Generative design for performance-based building envelope design

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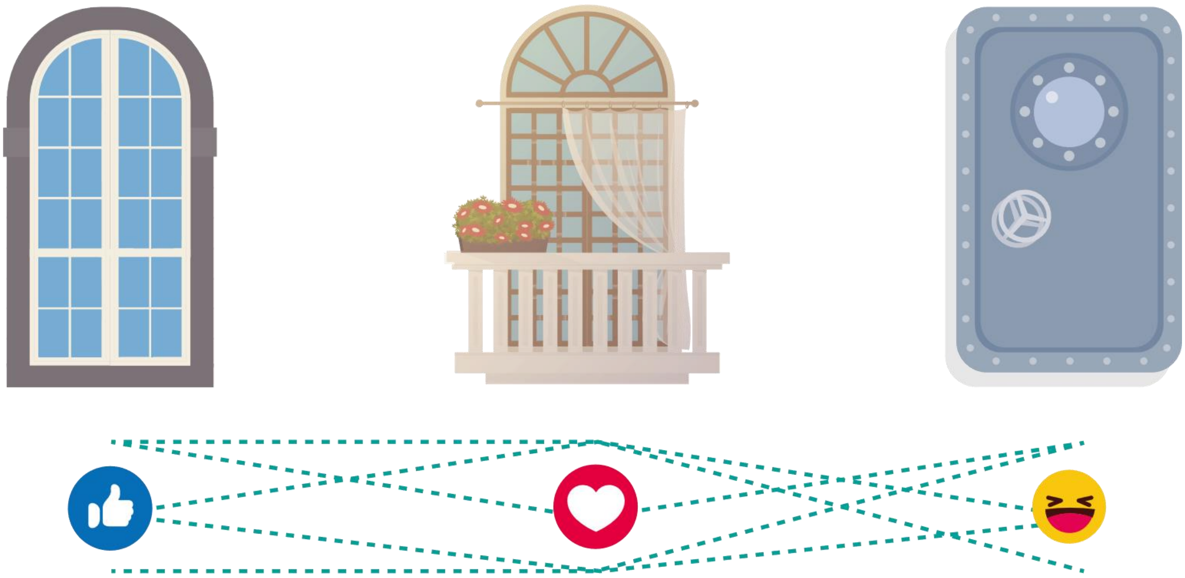

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Synopsis

This project is focused on proposing a new way of the façade design in the initial design phase in connection to Indoor Environment Quality. The new proposal is based on generative design. The report involves theoretical and analytical parts, also prototype development. The whole work process is discussed and summarized in the conclusion.

Abstract

This report suggests a new process of building façade design at the initial design phase. By helping the architects to understand indoor environment quality engineer's requirements and improving the collaboration between actors, mistakes in later phases can be eliminated. The problem is formulated as *"How IEQ can be improved during the initial design stage, before first performance simulations?".* The new process includes generative design and such tools as Autodesk Revit, Dynamo and Refinery are used. As a case, a mass model of an existing building which is located at Visionsvej 53, 9000 Aalborg, Denmark, is created.

By researching, analysing and developing the prototypes, it can be concluded that the assessment of the IEQ factors to design the building facade in the initial design phase can be done with the help of generative design. By means of generative design, hundreds of design options are generated and optimized based on the required IEQ factors which facilitate the designers to develop the design in a more effective way than the traditional design method.

Keywords: initial design phase, generative design, Dynamo, Refinery,

Contents

Introductory

This report is written as the Master Thesis for program Construction Management and Building Informatics. The main topic is Generative Design which is investigated as a possibility to be implemented during the initial design stage, taking into consideration Indoor Environment Quality. This report consists of 9 Chapters.

1 Introduction

The idea of the thesis is to consider Indoor Environment Quality (IEQ) in the buildings from an initial phase. It is intended to be done by means of the Generative Design process. This Chapter starts with an issue background showing that problems with indoor climate exist. Afterward, the focus area part narrows down the problems to a particular part of the building – façade, and problems with IEQ. Further, the existing design process is presented and analysed. It is based on the interviews conducted during the project. Subsequently, an initial problem is formulated which in further Chapters will be developed into a final problem formulation. Lastly, the project scope is indicated.

1.1 Issue background

The term "indoor environmental quality" (IEQ) refers to the quality of internal building conditions that bring comfort environment for both physical and psychological to the inhabitants (Omer, 2008). This comforting environment is a result of natural and humanmade sources which generates the factors that can directly impact on the building energy consumption and well-being of the building users. Indoor environmental quality has gained a compelling interest globally, especially in most of the developed countries as people spend nearly 90% of their time indoor (Klepeis *et al.*, 2001). This rising concern in IEQ has driven humans to improve IEQ through technologies such as inventing machines for better lighting and thermal conditions. But this development has attributed to higher energy consumption and Green House Gas emission. The total estimation of energy consumption in the building sector that is used for supporting IEQ accounts for over one-third of the global energy usages (Omer, 2008). As a consequence, there is an attempt by European Comission (2010) to publish a new commission of "a nearly zero energy" which will enforce by the year 2020 to reduce the energy usages from the building sector. Additionally, the higher energy consumption contributes to project cost overrun during the maintenance process. Over than fourth-fifths of the operating cost derives from energy usages, which poses a significant issue in terms of economic aspects. (Morell, 2005)

Furthermore, poor IEQ causes a negative effect on the inhabitants. The lack of thermal comfort in workplaces can degenerate human productivity and deter physical and mentality functions. Every

1 Celsius that is exceeded by the thermal comfort area (21-25 Celsius) can reduce productivity by 2%. (Mujan *et al.*, 2019) The total estimated loss of ineffective production from poor indoor comfort accounted for a significant amount for over 15 billion pounds in the UK in 2011 (Center for Mental Health, 2011). This issue also poses a crucial impact on people's health, as insufficient daylight in the building can cause stressful and mentality illness. Even though there are technologies that try to imitate the daylight functions, the side effect from the use of artificial daylight can interfere internal human clock, which impacts people's health and working productivity (Mujan *et al.*, 2019).

Many factors contribute to the low quality of IEQ. Through several investigations, one key to this issue is due to improper building design. As mentioned previously about the excessive building energy consumption from the poor thermal comfort, the main reason for this poor thermal comfort stems from the low quality of building design related to its layout, shape, and façade (Raji, Tenpierik and van den Dobbelsteen, 2017). Another research conducted by (Assali, 2015) on the investigation of "Improving IEQ through the design integration of a natural system in architectural design" has found that by changing building elements such as windows, roof, and materials that suite to natural contexts, this can contribute to a better IEQ.

However, to achieve an effective IEQ through an architectural design is challenging. In order to optimize IEQ, this requires a proper design decision based on the different objectives of the IEQ criteria (Lauridsen and Petersen, 2014). Especially during the early design stage where most of the information is still uncertain, designers such as architects and engineers may experience difficulties in investigating the effective design approach. Nevertheless, the implementation of the design evaluation tools for filtering design alternatives may not be an appropriated solution as they do not give suggestions for further design development (Lauridsen and Petersen, 2014). Thus, in order to research for another suitable solution, further research is conducted and presented in the following Chapter.

