Computer-Aided Three-Dimensional Interactive Application) was pioneering. The building, elaborated between 1991 and 1997, was conceived at the turning point between analogue and digital practice. Nowadays, this kind of geometry can be managed more efficiently, thanks to the support of technologies in the designing process.

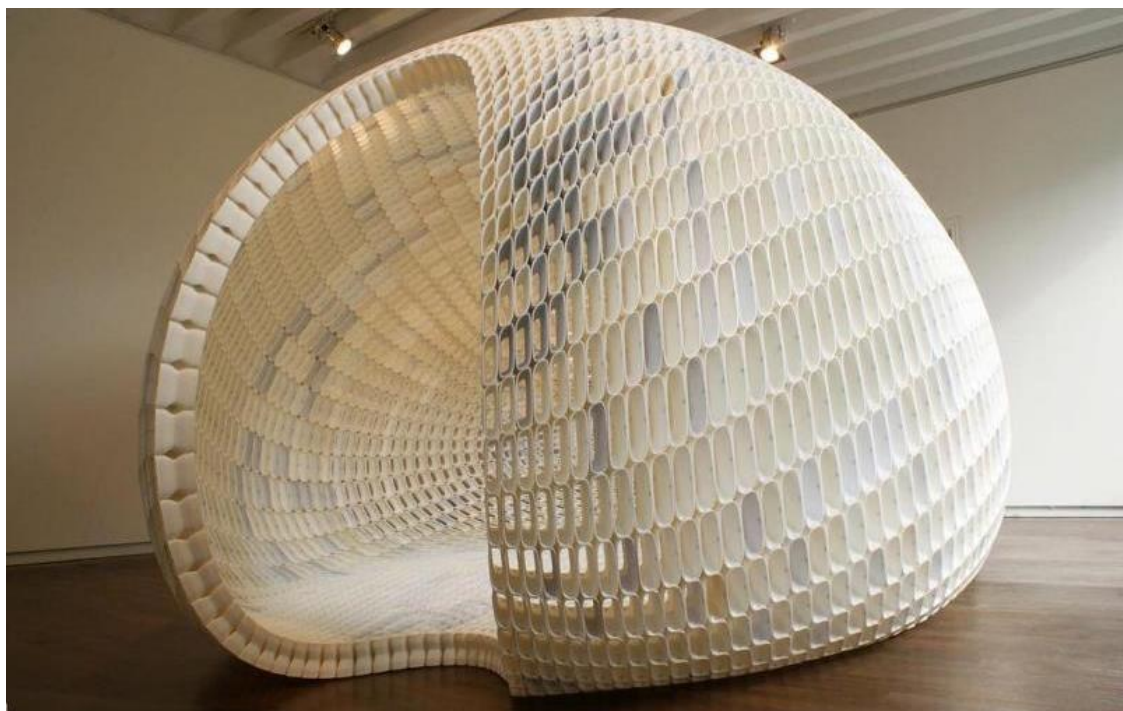


Figure 10 - Pavilion Made of 3D Printed Pieces by the designer Michiel Van Der Kley (2014)

3.3.2 Automate tasks

There is a lot of tasks very repetitive in Revit: an example could be creating sheets. Create one sheet is not so tricky, the annoying problem is when it has to be created 50 or 100 sheets. Using a Dynamo node it is possible to automatise the tasks. Once the scripts are created, they are available from Revit executing Dynamo Player. Other tasks could be the creation of plans, creation of floors, roof and walls from points and lines, creation of MEP elements from lines, levels creation for a skyscraper, numeration of sheets.

3.3.3 Access to Data

A Revit model can be considered a database of information, but getting that data is not as easy as it should be. It is possible to create schedules from Revit of course, but sometimes it is expected to add or calculate values. Dynamo provides with an easier procedure. Dynamo enables to import and export information from and to Excel. Through information importing from Excel, new parameters can populate the objects of the database model automatically, avoiding human errors generated from a manual insertion.

3.3.4 Explore multiple design possibilities

Dynamo, it is also a reliable design tool. With Dynamo, design becomes a process as we explicitly define the generative design rules and with the help of some specific tools, like Refinery, Optimo, it assists the designers to analyse, compare and lastly choose the best designing solutions.

3.3.5 Test Performance

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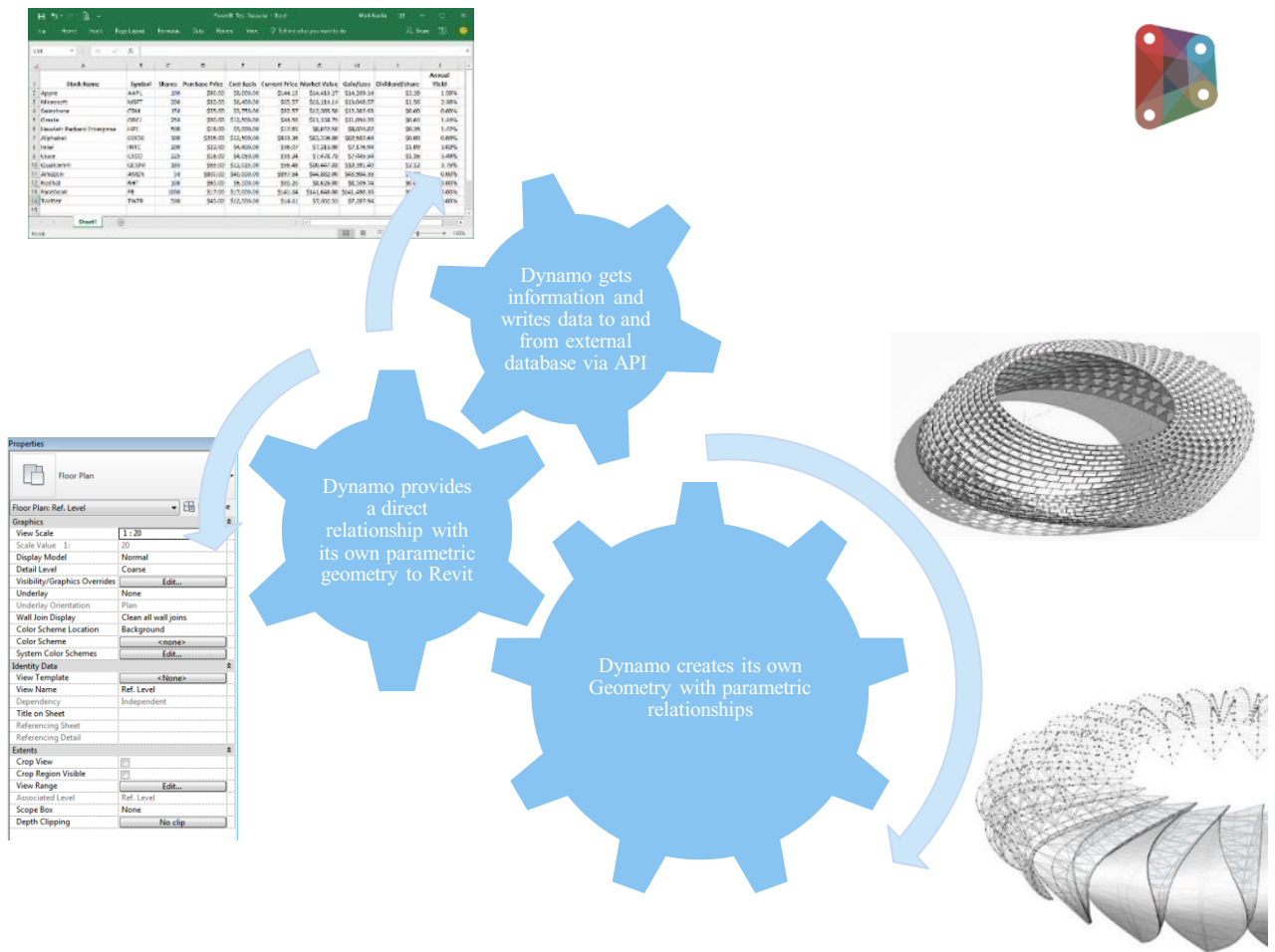


Figure 11 - Example of a Dynamo workflow

3.4 How do the designers' work change?

The research led by Davis et al. (2013), addresses the theme of how the role of the architects is changing. Architects are expert coordinators because they know how to bring together the many constraints and parameters that define the boundaries of a project. The coordination of a construction process and creation of the design environment itself has become the designer's domain. Besides, the design environment is continually changing: during the various phases of the project, and often radical changes occur of the initial project. Therefore, it requires dynamic minds to coordinate the project.

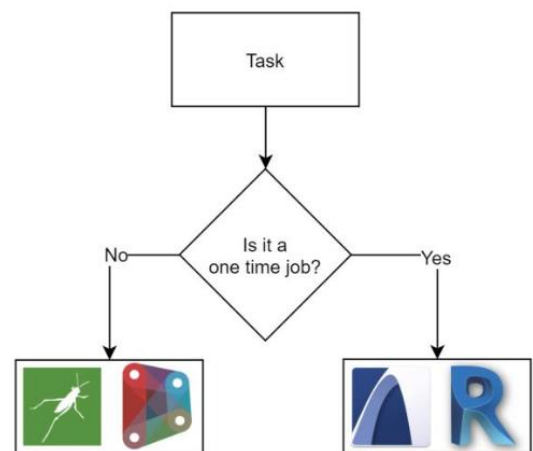


Figure 12 - Use of BIM tools

The advent of BIM and consequently, the application of computational design in the AEC industry have

allowed the generation of dynamic projects. This evolution has provoked a new role for the designers. In order for the environment to adapt quickly, the designer must ensure that the relationships between components are flexible enough to accommodate unexpected changes. If the designer does not do this, there is no other solution than to disassemble the model and restart it completely. If such a problem occurs, it will at best, cause an unexpected delay in the project. To overcome these difficulties, architects must play the role of actively maintaining a flexible environment relationship between components. The creation of generative scripts, the introduction of computational design in the architect's vehicle can ensure this flexibility.

3.5 Software Limitation

There are some limitations to the use of Dynamo. These limitations can influence the script's execution. Most of them result from the fact that managing the scripts for a large project with Dynamo is a challenge due to the considerable amount of information to be processed. Dynamo requires quite extensive hardware. Even a relatively small Revit model requires a considerable amount of computing RAM power. It means that the script is best suited to run on a computer with better hardware when access to various options is available.

It has been observed that combining a large amount of data into a list consumes significantly more memory and processing time, and sometimes the software crashes during execution. It is, therefore, necessary to monitor the memory consumption of the script and to avoid the use of too large lists. Therefore, it is generally decided to distribute the data over several lists instead of having one extensive list. If the script is too complicated, the time needed to execute it in Revit is very long. Therefore, it is recommended to split the script to avoid asking too much information to the software for processing. It has also been noticed that if the Dynamo file has been open for a long time, the script will not run and it will be necessary to close and reopen the file. These limitations regard a general problem that can be solved using tricks or easily a powerful machine.

In the modelling phase, a significant limitation in the development of the scripts is the unidirectional nature of the data obtained. Consequently, a change of parameters in Revit is not accompanied by a modification of geometries in Dynamo.

However, despite this, it is believed that the advantages in the visual programming tools use are much more consistent compared to the disadvantages.

4 STATE OF ART: APPLICATION OF COMPUTATIONAL DESIGN IN A BIM WORKFLOW WITHIN THE AEC INDUSTRY

In this section, the state of the art of Computational Design has been examined. In which area and at which stage of the design process the computational Design is more attractive and successful? In which area is it still at the embryonic stage of research?

Exciting research led by researchers or architectural and engineering company will be reported.

4.1 The RIBA stages

The Royal Institute of British Architects published the RIBA Plan of Work (“RIBA plan of work - Designing Buildings Wiki,” 2020). It organises the designing and construction process into eight stages and explains outcomes, information exchanges and main tasks, required at each stage. The latest version, published in 2020, provide more emphasis on sustainability and Building Information Modelling (BIM) and also, the work stages have been restructured and renamed:

- 0 – Strategic definition: the outcome is achieving the client requirements;
- 1 – Preparation and briefing: the outcome is the Project Brief, approved by the client and confirmed that it could be accommodated on the site;
- 2 – Concept design: the outcome is the architectural concept, approved by the client and aligned to the project brief;
- 3 – Spatial coordination: the outcome is the architectural and engineering information spatially coordinated;
- 4 – Technical design: the outcome is all design information required to manufacture and construct the project completed;
- 5 – Manufacturing and Operation: the outcome is the manufacturing construction and commissioning completed;
- 6 – Handover: the outcome is building handed over, aftercare initiated and the conclusion of Building Contract;
- 7 – Use: the outcome is the building used, operated and maintained efficiently.

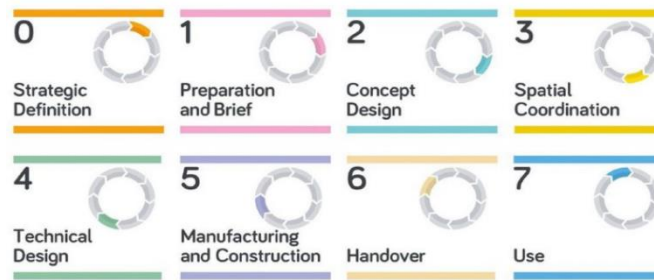


Figure 13 - The RIBA stages

It is importantly defined the stage of the construction process, in order to recognise requirements, delivery, milestones and outcomes. I will analyse some of these stages and in which way the computational design can provide a good ally during a BIM workflow.

4.2 Stage 2: Concept Design

Stage 2, corresponding to the ‘Concept Design’, includes design proposals of the project. The conceptual design is the first response of the design team to the project briefing. Afterwards, it is followed by the “detailed design” or “developed design”, in which all main building elements are specified.

If the BIM approach is used, the architectural concept at this stage can be described by masses and diagrams representing general elements. The project information model must include reports, representations, and additional information related to the building components. At this stage, it may be necessary to create a 3D visualization to help employers, consultants and other stakeholders understand the basic concept of the project. At the end of this phase, the consulting team will produce a conceptual design report for the client, describing the fundamentals of the concept design, that will be deeper explored in the following design phase. The conceptual design report will also include any instructions requested by the client.

4.2.1 Design Space Construction and construction Technology Implementation

The computational could be very helpful in the concept design phase because through the setting of input, output and constraints, facilitate the decision making. During the concept design phase, the possibilities are infinite, and the computational design allows us to make goals clearer and to achieve more rapidly the scope. The research led by Pena et al. (2018) within the architectural and engineering company Perkins and Will, involved professionals and students organising workshops in which they worked with Perkins and Will’s Research Labs. Design practice is becoming more based on computer as driver. The article mentioned describes a collaboration to meet the rising needs for new professionals.

They are conversant in a broad range of environmental, experiential, and economic metrics and in computational methods needed to find designs that maximise and balance performance. It was requested to the workshops' participants to explore the project's requirements and to summarise these in a script in Grasshopper, for example, the maximum number of floors, the maximum height of floors, the maximum footprint of the building, the minimum distance from the other buildings. These constraints, inserted in the file as algorithms, were used to simplify the process of concept development and to explicit the decisional making.

In a second stage, they asked students to test the geometries and each floor to understand how choices either improve or depreciate energy performance of the building. At this stage of design only architectural components such as glazing and massing were considered for changes. This allowed to understand the energy effects of the architectural decision making and how this decisions had a positive or negative impact on building energy consumption.

It was expected for the students to determine their project goals, generate results, and use both computation and intuition to test design and to drive it toward optimisation. The objectives of this method were to continue to observe and monitor building performance outcomes across from the early stages of the design process.

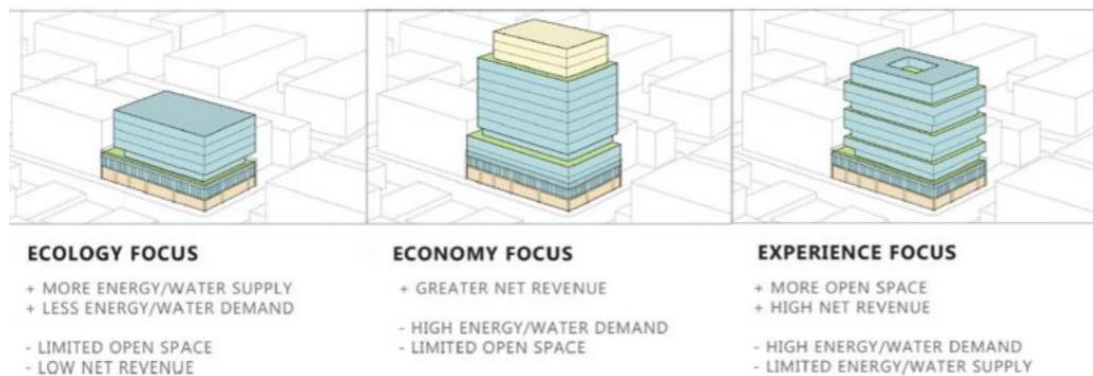


Figure 14 - Early studies to optimize various priorities (Pena et al., 2018)

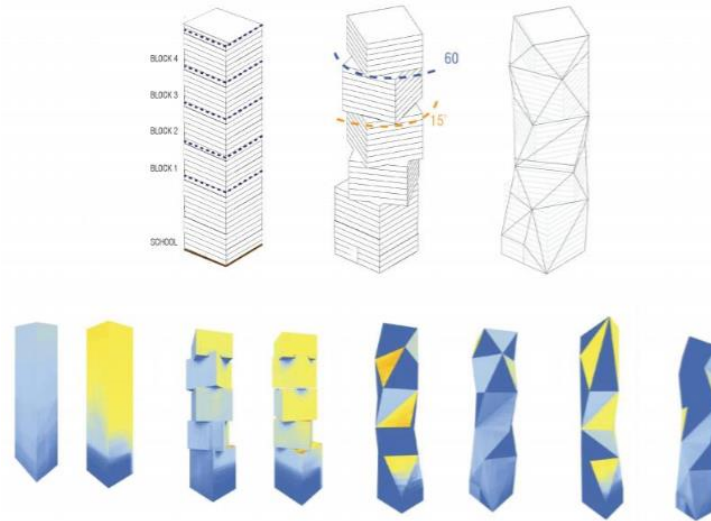


Figure 15 - Rotating and creating faceted facade to optimize energy demand (Pena et al., 2018)

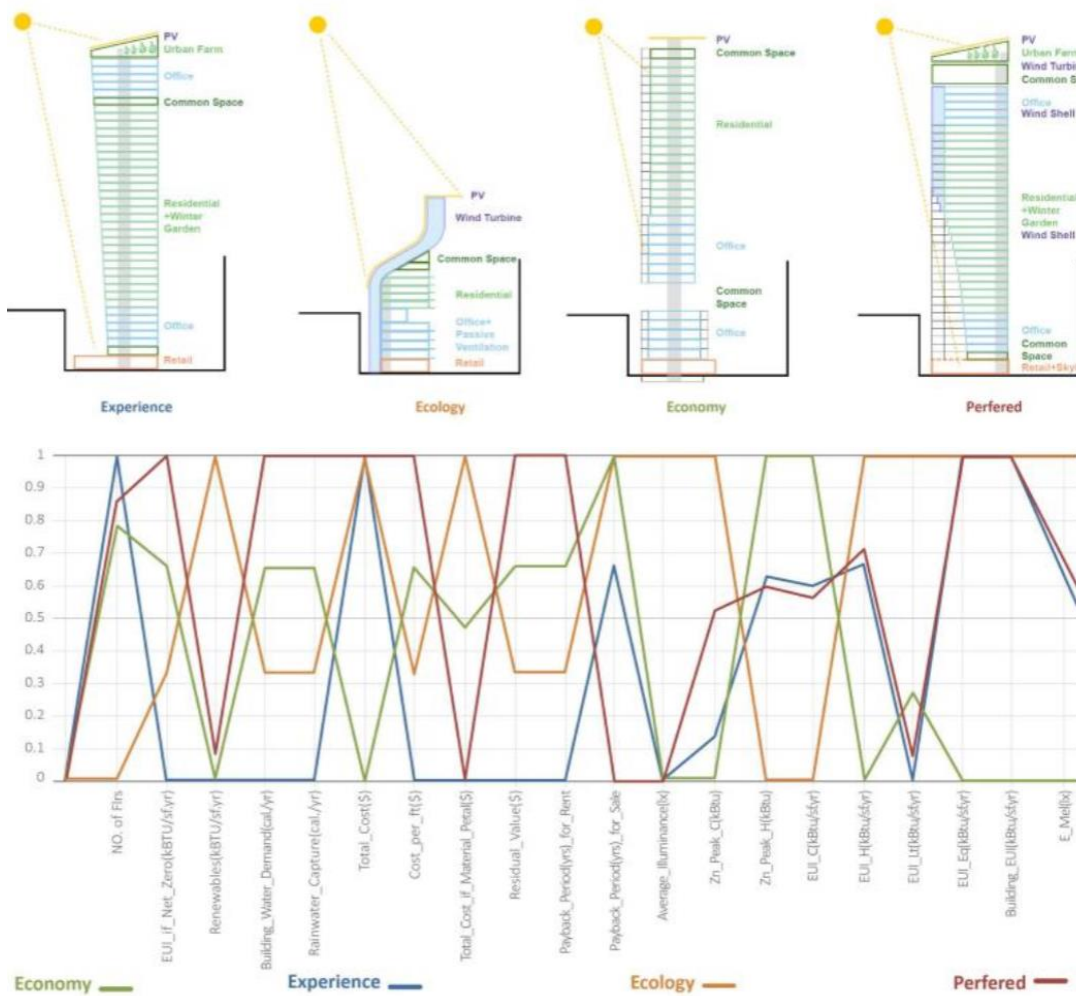


Figure 16 - Design Space with parallel coordinates plot of normalized data (Pena et al., 2018)

This strategy allows to make informed design decisions in an early phase and to understand the more massive ramifications of those choices. The results are: more and better options also for the clients and more cost-effective solutions overall for human-centred and high-performance spaces.

Conceptual design analysis provide methods to evaluate the energy building performance in an early phase. Immediately, the designing team can achieve the energy use demand of the project and compare the efficiency of orientation, building form and envelope solutions. The decisions made in an early phase of design can be very impactful on the energy use of the building, such as project location, building form, orientation, windows area orientation, envelope characteristics, lighting power densities, operational and thermal comfort ranges.

BEM (Building Energy Modelling) is a general term for hundreds of software programs, and it is used

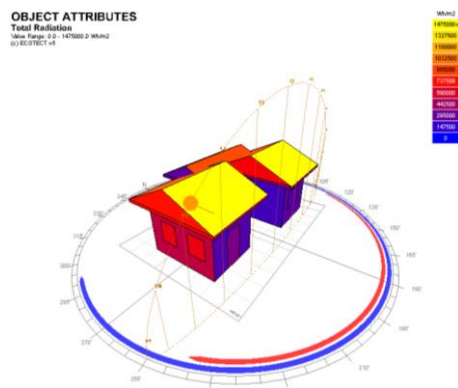


Figure 17 - Preliminary Solar Analysis during a Concept Design

for energy simulation of buildings. Recently, visual user interfaces for programming, that allows users to create customized and flexible algorithms for energy analysis, has spread. Being Dynamo a plug-in integrated into Revit many interoperability problems, that can raise between Revit and energy analysis tools, can be overcome. According to recent surveys, the energy analysis tools may be demand building specifications, which are usually non-existent in the initial architectural design phase. Usually, they require considerable time to build simulation models and become

unacceptable to use in a design process, when the decisions are continuously in movement.

The research led by Karen Kensek et al. (2015) describes in detail how Dynamo could be efficient in the first solar analysis of a building. The case study number 3 shows the use of an attractor point to define the solar shades of a façade. The point represents the sun and it changed position depending on the location and weather conditions. The parametric panels of the façade reacts to the position of the point attractor.



Figure 18 - Parametric Panel responding to the position of the attractor (Kensek, 2015)

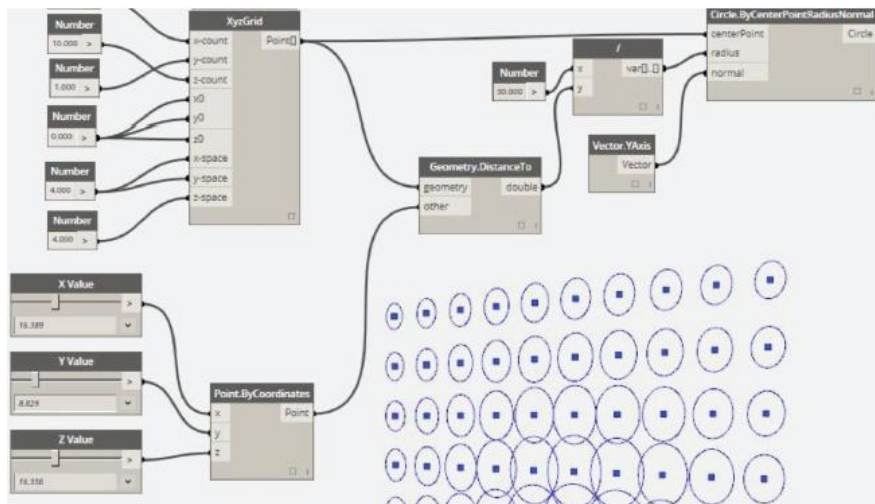


Figure 19 - Attractor sketch in Dynamo (Kensek, 2015)

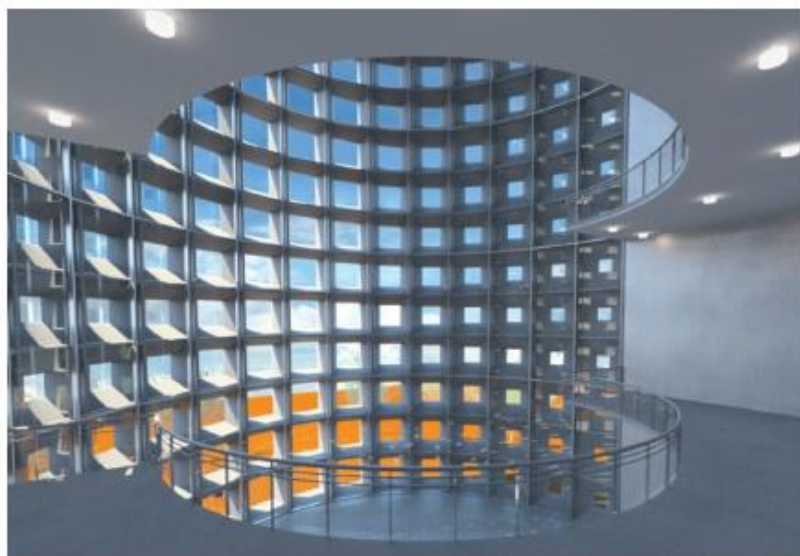
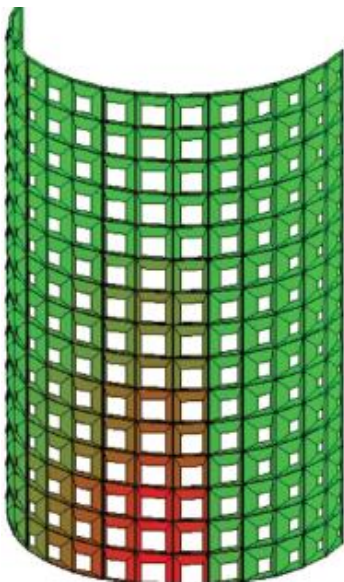


Figure 20 - Panel changing color in response to solar angle (Kensek, 2015)

4.2.2 Automation of Floor Plan design

Space planning is a process that always requests much time. The designers have to generate a solution considering and satisfying many factors and constraints. The internal spaces have to be organized, considering many relationships between each other. Generally, there is no single answer to the problem but many that have to be evaluated. The help of computational design, in this case, allows to combine

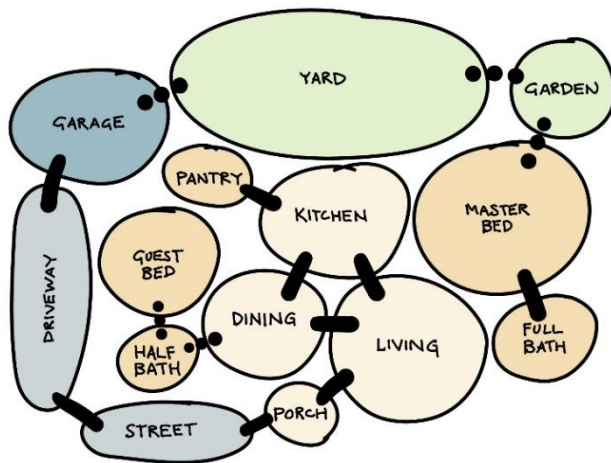


Figure 21 - Bubble diagram for space planning
(Dynamo Team, 2019)

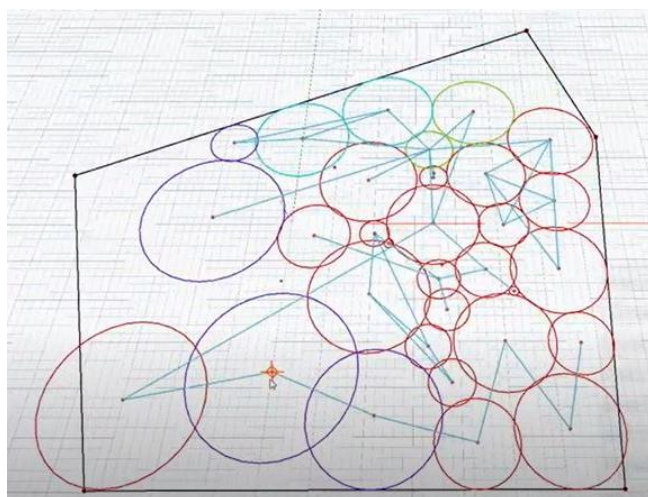


Figure 22 - Representation of the bubbles spaces in
Dynamo

all the constrains, provide all solution and choose the best one according to the requirements. In many papers, this complex problem has been studied. In Dynamo web site (“Visual scripting environment for designers | Dynamo,”) is reported a study about the space planning automation. This study uses a package of node called DynaSpace developed by Long Nguyen and Mohammad Rahmani Asl.