1.2 Focus area

As stated in Chapter 1.1, a significant reason for a poor IEQ stems from the deficiencies in the design of a building. Notably, the design of a building facade, which plays a vital role in terms of IEQ and energy consumption as it protects the energy transmission between inside and outside of a building. Additionally, the functions of the façade can dominate the well-being of inhabitants because the façade design can impact the quality of visual comfort, daylight, and natural ventilation. (Johnsen and Winther, 2015) Thus, to design an efficient façade, several factors are needed to be taken into account.

Traditionally, to design a façade, architects are focused on the architectural design concepts which are presented by graphical drawings or, simple 3D models with a low level of accuracy can be created. Hereafter, the design will be developed for a higher level of detail in order to collaborate with stakeholders in the later project development phases. However, the design decisions occurring during the early design stage are significant as they can impose the direction and quality of the project, especially when the demands in IEQ are crucial. As a consequence, the designers are inevitable to encounter with a highly sophisticated design method during this stage to achieve the best outcome of their design. One of the complexity is to involve the integration of building performance simulation (BPS[1]) within the design process to ensure design quality can reach a certain level of project requirements. (Ochoa and Capeluto, 2009)

Even though employing BPS to the project brings several benefits, it is challenging to integrate the tools in the early design stage. Firstly, to incorporate BPS in the early design stage is sophisticated. It is not compatible with architects as most of the information that is used for analysis input in this stage is still uncertain. (Attia *et al.*, 2012) There are only about 10 out of 400 BPS applicable in the early design phase (Jensen, Maagaard and Ostergard, 2016). To analyse the model in BPS, there is a demand for a high level of model development, but most of the designers always focus on the creation of simple geometry to represent a concept during this early design stage (Attia *et al.*, 2012).

Furthermore, as the designers work with different tools and platforms, this can lead to the interoperability problem. The term interoperability refers to the possibility of the exchange of data among various digital tools to achieve smooth workflows and improve the collaboration. Utilizing interoperability data among different applications can be exchanged which can lead to avoidance of reproduction of data. (Eastman, Liston and Wiley, 2018) The interoperability problem from the use of different tools and standardization among professionals is, i.e. creating a model in a proprietary file format that causes an issue for BPS integration (Lin and Gerber, 2014).

Another significant issue from the use of BPS is the ability to attain active feedbacks from the tools. The outcomes from BPS software are designed as evaluation rather than guiding new optimization of the design options, if the first design cannot achieve IEQ criteria, the designers have to spend time, cost and labour to explore better new design alternatives. Especially, when the project is in the early design stage where most of the project input information is uncertain, to bring active feedback and design suggestions is unlikely to be possible in the conventional design process (Lin and Gerber, 2014).

[1] Building performance simulation (BPS) is a computer-based simulation tool that is used for analysis the building in various aspects from design to operation. The BPS has played an important role in the area of building sustainability due to the higher demanding of green building design. Due to this higher demands, the BPS tools always be employed in the design process to ensure the design quality of he building. (Hensen and Lamberts, 2012)

The abovementioned demonstrates the difficulties of façade design based on IEQ objectives. Even if there is an attempt to integrate BPS into the design process, such issues as the improper level of information, lack of interoperability and unavailability of active feedbacks are causing problems for this integration. This suggests the need for the new tools/processes which can work with various level of input information, generate guidance on performance and provide design options, and support interoperability which will, in turn, improve the design quality and bring a better building performance.

1.2.1 BIM and indoor environmental design

Building Information Modelling (BIM) is a digital modelling technology that encompasses a set of processes to analyse, communicate and produce building models. As it is written by Eastman (2018), architects were the ones who started using electronic building models, then building owners, engineers and contractors began thinking about adding useful information to those Building Models. Thus, the word *Information* was placed in the middle that results in acronym – BIM (Eastman, Liston and Wiley, 2018). Nederveen (2010) in NBIMS-US[2] defines BIM as "*a model of information about a building that comprises complete and sufficient information to support all lifecycle processes, and which can be interpreted directly by computer applications. It comprises information about the building itself as well as its components, and comprises information about properties such as function, shape, material and processes for the building life cycle*". BIM is based on parametric objects, which makes it different from traditional 2D objects. Nowadays, BIM is involved in each area of the construction project (design, HVAC, BPS, structural, etc.) Besides just the creation of a model, it allows collaborating utilizing digital models between actors. Thus, it raises the interoperability and smooth workflows. (Eastman, Liston and Wiley, 2018) This report is focused on indoor environmental quality, where BIM is an integral part. It can play a crucial role in analysing, predicting or comparing IEQ in existing or new buildings. Nowadays the use of BIM tools for IEQ is increasing due to the regulations and intention to reduce energy performance of a building, provide inhabitants with efficiency indoor climate (Habibi, 2017).

1.3 The existing workflow of building and façade design

In order to clarify the issues presented within Chapters 1.1 and 1.2, the authors interviewed an engineer and an architect (Appendix 2 and 4) to acquire information on the current process regarding building and façade design. In addition, besides the interview from the industry actors, the authors performed the literature review - "Method and Simulation Program Informed Decision in the Early

[2] National BIM Standard – United States

States of Building Design" (Petersen and Svendsen, 2010), "Managing construction project" (Winch, 2010) and "The Constructing Architect's Manual" (Müller, 1997) to support this finding.

Figure 1 presents the interview information based on the sequence model in the contextual design method. It illustrates the process of how the different actors perform during design phases that are necessary to be completed before processing into the next task (Holtblatt and Beyer, 2018). This model focuses on the process of designing the building façade that has been created based on the requirements of sustainability conditions. The working phases shown in this model are divided into 3 stages, which are brief design, preliminary design, and design development.