This node reproduces the same mental design process that occurs in the preliminary phase of the design. Generally, the designers start to generate some schematic plans trying to combining all the requirements. Sometimes they come up with bubble schema in order to show dimension and relationships between space. The node provides the same process, but the difference is that the machine can provide all the solutions that satisfy the rules defined.

The purpose of the study proposed (Dynamo Team, 2019) was to arrange ten rooms of a clinic within the given site boundaries. A circle describes each room with an area size defined. Also, each room belongs to one of the departments present in the clinic. The study wanted to find a bubbles organisation to meet the requirement as far as possible. The requirements, such as the space ID and name, dimension, adjacent space and

departments, were specified in an excel file. The image shows how DynaSpace node tries to move the bubbles representing the rooms according to the requests and restrictions. At any given time, it is possible to drive a particular bubbles room and move it to another location. The other bubbles rooms will react accordingly, as the algorithm tries to fulfil all requirements and restrictions as far as possible.

Based on a preliminary study, it is possible to quickly arrive at the design concept, taking into account all requirements and constraints.

4.3 Stage 3: Spatial Coordination

The stage 3 consists in the preparation of spatial coordination, including coordinated and updated proposals for structural design, building services systems to test the architectural concept, specifications definition, cost information and project procedures under design programme. The process is usually divided into stages. It can help set milestones for delivering progress reports and preparing information for approval. Spatial coordination is a new stage added by the RIBA plan work 2020 and replaces Development Design in the 2013 edition. It suggests that the spatial coordination stage is made to test and validate the Architectural Concept, to ensure that the architectural and engineering information prepared at Stage 2 are coordinated. In this phase, it is expected that the Architectural Concept should remain unaltered and, although detailed design or engineering tasks may require modifications to make sure that the building is Spatially Coordinated.

4.3.1 Generation of Architectural parametric components for Cultural Heritage

This section reports on research conducted by Sampietro et al. (2019) an Italian team. In particular, they led a renovation of a historic building and proposed a computational approach to obtain the necessary information, such as cost plan, project strategies and framework specification. The researchers focus the paper on the design development requirements phase when the architectural concept and strategic engineering requirements are already defined.

In general, when talking about the architectural, engineering and construction (AEC) industry, it is referred to new buildings. Today, however, existing buildings are increasingly being reclaimed. The Italian historical context, for example, places this question at the centre of many considerations due to the economic and environmental conditions. For example, the need to rehabilitate cultural heritage is becoming more important than new construction.

The HBIM is the application of BIM technology to historical heritage. The acronym HBIM stands for Historic Building Information Modelling and was introduced in a scientific article written by professor Murphy of the Dublin Institute of Technology in 2009. HBIM is a new way of modelling existing buildings, using the BIM process and developing models as a database, that contains and manages

information. It is a technology that allows reproducing an existing building through a 3D model that can simulate the reality. The first phase of an HBIM process is the survey: usually, a digital survey that is executed with tools like a laser scanner or photogrammetry. The point clouds produced by the tools is a set of points with defined coordinates in space, and it can be adopted as a reference for modelling. The BIM incorporation into the cultural heritage is still an approach that is being explored. The biggest hurdle is the modelling phase. Therefore, it is necessary to elaborate on simple methods to obtain BIM models that ensure quality. Each historical building is different, belongs to different historical periods and has suffered different types of damage. Furthermore, the model should contain non-geometric data, such as historical information and analysis of degradation or deformation

Many studies conducted in recent years studied the process and tests the workflow to obtain a model with accurate geometries and data information. The computational design helps to give great help in reproducing historical buildings, and especially in integrating a meaningful amount of data. The computational design contributes to give a big help in the reproducing of historical building and integration of a meaningful amount of data. The aim of the research led by Sampietro et al. (2019) was *“to show how the application of the computational design can speed up and improve the realization of complex geometries typical of the historical architecture and automate some processes in the design phase. The object of the research is the building housing the Cento Art Gallery, damaged by seismic events of May 2012”* (Sampietro & Bergonzoni, 2019, p. 306).

The nature of the information collected in the traditional BIM models is different from an HBIM model. First of all, HBIM model needs a survey and documentation of the state of arts to define the intervention. With the spread of the BIM methodology, it was noticed a growing adoption of Computational Design techniques. The Computational Design approach enables to produce a generative algorithm in order to define the geometries, also the most complex. The method to reproduce forms studying the geometrical relation between elements is called shape grammar and can be applied in computational design through the use script: a group of rules defines the relationship between lines, points, planes and solids and they are applied recursively. It allows the management of multiple shapes based on geometrical rules and repetitions.



Figure 23 - Elevation of Pinacoteca Guercino (Sampietro & Bergonzoni, 2019)

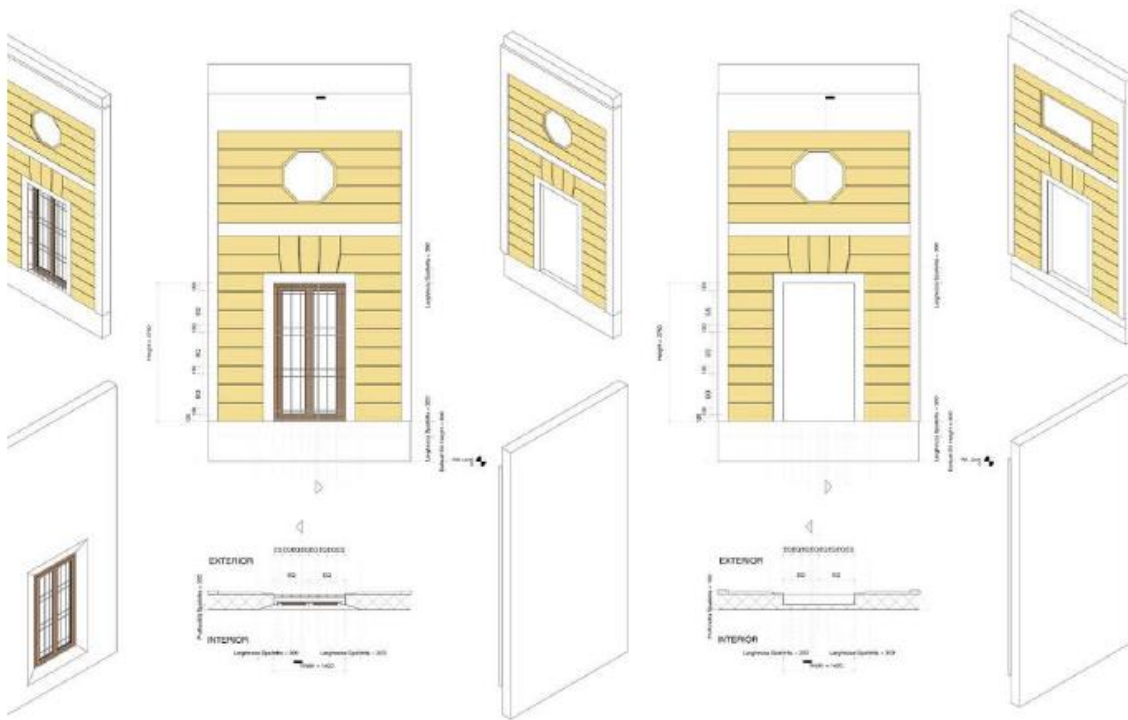


Figure 24 - Geometrical relation between elements (Sampietro & Bergonzoni, 2019)

The intervention of computational design can help but not solve everything, because it is difficult to find two perfectly identical elements and can apply the same procedure. In this study, the adoption of generative grammar allowed the realisation of the vaults elements. It reduced the time for the realisation of the component and the extraction of geometric information. Once the generative design was conceived, it was demonstrated that it was reasonable to obtain different elements differing by a few centimetres without requiring particular users ability in the control of the software. The research outlines

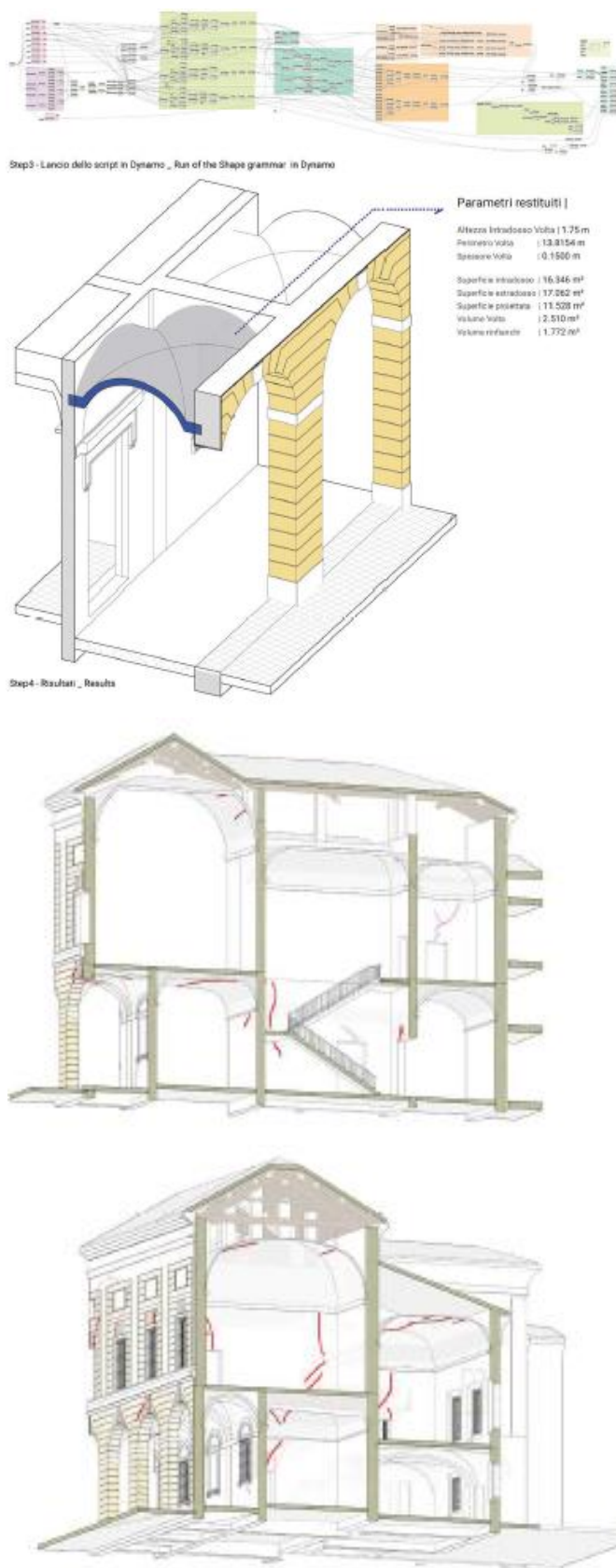


Figure 25 - Definition of geometries and damages of elements (Sampietro & Bergonzoni, 2019)

the principal limit of Dynamo components: the data returned by the program are unidirectional, any alteration of the parameters in Revit does not follow the variation of the geometry. In a second moment, they focused on the graphing and quantified interventions on the walls through an algorithm. Cracks have been grouped according to their trend (vertical lesions, diagonal, parabolic...) and their size (width, extension). The lines representing the damage were in three-dimensional space. This method allowed a drastic reduction in the time.

Computational design collects and organises data and defines relationships between entities. The BIM model is a database of information used for storing information in order to promote interoperability and sharing between the actors during the whole lifecycle of a building. It is legitimate, as they assert, to believe that computational design can be a necessary tool. They realised that the significant disadvantage is that the data obtained through this procedure risk to be lost when exported in a non-proprietary format. The elements created does not belong to a category classifiable, so when they are exported in a non-proprietary format (.ifc format for example), they cannot be allocated to a specific group of objects.

The process proposed is not a unique way to operate but the results obtained are not easy to achieve using different methods. It is considered as a starting point for other tests, and they do not pretend to propose the computational design as the only possible answer to the HBIM problems.

4.4 Stage 5: Manufacturing and Construction

Offsite manufacturing and On-site Construction is the stage under the construction programme and resolution of design issues from the site. RIBA plan of work 2020 introduced a new stage called “Manufacturing and Construction” replacing “Construction”, and it reflects the increasing use of manufactured elements in construction. As the construction industry moves towards more widespread use of offsite manufacturing, greater emphasis is also being placed on logistics to get materials and components to the site, and on managing suppliers. Stage 5 concludes by issuing a practical which permit the delivery of the completed outcome to the client.

4.4.1 Prefabrication Optimisation

From the beginning of the 20th century, the method of prefabricated building construction developed very quickly worldwide and conquered a large part of the population. A prefabricated building is a building that consists of prefabricated elements that are assembled on site. This success is due to the fact that by producing outside the site, construction time and costs can be reduced. The construction industry is increasingly characterised by the introduction of standardised design, industrialised production, mechanised construction and information management. The combination of BIM technology, design and construction of prefabricated structures can bring advantages and realise the integration of design, production, construction and operation and maintenance. Therefore, BIM technology can provide enormous support to maintain the excellent functional characteristics of the prefabricated component system and enhance its potential application value in practice.

Prefabrication is nowadays a standard in housing construction in many countries. It is considered safer, faster, cleaner and also cheaper. Being produced in the factory, they replace much manual operation, thus saving time. This construction approach is in line with the sustainable requirements achieving the saving resources purpose: much material can be recycled, like steel formwork, wood template. Moreover, for the type of construction approach, the noise is reduced, and dust flying is shunned. Consequentially, environmental pollution has been adequately controlled. Another advantage is the reduction in site costs.

Today, prefabrication provides a wide range of technologies that help to achieve a variety of design results. This, with BIM development, has opened up a whole new world of possibilities for architects. The special feature of the prefabricated building is its flexibility: this concept opens up a new direction

in how the house should be thought. A house should be versatile according to the needs of its users and change over the course of its life. Analysis of the past and the technologies currently available express a general opinion: versatility increases with the manual workability of the material used and decreases with the size of the prefabricated elements.

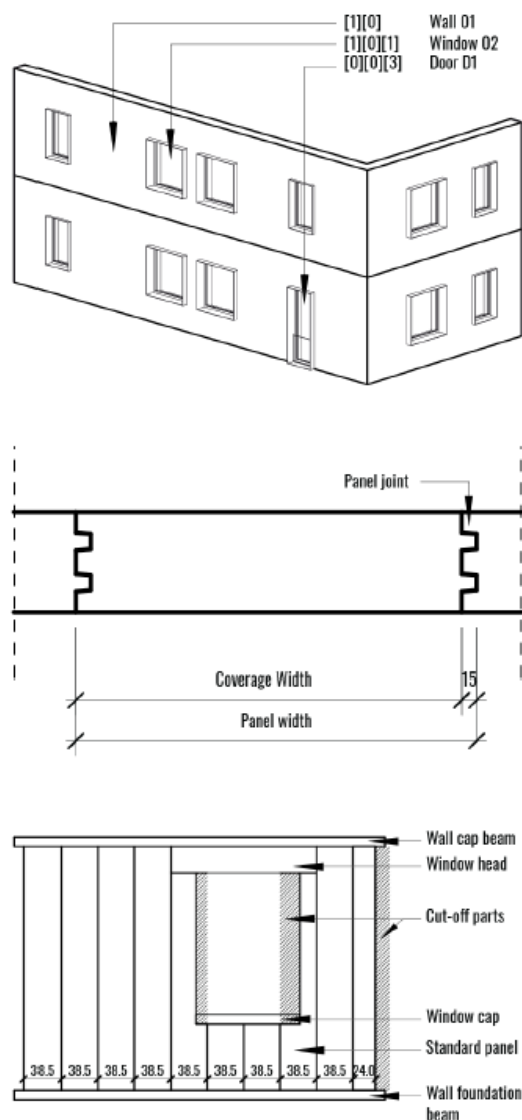


Figure 26 – Horizontal section and subdivision of a solid wall (Ostrowska-Wawryniuk, 2019)

The research led by Karolina Ostrowska (2019) wanted to find a prototype solution for adapting a single-family house design to the purpose of DIY-oriented timber prefabrication. The research aimed to find a relevant alternative to traditional construction techniques, using small-element solid timber prefabrication. At the same time, the solution presented aimed to preserve architectural diversity through the application of customisation approach. She wanted to maximise the benefits of serial production by generating as many repeatable elements as possible. In order to achieve these objectives, she proposed an algorithm based on the BIM tool that allows the automatic generation of the geometry of the prefabricated wood panels.

She has chosen a solid timber structure for the house because the elements can be realised with more straightforward fabrication techniques and can be manually adjusted on site. The wooden elements allow the internal versatility of the house through the possibility of moving and the simple carpenter connexions between the panels. At the same time, wood offers a pleasant environment in terms of climate comfort. To allow natural movements of the timber elements, the required weight of the elements must be kept

within limits, so that they can be handled manually by 2-3 people. The BIM model had a significant role in this research (Ostrowska-Wawryniuk, 2019): it contained all the information required, and it calculated the dimension of the elements respecting the lightweight. At the same time, timber

construction causes waste in the form of unusable fragments. Therefore, this study aimed to simulate the prefabricated structure and to optimise the material during production. The model was generated using Dynamo scripts run in Autodesk Revit.

The research was divided into different phases. During the first phase, the algorithm was adopted to compute the maximum size of the wood entities, taking into account the thickness, unit weight and the control of the elements. In the second phase, the model is investigated by the algorithm to obtain its geometric structure. In the third phase, the optimisation was carried following three rules: the maximum panel width obtainable taking into account the weight constraint; the minimum material wasting, so the leftovers panels can be reused in other parts of the structure; the minimum number of geometric type. The research claims (Ostrowska-Wawryniuk, 2019) that the BIM approach enables real-time simulation in the prefabrication area. It allows for improving the decision-making process in an early design phase. In fact, due to the optimisation approach, the BIM model allows to relate different solutions and to make the best choice. The research shows not only how to reduce material waste, but also how to reduce the number of skilled workers. The prototype presented is part of broader research in the use of BIM environments for design using prefabrication. It is an inspiring example of the benefits of BIM and computer-aided design in the construction industry.

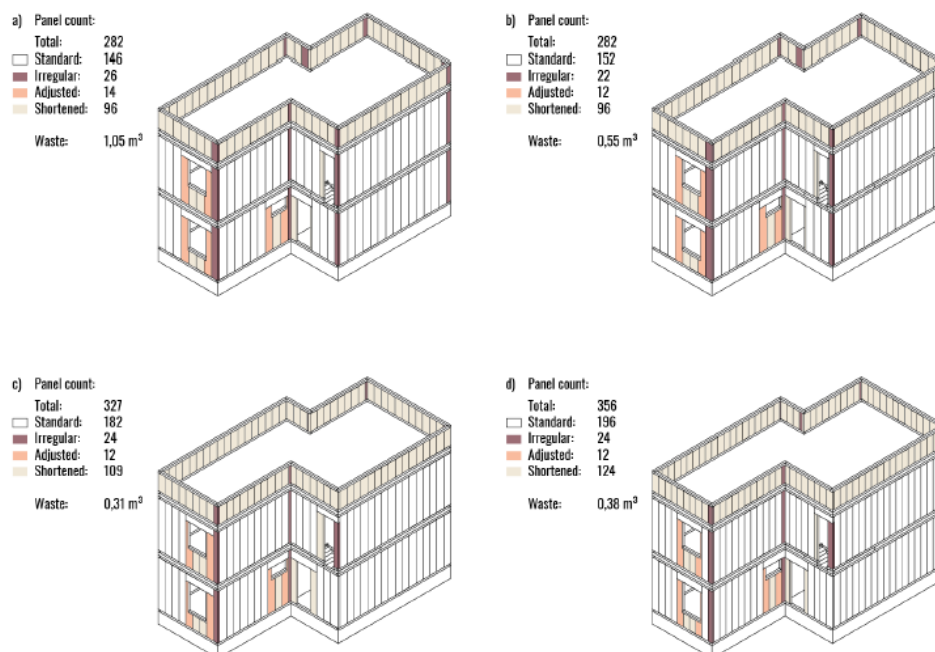


Figure 27 - Comparison of panelisation results (Ostrowska-Wawryniuk, 2019)

4.5 Stage 7: Use

The “In-Use” stage of the RIBA Plan of Work regards the manutention phase of a building. Consultants might provide as-built drawings, any discussions regarding future alterations or additional work, or general advice to the client-post construction concerning: maintenance, energy certificates or consumption, letting or tenants queries, general manager of facilities. These services, if necessary, should be outlined in the initial appointment agreement.

4.5.1 Management of metadata into BIM model

The operation phase of the building required important information that are not properly geometric, such as the condition of the MEP system or the envelope status. The maintaining cost of this information in the BIM model has hindered the adoption of BIM at this stage.

The research led by Khaja et al. (2016) suggests winning this barrier using Dynamo tools to manipulate and transfer information among the management system and the BIM model. BIM use for facilities management demands a meaningful quantity of non-geometric information to support the preservation of the building. The BIM model become a “data container” as well as a Common Data Environment, according to the research.

The figure below illustrates the workflow using parametric tools: the data from a CAFM (Computer Aided Facilities Management) system are transferred into the BIM CDE. To protect the integrity the data is copied and exported using an intermediary format like .xls (Excel file). Visual Basic for application (VBA) macros are used to order the data and fill in the value of the shared parameters defined in the BIM model. Dynamo scripts are executed, and the lists of data collected are exported into the BIM CDE. The data is, therefore visualised in the 3D model as parameters value within the evolving BIM model of the facility.

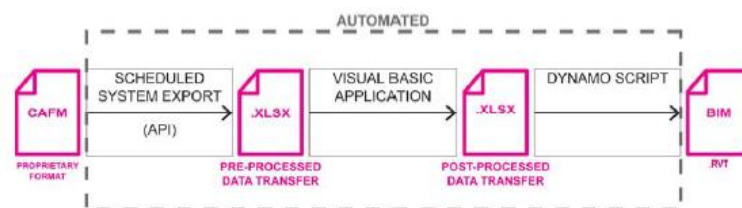


Figure 28 - Generic CAFM to BIM CDE automation process (Khaja et al., 2016)

This procedure has been applied several times in different case studies. In each of these studies, Dynamo has provided a method for extracting data from an Excel spreadsheet and updating shared parameters with a variety of data types (strings, numbers, integers, and T/F flags). In this research the non-geometrical information has included information of ownership, functional group, seating capacity, and signage. This tool facilitates automatic updates of the BIM model, significantly reduces the time required

to maintain a BIM model throughout its lifecycle and allows a lot the FM team to benefit from BIM visualisation.

5 FOCUS ON THE ROLE OF BIM IN THE PREFABRICATION INDUSTRY

TRIMO

The case study has focused on the prefabrication industry and how new technologies development can be beneficial to companies. In particular, the research has focused on a project realised by TRIMO, a Slovenian manufacturing company that produces wall and roof prefabricated components.

This chapter analyses TRIMO and their level of digitalisation, focusing on their workflows and processes.

The first section provides with an overview of norms and standards necessary to regulate the digital flow of information, to automate processes within the prefabrication sector. It also gives a summary of new technologies in the manufacturing industry, focusing on the production of prefabricated elements, which have been improved thanks to computational design strategies within BIM tools and workflows. This research presents a point of view for future technologies implementation in TRIMO.

Afterwards, the subsequent paragraphs presents a detailed analysis of the current processes of TRIMO, the software utilised and the information management.

The final paragraph highlights computational design strategies adopted to create a library of scripts that can automatise repetitive and manual procedure during the design phase of every project.

5.1 The importance of the Standards to manage a database of information

In the last years, digitalization has mutated a lot of industrial sectors, obtaining a notable increasing the quantity and quality of production. In the AEC industry, the digitalization has increasingly been adopted during all the processes of a project, but it is late and behind other industries. It is not unusual for vital information to be lost because it is still delivered in the form of drawings, either as physically printed plots on paper or in a digital but limited format. This gap in the workflow extends throughout the entire construction process: in the design, construction and operation phases, and in essential deliveries between these phases (Borrmann, Koch, & Beetz, 2018).

The processes involve many actors from different fields and, because of that, it is necessary a continuous exchange of information. Until AutoCAD was the main tools used during the process, it caused much loss of information and efforts to insert information manually requiring additional work. It was a further source of errors.

By applying the BIM method, the use of computer technology in the design, engineering, construction and operation of built facilities is realized. The BIM model represents a store of information collecting from the first phase of the designing process. This approach improves the coordination of design activities, the integration of information, the setup and control of the construction, the information delivered to the manufacture. By reducing the manual placement of data to a minimum and enabling the

consequent re-use of digital information, errors are avoided, which in turn increases productivity and quality in construction projects. According to National BIM standards, Building Information Model is *“a digital representation of physical, mechanical and functional characteristics of a facility and a knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from starting to ending of the project”* (“NBS National BIM Library”), including the three-dimensional geometry at a defined level of detail. The information inserted could be related to the material information, the type of component, the material quantities, the costs. They are exchanged and used during the whole lifetime of built facilities.

BIM is a technology tool for interdisciplinary coordination platform that connects architects, designers and builders. Using BIM many clashes and issues can be settled during the design phase, avoiding problems during the construction, loss of time and money. Sometimes this information could be inserted manually. Dynamo represents a next step towards the automatization of the process and the reducing of time and money. BIM allows us to navigate through an enormous amount of information collected in a database. Dynamo simplifies the search for data and avoids the manual process of storing and identifying information. The introduction of computational design enhances accuracy, speed and improves adherence to money and schedule, and increases productivity rapidly.

5.1.1 The UNI 19650

Architecture is an old profession, and a century ago, an architectural team was made just by architects and engineers. The designing’s team today looks very different: owners, developers, architects, structural engineers, MEP engineers, general contractors contribute to the construction. Each of them has different software and technologies and their way to communicate. The introduction of BIM in a construction process contributed to creating a coordinated and collaborated environment, helping connection. BIM is mostly developed around the world but not grown in the same way. To have a more collaborative process, also among stakeholders from different countries, it is essential to establish a universal language that can lead to improving the efficiency and quality of the implementation process.

The ISO, International Organization for Standardization, has developed the norms to support the BIM process internationally by setting international standards in processes. The ISO 19650 is meaningful since it describes the processes using BIM, how to organise, digitalise and manage the information about building and civil engineering work. During the life cycle of a built asset’s information will be produced, exchanged, and delivered. ISO 19650 proposes concepts and principals to support the management of the information by encouraging collaboration between the participants. To use BIM efficiently, a project should begin with defining the BIM requirements. Owners and delivery teams should establish processes, standards, and deliverables for BIM projects that can be shared and agreed upon on an ongoing basis by the owners and the rest of the project team. The ISO 19650 part one summarize the information management process around the Common Data Environment. The CDE is

the unique source of information that receives, manages and share information and documentation of the project. It is a powerful method that allows reducing the time and effort required to check and reissue information, supporting the information management process. During the project, the Common Data Environment contains information which quantity grows according to the project phase. Before using the Common Data Environment process and start the project and asset management, the client defines the information requirements to potential delivery teams.

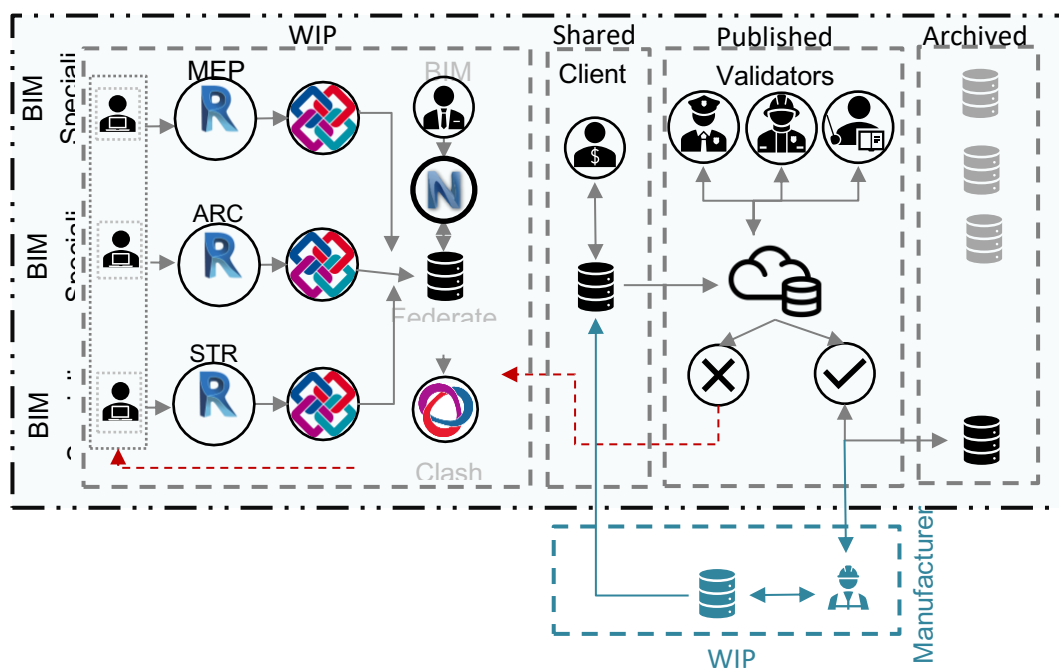


Figure 29 - Workflow of Information Management among a process

BEP stands for Building Execution Plan and specifies the building information required. It describes the process of exchange information during a designing process in a collaboratively digital environment, and then creating, sharing, accessing and using information during all the lifecycle of the building. The BEP guides the stakeholders during the project, establishing from the beginning the main constraints: the model sharing, format of the sharing file, software programs, the team and the contacts, role and tasks of each team and their components, the model uses and the milestones during the process, the LOD (level of development), of the model according to the project phase and the naming convention.

All this enables the project team to figure out more clearly the deadline to respect, the required work and why that work is critical to the project’s success. A fundamental point for the success of the collaboration is to identify the model uses to integrate or extrapolate just the information required for that scope. Each team has to know its modelling tasks.

An important question related to the argument of this thesis is: will the design models be used for fabrication and installation? The answer could be positive or negative.

A model realised with a fabrication purpose demands a high level of detail so that the detailed information can be used for fabrication. If it is used in the installation, it also requires to have a high level of detail and accuracy that it can be installed correctly out in the field.

Contrariwise, if the model that is created by subcontractors or general contractors will be used for fabrication or installation, do the architects need to take a look at that model before it is used out in the field to approve those models or not? In general, the possibilities are infinite. For this reason, the entire process has to be organized and documented in the BIM execution plan. Therefore everyone understands who will be looking at the model and who will be approving the model.

Therefore an essential step of the BEP is to establish the BIM uses in order to achieve the BIM goals. Pennsylvania State University defines BIM Use as a method to accomplish specific objectives during a facility's lifecycle. It has been identified 25 BIM Uses organised into five main categories according to the project phase: gather, generate, analyse, communicate and realize. The BIM uses are related to the Building Information Model, and they define with which purpose the digital BIM model will be used. To determine which BIM Uses is the best fit for the project, the owner or stakeholder defines the requirement. For each of those BIM uses, the team needs to describe what data they require bright and at what stages. Then based on data, or we could say LOD required, and through discussion, the team will distribute roles.

The introduction of BIM brings numerous new tasks and responsibilities for the management and coordination of BIM roles in the team, but also new professions. The most important roles are the BIM Manager, the BIM Coordinator and the BIM Modeler.

Once defined, the BIM uses of the models and the responsibilities, it is crucial to establish the model objects' LOD relying on the required data. LOD was introduced by AIA (America Institute of Architects) in 2008. Furthermore, in 2013 the LOD Specification was published, becoming the point of reference of several BIM guidelines in many countries. Today is the dominant system. The level of development defines for each stage of the project how deep the BIM model will be developed regarding two categories: level of detail for the geometry and level of information for the quantity of data.

The choice of required information level is calibrated to the project stage and documented in the BEP. It allows designers, engineers, contractors, any stakeholders, to focus their work on what is needed. At the beginning of the project it is essential to define the LOD to achieve. There are six levels: LOD 100 and 200 is generally for the initial phases of design, LOD 300 for design development, LOD 350 for construction document, LOD 400 for construction, and LOD 500 for as build. LOD 350 is a new level requested for coordination purpose. Moreover, LOD 400 is defined by mounting detail, model assembly detail and information, so that the manufacturers can produce from those drawings and be able to go out

on-site and assemble whatever it is that they specialize in. Define the LOD allows to achieve an efficient model, avoiding waste of time modelling not useful part.

Ari Monteiro et al. (2016) has discussed in his research about the use of VPL for achieving LOD 400 to a BIM model. Usually, increasing the level of detail of a BIM object is associated with many repetitive tasks that could be automated to reduce the time required for this. The use of VPL to achieve a BIM LOD 400 model in an automated way has been little investigated. As Ari Monteiro et al. (2016) say, if these tools are tightly involved in the design process, it is crucial to take advantage of the fact that they are also used in the modelling process. It is possible to model the assembly rules of a building system by creating algorithms that express the relations. For example, it is possible to model the rules for the distribution of entities of a masonry system and apply them in the BIM model.

“The result of this processing is the automatic insertion of BIM components for each wall selected. The key idea for the use of tools based on VPL is modelling the rules of certain design discipline and applies these rules on BIM model components to generate results.” (Monteiro, 2016)

5.2 BIM in Industrial Prefabrication

Compared with other technical sectors, building construction is predominantly associated with the production of individual entities made on-site using trade skills and craftsmanship. Due to the moderate degree of automation and the corresponding higher level of craftsmanship and improvisation, the productivity levels in the building industry have stagnated. All of this is associated with lower profits in the building industry.

To achieve cost efficiency and quality, the construction sector, like other industries, will have to improve the automation level of production processes. Today, the construction industry uses industrial production processes mainly for the prefabrication of steel components. In steel production, automated methods are used for thermal cutting, welding, drilling and marking steel elements. These systems are managed by numerical control (NC) data. (Schreyer & Pflug, 2018)

As stated by Schreyer et al. 2018, (2018) the production follows steps, that have to be coordinates and the design must considerer not only the technical requirements but also logistics of production and transportation, for example, the maximum size, position, direction of assembly and future maintenance needs. Industrialization in construction means a high-level use of standardization of products, elements and modules. The manufacturing processes have already been improved in other industries, such as automotive, airlines long ago and in plant engineering recently.

Furthermore, more and more construction companies are looking at manufacturing industries to see if there are principles, processes or tools that can be applied for the construction industry. Generally,

during a production process, the digital information from a Computer-Aided Design software must be processed by a Computer-Aided Manufacturing, and the instruction for the production are transferred to a production machine. Without a 3-dimensional designing, contractors risk realizing parts and pieces that may not fit together as intended once installed on the job site because the designing of prefabricated materials is a difficult task. However, through the use of a BIM 3D models coordinated between all the disciplines, each system will fit and install according to the design. Contractors can create a fabrication-level model, which is then used in a Computer-Aided Manufacturing (CAM) tools and machine tools to create the building component or part with accuracy and quality.

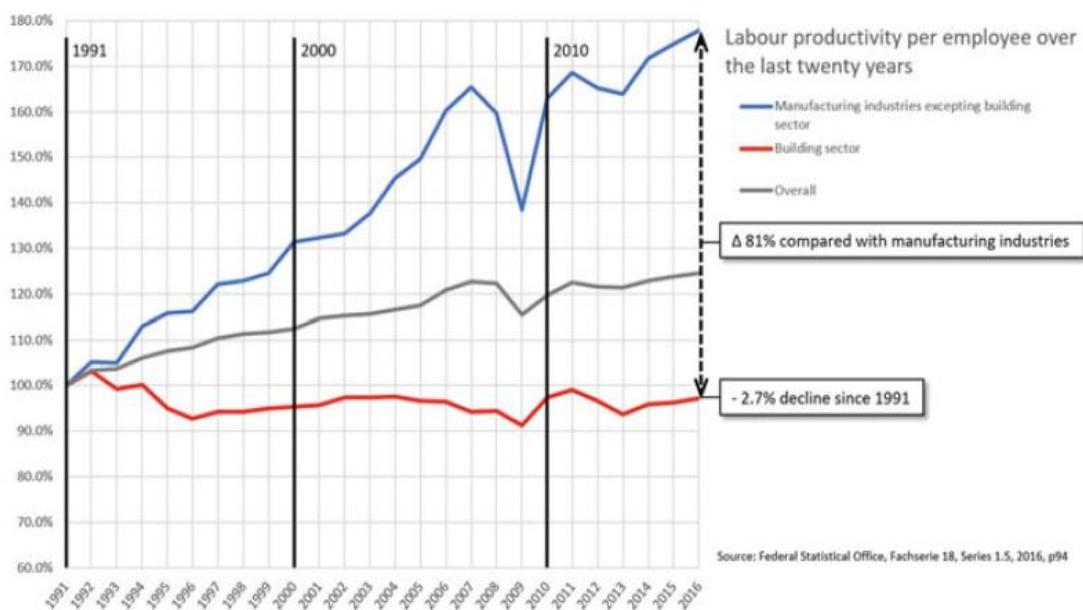


Figure 30 – Building sector productivity compared with other industries (Schreyer & Pflug, 2018)

5.2.1 Advanced Machinery for fabrication in construction

The research led by Naboni et al. (2015) investigated the production machinery. The acronym CAD/CAM refers to the integrated use of software systems for computer aided Design (CAD) and computer aided Manufacturing (CAM) to simplify the transfer of information from the initial design phase to the subsequent production phase.

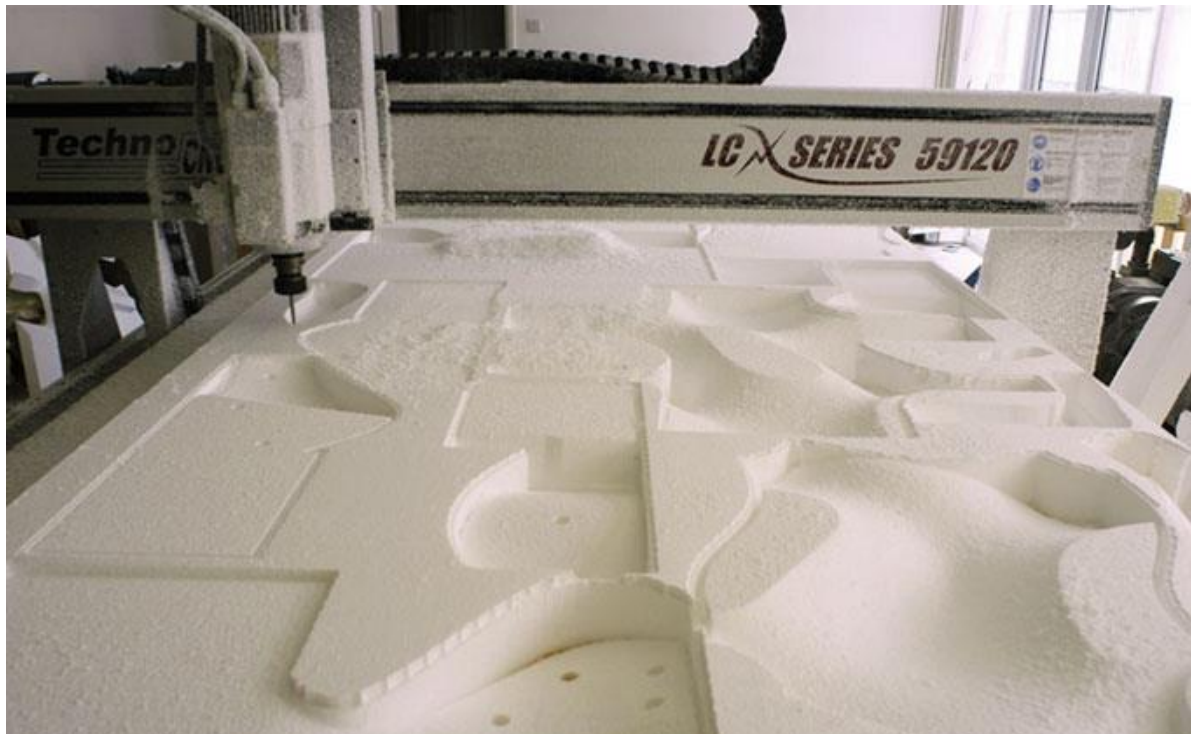


Figure 31 - CNC milling with a 3-axis milling machine (Naboni, 2015)

The Computer Numerical Control (CNC) machinery tools are examples of the production machine. They receive the information from the CAM application and manufacture the product. In commerce, there are different type of CNC machinery tools, the choice depending on the purpose. Subtractive production process corresponds to the first phase. It works with the removal or division of virgin material from an original object, reducing the volumetry. This kind of process can be distinguished into two groups: the cutting process and the mechanical subtraction process. The cutting processes is employed mainly on flat elements, allowing variations in thickness and for this reason, it is also called "2D fabrication". One of the most popular CNC machinery tools is the CNC laser cutter, that is based on the use of a high-intensity energy ray of light (laser). Usually, in the form of sheet metal or tubes, the original material is cut by laser energy. It is heated strongly in an extremely short time to produce a clean surface. The laser could not only cut but also mark the materials. Other examples of CNC machine tools are the CNC Milling, the CNC water jet Cutting...

The CNC Bending and CNC Hole Punching belong to the formative process group. The formative processes correspond to a secondary phase. The initial product is semi-finished, and the techniques are applied to reshape its geometrical properties through the use of heat or steam forces. These procedures are mainly practised to metal or plastic materials but also wood and mineral materials.

Crawford Architects in July 2009 were hired by Zahner, engineers and metal fabricators based in Kansas City, to design their expansion of their factory. The new building has been intended to represent the

engineering and metal fabrication services that the company Zahner Factory offers, and thus provide an exhibition for its production abilities. The building façade has been made of custom-made aluminium panels designed with the latest software developed and manufactured with Computer Numerically Controlled machines.



Figure 32 - The Zahner Factory façade (Naboni, 2015)

The panels and the structural system, realized by Zahner factory, has been influenced by the natural geometrical shapes of sand and waves. For this project, a new software called ShopFloor was developed. It was a web-based platform used during the design phase to manage complex buildings. During the fabrication phase, software such as CATIA was employed to produce the vertical shading element of the façade system.

In addition to the CNC machinery, the Robotics and Additive Manufacturing machines are used in industrial construction for fabrication.

The Robotic Fabrication, controlled by computer, is generally used to move elements and assembly materials. It is a type of mechanical programmable device with capacities similar to the human arm, and it has also been adapted for construction. To use the robots, usually it is demanded to the architects to migrate from CAD software to machines, using a simple workflow. This procedure consists mainly of transferring construction trajectories, using programming languages like Python and C++. They help the architects to control the paths of the robot. The growing ability of architects to control robots encourages the interaction between design software and machines in a complete integration of the two systems. This has the ambition to offer several development directions, changing the typical linear process from design to construction (Naboni, 2015).

Since 2005 the duo Gramazio and Kohler, based in Switzerland, has been investigating the potential in architecture of robotic fabrication at ETH in Zurich. In particular, they studied robot-supported additive

manufacturing processes and their effects on architecture and construction. To this end, Gramazio and Kohler have begun their research studying simple construction elements such as brick and have tried to explore the potential of robots in construction.

The aim of the research was to take advantage of the robot production, without trying to come up with processes that imitate the man in the construction. Due to digital fabrication methods, new configurations for facades are possible through 3D manipulations of the elements composing the facades. In the Keller AG façade, Gramazio and Kohler have created a diagonal brick structure located in front of the glass façade. The bricks have been revolved around their vertical axis and gradually shifted, creating a diagonal composition that produces a play of light and shadow internally. Working with elementary elements, such as bricks, allowed the designers to focus more on combining digital design and manufacturing without having to develop complex building components (Naboni, 2015)

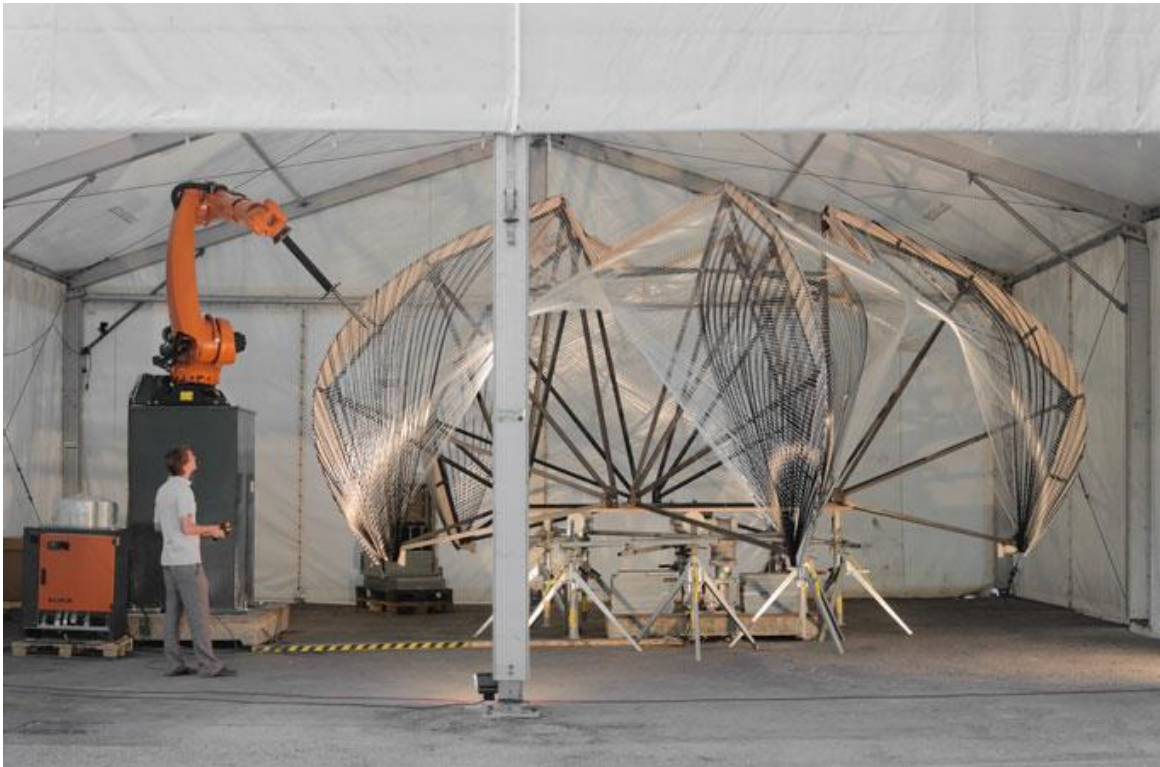


Figure 33 - ICD/ITKE Research Pavilion 201 2(Naboni, 2015)

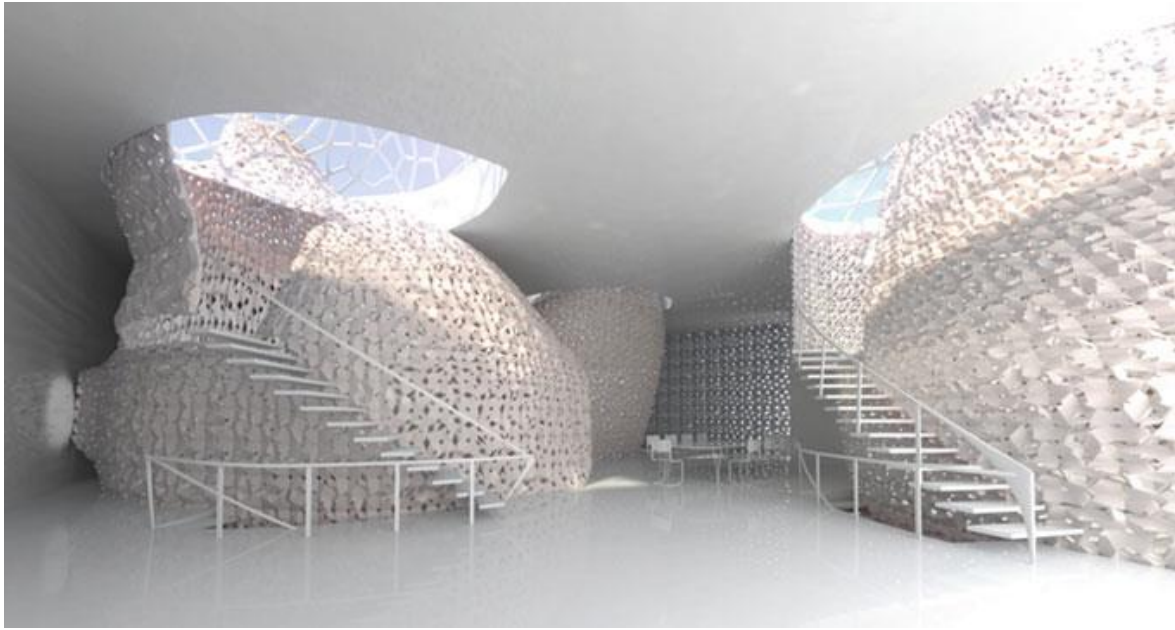


Figure 34 - 3D printed house (Naboni, 2015)



Figure 35 - The design of the façade (Naboni, 2015)

The Additive Manufacturing (AM) is a method executed through the addition of successive layers of materials with the use of one instrument. Commonly known as 3D printing, it is a physical and chemical process, that starting from a CAD model lead to the creation of solid homogenous forms composed of materials like liquids, powders, gas and fibre.

As Naboni et al. (2015) claimed in their research, there are obstacles to the spread of this construction method: for example, the size of the available machines compared to the scale of the buildings. In response to these limitations, major researchers have been busy in recent years developing large-format 3D printers and simultaneously testing various materials with suitable properties for use in construction. The 3D Print Canal House has been designed by the architectural firm DUS Architects in Amsterdam. The designers intended to print the whole house, to explore and improve new solutions for the additive manufacturing of large structures. The house was opened the first time on March 2014, representing an open exhibition space where visitors can be informed about the technology employed, the new solutions and techniques experimented, and where they can attend the printing and construction process. The 3D Print Canal House has several rooms, made by different elements designed by 3D modelling techniques, printed and assembled on-site.

In this research (Naboni & Paoletti, 2015), a particular weight is allocated to the use of software, that can help increase the possibilities of the project, and the materials employed. They investigated the use of parametric software that allows changing and adaptation to the dimension and design parameters. The materials utilized for developing the house were particular plastics produced by the German chemical firm Henkel, mainly obtained from natural sources. The use of natural material supports the primary goal of designers: the recycling and sustainable of the approach.

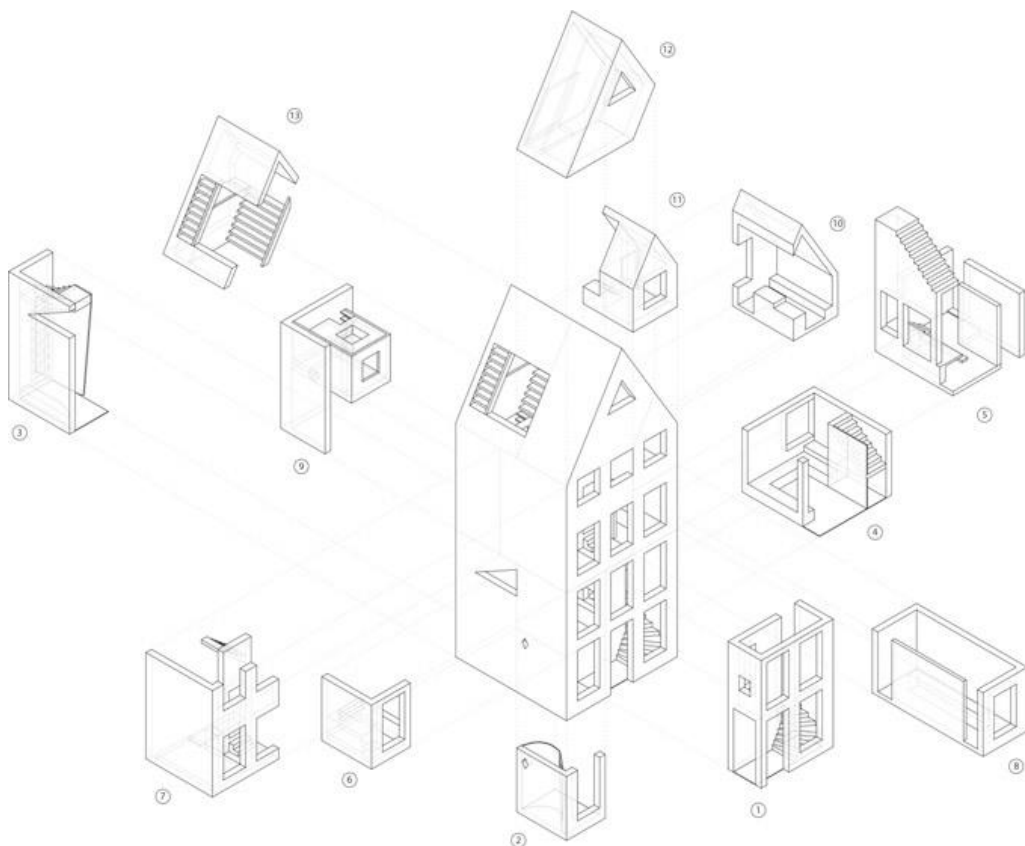


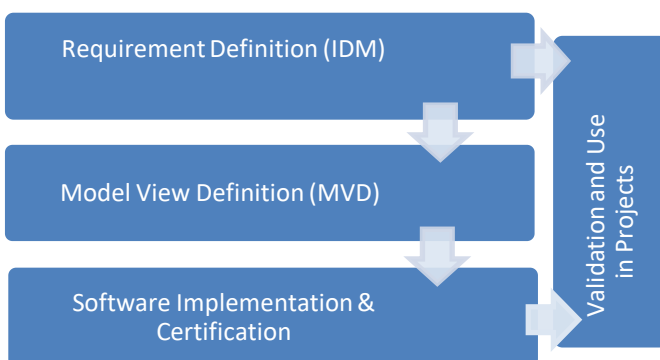
Figure 36 - The 3D Print Canal House (Naboni, 2015)

5.2.2 Various aspects of the interaction between BIM and the prefabrication

BIM is widely adopted in prefabrication because it helps in analysing data. In fact, BIM aids to fit the modules so that there will be no leaks and to give perfect connections into the building. Using BIM, many difficulties related to transportation in a constraint space have been solved. By the 3D visualisation and the computation in Dynamo, the location of the modules can be studied to have maximum efficiency, avoiding waste of space during the transportation. Other significant advantages using BIM regard the Level of development of the elements: prefabrication requires a high level of details in terms of geometrical and non-geometrical information and BIM can provide this level of accuracy. The designing team should be sure that the BIM model is interoperable with the software used in the prefabrication field. Thus, the contractors can use the BIM model and generate details for the production in their prefabrication software: starting from the objects placed in the model, they can develop the high level of detail requested for the production. When the details are approved, the products can be fabricated with machine tools.