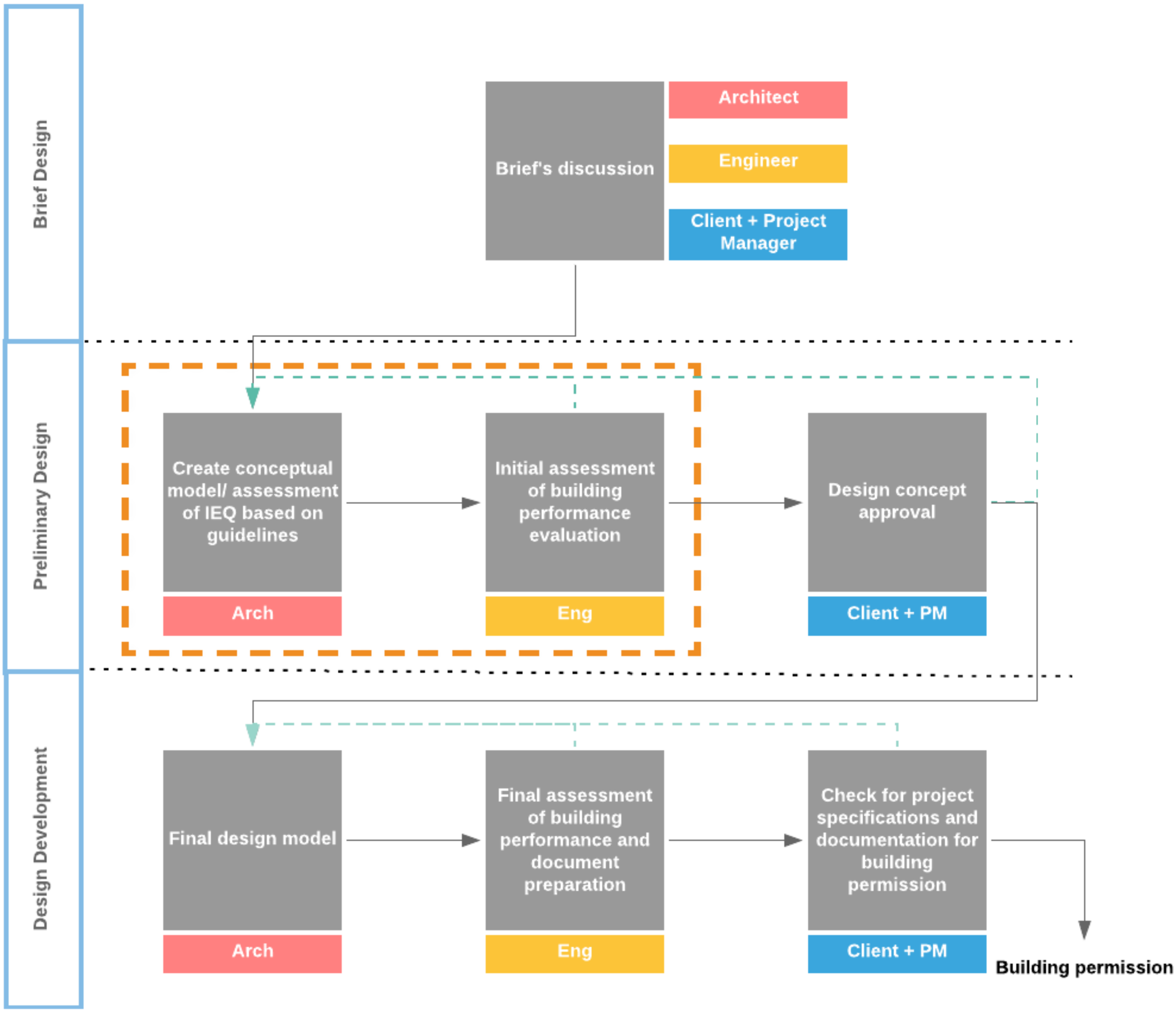


Figure 1 : Present workflow of the building design

The brief design stage is where the project stakeholders set up the start-up meeting to discuss the project requirements and limitations (Winch, 2010). The client and project investors specify the classes of different factors such as ventilation, acoustics, etc., which are based on Danish Standards[3] (DS). The purpose is to achieve a better IEQ and/or energy demands than a just minimum. To select the building classes, it depends on the building type, project budget and the owner's vision, for example, the hospital is the building type that is needed to achieve the highest building class (A) for indoor climate. After the owners have agreed on their requirements, an engineer will start assessing these requests and structure a design guideline for an architect. These design guidelines give the necessary information that can facilitate the architect to fulfil the minimum standard of the selected building class i.e. percentages of glazing area of the façade (Appendix 2).

The next stage is the preliminary design. This project stage stems from the area of project conception development that various consultants come to develop the building design based on the project requirements and design guidelines. The first actor, who starts to develop the design is an architect, who will create the architectural design based on the guidelines and produce simple 3D geometries to express the architectural conception (Winch, 2010). Hereafter, the conceptual models and drawings are transferred to the engineer for performance evaluation through BPS tools. If the proposal cannot fulfil the project requirements, the engineer will reject and ask the architect for adjustments by giving some suggestions. This process happens iteratively until the proposal meets the conditions which will then be presented to the clients and project manager for approval. (Appendix 2)

After the design approval from the client, the next step is the design development. At this phase, the approved proposal from the previous phase will be further developed. Building details and materials are specified in the model by the architect before transferring it to the engineer for assessing the performance calculation. The last step of the stage is when the engineer prepares necessary documents to apply for building permission and sends them to a project manager to proceed with the submission to the authority (Müller, 1997).

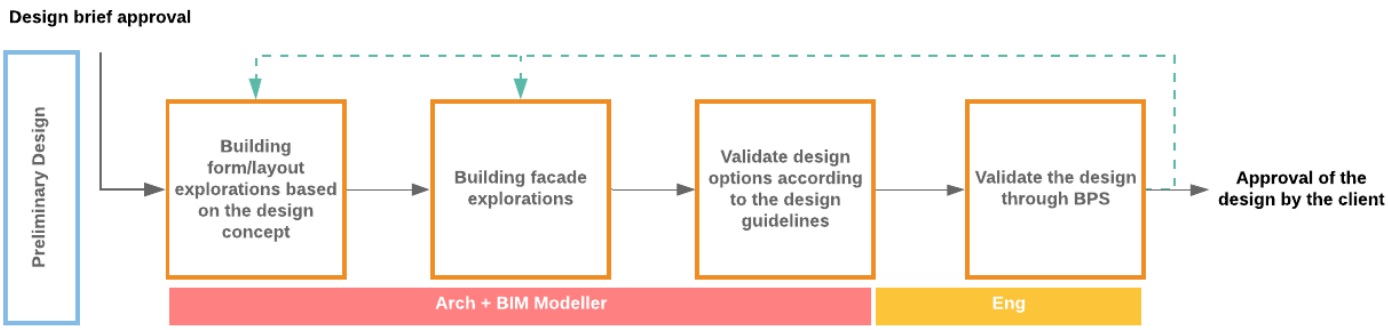


Figure 2 : Preliminary design step of the building.

[3] Danish Standard (DS) – is a non-profit commercial organization which provides standard solutions for different areas in the construction industry in collaboration with the international standardisation companies. (DanskStandard, 2019)

The work process in the preliminary stage design is where this research focuses (Figure 2). The study conducted by (Petersen and Svendsen, 2010) explained that the building design is an iterative exploration process where various building forms and facades that can achieve the functional requirements are introduced and validated to ensure the design fits a particular context. This information also gets support from the interview that the authors have conducted with an architect (Appendix 4). To start the building design, the architect initiates the building design concept that complies with the design guidelines. Hereafter, the architect explores the building layouts and comes up with the idea of building forms with the assistance of a BIM/3D modeler following the building concept. Within this stage, the idea of building façade may appear which depends on the project to project or architectural concepts. Some of the most appropriated building forms that can fulfil the design concept are selected for further development. The design concept can also be applied to create a building facade after the building forms have been selected. After the facades have been created, the architect will select the most satisfying alternative based on the design guideline for further check with the engineer. The engineer assesses the design evaluation by using BPS tools such as BSim for indoor climate and Be18 for energy performances. If the design cannot meet the project requirements, the engineer will bring proposed amendments based on his/her experiences and perspectives to the architect. This iterative process of the design and evaluation occurs manually between actors until the project requirements can be fulfilled.

1.4 Initial problem formulation

As previously mentioned in Chapter 1.1, regulations regarding building energy are becoming more and more strict, whereas indoor environment quality is a component of it, that is why it can be challenging to achieve the necessary IEQ requirements without new processes or ideas. Besides inside factors such as ventilation, heating, etc., the IEQ is also influenced by building design, especially, facades (Raji, Tenpierik and van den Dobbelsteen, 2017).

At the initial phases of a project, IEQ is not considered as much, only some general and/or minimum guidelines can be given to an architect that has to be followed while designing a building (Appendix 2). The necessary calculations and analysis are made in later phases, that can cause additional reworks and unsatisfaction from a client.

IT is rapidly developing in the construction industry and new digital tools and processes are being implemented. Nowadays to do the IEQ calculations or analyses, different digital tools can be used. But the disadvantage of those tools is that, firstly, the project must have a high level of detail (or information) and, secondly, they do not provide any further guidelines but just show if the project fulfils the requirements or not. If requirements are not fulfilled and changes have to be made, that will be based on the engineers' feedback which comes from their experience and perspectives. The process of building design exploration, evaluation and feedback happens iteratively and manually until the design meets the requirements. However, it would be very beneficial to base a building design already at the initial phase on the necessary regulations. This leads to the initial problem formulation of that report, which is:

"How IEQ can be improved during the initial design stage, before first performance simulations?"

The above-mentioned problem is intended to be improved by means of digital tools. In the Problem Analysis part, the problem will be investigated and potential solution(s) analysed with the help of Logical Framework Approach (LFA), Chapter 3.1.

1.5 Project scope

This project will be focused on rearranging an existing design process during the building initial phase with the purpose to find a possibility to early implement indoor environment quality parameters. What is meant by the initial design phase is the conceptual design, the problem-setting and the creative phase (Petersen and Svendsen, 2010) which starts from the client's brief till the first client's approval of the concept. The development will contain digital procedures as technology is being implemented more and more in the construction industry. It can support 'intelligent' functionality and automate the processes (Nederveen, Beheshti and Gielingh, 2010). In Chapter 1.2 is mentioned that facades are playing a significant role in regard to IEQ, thus the project is scoped down at considering only those parts of the building together with IEQ factors: daylight, thermal and visual comfort.

The case for the project is the existing COWI building, located at Visionsvej 53, 9000 Aalborg. The mass model with surroundings will be created in Autodesk Revit. This case was chosen with the purpose to see what design options will be proposed based on the analysis in the report.

The idea of this project is to consider the requested guidelines of IEQ for facades at the beginning of the design stage and before the first analysis/calculations made by indoor environment specialist. By implementing it, the probability of fulfilling the requirements and getting proper results in later phases is rising. Thus, the iterative process of the design concerning IEQ can be minimized or avoided which can save time and money for the company and the client.

During this project, the actual calculations or building performance simulations will not be carried out as they are out of the scope. The focus is on the information management aspect.

2 Methodology

2.1 Contextual Design

This research is based on the contextual design which is a methodology of IT development systems. The process starts with the investigation and data collection to clarify user requirements. Then, these requirements are implemented and executed through the prototype. The feedbacks are gathered followed by the analysis to decide on the improvement of the new system. The contextual design consists of 2 sections, which are 1. Requirements and Solutions 2. Define and Validate Concepts. In each section, there are 4 sub-areas corresponding to the method and solution (Figure 3).(Holtblatt and Beyer, 2018)

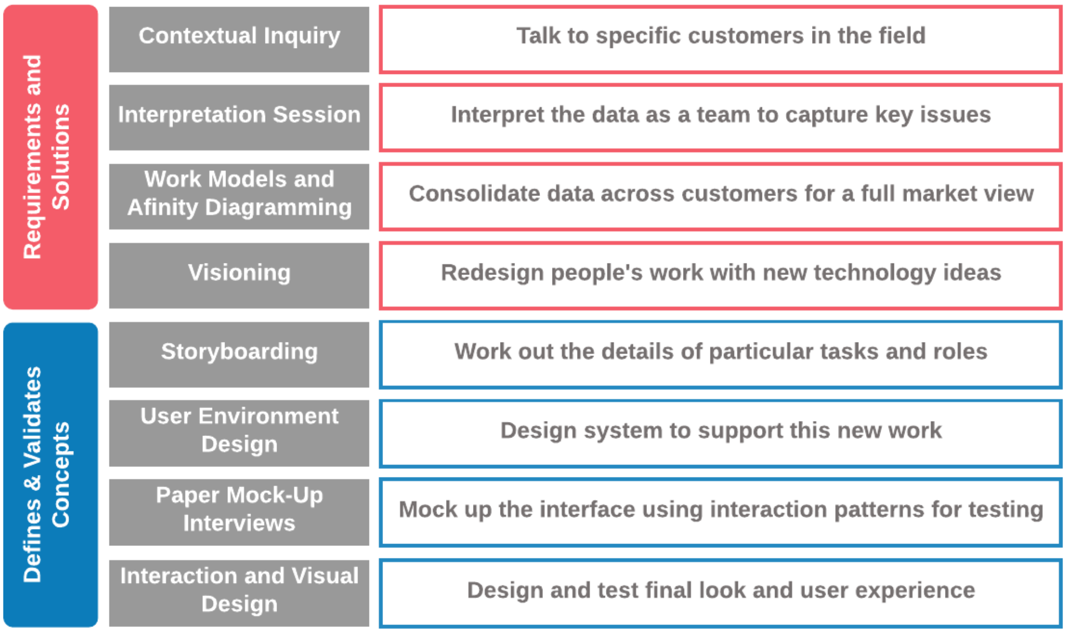


Figure 3 : The 8 sub-areas of the contextual design which are grouped into 2 main sections which are 1. Requirements and Solutions 2. Defines & Validations Concepts. The diagram is adapted from (Holtblatt and Beyer, 2018).

As the contextual design underlies the structure of this research, Figure 4 below illustrates the eight sub-elements and the description of the sequence of each element in the contextual design method.