The exchange of a BIM model between the parties involved is a significant advancement over the traditional 2D files transfer. In the context of exchanging information, we need standards because it enables the gradual automation of information management. To exchange BIM-based information between tools, we need an open, common data exchange format. IFC (Industry Foundation Classes) file are the most used Open Data Exchange Format for Building Industry.

The research led by Xu at al. (2020) addressed the vital role of the Industry Foundation Classes (IFC). It is an open standard that allow the interoperability between software and contains specific information of each elements of the building and their relationships. However, different researches have proved an inflexibility in the IFC. It is a powerful open format exchanging file, but It is still a defective method. It is a format that can be accessible by all the BIM tools, but unfortunately, it has still some complications.



Building SMART has introduced as solutions of this inflexibility the Information Delivery Method (IDM) and the Model View Definition (MVD) approaches. They represent the required information must be contained in the exported IFC model for a specific use-case. The IDM, normed by ISO 29481, is manifested when the team is formed, and a

program is defined in the third step of the information management process. ISO 29481 defines the methodology and file format to achieve strong coordination between the actors.

The ISO describes how the coordination processes should be identified, and the information required should be delivered. An IDM maps the interactions between team members, exchange requirements,

their transactions and processes It shows who should create, use and benefit from the information flow. It promotes digital collaboration in the building process and provides basis for interoperability in information exchange. In the meantime, MVD should implement the IDM and check whether the derived information complies with the standards. A standard Model View Definition is a subset of the industry foundation classes, IFC schema. It can be used to filter data in software tools following specific exchange requirement. For example, for energy analysis, we only need the envelope of the project.

On Building SMART, it is possible to achieve 128 different IDM documents with different status and purpose. A lot of researches are focused on specific uses of the BIM model and on how the IDM can manage and standardize the exchange processes. In particular, the mentioned paper represents relevant research and develops an IDM-based methodology for more reliable prefabricated construction delivery. Their approach proposes to extend the IFC concept to prefabricated construction. It inserts the developed ontology of prefabricated construction into the IDM standard and manages it in a database (Xu et al., 2020).

Compared with traditional on-site construction, prefabricated construction requests an higher amount of information to exchange among stakeholders involved in the process because the stakeholders are more. The procedure is complicated because the elements that have already been realized and arrive at the construction site must be placed exactly as they are designed and must correspond exactly to each other. Moreover, in many cases the prefabricated construction exists alongside traditional in-situ concrete construction. Process management and cooperation are essential, as the prefabricated elements must work together with different construction methods.

The preparation process of information exchange consists of two phase: the requirement delivery and data delivery. The IDM (Information Delivery Manual) is the basis for delivering the information request based on the IFC system. It defines each phase of the specific project, the information required by every stakeholder during each step. Then the MVD (Model View Definition) maps the information requirements. If the process is well defined, this leads to the reduction of redundancies in information delivery, to the avoidance of information loss and to an increase in delivery efficiency.

During the Data Delivery process, the delivery requirements are converted into data information. This means: carefully defining the IDM standard, mapping the IFC entities with the IDM standard to form information sub models, defining the MVD according to the software delivery requirements and generating the information sub models.

The exchange of information occurs through an IFC file, that is widely utilised in the industry. Even though the prefabricated method takes an essential role in the AEC industry, there is no support in IFC. The mentioned paper expresses the lack of IFC representative support for the prefabricated construction industry. The researchers list several representative prefabricated component properties and the relationship between classes, that are added to the IFC as extended attributes using the EXPRESS -G language. The figure below, extracted from the paper, shows what they propose.

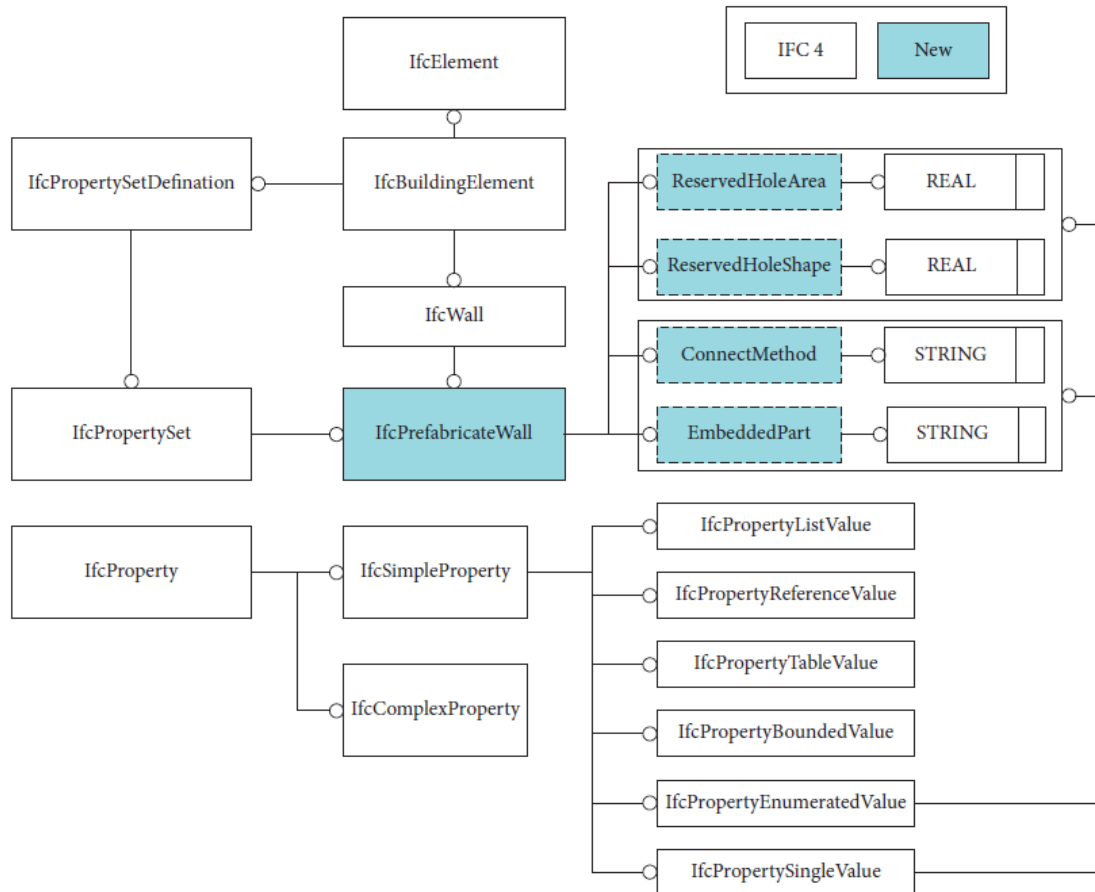


Figure 37 - EXPRESS-G diagram for Prefabrication Wall Extension (Xu et al., 2020)

The purpose of this study was to enlarge the concept of IDM for prefabricated buildings in such a way that the information needs can be documented. The data must be managed in order to improve interoperability. It is therefore essential to create a database containing the data developed by the proposed approach to facilitate the delivery process. It allows stakeholders to use it in a user-friendly way. In this study, the researchers have proposed a webserver and User-Interface (UI) for the implementation process. The IDM has been stored into a relational database, and a User Interface has provided a simple way for users to manage data and export the information among stakeholders. According to the stakeholders involved in various processes, the users have selected the corresponding model creator (the architectural model) and model receiver (structural MEP or manufacturer). Afterwards, the users have received the exchange requirements exported in EXCEL format from the webserver.

This study provides a workflow to facilitate the exchange of information in prefabricated construction. Basically, they have suggested a database as a collection of information requirements in the field of prefabrication. In this area, the challenge for the parties involved is usually the specification of BIM objects, mainly due to the lack of a useful IFC scheme for prefabricated construction. The IDM can be

employed to create the knowledge fundamentals of the prefabrication domain to ensure the correct information delivery of the entities of the model. All information is inserted into a database and can be recovered more quickly. As Xu et al. (Xu et al., 2020) claimed, in order to facilitate and automate information exchange as a next step, it is crucial to explore the development of a global IDM server for the AEC industry to reuse exchange requirements.

5.3 Case studies

5.3.1 Brief Analysis of the company, its BIM capability and general processes involved

TRIMO is a company specialized in envelope building: it creates system solutions for roof and wall, applied on designing project. In general, a production process is divided into several steps.

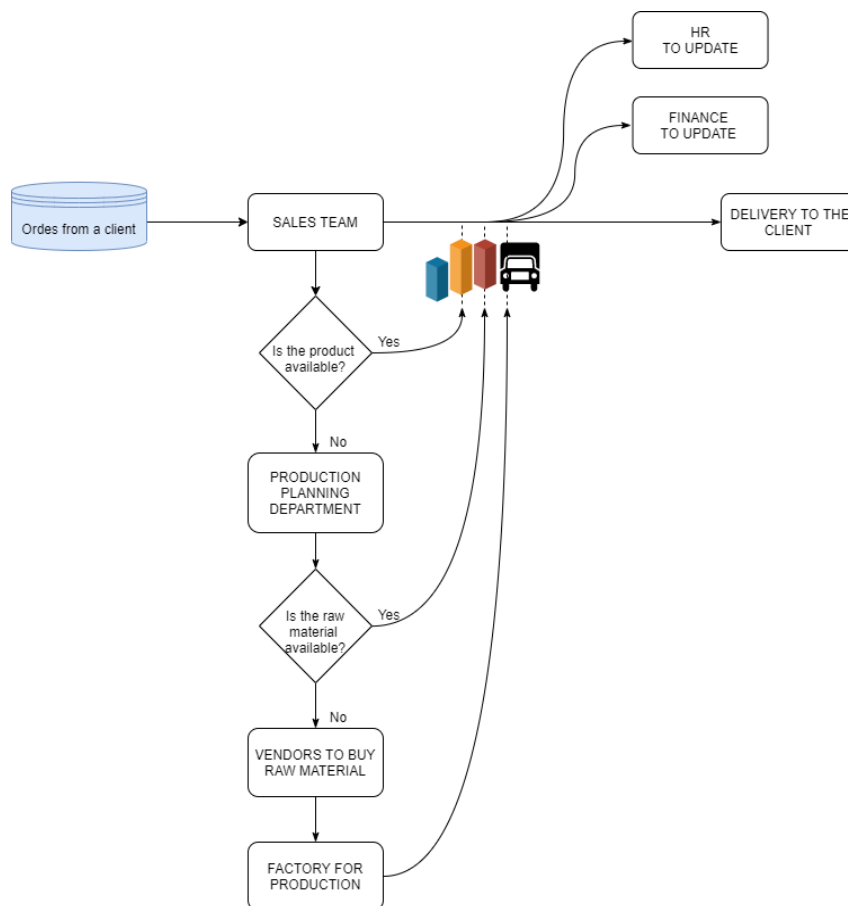


Figure 38 - General Step of Production Process

A client contacts the sales teams and asks for a specific product. The sales team requests about the products availability to the inventory department. In case the product is not available, the production

planning department is contacting by the sales team to manufacture the product. The Production Planning Department verifies the availability of raw materials. In the case of raw materials lack, the production orders and buys other supplies from the vendors. The raw materials are transferred to the internal factory for the actual production. Finally, the created products are sent to the client, and the finance department is updated with loses and revenues, generated respectively by the purchase of raw material and sale of the finished product. All departments update the HR for any human resource related issues.

The production process in TRIMO follows the steps explained above. In order to respond to the specific case, TRIMO receives orders for products from external actors. The salesperson determines the order by identifying the quantity and characteristics of the products. Since the amount of information is very large and cannot be managed manually, the collection and management of all information is done by SAP (Systems Applications and Products in Data Processing). SAP is a software solution very useful for the managing of business procedure and client relations. The SAP system is organised in modules that support every aspect of business management. SAP represents an ERP (Enterprise Resource Planning) and describes a centralized system. The data is maintained in a central location and shared by different departments. It allows all departments in the company to access information or data from other departments, and all departments regularly update the central information system. Therefore SAP helps to overcome a variety of problems related with data management, enhances productivity, allows a better inventory management, promotes quality, reduces material costs, provides an efficient human resources management, increases profit.

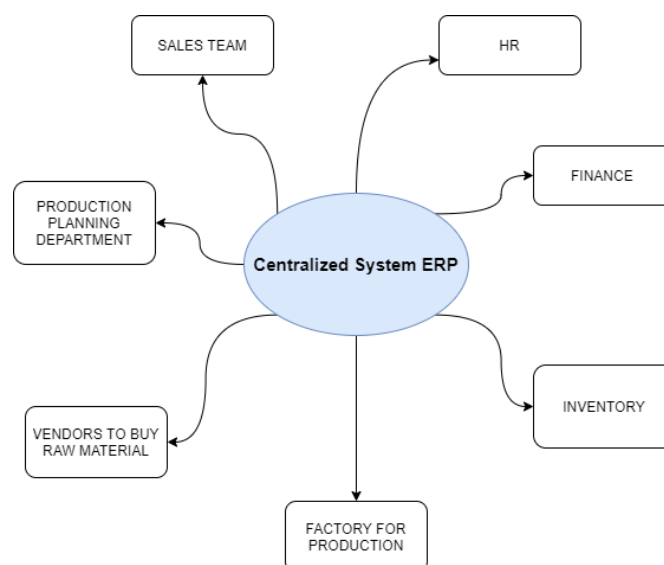


Figure 39 - Centralized System ERP Schema

Detailing the benefits, SAP standardises data across an entire company or multiple company. For instance, if there is a part that needs to be required every time the inventory reaches a certain threshold, rules can be set up to automatically order new part from the vendors. It facilitates better decision-making because all of business' processes are in the same system. Access to this information in real time enables decision-makers to collaborate, solve problems and spontaneously identify opportunities. SAP is known for prioritizing an organization's security and compliance. Some SAP's features allow for appropriate segregation of duties. It ensures only those who should be able to see sensitive information or make business decisions have the access to do so. It's also possible to customize SAP configuration settings with a company's policies, ensuring compliance across the system and with federal regulations. On the other hand, SAP also has some negative aspects which constitute a limitation: SAP is notorious for a very high total cost of ownership. There are very high acquisition and implementation costs, paired with recurring maintenance costs.

After the integration of information on SAP, the engineer's team, starting from the architectural project, can proceed with the development of the detailed drawings that will be sent to the factory for the production. The figure below shows schematically a common TRIMO process that involve SAP.

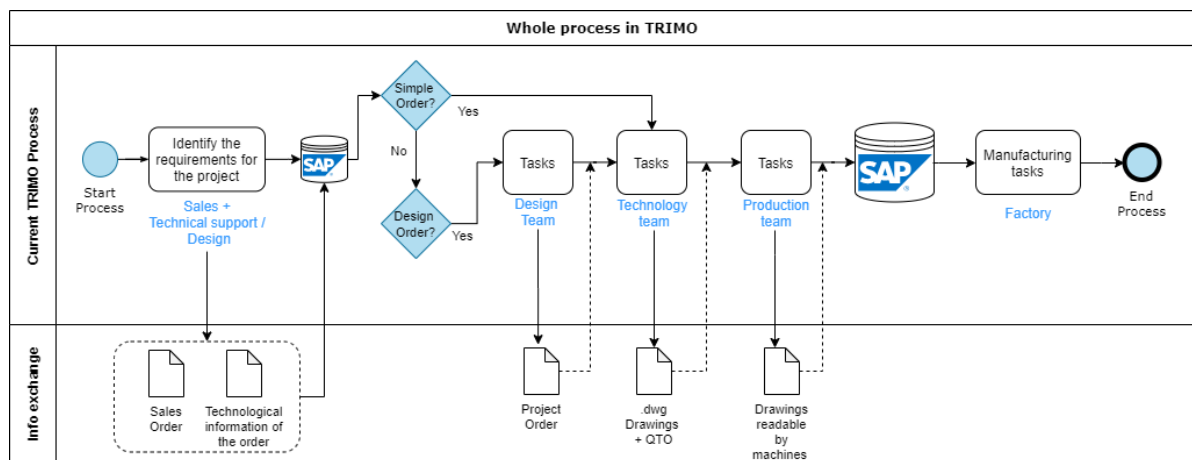


Figure 40 - Schema of a general current process in TRIMO

The company is already oriented to database concept. Indeed, through the use of SAP, they are already aware of the importance of helping software to manage the significant amount of information. Despite the database-oriented, the company has a level 1 of BIM maturity because the process is based on reception and elaboration of .dwg drawings, sent to the factory for the production. The engineers team receives the .dwg files of the project, elaborated by external offices, and the information from SAP to implement the drawings. Furthermore, they have developed a web library of 3D BIM objects, available

for both ArchiCAD and Revit. These features could be considered a good start point in the transition of BIM.

The purpose of this thesis was to demonstrate that BIM can give significant support to the manufacturing preparation process, and the passage from level 1 to level 2 is mandatory.

To date, the design phase is performed using CAD software and an AutoCAD plug-in that they believe can automate the processes. In this research, it has investigated this design phase, giving an alternative based on BIM and computational design. Their processes have been established for many years, and the BIM transition is still not considered. A drastic shift to BIM is even perceived as unnecessary. But what will happen in the company when BIM technologies seduce all phase of the construction processes around the world? A leading company like TRIMO must start to implement its processes, so as not to fall behind when it is too late.

5.3.2 Analysis of the design phase and the family objects

With the growing use of BIM applications worldwide, the role of prefabrication is increased and the use of digital objects that represents their manufacturer components as well.

TRIMO has in its channels a BIM library of families freely downloadable and usable for the model envelope and video tutorials that explain how to use them. The library contains Revit and ArchiCAD families, and the video tutorials are for Revit and ArchiCAD as well. To develop the thesis, it has been considered useful the families library. It is on a primordial state, but these BIM objects have the power to assist the designers in selecting the most appropriate component that aligns to design intent and to improve the workflow between designers and production disciplines. This research has demonstrated the powerful utility of the computational design within BIM and the BIM itself, especially in the manufacturer field. Since there is no use of BIM in TRIMO company, it is crucial to influence with BIM technology each phase of a project, starting from the initial phases. The intent of this study was not to intervene in the production discipline, but to show the practical utility of the BIM technology affecting the design phase. Usually, this phase is considered the preparation phase that provides suitable information used to produce the panels. In view of future development of the TRIMO company towards new production technologies, it was important report the research led by Hamid et al. (2018) that has studied the benefits of the application of BIM objects especially when is used the CNC machinery. TRIMO company uses conventional machines and not advanced technologies but in general, during a manufacturing process, geometrical and non-geometrical data have to be produced and read by machines.

The research (Hamid et al., 2018) has examined the CAD and CAM (Computer-Aided Design and Computer-Aided Manufacturing) systems that relate to a group of technologies used for the design, analysis and manufacture of components. As mentioned in chapter 4.2, three basic elements are required for a CAD / CAM system to work: first, an application to create the object to be realised (CAD); second, an application through object geometries are read and manufacturing processes are specified in the form of instructions (CAM); third, at least one CNC machine that produces the desired part of the object and converts the instructions from the CAM application into machining operations organised in a specific order. Based on these considerations, the research (Hamid et al., 2018) has proposed a workflow that benefits from a BIM technology that attempted to go beyond the workflows associated with CAD /CAM and CNC applications. To this end, BIM objects played a crucial role and must be informed by manufacturing instructions. In fact they wanted to link the BIM object directly to the production, jumping the phase intermediate. This type of workflow would exploit the machine-readable advantages of the BIM technology; whereby the information from BIM design models directly informed the production of elements. To achieve this workflow, however, the BIM representations must consider the knowledge of how the components are realised. Therefore, a different type of knowledge is required to link BIM applications to CNC manufacturing: machining knowledge (Hamid et al., 2018). Therefore, with the development of BIM technology, it grows the necessity to replace conventional CAD / CAM workflows, through the introduction of BIM components and BIM applications. An increasing number of practical implementations have begun to explore the potential collaboration between BIM and CNC technologies.

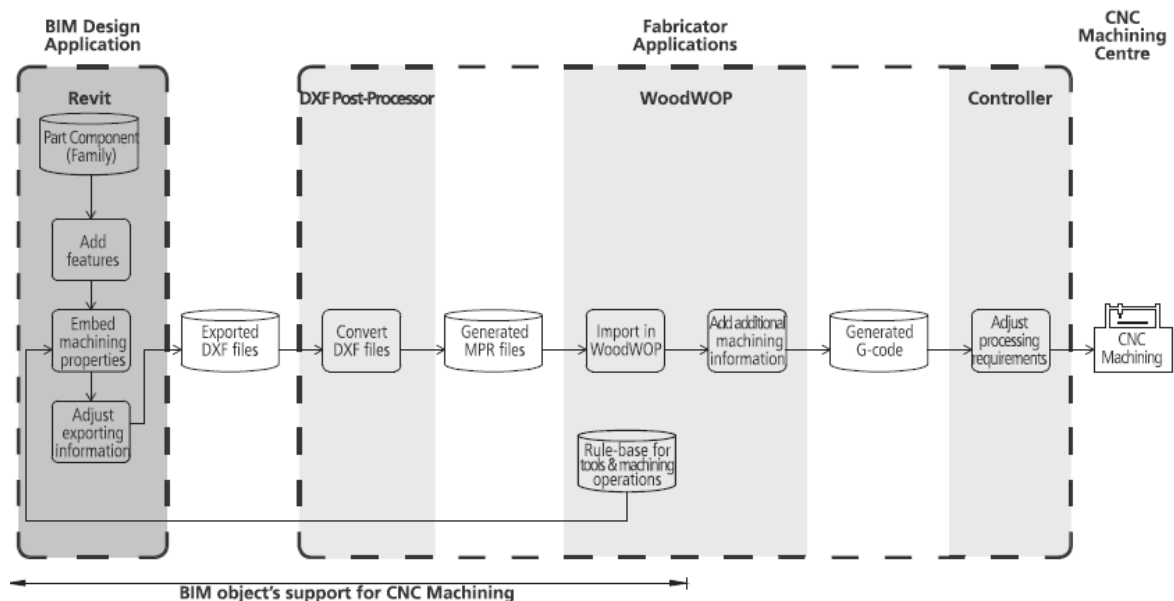


Figure 41 – Workflow that use BIM object for CNC machining of parts (from Hamid et al., 2018)

The cited research (Hamid et al., 2018) has focused on the production of wood components employing a Homag 3-axis CNC machining centre. In the research, they have proposed a workflow that allows the interaction between BIM component and CNC machinery, using DXF (Drawing Exchange Format) file as an exchanged file from the design phase. The WoodWOP is the programming application used during the CAM process. In order to allow switching between application, the geometry and features in the DXF file have followed a specific naming convention based on the database of the machine, to be interpreted by WoodWOP. Thus, the information contained in the drawing files has been transferred as machining instructions. The conversion process could fail for lack of layer naming structure. Indeed, these rules were associated with CNC machining operations.

From their study (Hamid et al., 2018), it has been emerged that the BIM objects have to be enriched of 5 kind of parameters: dimensions, constrains, materials and finishes, visibility (parameters used to control the visibility of certain parts), identity data.

The research has shown the possibility of improving the workflow between designers and producers. However, it also has indicated that this is an area not yet entirely clear. This research has focused on a manufacturer with specific knowledge and a particular manufacturing process for planar or prismatic units. Therefore, this research did not provide a general answer to a general production improvement through the use of BIM objects. The approach outlined in the paper could be applied to further research using object BIM libraries within a manufacturing company.

The paper in the final chapter has suggested other avenues for this research. G-code is the language used by users to say computer-controlled machine tools how to produce something. The G-code instructions tells the motors which path to take and how fast to go. As long as the basis for most CNC machines is G code and further research could focus on developing knowledge that support the generation of G code for component manufacturers using BIM authoring applications. The researchers also have suggested a longer-term plan that could break free from the disadvantages of G-code by focusing on integration between IFC and STEP-NC. STEP, the standard for the exchange of product model data, (ISO 10) is a neutral file format used to share information in CAD system.

Such an effort could enhance information exchange between stakeholders who adopt BIM and fabricators using CAM and various CNC machines. In this context can be used documents as Information Delivery Manuals (IDMs) for different cases, improving their exchange requirements and describing specific domain of the Model View Definitions (MVDs).

The mentioned research it has been considered very interesting, because it has analysed the use of BIM objects allowing the enhancing of the workflow between designers and fabricator. The BIM process has altered the way manufacturers and designers interact and cooperate. Offering high-quality BIM objects that are easy to access and download enables stakeholders to integrate their products into the design process at an earlier stage. Therefore, it becomes a valued resource of knowledge that is invited to

participate in and contribute to decisions about the design. From a manufacturer point of view, that means new business opportunities and new sales process. The design decisions can be better informed. By creating a BIM object model, there are possibilities to simulate a series of tests to see how different variables affect the function and performance of the product.

5.3.3 Detailed analysis of the current processes involved in the design phase

This research investigated the design phase processes. Generally in a normal design process in TRIMO, they receive the dwg file of a project, and the engineering team develops the detailed drawings to send to the production. During the design phase, the engineers have to propose a technical solution for the envelope system elaborating elevation drawings of the building, detailed drawings of the architectural connections and tables of panels quantities. They receive from the management team, through SAP modules, technological information of the panels preferred for the project. The technical information are entered manually in the tables of quantities. TRIMO uses a “Material Code” to identify the panels in SAP. This procedure helps in to prepare the “sales order”. Afterwards, enriching with detailed information by the technical support, the package becomes the “production order”. The general scope of the procedure is to describe in detail the panels and their features in order to provide suitable information for the production. The package sent to the factory for the production phase at the end of the design phase, is comprehensive with Quantity Take Off and technological information of the panels, and detailed drawings of the project.

Usually, the technological information appears in the tables as numerical or alphabetic codes. They give information about the typology of panels: the thickness, the color of the external sheet, the typology of insulation, the color of the internal sheet.

All the characters form an identification code for each panel. The figure 42 and 44 show examples of a table that, in the current workflow, enrich the drawings sent to the production. The tables contain the Identification code (Cladding element name) of the panels and also the width, the length, the color of the external sheet and the total area. The panels with the same “Item” have the same features.

Moreover, in the elevation drawings, the panels and the façade to which they belong contain tags, in order to make clear the identification of the panel and the façade containing the panels. All the process is performed manually, and it takes a lot of times. It is normal in this kind of workflow to lose information or insert wrong information.

Q150-1000 9010 PVDF 70/9010 SP 50-KT

Q	150	1000	9010	PVDF	70	9010	SP	50	KT
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Figure 42 - Example Identification Code

CODE	Meaning
F	Trimoterm Facade
Q	Qbiss One
QS	Qbiss Screen
150	Thickness of Panel
1000	Width of Panel
PVDF	
HPS	
PUR	External protective coat
SP	
70	Thickness of External Sheet
9010	RAL of internal sheet
SP	Internal protective coat
50	Thickness of Internal Sheet
KT	
KS	
K2	Type of wool
K4	

Figure 43 - Meanings of code

Wall: F1	Area: 148,268 m ²	
80031258	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	148,268
Material ID	Naziv fasadnega elementa	Area [m ²]

1	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	1	934	TRAFFIC RED	0,934
2	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	1	1200	TRAFFIC RED	1,200
3	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	1	1200	TRAFFIC RED	1,200
4	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	1	1200	TRAFFIC RED	1,200
5	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	1	1200	TRAFFIC RED	1,200
6	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	24	2800	TRAFFIC RED	67,200
7	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	24	3000	TRAFFIC RED	72,000
8	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	1	934	TRAFFIC RED	0,934
9	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	4	300	TRAFFIC RED	1,200
10	Q150 M-GS-TRAFFICRED PUR070/9002SP060-K4	1000	4	300	TRAFFIC RED	1,200
Item	Cladding element name	Width	Piece	Length	Dec.trim	Area [m ²]

Figure 44 - Example of table containing technological information

The case study of the presented research is the KJG Business Centre, built in Bratislava, Slovakia and completed in 2015. TRIMO and Bouda a Masár architectural firm provide an integrated building envelope solution for the KJG Business Centre. KJG Business Centre is a mixed-use building complex, composing by offices, production and storage facilities. The different uses give different façade types

to be applied. The exterior building appear formed by three cubes coated by red panels and connected by a system of glazed façade and grey panels.



Figure 46 - KJG Business Center



Figure 45 - KJG Business Centre

5.3.4 The proposed process and workflow

Before to talk about the design phase, which is the one investigated, it is crucial to understand the context in which the 3D model and the production information required could be shared. A BIM implementation is not just the use of BIM software, but it consists of following rules that allow the standardization of the processes.

The following figure 47 gives a general overview of the BIM implementation. A EIR and consequently, a BEP are created and exchanged between the process participants. The CDE is created to share the BIM model containing the information according to the requirements. Several actors with different tasks will be involved in the process. The TRIMO company will intervene after the end of the architectural design process.

The practical phase of the research is described in the following chapters. It is illustrated how computational design applied to a BIM model can support the design process and speed up the workflow. It is provided an alternative process to TRIMO procedures, which are still closely related to AutoCAD. For the development of the model the files was received in *.dwg* format from the company TRIMO. The files contained the detailed drawings of the project developed in AutoCAD and a few information about the workflow. Unfortunately, much information has been omitted or not transmitted, and it was not possible the cooperation with the employees involved in the processes.

Despite the difficulties, the research would point out the advantages of computational design to overcome some repetitive and tedious tasks, similar in every project. Usually, some of the tasks requested by the production team to develop the drawings are very repetitive and similar in every project. In the process presented, the BIM manager should provide standards for archiving the scripts. A library of scripts should speed up the whole process, but the scripts should follow a standard structure to be understandable.

The workflow of figure 48 shows how the software is used in the demonstration. The information has been divided into two groups: the geometric information and the non-geometric information. It has been assumed that the BIM Manager shares the information requirements. Depending on the typology of the information, the workflow has preferred a different tools use.

The workflow presented in figure 49 shows more in detailed the steps followed during the research. It defines the use of the scripts according to each single process. The scripts have been developed in Dynamo and run in Revit. In specific cases the spreadsheets developed in Excel have interacted with Dynamo and Revit. Through the use of scripts, the model has been implemented with increasingly information, required for the production phase.

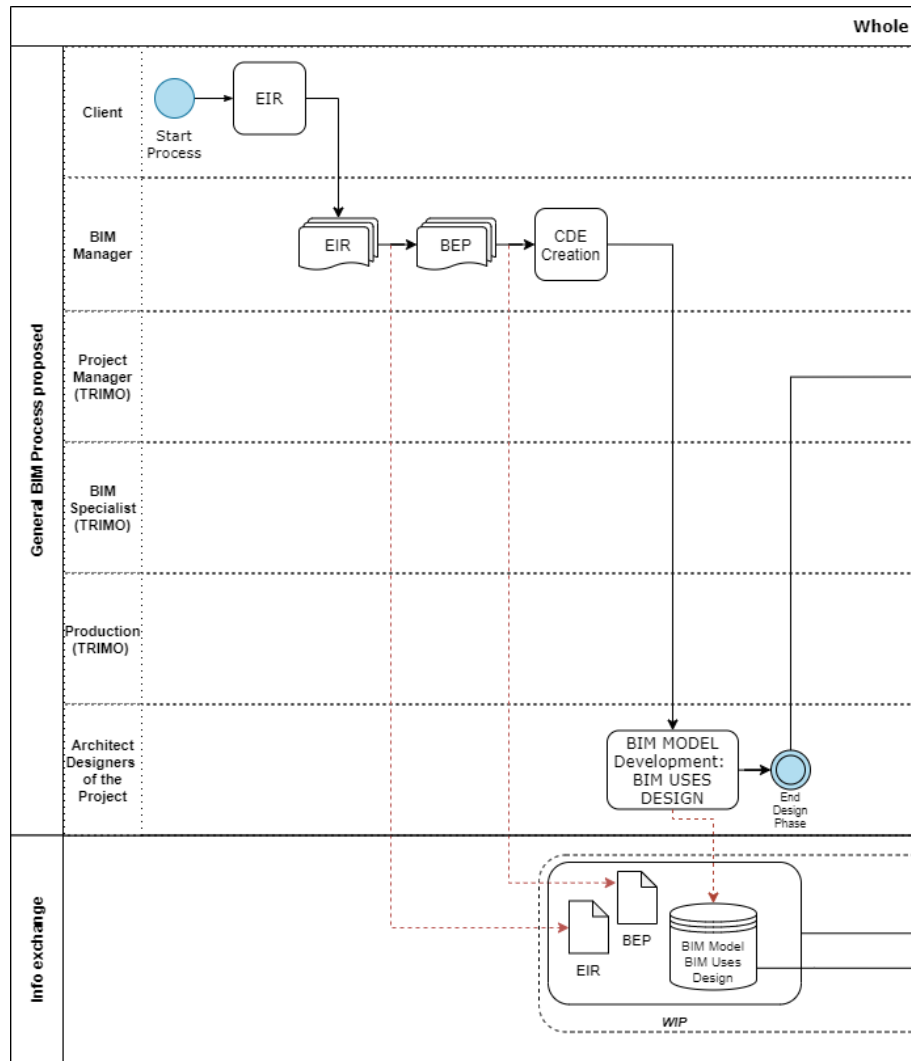
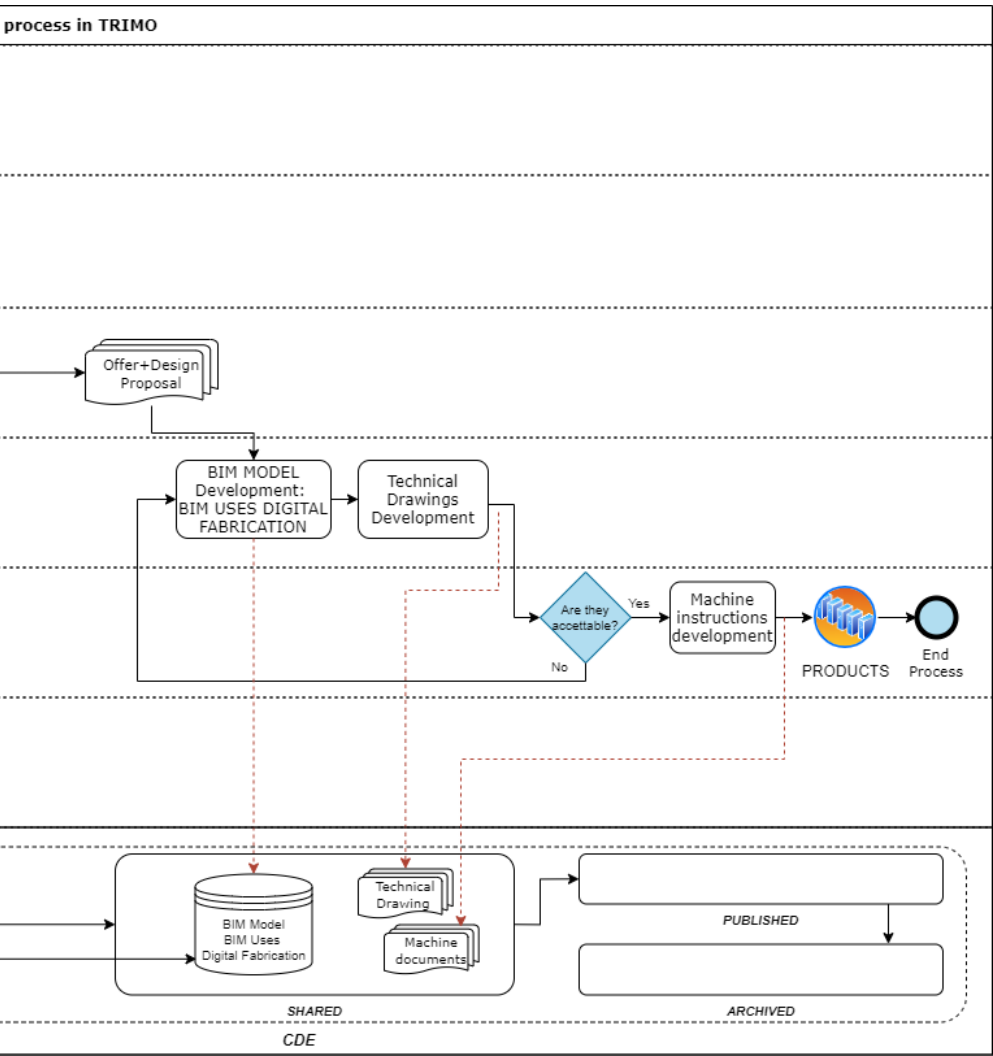


Figure 47 - BIM process proposed



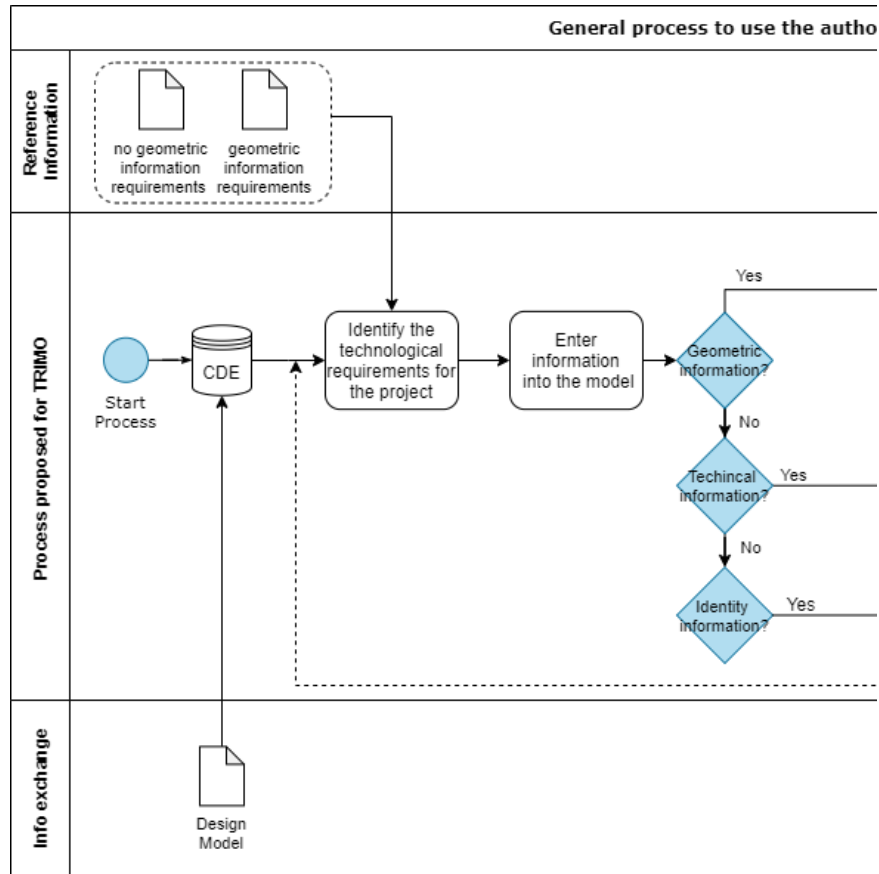
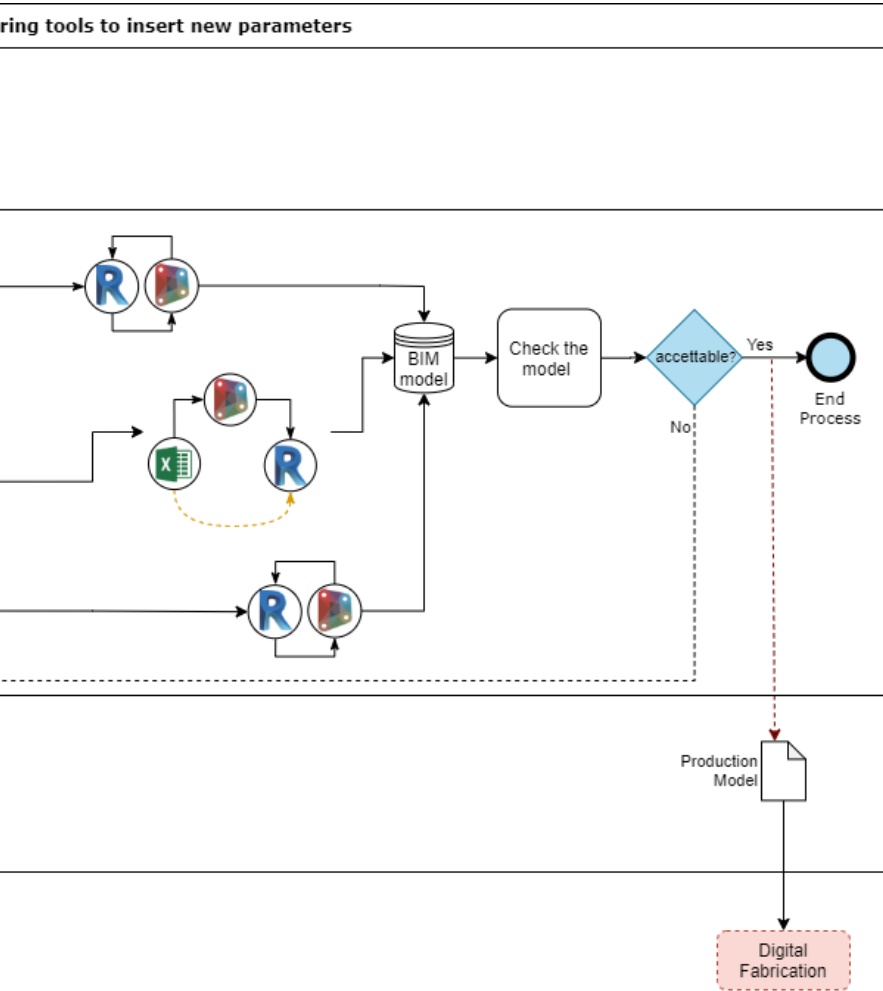


Figure 48 - Software use process



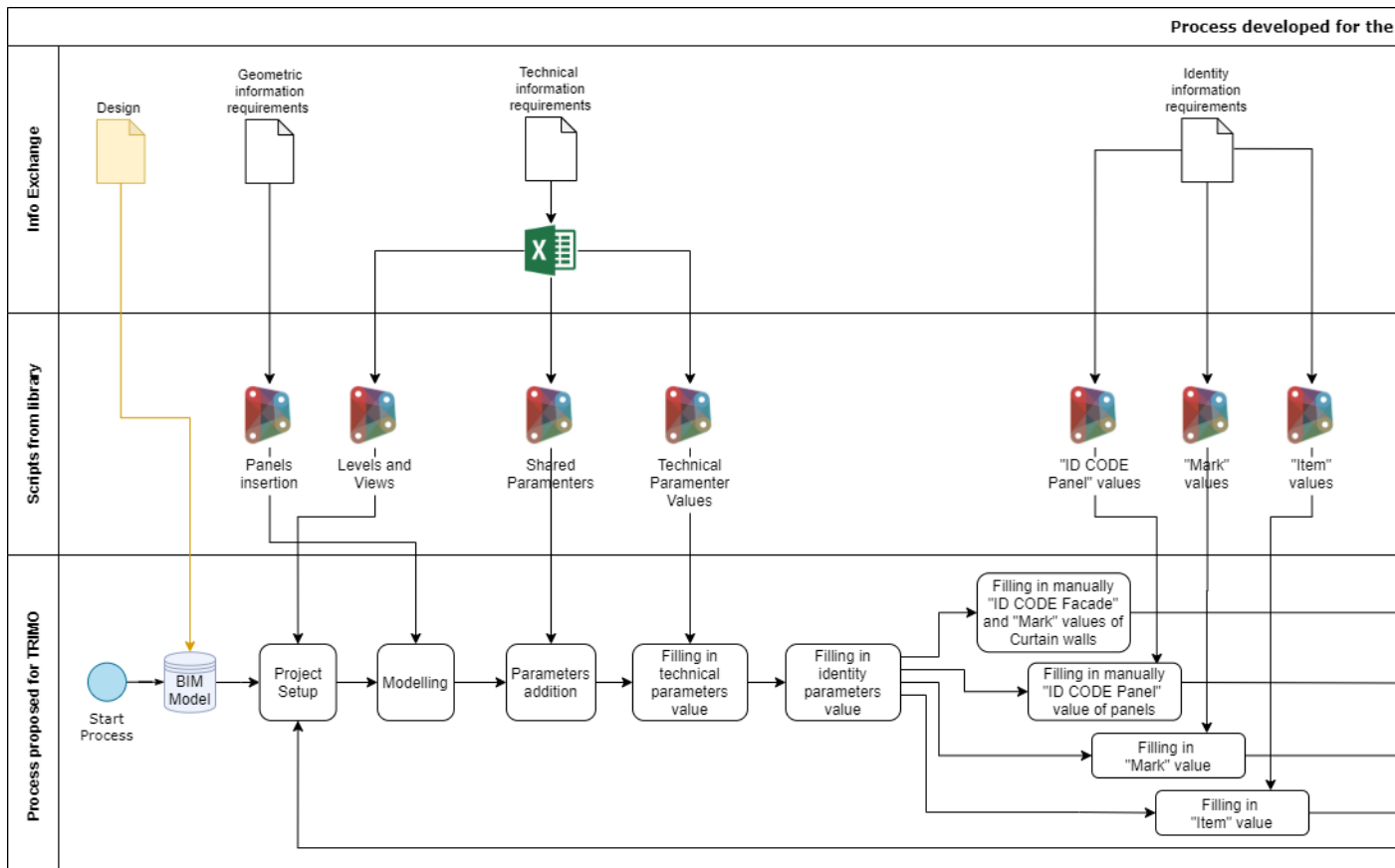
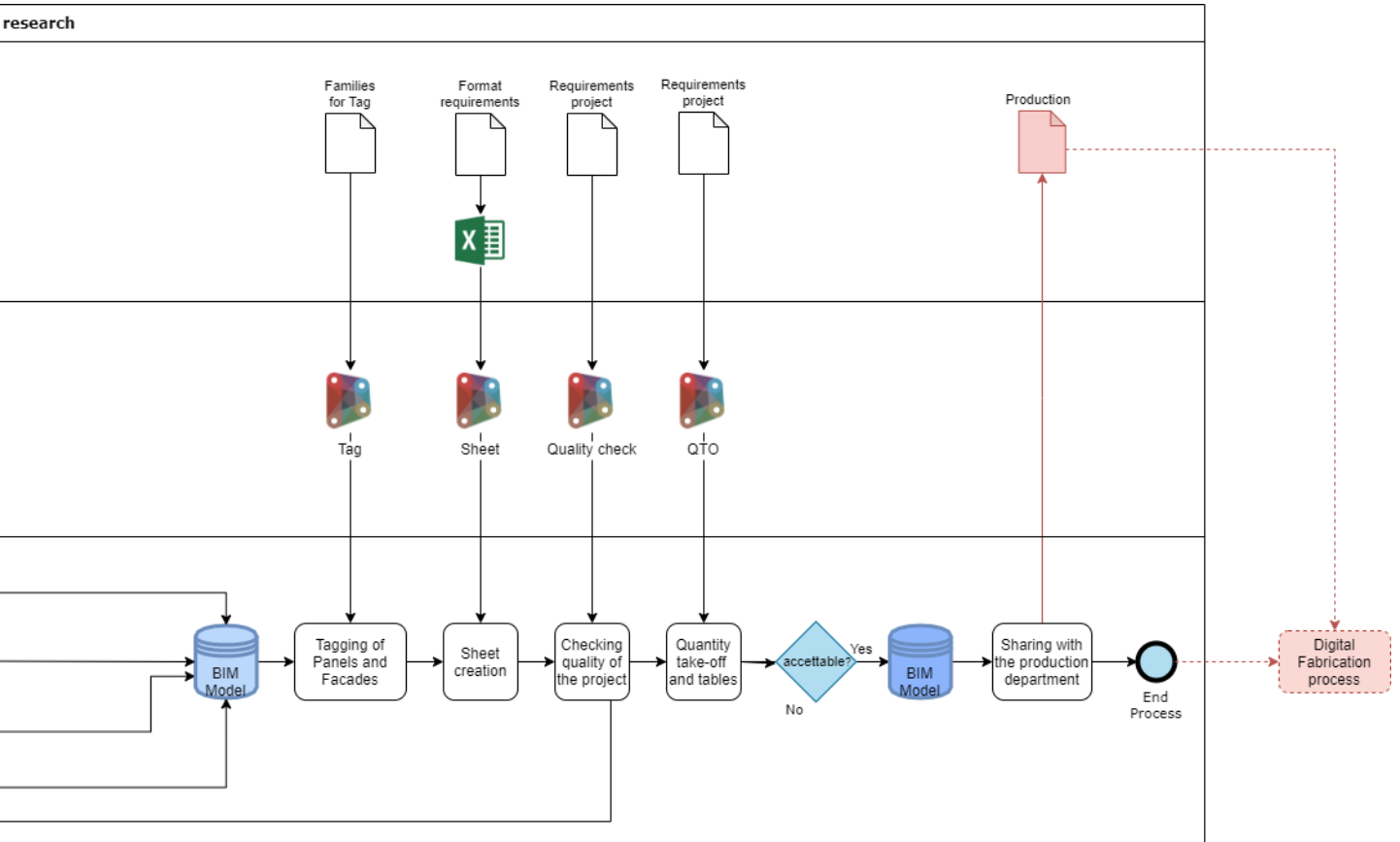


Figure 49 - Workflow developed during the research



5.3.5 Project Setup Phase

The .dwg files of the project were received and the entire building was modelled in Revit. Although it is not typical for a production company to receive a project developed in AutoCAD and decide to perform it with BIM software, the study still has wanted to show the modelling phase.

In the automatization process is very important to incorporate excel sheets. Given the fact that the information are exchanged with SAP tables, and a BIM manager should coordinate the operations, the adding of Excel software in the processes should be not hard.

The workflow below shows the process to automatize levels and view in a Revit file. Using an excel document and organizing it in a way well readable by Dynamo the scripts can be re-proposed for every projects, just changing the information in the excel sheets.



• Follow the naming convention

Name	Elevation
ARC 0	0
ARC 1	5000
ARC 2	9000
ARC 3	13080
ARC 4	13590
ARC 5	17600
ARC 6	18000
STR 0	-200
STR 0a	-500
STR -1	-1700
STR 1	4880
STR 1a	4580
STR 2	8880
STR 2a	8580
STR 3	12880
STR 3a	12580
ARC 4a	13080
STR 5	16880

<Level Schedule>	
A	B
Name	Elevation
ARC 0	0 mm
ARC 1	5000 mm
ARC 2	9000 mm
ARC 3	13080 mm
ARC 4	13590 mm
ARC 5	17600 mm
ARC 6	18000 mm
STR 0	-200 mm
STR 0a	-500 mm
STR -1	-1700 mm
STR 1	4880 mm
STR 1a	4580 mm
STR 2	8880 mm
STR 2a	8580 mm
STR 3	12880 mm
STR 3a	12580 mm
ARC 4a	13080 mm
STR 5	16880 mm
STR 5a	16580 mm
STR 5b	16400 mm
STR 5c	16100 mm
STR 6	17580 mm

STR 5a	16580
STR 5b	16400
STR 5c	16100
STR 6	17580

Table 1 - Excel tables of the levels in the project

Name	Level
ARC 0	ARC 0
ARC 1	ARC 1
ARC 2	ARC 2
ARC 3	ARC 3
ARC 4	ARC 4
ARC 5	ARC 5
ARC 6	ARC 6

Table 2 - Excel tables of the views in the project

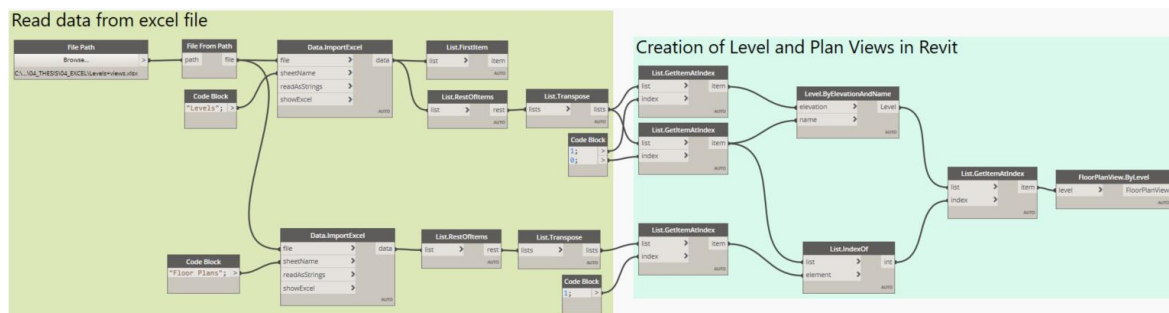


Figure 50 - Script in Dynamo for the creation of level and Plan views in Revit

5.3.6 The modelling phase

The company has developed a library of families. It can be freely downloaded from the web site of the company. The library can support a partner design company to reach the right level of detail of the project and also facilitate TRIMO to receive a model that will not need significant changes.

The BIM objects are divided into two categories: cladding and detail. The elements belonged to the cladding group are the main objects, and they were inserted in the model using the curtain wall object. Once the curtain wall was created, the generic panels of the curtain walls were replaced with a different type of TRIMO’s cladding objects, according to the project.

The families are parametric, which means that it can be adapted to each façade. The second categories contain angular elements, doors, parapets, windows and support elements. The way to insert these elements in the Revit model is different from the cladding elements. The angular components can be placed using the structural column family. This method has involved some problems, like the impossibility to insert a window in the angular of a façade. Windows and doors were added in the model replacing panels of the curtain walls. The figures below show the curtain walls formed by groups of panels and the parameters of the selected panel.