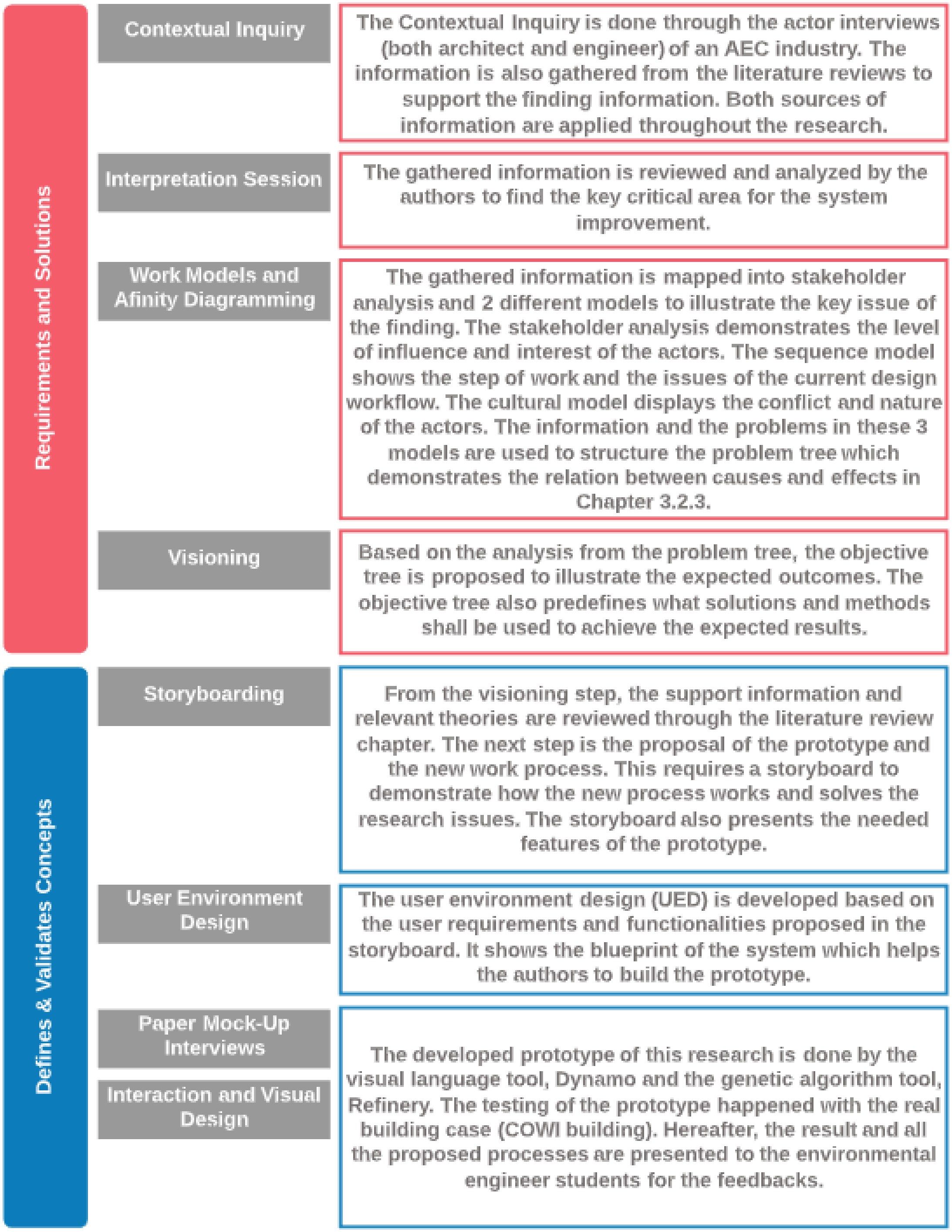


Figure 4: The contextual design of this research

2.2 Technique and tools

2.2.1 Logical Framework Approach

This project includes the following steps of Logical Framework Approach (LFA) - Stakeholder analysis, Problem, and Objective trees which are found to be relevant and help to investigate the problem thoroughly. The use of these tools is explained below. However, LFA includes other tools but those are not included in this project. (EU Integration Office., 2011)

Stakeholder analysis

This step is included in the project with the purpose to identify relevant stakeholders to the issue presented and analyse their interest and power in regard to it. The analysis is made based on the overall construction industry, meaning that it is not for a particular company.

Problem and Objective Tree

During that step, 2 diagrams ('trees') are created with an aim to see, firstly, the problem with its Causes, Core issue, and Effects. Secondly, as a positive reflection of the problems, the Objective tree with its Results, Project Purpose, and Overall Objectives.

A more precise description of stakeholder analysis, problem and objective tree can be found in Chapters 3.1.1, 3.2.3, 3.2.4.

2.2.2 Interviews

During the research, two interviews are carried out at the start of the project. The purpose of the interviews is to get an overview of how the initial design phase is done nowadays. Two interviews represent diverse points of view because of the different specialization of the interviewees.

Interview guides, which are available in Appendix 1 and 3, were made to keep the conversation on the right track. Interviews with the following professionals were conducted:

Nanna Dyrup Svane - Energy & Indoor Climate engineer at MOE A/S

Tima Bagheri – Architect at Sembyg

Furthermore, at the end of the project, one interview with three Building Energy Design students was conducted to get feedback on the work done. Transcription of the interviews can be found in Appendix 2, 4 and 5.

Problem Analysis

3 Root Cause Analysis

In this Chapter the problem is analysed to get an understanding and overview of the causes and effects. The analysis is based on the Logical Framework Approach and particular work models from the contextual design. The analyses are carried out relative to the initial design stage which implies the process done starting from the first meeting with the client (brief) till the first approval of the building design by the client. The analysis is supported by literature and conducted interviews (Appendix 2 and 4).

3.1 Logical Framework Approach

In Chapter 2.2 is mentioned that particular steps of LFA are implemented in the project. LFA is a tool for planning and management, it helps the authors to analyse and structure information considering different aspects of a particular problem (EU Integration Office., 2011).

3.1.1 Stakeholder Analysis

To identify potential stakeholders within the initial design process, a stakeholder analysis is carried out. Figure 5 illustrates particular actors who take part directly and indirectly in the process while the first design needs to be made for the client's approval. The presented analysis shows the interest and power of the stakeholders on the design of the building. By the *power* is meant if an actor has a lot of power to bring some changes into the construction project or if the power is low and unlikely to exert any pressure, the *interest* implies whether the outcome of the design in an early stage is on behalf of a specific stakeholder (Nicholas, 2017).

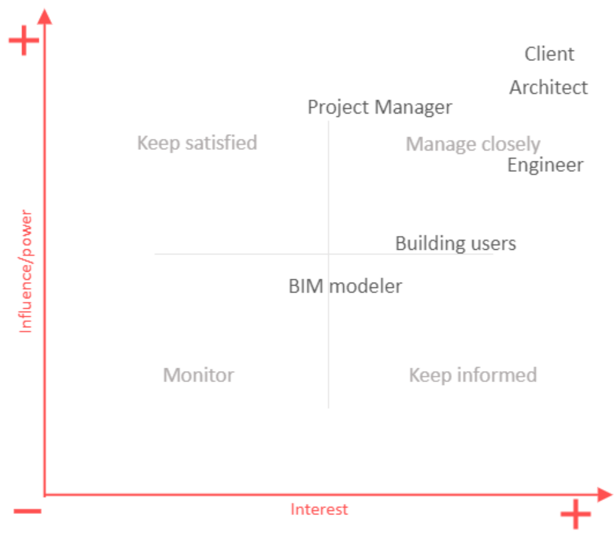


Figure 5: Stakeholders included in the initial design stage

The biggest interest and influence in such a case has the client who is paying money to get the desired result. However, it must be noticed that sometimes the power of the client, and also architect, for the design of the building can be limited by local regulations where e.g. façade materials can be determined (Designing Building, 2019a). Architects are specialists in designing that is why they have also high interest as well as high influence in the design process (A. W. Charleson and Pirie, 2009) as described in Chapter 1.3. The engineers, in a particular case indoor environment engineers, are supposed to give some general guidelines to the architects at the first meeting with the purpose to achieve good IEQ (Appendix 2). The design based on general guidelines cannot guarantee that the calculation or analysis made afterward will show acceptable results. So, the engineer has a high interest in achieving appropriate façade design at the beginning but still, the architect is in charge of the look of the façade what reduces the power of the engineer (A. W. Charleson and Pirie, 2009).