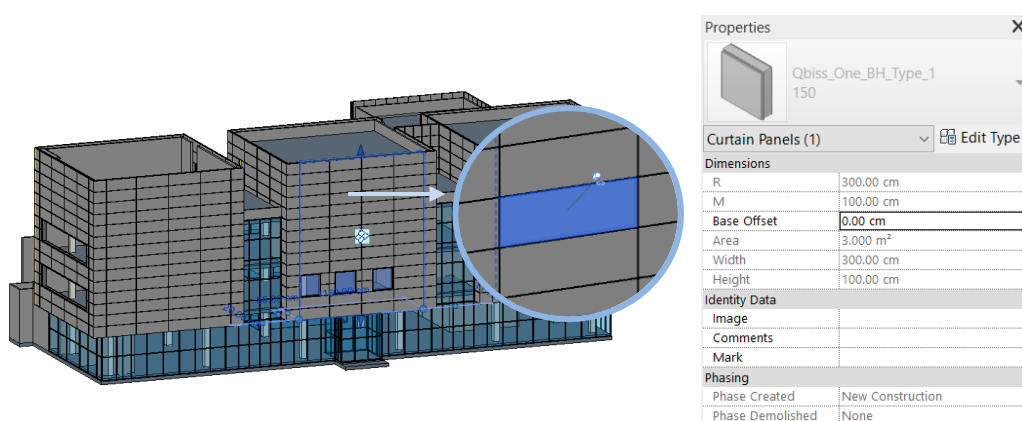


Figure 51 - The model and the elements composing it

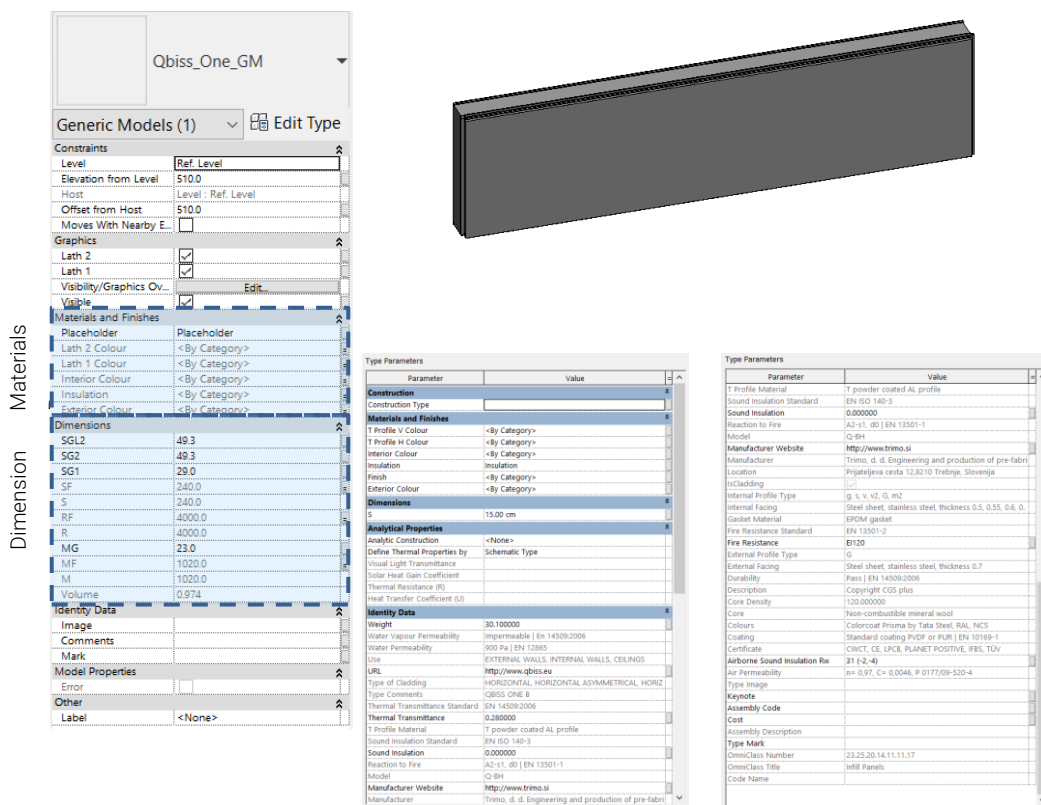


Figure 52 - Starting proprieties of a panel

In this transition period from CAD to BIM and given the fact that they usually starting from .dwg file of the project delivered by external designers, it has been considered useful find a way to automatise the modelling from dwg lines. With this approach, it is possible to have a library of Dynamo helpful script for the creation of walls or curtain walls and available during the transition from dwg file to a Revit model. In Dynamo, by selecting the lines and changing the family and the associated levels of the walls, it is possible to adapt the script according to the project.

The figures below show two different approaches for the creation of the panels façade using Dynamo scripts that run in Revit. Through the first approach, curtain walls were created from a line. The parameters of the curtain walls could be modify according to the project decisions. The second approach was applied to use adaptive components, creating the panels façade starting from a wall object, selecting the edge of that object and creating a list of points. The points were subdivided into lists, and each list contained the 4 points that the adapting components have used to fit in the space.

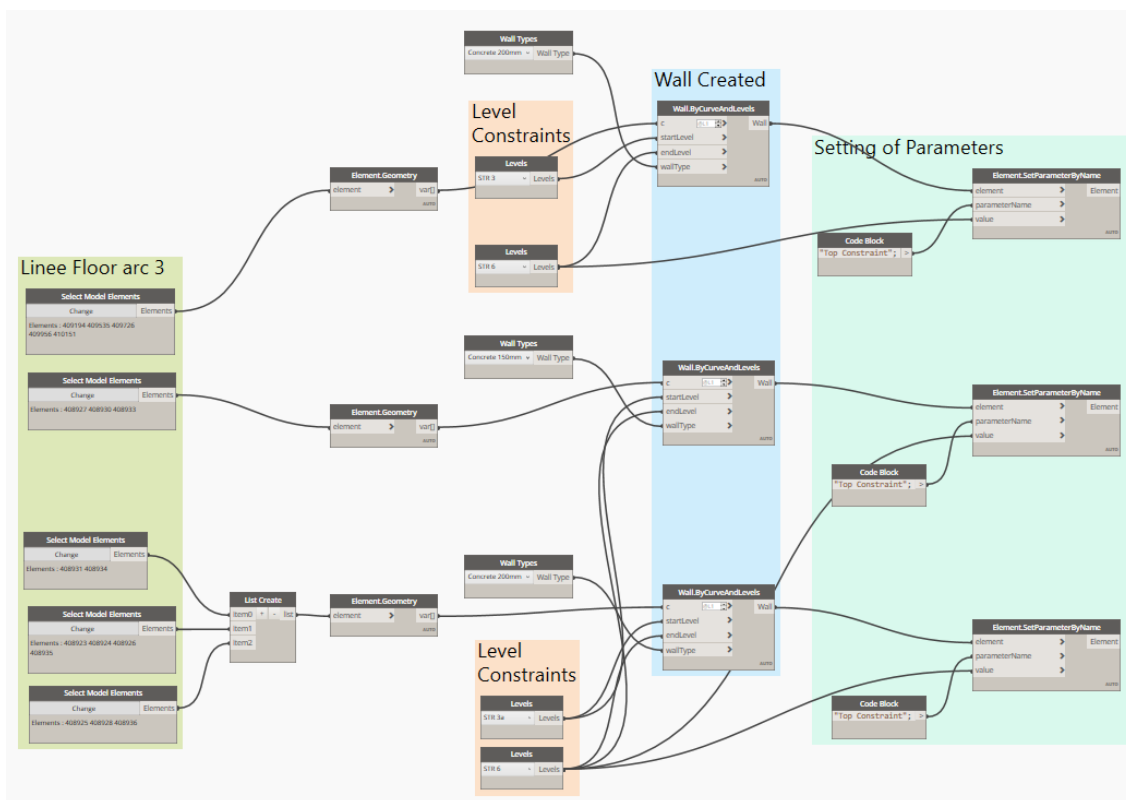


Figure 53 – First approach: Dynamo Script for the creation of walls from lines

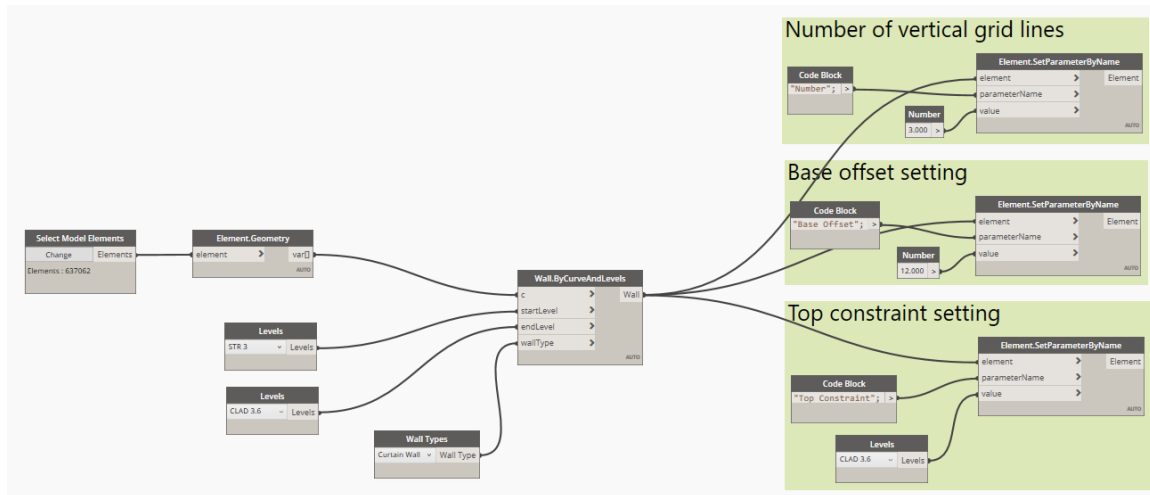


Figure 54 - First approach: Dynamo Script for the creation of curtain walls from lines

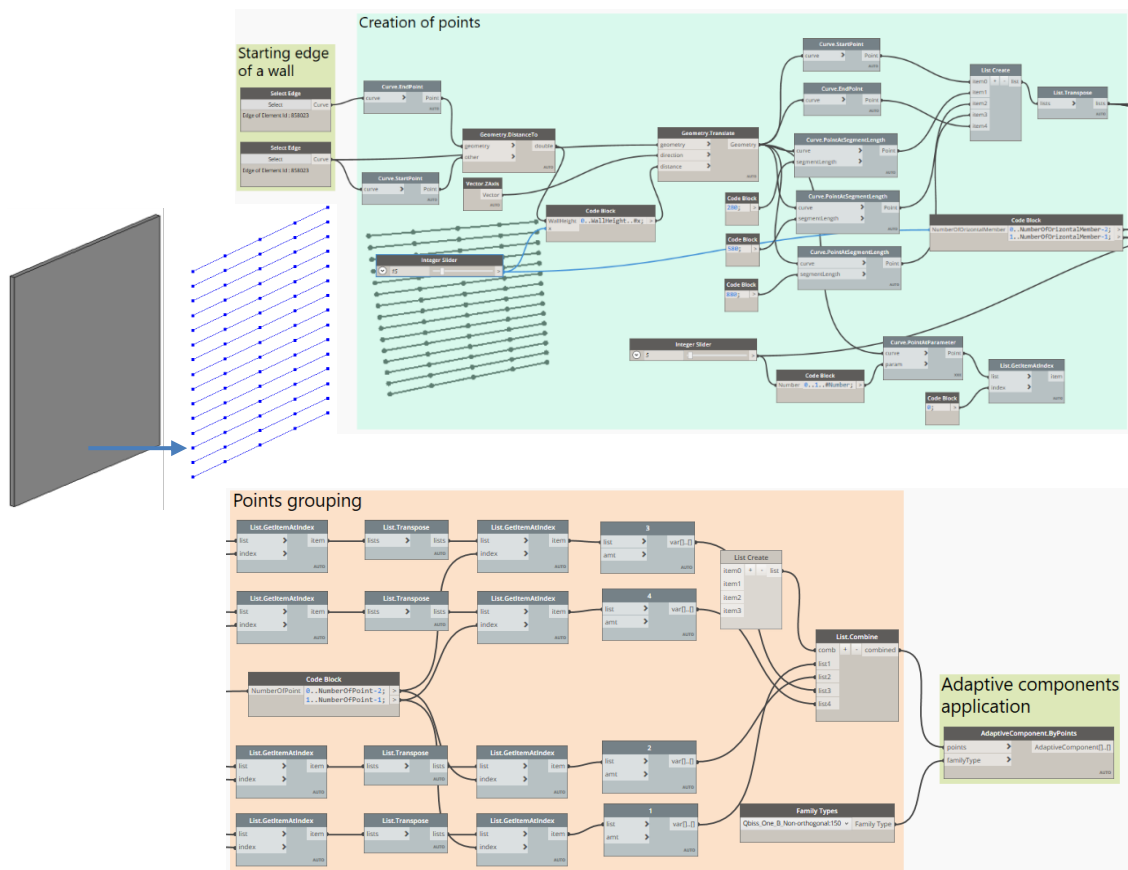


Figure 55 – Second approach: Dynamo script that use an adaptive components

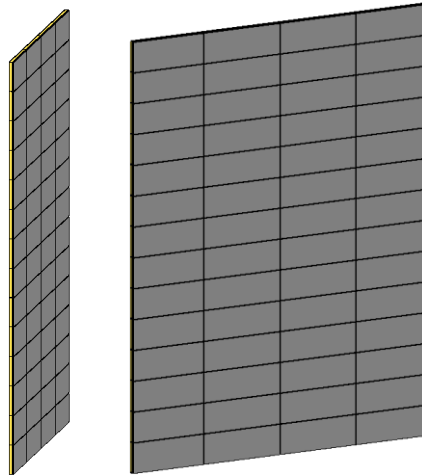
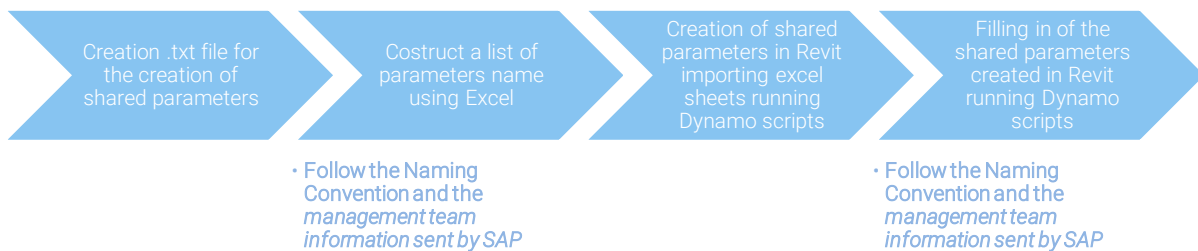


Figure 56 - The panels facade

5.3.7 Creation Of Shared Parameters

To assign the code to the Revit objects, Dynamo was executed. Usually, in TRIMO, the engineering team receives the technical information of the project panels from the management team using SAP modules. Since the documentation received from TRIMO was not enough, the information exchange between the management and engineering team in TRIMO was simulated using Excel files.

The workflow below shows the steps to create the parameters and the corresponding values of the Curtain Walls, the rectangular panels belonged to the Curtain Walls and the angular panels in Revit:



The workflow had been implemented with the help of Excel sheets and Dynamo scripts. First, the *.txt* file for storing the shared parameters was created in Revit. Then an Excel file with sheets of parameter values was created to enrich the properties of the curtain walls and curtain panels. The following tables show the Excel sheets created for the second step of the workflow. One table was used to create the façade parameters, the other to create the parameters of the panel. The values entered in the tables were essential for creating the shared parameters. The shared parameters are definitions of parameters that can be added to families or projects. Usually, shared parameters are stored in an independent file (*.txt*); it allows access to the file from different families or projects. Each Excel sheet had been imported into

Dynamo using the *Data.ImportedExcel* node to create a usable list of values in Dynamo. In the same way, the shared parameters had been assigned to the angular panels (structural column family).

Parameters Name	Group Name	Type	Group	Instance	Category List
ID Code Facade	Identification Facade	Text	PG_IDENTITY_DATA	True	Walls
Colour of Facade	Materials Facade	Text	PG_MATERIALS	True	Walls

Table 3 - Excel tables of the façade parameters

Parameters Name	Group Name	Type	Group	Instance	Category List
ID Code Panel	Identification Panel	Text	PG_IDENTITY_DATA	True	Curtain Panels
Item	Identification Panel	Integer	PG_IDENTITY_DATA	True	Curtain Panels
Type of Panel	Identification Panel	Text	PG_IDENTITY_DATA	True	Curtain Panels
Thickness of Panel	Dimension Panel	Length	PG_GEOMETRY	True	Curtain Panels
Colour of Panels	Materials Panel	Text	PG_MATERIALS	True	Curtain Panels
External Protective Coat	Other Data	Text	INVALID	True	Curtain Panels
Thickness of External Sheet	Dimension Panel	Length	PG_GEOMETRY	True	Curtain Panels
RAL of Internal Sheet	Other Data	Integer	INVALID	True	Curtain Panels
Internal Protective Coat	Other Data	Text	INVALID	True	Curtain Panels
Thickness of Internal Sheet	Dimension Panel	Length	PG_GEOMETRY	True	Curtain Panels
Type of Wool	Other Data	Text	INVALID	True	Curtain Panels

Table 4 - Excel tables of the panels parameters

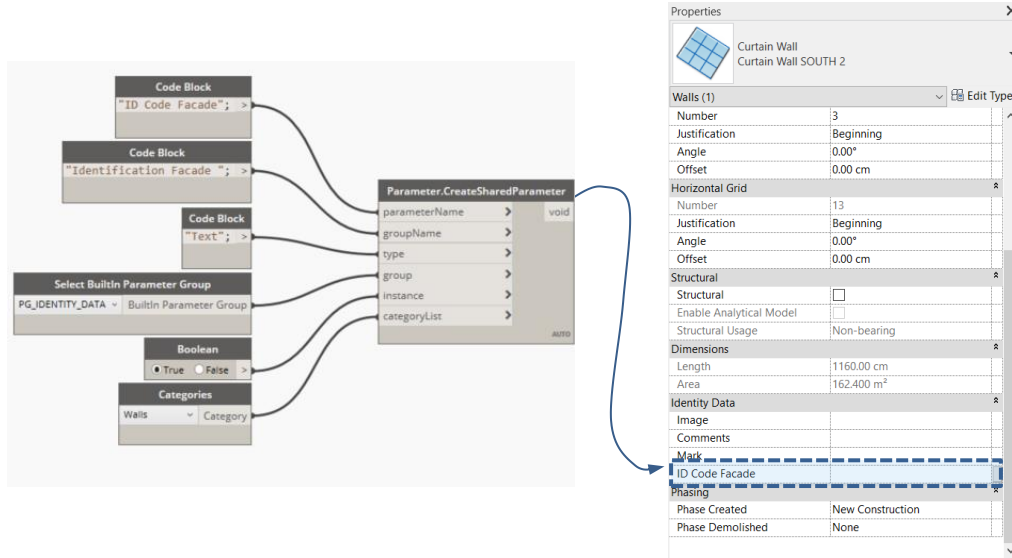


Figure 57 - Script for the Shared Parameters creation of the facade

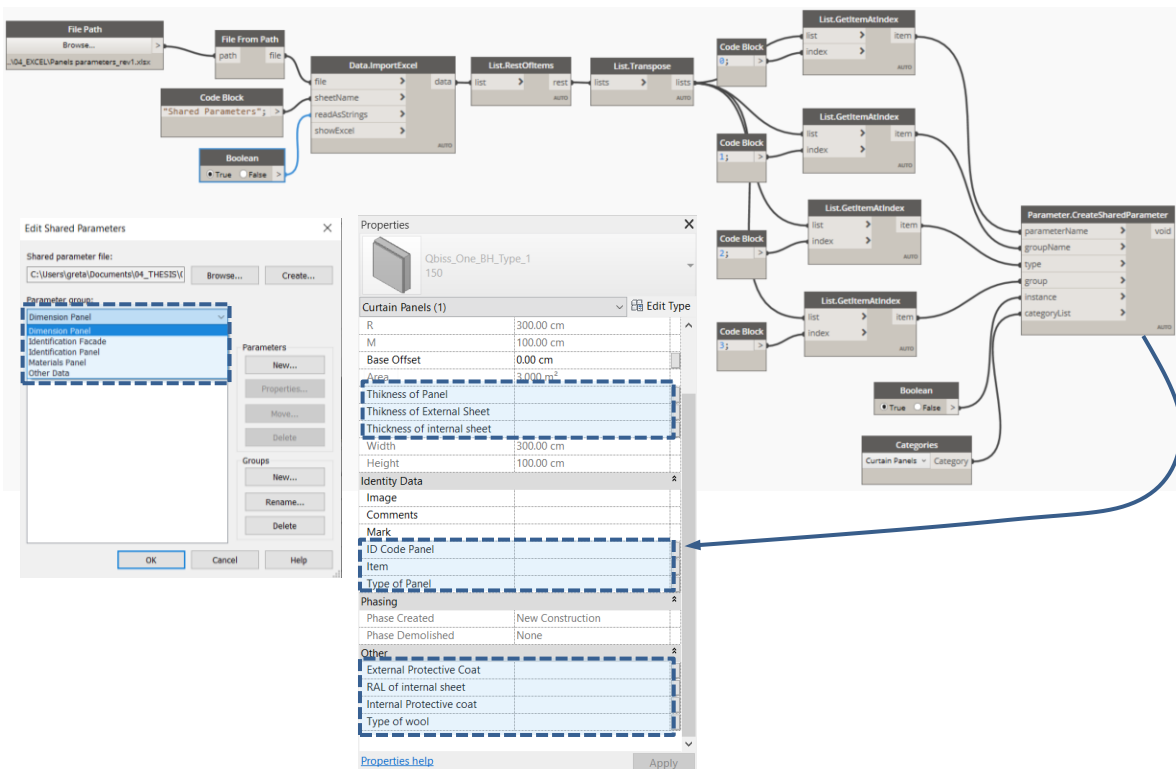
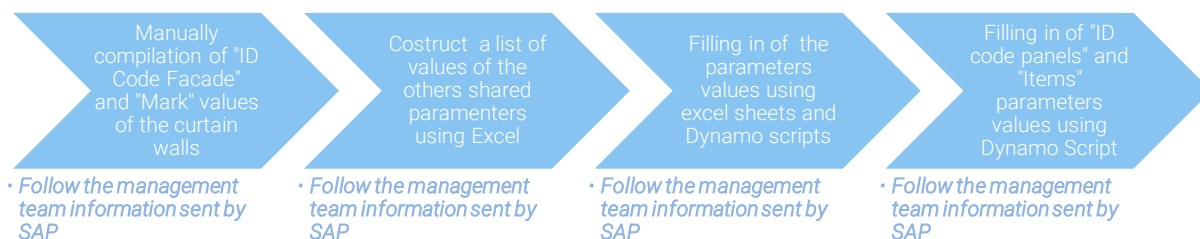


Figure 58 – Script for the Shared Parameters creation of the panels

As the figures show, the shared parameters are the name of parameters added to the Curtain walls. At that moment, the each shared parameter did not contains a value.

5.3.8 Filling in of the parameters value

The elements of the model had been divided in two macro groups: the rectangular panels belonging to the curtain walls families and the angular panels created using structural columns objects.



To start to fill in all values of the shared parameters, the “ID code façade” and the “Mark” parameters values of each curtain wall were inserted manually in order to distinguish the elements. They were just 20 different values, so it was still manageable.

The second step of the workflow consisted in the creation of two different tables containing respectively the parameters values of the red panels and grey panels.

Type of Panel	Thicknes s of Panel	Colour of Panels	External Protective Coat	Thickness of External Sheet	RAL of Interna l Sheet	Internal Protective Coat	Thicknes s of Internal Sheet	Type of Wool	Name of Colour
Q-Qbiss One	150	M-GS-TRAFFI C RED	PUR	70	9002	SP	60	K4	TRAFFI C RED

Table 5 - Excel Tables containing Parameters values of Red Panels

Type of Panel	Thicknes s of Panel	Colour of Panels	External Protective Coat	Thickness of External Sheet	RAL of Interna l Sheet	Internal Protective Coat	Thicknes s of Internal Sheet	Type of Wool	Name of Colour
Q-Qbiss One	150	M-GS-GREYA L	PUR	70	9002	SP	60	K4	GREY ALLUMINIUM

Table 6 - Excel Tables containing Parameters Value of Grey Panels

The Excel Tables 5 and 6 were imported in Dynamo scripts in order to create lists containing those values and populate the parameters. The values contained in the tables were inserted using the Dynamo script below: in fact, through the use of excel data a lists of values had been created and exported in Revit. The same procedure was used for the red and grey rectangular panels. The Dynamo script used for angular panels was a little different. It had respected the same steps but since the objects belong to a different family (structural column) the selection procedure was different.

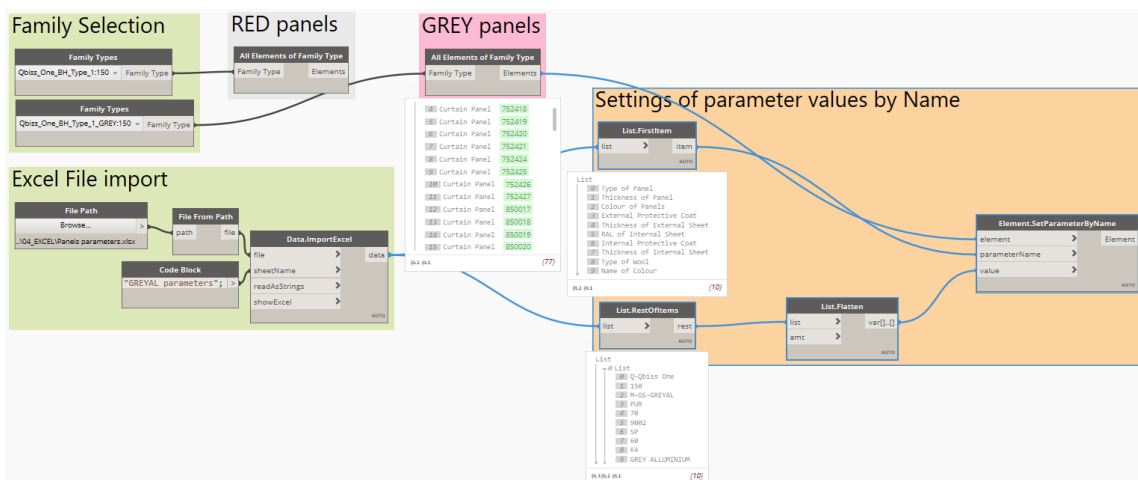


Figure 59 - Dynamo script for the setting of parameter values

The parameters “ID Code Panels” and “Item” had requested a more complex scripts.

The “ID Code Panels” is the identification code, it is a long code containing the important technical features of each panel. For the creation of its values the scripts had used string nodes connecting together symbols, characters and numbers.

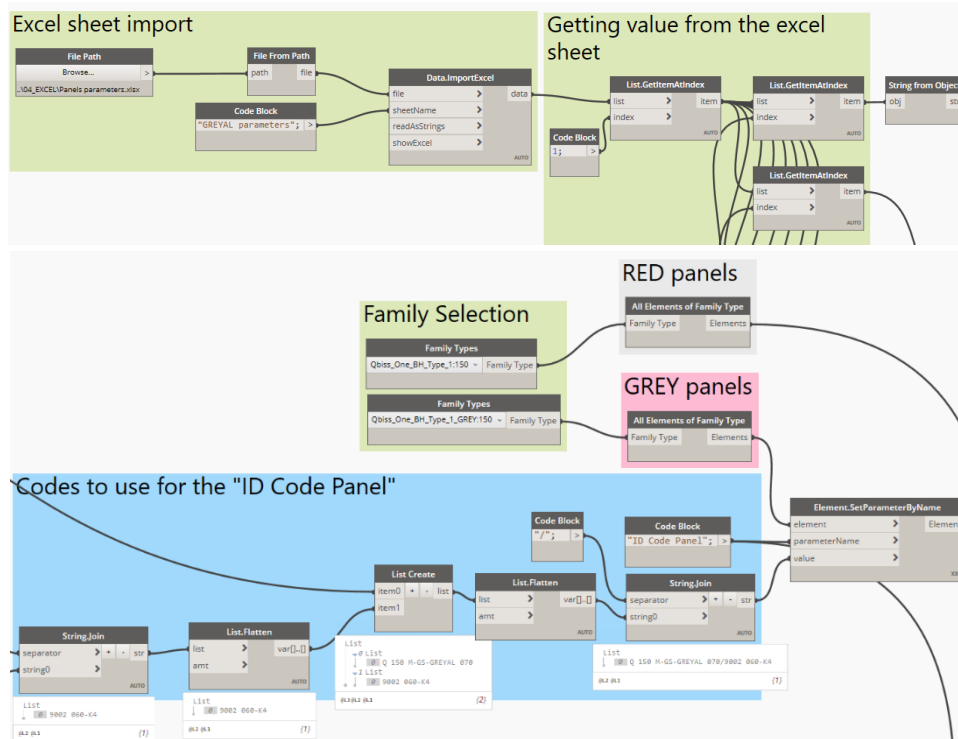


Figure 60 - Dynamo script for the creation of the "ID Code Panel" parameter value

The “Item” is a parameter that allows to distinguish the panels according to the dimension and the affiliation to the façade: panels with same dimension could have different Item because they don’t belong to the same façade. In order to populate the “Item” parameter the script was organized in order to select all the panels of the model and grouped them in lists according to the same facade. To do this, the value of the “Mark” parameters was taken into account: a script populated the “Mark” value of each panel with the same “Mark” value of the curtain wall to which it belonged.