Architects have close collaboration with BIM modelers as firstly the idea is represented as a sketch and, later, built up in a software (Appendix 4), which is a BIM modeler responsible for (Eastman, Liston, and Wiley, 2008a). In the analysis architects and BIM modelers considered to work in the same company whereas the architect is responsible for the design idea(s) but the BIM modeler creates the digital models. As it is mentioned in (Eastman, Liston and Wiley, 2018) sometimes architects claim that using BIM tools is time-consuming at that phase and prefer hand sketches. That happens because of the complexity of BIM tools which require a long study period. Thus, it would be more reliable, easier and faster to present the sketch to the BIM modeler who can create a digital model (Eastman, Liston and Wiley, 2018). As the design is already created, the task is to make it digital, thus, BIM modeler has power only while working with the model and does not have a high interest in the design.

Another stakeholder who has high power and interest not only in the initial design process but the whole construction project is the project manager. He/she is responsible for the whole project, that is why it is important that the building is aesthetically pleasing and fulfills all the necessary requirements. (Eastman, Liston and Wiley, 2018)

The building users are also included in the analysis, the users or customers are considered to be the most important stakeholders according to (Nielsen, 2005). They are considered to be direct stakeholders, thus they have an interest in the quality of facade design as it has a direct effect on the well-being of the users as explained in Chapter 1.1. In addition, they have influence while considering building type (office, domestic, etc), occupancy time, etc. also can provide useful feedback. (Designing Building, 2019b) Much higher influence and interest are present when the client(s) and building user(s) are the same people.

All in all, by studying the stakeholder analysis it can be noticed that there is a gap in communication between architects and engineers (IEQ). They both have high interest, whereas for an architect it is aesthetically pleasant design and fulfilled requirements for an engineer (Designing Buildings, 2019)(Nicholas, 2017). However, the architect still has a bit more power in a design process supported only by general guidelines from an engineer(A. W. Charleson and Pirie, 2009). Such guidelines are given on a paper or as a digital text document (Appendix 2). Thus, it can be difficult for an architect to interpret such guidelines into the design that is why it would be beneficial to involve new digital step(s) into the initial design process that can help to achieve multi-disciplinary objectives. Such a method would raise the probability of achieving the necessary IEQ results in the initial design phase.

3.2 Analysis of the present workflow

In the following sub-Chapter, the work sequence of a construction project in a company and cultural approach between different actors are presented in diagrams. Those diagrams are two work models from the contextual design method. These models were chosen with the purpose to show the overall design process, actors and conflicts faced during construction projects. (HOLTZBLATT and BEYER, 2017) By means of the models, the authors get an overview of the regular work process and also the cultural approach of involved actors, thereby analysing where and why conflicts appear.

3.2.1 Project sequence

In the contextual design method, the sequence model is used to demonstrate the activities that need to be accomplished in every step of work. (Holtblatt and Beyer, 2018) The sequence model in this section will give the reader the overall framework of the current building façade design associated with IEQ. The model also demonstrates the conflicts that can happen from the poor IEQ building design throughout different project stages. The explained information below stems from the interviews (Appendixes 2 and 4) and following literature (Petersen and Svendsen, 2010), (Eastman, Liston and Wiley, 2018) and (Winch, 2010).

In this sequence model (Figure 6), 2 main stages of the building façade design and the relevant project actors are taken into consideration. This model begins at the preliminary design stage, which starts from formulating brief designs to the design approval from the client. The Figure illustrates that in order to start the building design by architects, the brief designs and design guidelines are delivered by a project manager and indoor climate engineer to specify a project framework. After the architects receive these documentations, they will start investigating the building concept based on these guidelines. Hereafter, building geometries are created by using BIM platforms, such as Revit, etc., to visualize the concept. (Eastman, Liston and Wiley, 2018) Afterward, the architects will explore the building forms followed by building facades respectively until they find the most satisfying option. (Appendix 4) The building model created within this stage will be a base for project development in the later stages for all project disciplines (Eastman, Liston and Wiley, 2018). However, as the received guidelines and information within this early design stage are uncertainty and dynamic, this can cause a high probability for the architects to explore the building design in the wrong direction (Winch, 2010). Additionally, due to the manual design exploration process, the architects lose an opportunity to consider other quality design options that demand more labour and resources to produce these potential design alternatives (Capeluto, Grobman and Yezioro, 2010).

When the architects have finished the first conceptual design model, they will send this model to the indoor environment engineers. The engineers start assessing the model evaluation by using BPS tools (Petersen and Svendsen, 2010)(Appendix 2). The building façades and layouts are analysed to validate the design meets the client requirements and complies with the regulations. After the engineers have evaluated the design, the project manager will set up a meeting for discussion. The issues, such as an insufficient area of glazing, overheating, etc., are discussed with suggestions from the engineers (Appendix 2). Here, another problem can arise as the recommendations can be based on personal views and experiences, which leads to a conflict between actors. The design iteration loop, as stated in Chapter 1.3 and Figure 1 happens until the design fulfils the requirements.

The final part of the preliminary design stage is the conceptual project estimation based on the architectural BIM model. The project cost and schedule are planned from the conceptual 3D model by incorporating estimation calculations based on previous projects (Eastman, Liston and Wiley, 2018). Nevertheless, if the input information for estimation is inaccurate due to a building design deficiency related to IEQ, this can lead to the mistake of project time and cost analysis. Additionally, if the client is dissatisfied with the design due to a project schedule delay and over budgeting, the project may be discontinued or requested for a redesign (Winch, 2010).

The next stage is the design development which aim is to develop the final building models to prepare documents for building permission. This stage starts with the other project actors, such as structural engineer and MEP engineer, who create discipline models based on the received conceptual design model. The MEP engineers design installation plans that can fit the space outlines defined by the architects (Eastman, Liston and Wiley, 2018). However, if the design of the building cannot fulfil the IEQ requirements from the indoor environmental engineer, the MEP engineers inevitably demand a better heating, ventilation and air conditioning system (HVAC) to improve the IEQ as explained in Chapter 1.1. As a consequence, the MEP engineers can encounter with insufficient space for HVAC systems that require the architects to revise the design.

The process continues iteratively until the design issues have been resolved following by the final construction planning. The problem with the construction schedule can happen if the design period is overspent. The project manager has to tighter the execution period in order to hand-in the building on time. (Winch, 2010) The results can lead to the risk of financial problems due to the demanding extra labours and machines on-site. In addition, when the building is handed-over and starts operating, the poor IEQ due to the improper building design can lead to high energy consumption and health issues of the inhabitants, as stated in Chapter 1.1.

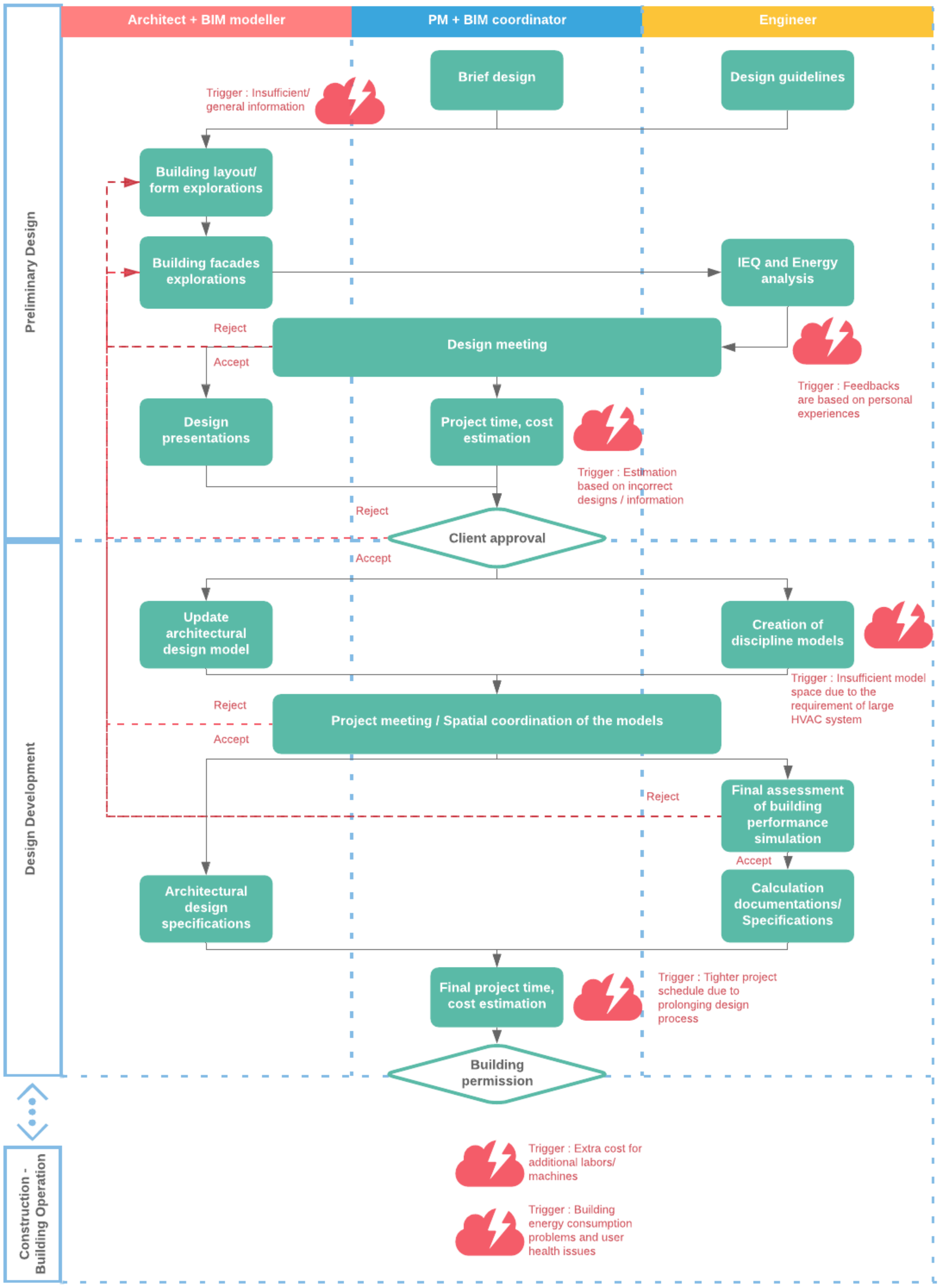


Figure 6 : Sequence model - an overview of how the project tasks are proceeded. The model also demonstrates the relation of causes and effects of each tasks between the project actors and project stages.

3.2.2 The cultural approach between stakeholders

The cultural model seen in Figure 7 shows the culture and policy of the particular actors that can limit the initial design process work. Each circle indicates one actor that was taken from the stakeholder analysis, which is presented in Chapter 3.1.1, and the lighting is pointing out the conflicts during the work.

As shown in Figure 7, the client is putting the demands of what is wished to be achieved, so later, building users will be satisfied with living or working in such a building (Appendix 2). The biggest constraints that slow down the process are seen between the architect and the IEQ engineer because of two different areas of focus (Charleson and Pirie, 2009). By receiving text guidelines from an engineer, the architect has to 'translate' them into the design by himself (Appendix 2), (Negendahl, 2015). Because of a lack of knowledge, small experience or misunderstandings the guidelines might be interpreted wrong (Flury, 2012). Subsequently, there is a need to change the design many times what leads to the fact that the BIM modeler constantly has to change the digital models. As a result, there is a risk of project schedule delays.

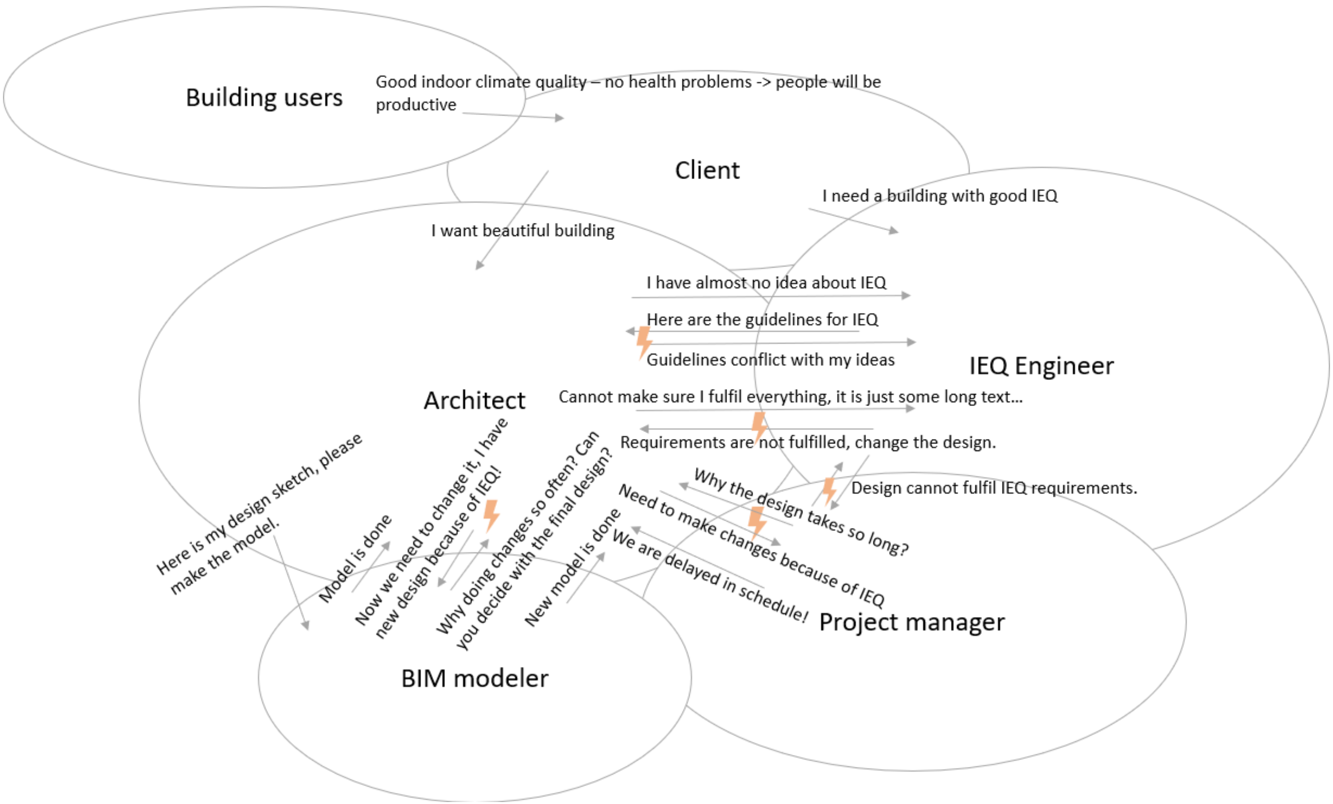


Figure 7: Cultural model showing the culture and attitude of different actors during the initial design process, emphasizing difficulties between the architect and IEQ engineer.