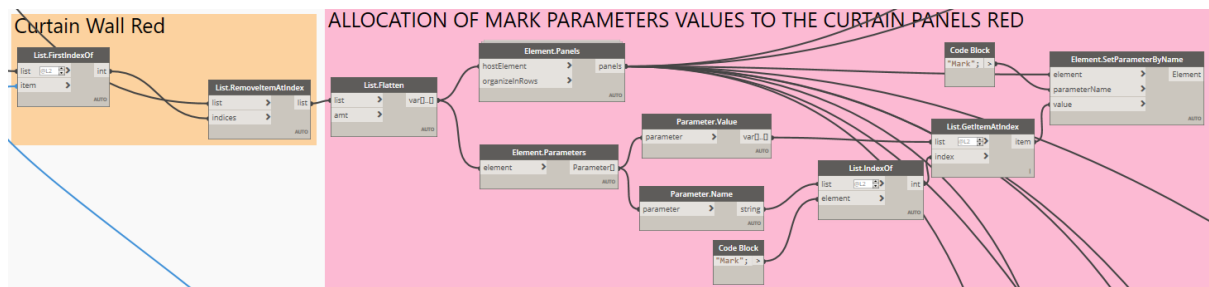


Figure 61 - Script to fill in the "Mark" values of the red panels

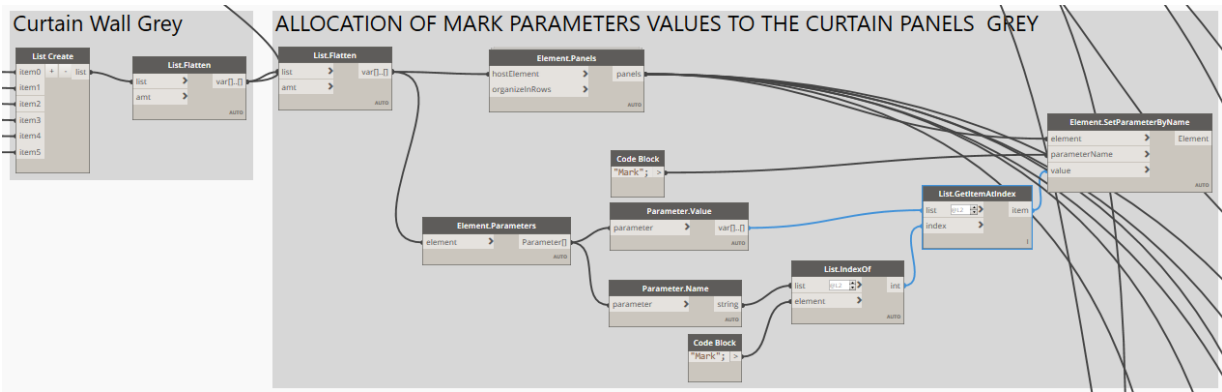


Figure 62 - Script to fill in the "Mark" values of the grey panels

After that the panels were grouped according to the “Mark” and so to the belonging façade, and to the dimensions. I attributed the “Item” values to each generic panels according to the project requirements.

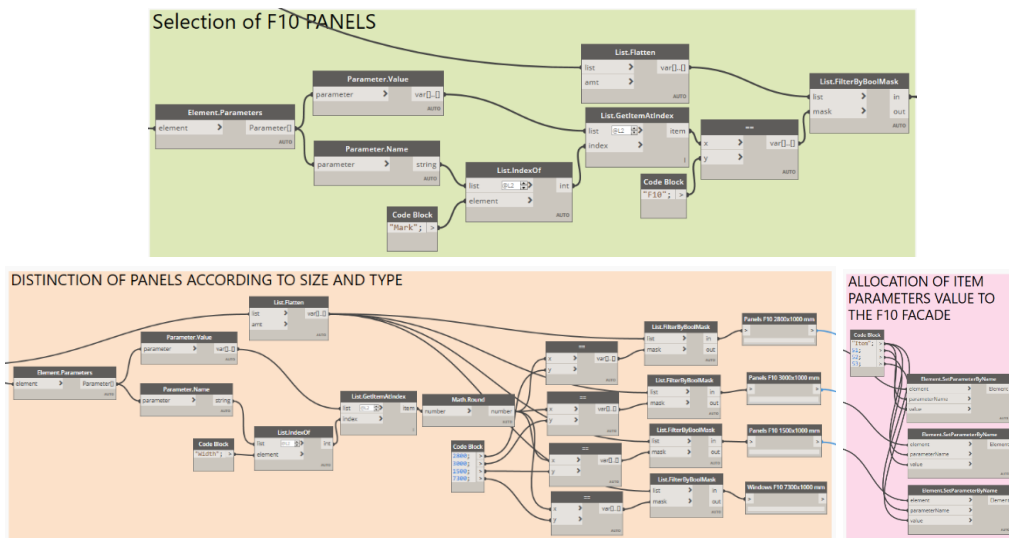


Figure 63 - Script to fill in the "Item" values of the rectangular panels

The Dynamo script used for angular panels was a little different. It had respected the same steps but since the objects belonged to a different family (structural column) the selection procedure was different. The “Mark” value of the panels was assigned manually in Revit, according to the required information. Afterward, the script below was created.

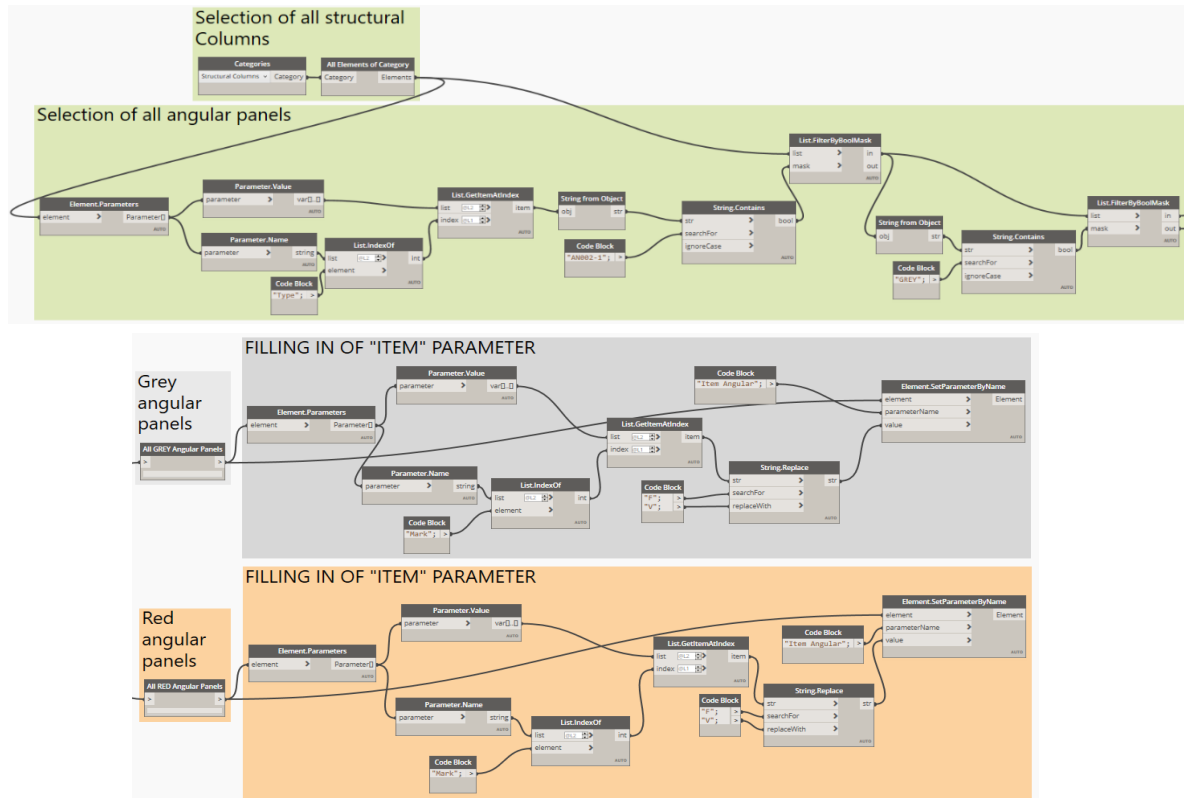


Figure 64 - Script to fill in the "Item" values of the angular panels

The following figures show the parameters obtained at the end of the process.

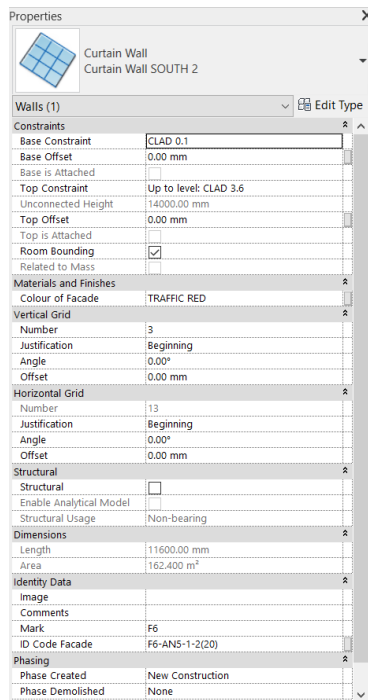


Figure 67 - Curtain Wall Properties

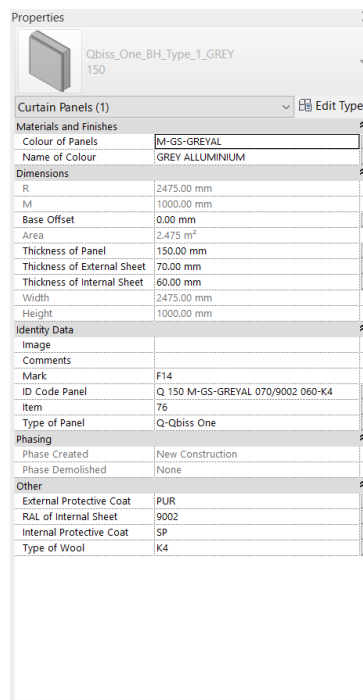


Figure 67 - Rectangular Panels Properties

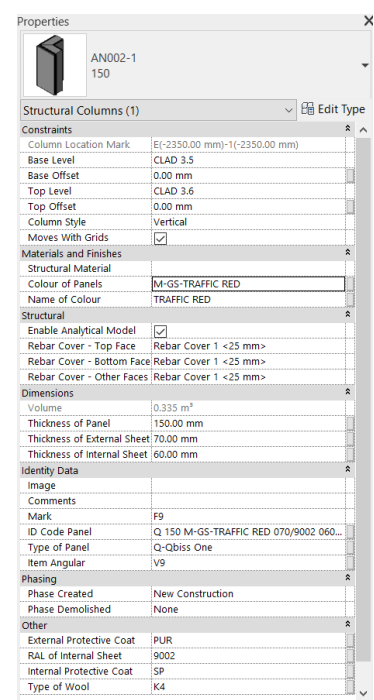
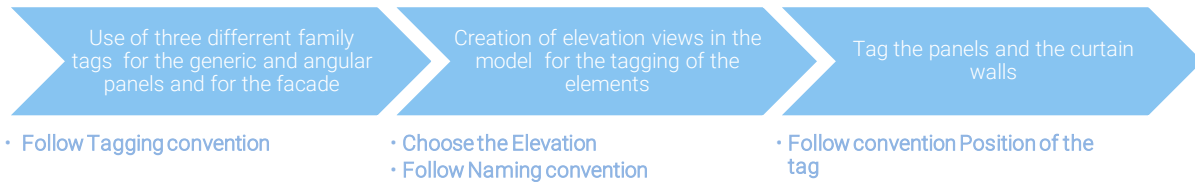


Figure 67 - Angular Panels Properties

5.3.9 Automatic tag of panels and façade

Another important task for the engineering team of the company is mark with tags each panel and façade. Usually, it is considered a very boring and repetitive task, but with a script adaptable to the different project can take few minute to be performed.



Every company should have its own standards to follow. It was assumed that the company has also a family library for annotations. Three types of annotation families were created: two that identify the generic and angular panels, and one that identifies the facades and therefore the curtain walls.



Figure 68 - Annotation families

The family tags have contained the information requested by the production team in order to identify each element.

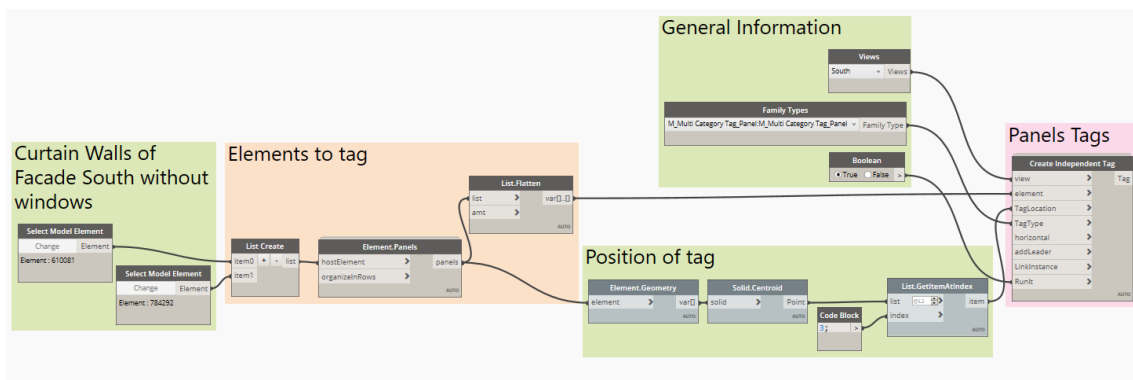


Figure 69 - Script to automate tag of elements

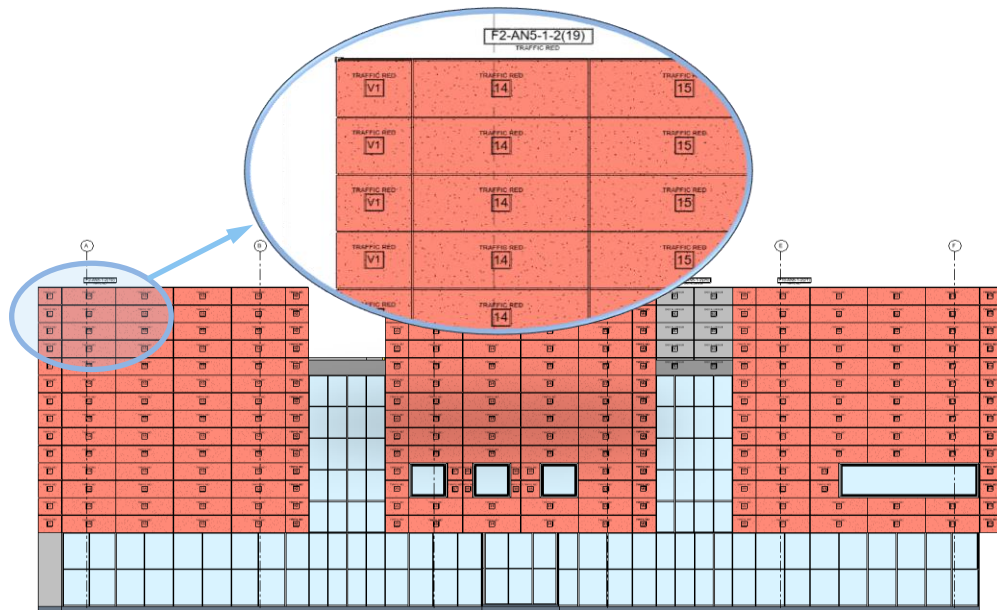
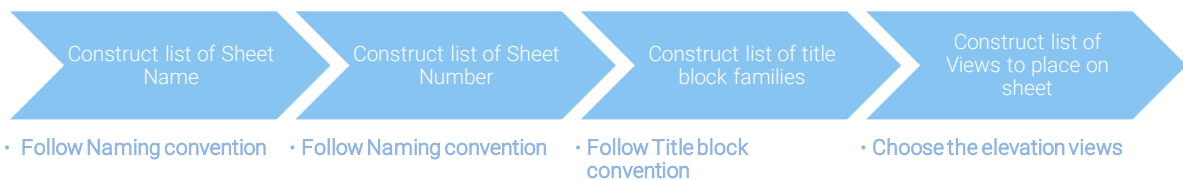


Figure 70 - South Elevation containing tag of elements

5.3.10 Creation of sheets



When it is needed to create sheets in Revit, the most convenient way is to create information with Excel, that are imported through a node running in Dynamo. There are some possibilities for sheet creation within Dynamo. In this case the node *Sheet.ByNameNumberTitleBlockAndView* was executed, that is a standard Dynamo node that requires, Sheet Names, Sheet Numbers, Title block Family Type, and View inputs.

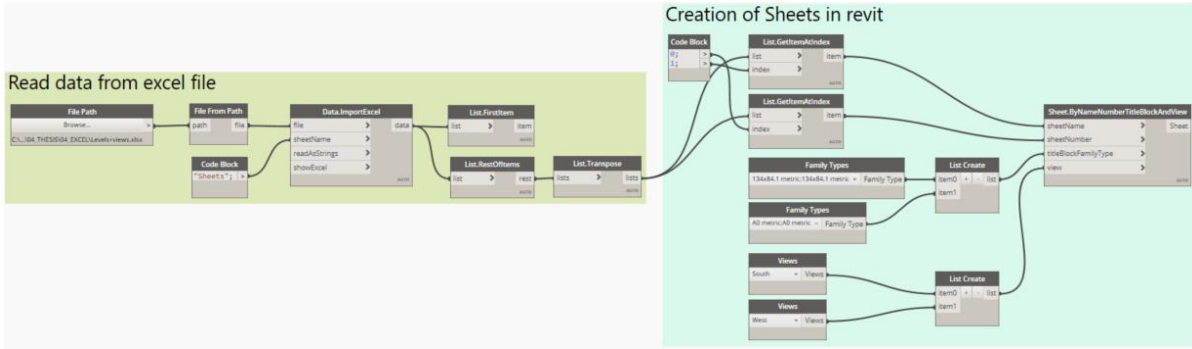


Figure 71 - Script in Dynamo for the creation of Sheets

5.3.11 Quality Check

During the design phase, especially during the insertion of parameters or objects, errors may arise. This script allows the investigation of the presence of elements not foreseen by the project, highlighting the elements in Revit. In the first example the presence of curtain panels with thickness different from 150 mm was investigated: for the project all the panels should have 150 mm of thickness.

In the second example, the correct insertion of the " ID Code facade" was examined. As already mentioned, the first step in this process of data compilation was the manual placement of the "ID Code Facade " values. The script demonstrated how easily the panels with the empty parameter value were recognized.

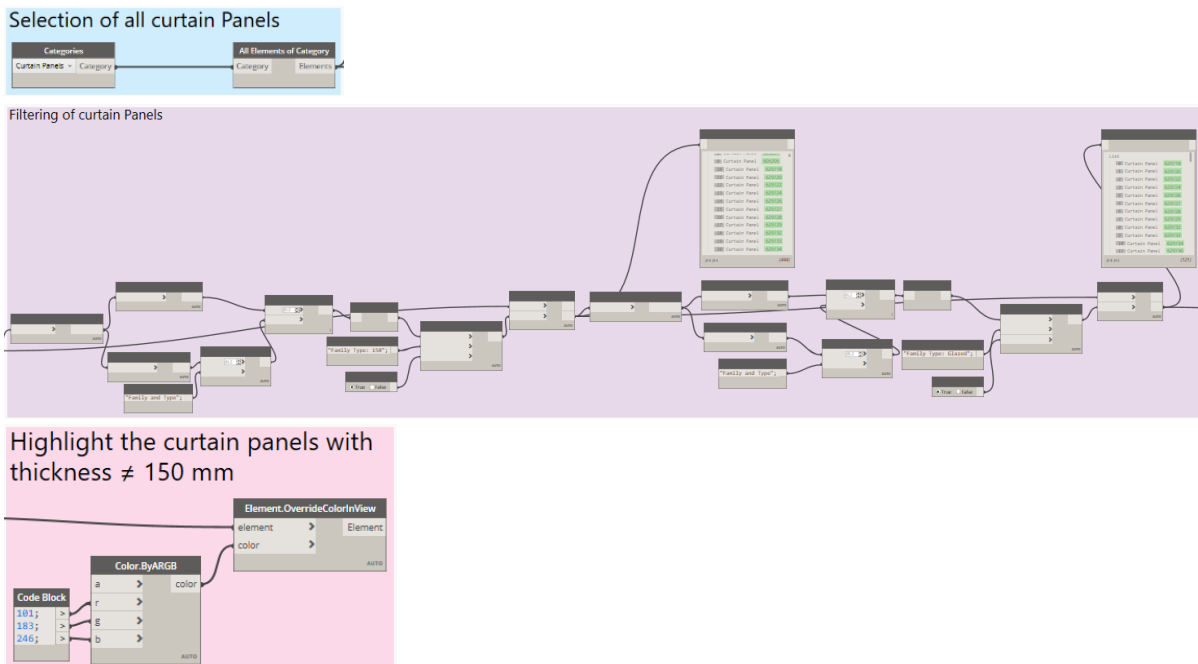


Figure 72 - Script of quality check of Curtain panels

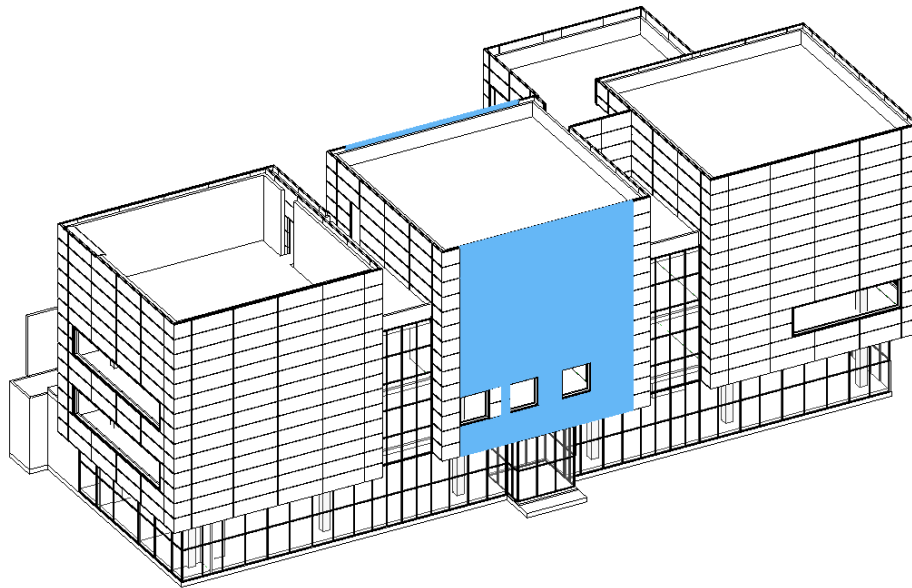


Figure 73 - Elements highlighted in the Revit project (blue colour)

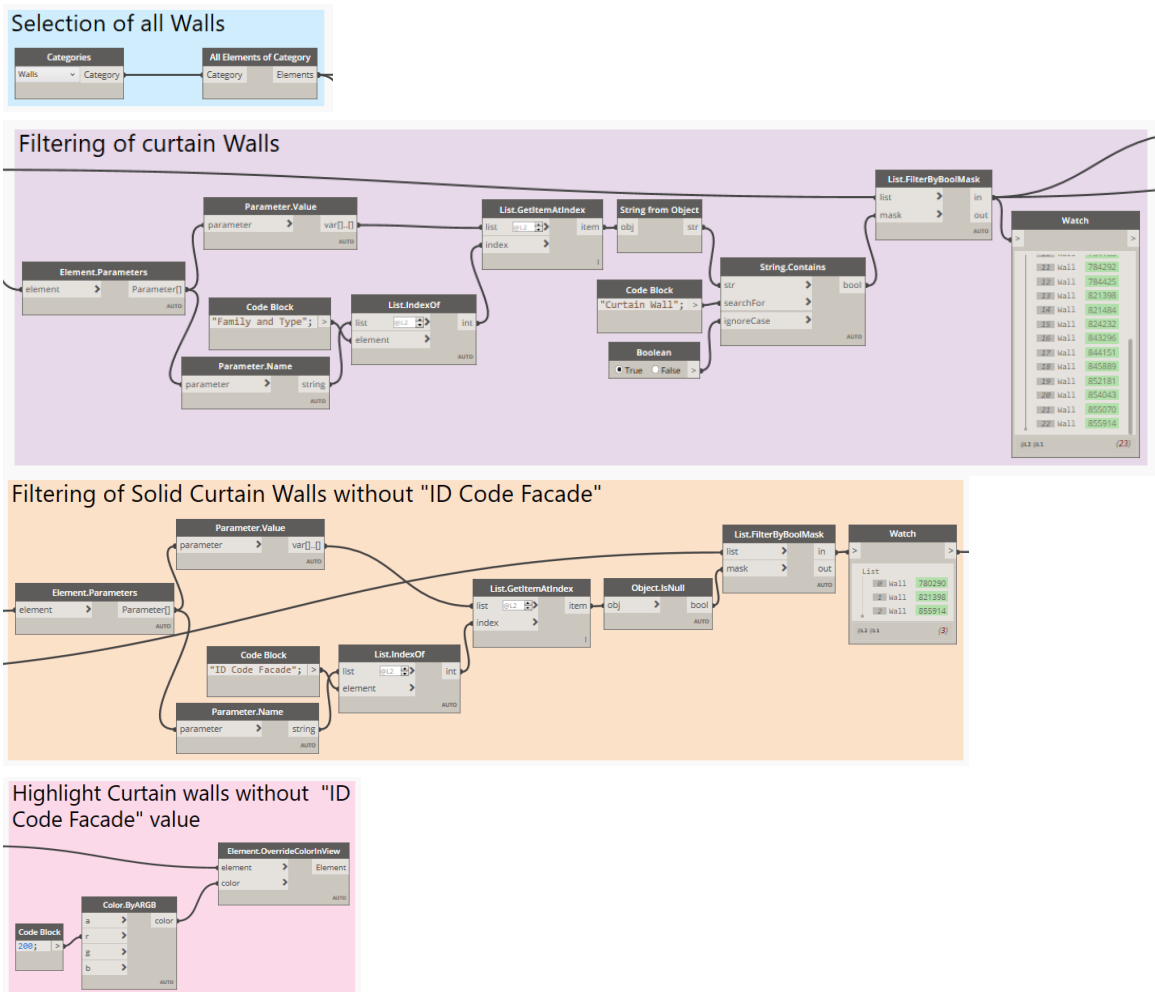


Figure 74 - Script of quality check of the Curtain Walls

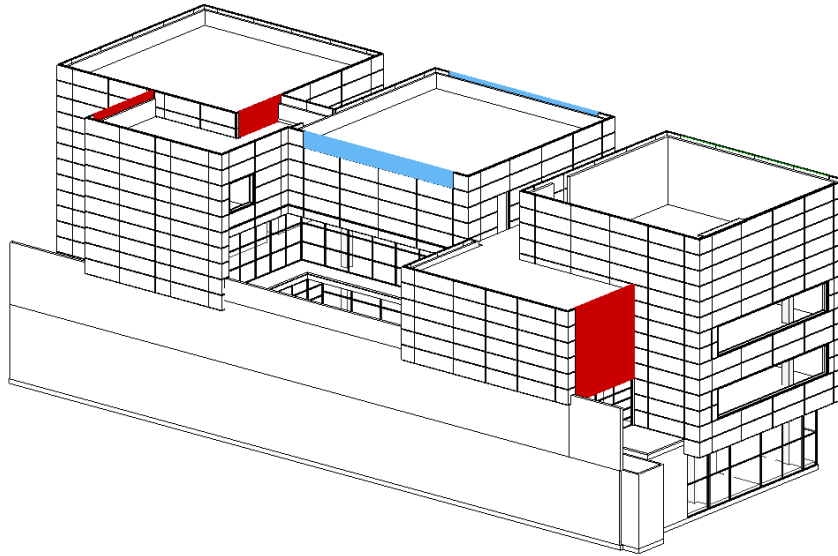


Figure 75 - Elements highlighted in the Revit project (red colour)

5.3.12 Quantity Take Off

The goal of the whole process was the quantity take off. The insertion of parameters and tags was required not only for the identification of the model elements but also for the counting of them. Through a script executed in Dynamo the schedules that report the total count, the areas of the panels and the parameters had been created.

In Dynamo the lists of elements to count and the schedules automatically grouped according to the belonging façade were created. Unfortunately, it is not possible automatize with a script the procedure to sorting/grouping of the panels in the schedules, that was executed manually.



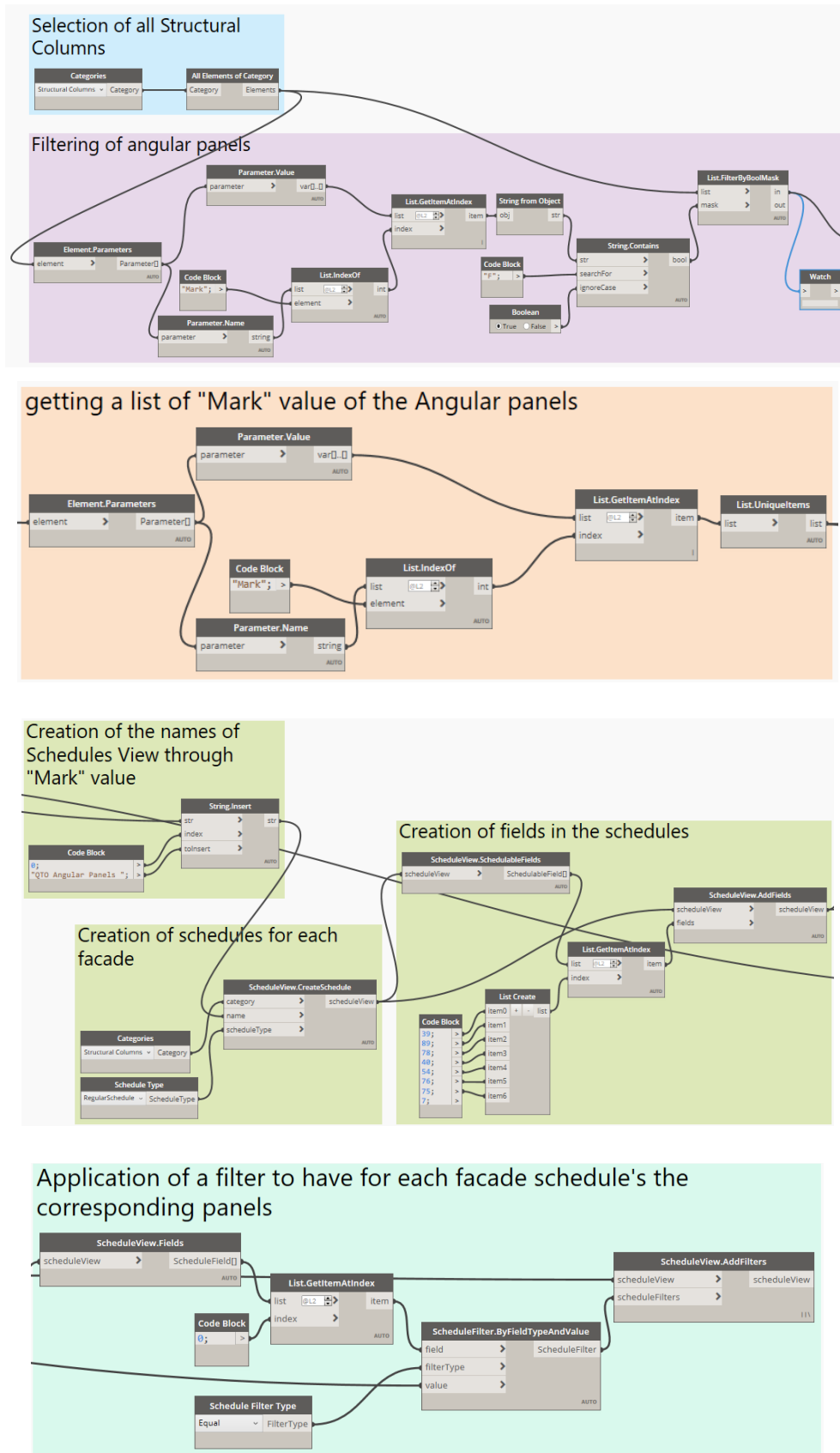


Figure 76 - Script for the creation of schedules

<QTO Panels F1>						
A	B	C	D	E	F	G
Mark	Item	ID Code Panel	Width	Height	Name of Colour	Area
F1	6	Q 150 M-GS-TRAFFIC RED 070/9002 060-K4	2800.00 mm	1000.00 mm	TRAFFIC RED	56.00 m ²
20						56.00 m ²
F1	7	Q 150 M-GS-TRAFFIC RED 070/9002 060-K4	3000.00 mm	1000.00 mm	TRAFFIC RED	60.00 m ²
20						60.00 m ²
F1	9	Q 150 M-GS-TRAFFIC RED 070/9002 060-K4	500.00 mm	1000.00 mm	TRAFFIC RED	4.00 m ²
8						4.00 m ²
Grand total: 48						120.00 m ²

<QTO Panels F2>						
A	B	C	D	E	F	G
Mark	Item	ID Code Panel	Width	Height	Name of Colour	Area
F2	14	Q 150 M-GS-TRAF	2800.00 mm	1000.00 mm	TRAFFIC RED	78.40 m ²
28						78.40 m ²
F2	15	Q 150 M-GS-TRAF	3000.00 mm	1000.00 mm	TRAFFIC RED	84.00 m ²
28						84.00 m ²

Figure 77 - Schedules examples of facade F1 and Facade F2

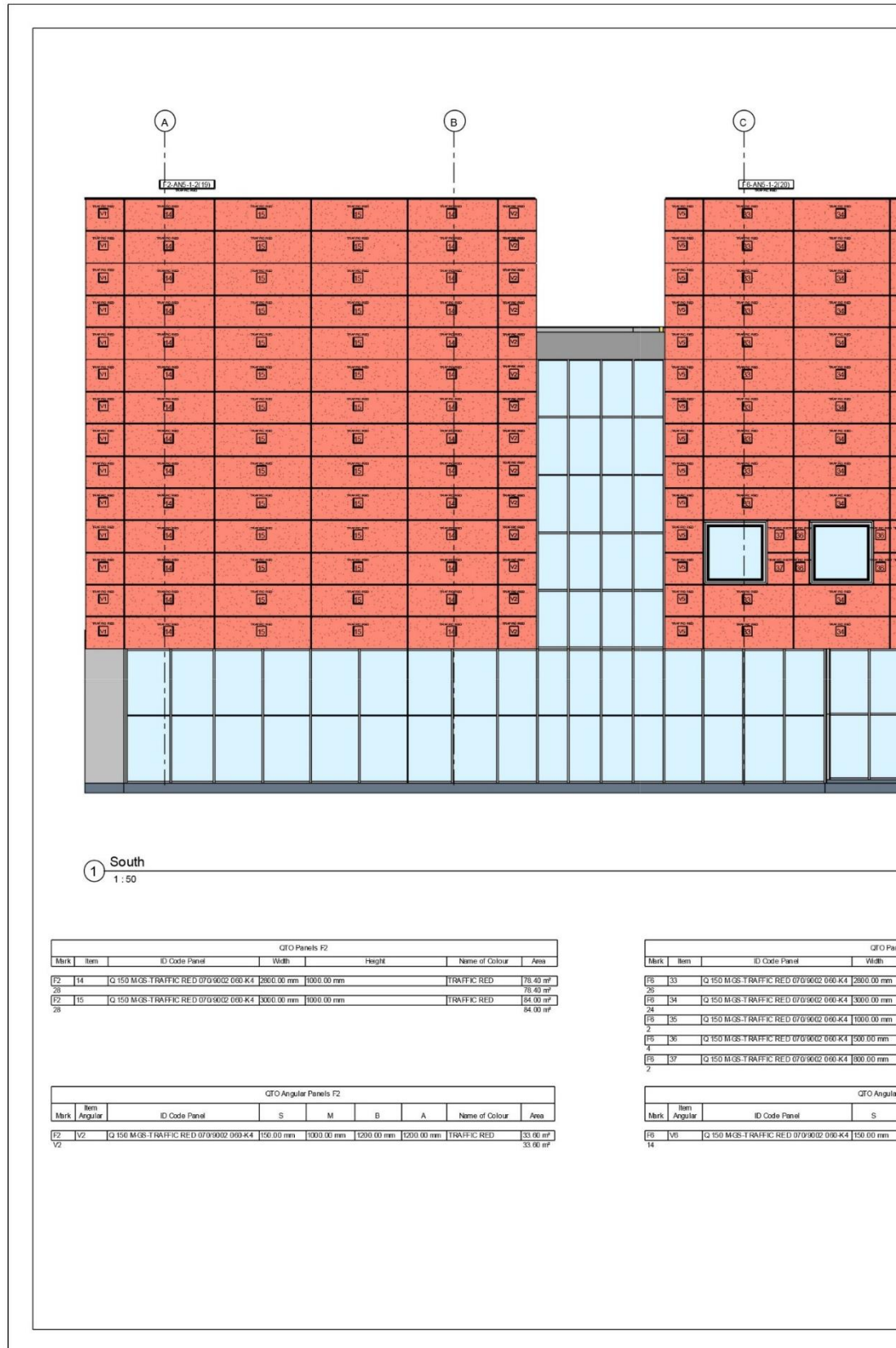
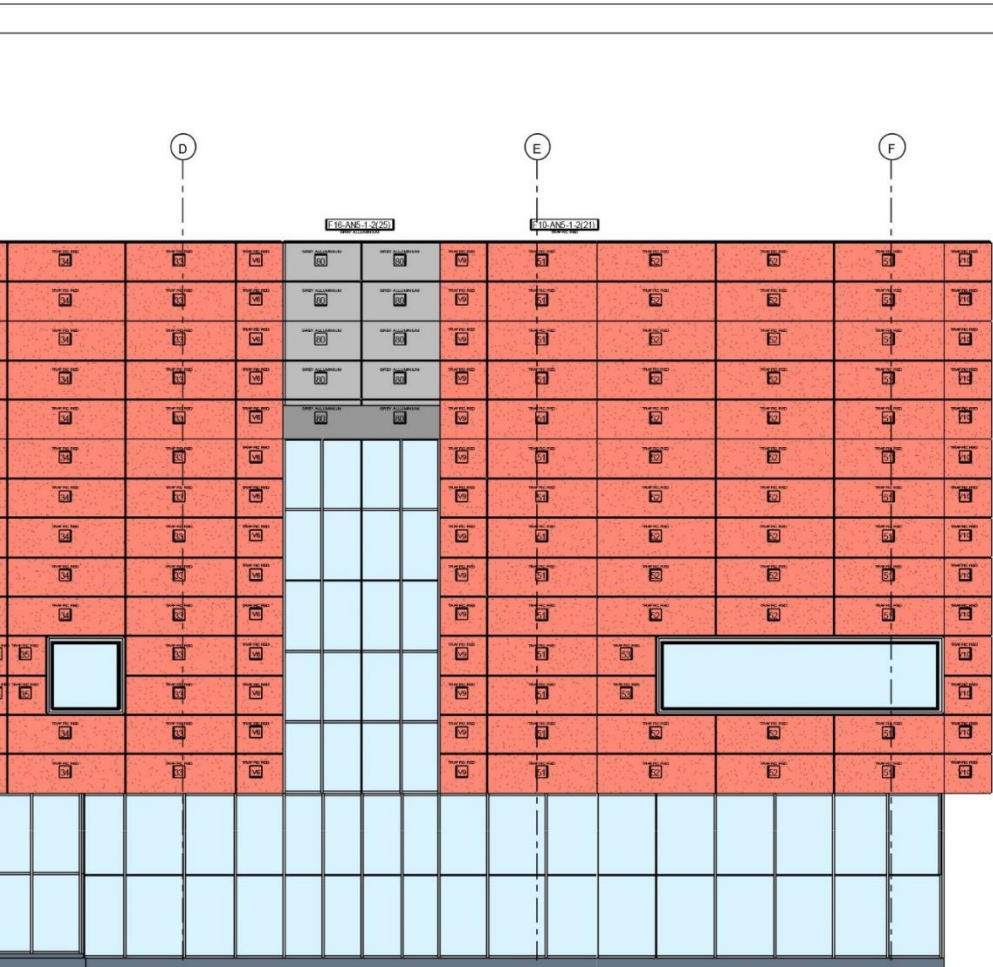


Figure 78 - Final Sheet example



Consultant Address Phone Fax e-mail
Consultant Address Phone Fax e-mail
Consultant Address Phone Fax e-mail
Consultant Address Phone Fax e-mail
Consultant Address Phone Fax e-mail

No.	Description	Date

Mark	Item	ID Code Panel	Width	Height	Name of Colour	Area
F9	S1	Q 150 M GS-T RAFFIC RED 07 0'9002 060-K4	2900.00 mm	1000.00 mm	TRAFFIC RED	2.80 m ²
F9	S2	Q 150 M GS-T RAFFIC RED 07 0'9002 060-K4	3000.00 mm	1000.00 mm	TRAFFIC RED	3.00 m ²
F9	S3	Q 150 M GS-T RAFFIC RED 07 0'9002 060-K4	1500.00 mm	1000.00 mm	TRAFFIC RED	1.50 m ²

Mark	Item	ID Code Panel	Width	Height	Name of Colour	Area
F10	S1	Q 150 M GS-T RAFFIC RED 07 0'9002 060-K4	2900.00 mm	1000.00 mm	TRAFFIC RED	2.80 m ²
F10	S2	Q 150 M GS-T RAFFIC RED 07 0'9002 060-K4	3000.00 mm	1000.00 mm	TRAFFIC RED	3.00 m ²
F10	S3	Q 150 M GS-T RAFFIC RED 07 0'9002 060-K4	1500.00 mm	1000.00 mm	TRAFFIC RED	1.50 m ²

Mark	Item	ID Code Panel	S	M	B	A	Name of Colour	Area
F10	V10	Q 150 M GS-T RAFFIC RED 07 0'9002 060-K4	150.00 mm	1000.00 mm	1200.00 mm	1200.00 mm	TRAFFIC RED	33.00 m ² 33.00 m ²

Mark	Item	ID Code Panel	Width	Height	Name of Colour	Area
F16	B0	Q 150 M GS-GREYAL 070'9002 060-K4	2000.00 mm	1000.00 mm	GREY ALUMINIUM	2.00 m ²

KJG Business Centre

Elevation

Project number	0001
Date	Issue Date
Drawn by	Author
Checked by	Checker

A-101

Scale	1 : 50
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6 CONCLUSION AND FUTURE DEVELOPMENT

The proposed BIM implementation has focused on the integration of computational design, as it is considered a powerful tool for information management.

The TRIMO company shall always manage and create information that shall be following customer requirements. In a design process and information exchange, the project usually undergoes many changes before it reaches the design phase. Often the architects themselves, who make the changes to the project, and the production company have to change the production drawings in a short time to meet the requirements.

Dynamo has largely demonstrated to be a powerful ally in this situation, as it allows quick changes by merely rerunning the scripts. In a company that manufactures prefabricated panels, the workflows generally follow a standard procedure. For this reason, the use of Dynamo and consequently, Revit could be beneficial. First, the company shall define the workflows and therefore, the standard procedure to be applied to each project. It has been shown that computational design can efficiently support the design phase, making data management much easier. It is necessary that the process shall follow the standard imposed by the BIM Manager. It is recommended that the company develops a library containing scripts for each phase of the design process and the BIM Manager provides guidelines for correct interpretation. The entire process can indeed benefit, speeding up the design and increasing production.

However, the use of scripts also has disadvantages. First of all, it requires a great deal of preparation. When information is entered through scripts, it is necessary to be very careful and know how to read the nodes and lists in Dynamo. It is easy to insert unsolicited information into model objects without being aware of it. If there is a lot of information, the parameters may be changed unknowingly. Such errors are difficult to control, and it is possible to lose the model control. With a high volume of information and complex scripts that need to be executed, a computer with a lot of processing power is required. Even when working with a relatively simple model, the processing is relatively high. We can conclude that many disadvantages are mainly related to the size of the lists and the number of connections to parameters in the model. Therefore, a rational use of lists in Dynamo is required.

This research focuses on the design phase and attributes importance to the BIM objects integrated into the process. It is crucial to develop them more efficiently.

The literature provides relevant insights into future developments in production technologies. If TRIMO will implement its processes introducing new production technologies, it would rely on the use of BIM objects connected to CNC machines. Therefore, further developments for the company could consist of the inclusion of more technological production machines that take full advantage of the implementation of BIM.

Each newly introduced technology brings progress, but also new issues that need to be optimized. The introduction of new production technologies could generate further researches on the use of BIM objects and interoperability between designers and production.

Future studies could focus on the development of object families to use the 3D model to transfer the information to production. The improvement of the BIM object will enhance the exchange of information between designers and manufacturers. The relevant knowledge of the manufacturers could be captured, investigated, implemented and directly embedded in the BIM object. The CNC machine could read this information via an intermediate programming language tools. In this way, the process could be streamlined and accelerated. The information processed by the CNC machine would come directly from the BIM model, and intermediate steps that could lead to data loss would be avoided.

To likely achieve this level of a production implementation, the state of the BIM technology must be mature and embedded in all processes. The next steps in research development should be to examine the interoperability concept and the IFC standard file. To facilitate the exchange of information, it is important to consider the importance of using standards in the definition of object properties. At this stage, the use of standard exchange files, such as IFC, could take over, allowing interoperability between design and production. Therefore, a future study could focus on the proper management of IFCs in the field of prefabricated production area, as this issue has not been addressed in detail or solved today. Even though the prefabricated method takes an essential role in the AEC industry, there is no support in IFC. The research should list several representative prefabricated component properties and the relationship between classes, that will be added to the IFC as extended attributes.

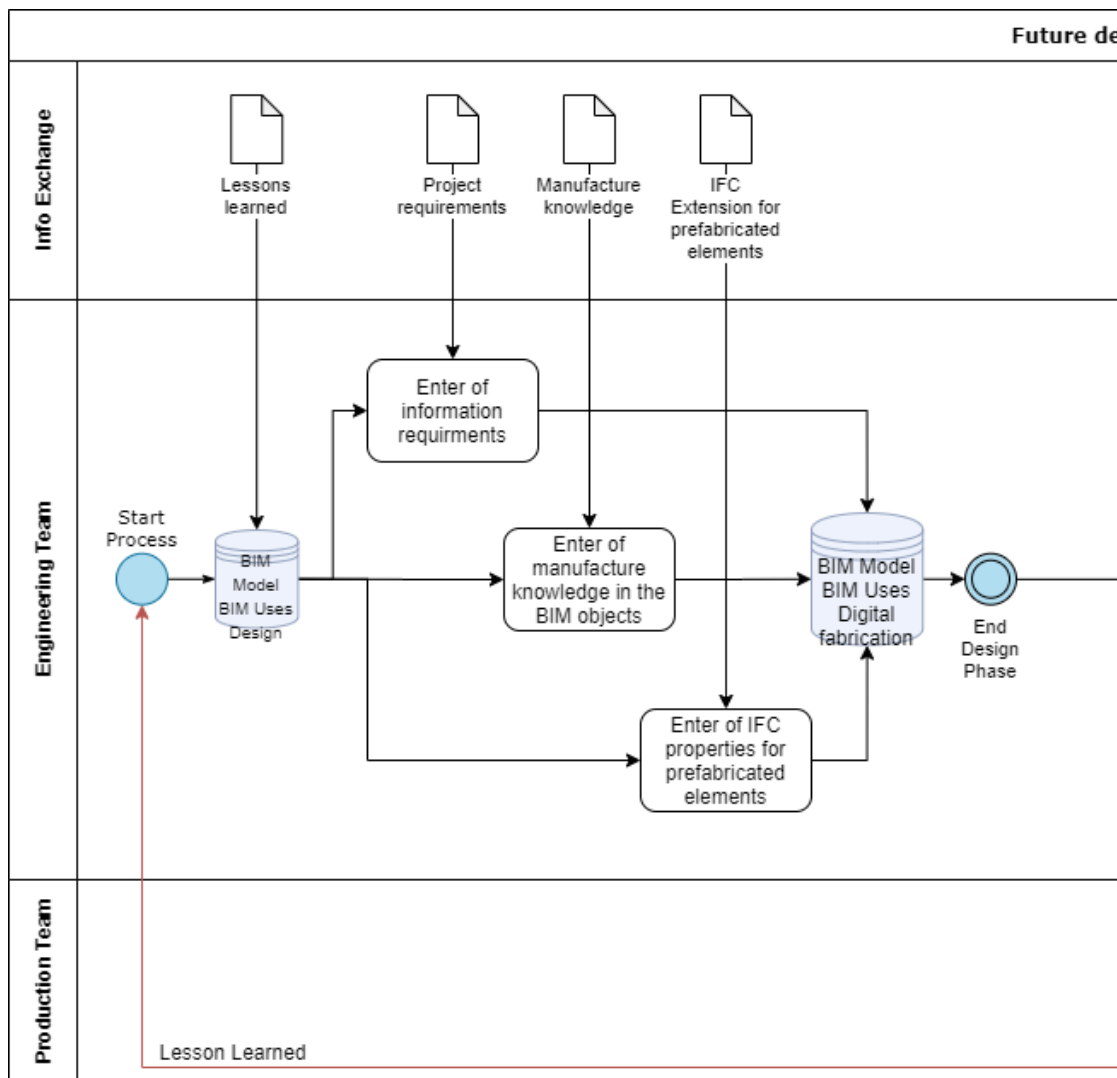
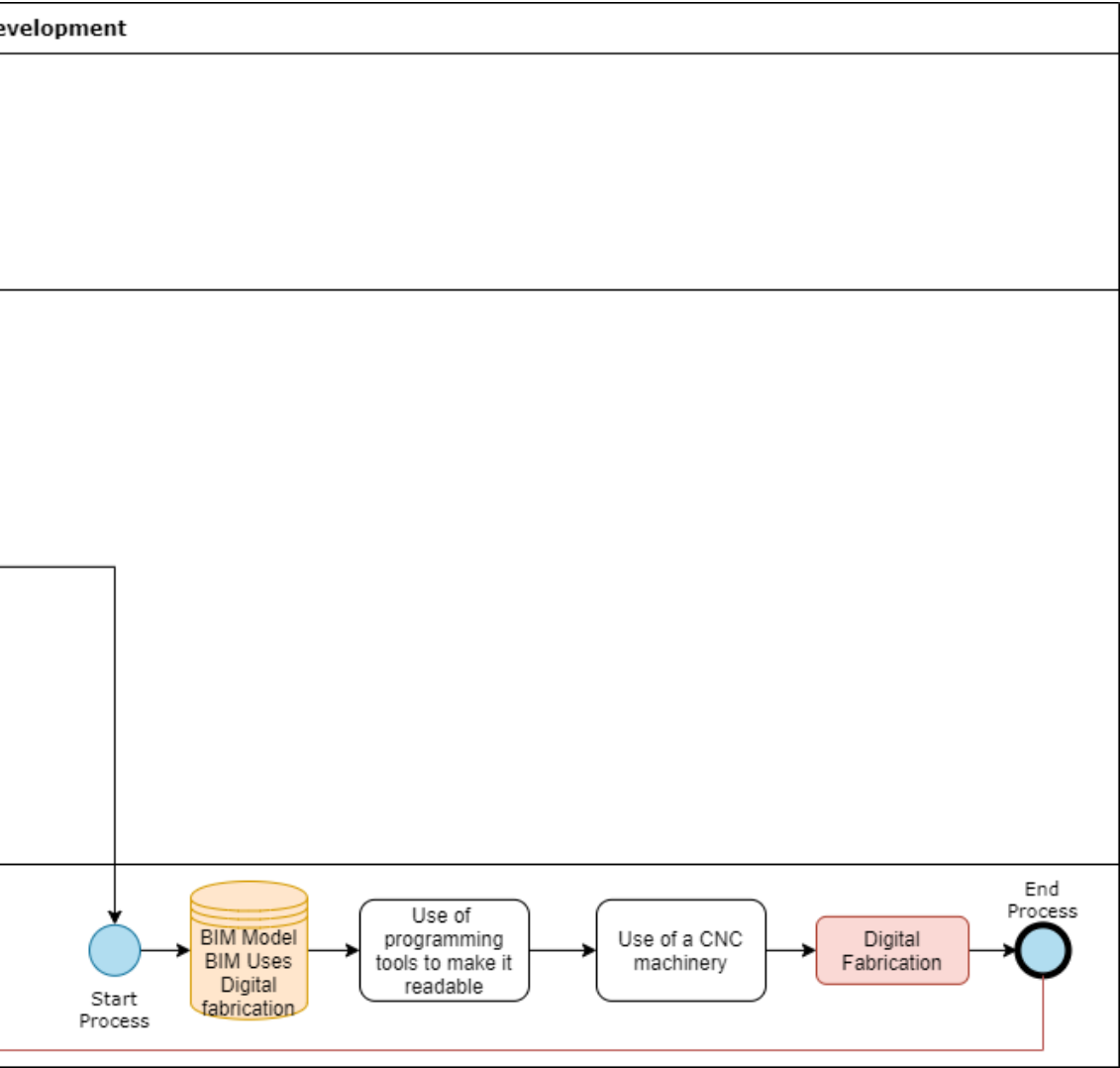


Figure 79 - Future Development process



7 ACRONYMS AND APPLICATION

3D	Three Dimension
AEC	Architectural, Engineering and Construction
AIA	America Institute of Architect
AM	Additive Manufacturing
ArchiCAD	BIM Software by GraphiSOFT
AutoCAD	CAD Software by Autodesk
BEP	Building Execution Plan
BIM	Building Information Modelling
CAD	Computer-aided-Design
CAFM	Computer Aided Facilities Management
CAM	Computer-Aided Manufacturing
CATIA	Computer-Aided Three-Dimensional Interactive Application
CDE	Common Data Environment
CNC	Computer Numerical Control
DXF	Drawing Exchange Format
Dynamo	Visual Programming Language Tool
ERP	Enterprise Resource Planning
Excel	spreadsheet application by Microsoft
FM	Facilities Management
Grasshopper	Visual Programming Language Tool
HBIM	Historic Building Information Modelling
IDM	Information Delivery Method
IFC	Industry Foundation Classes
ISO	International Organization for Standardization
LOD	Level Of Development
MEP	Mechanical, Electrical, and Plumbing engineering
MVD	Model View Definition
NC	Numerical Control
Optimo	Multi-objective optimization tool
PL	Programming Language
Refinery	Generative Design Beta by Autodesk
Revit	BIM Software by Autodesk
RIBA	Royal Institute of British Architects
SAP	Systems Applications and Products in Data Processing
STEP	Standard for the Exchange of Product model data

TPL	Textual Programming Language
TRIMO	Production Company based in Slovenia
UI	User Interface
VPL	Visual Programming Language
WoodWOP	Programming Application used in a CAM process

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