3.2.3 Problem Tree

During the problem analysis, the problem tree (Figure 8) is used to present the overall issues of the research project. The problem tree categorizes the issues into the causes, effects and the core problem through the supporting information from the contextual design method in the work models analyzed in Chapter 3.2.1 and 3.2.2 (EU Integration Office., 2011). With the analysis of the problem tree, it helps the authors to develop a better understanding of the root causes of the main problem which will, in turn, lead to a possible solution to solve the main project issue.

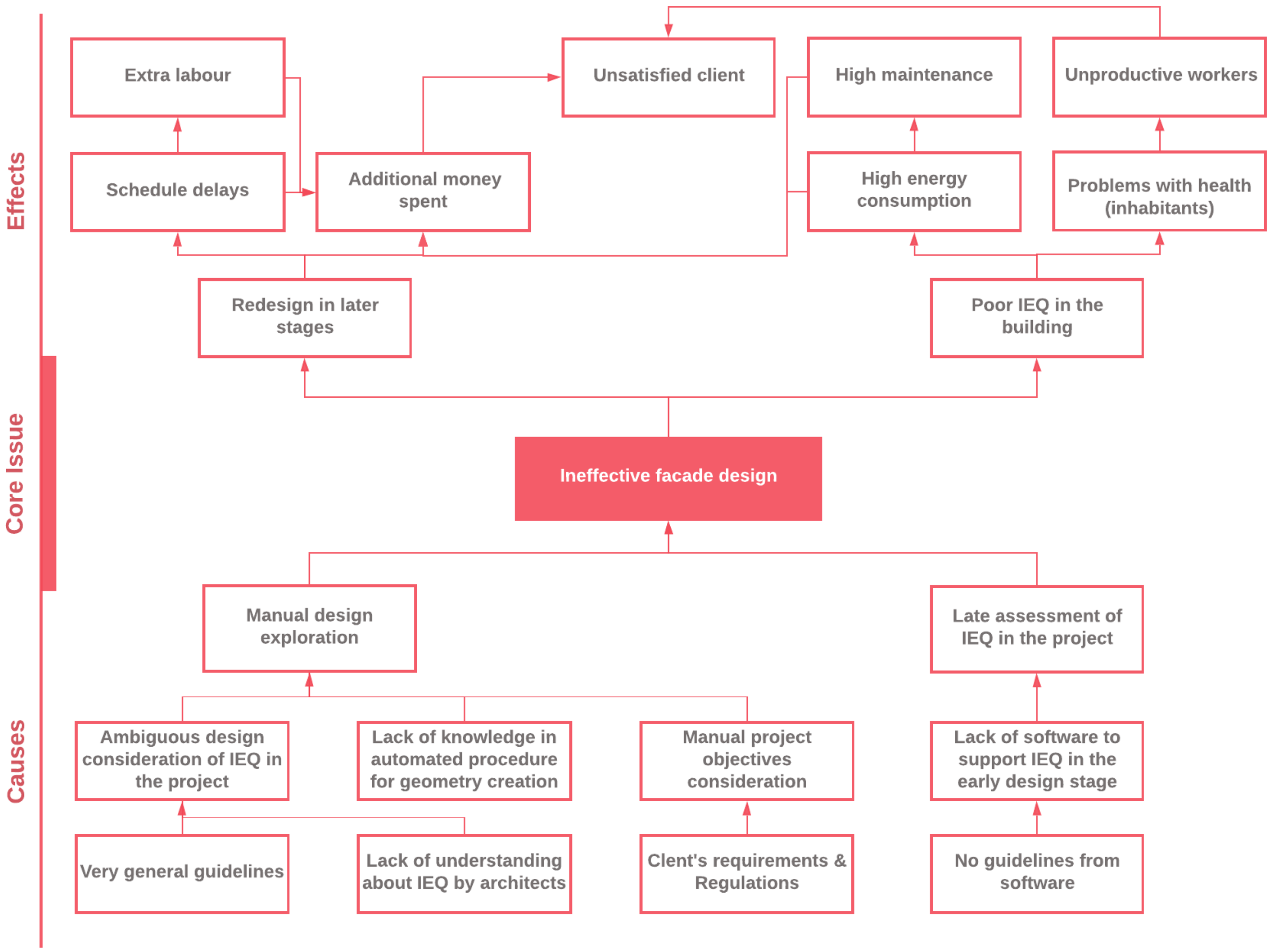


Figure 8 : The problem tree of an ineffective facade design.

The core issue of this research is an ineffective building façade design on IEQ criteria, as explained in Chapter 1.2. The ineffective building façade design in this report refers to the designing process that brings dissatisfaction results in terms of IEQ and also causes negative effects to stakeholders in the later project collaboration phases. The reasons for the ineffective façade design derive from 2 significant conditions which are the manual design exploration and late assessment of the indoor climate in the design process as explained in Chapters 1.2, 1.3 and 3.2.1. These causes contribute to the negative impacts of the project in the later stages such as poor IEQ in the building and project rework, as presented in Figure 8.

Various reasons trigger these causes. Starting with the manual façade design exploration, the problems such as unclear information from the project guidelines, lack of knowledge in automating the process and manual project objectives consideration are the primary factors that contribute to this issue. The architects explore the design options based on the received guidelines manually as explained in Chapter 1.3. The received guidelines usually come in text format which requires the architects to translate it into their design as described in Chapter 3.2.2. The architects use this information incorporated with their previous experiences to generate the design outcomes. This method can cause problems as the whole design process is manually done which affects the quality of the final product design as explained in Chapter 3.2.1. Additionally, the manual design exploration process can lead to a project dilemma when the designers need to consider multiple project objectives which, in turn, cannot achieve the necessary project requirements (Hou *et al.*, 2017).

Another cause of the ineffective façade design is the late assessment of IEQ in the project. As stated in Chapter 1.2, to assess the IEQ in the project, BPS tools within the design process are incorporated. But 2 major factors bring the challenge to integrate the tools in the early design stage. Firstly, there is a requirement for a high level of project development (LOD) for analysis (Attia *et al.*, 2012). Secondly, there are no active feedbacks for further project progress (Lin and Gerber, 2014). As a result, the architects may avoid encountering such difficulty and leave the assessment of the IEQ condition into the later stage when the environmental engineers are involved in the process.

There are several effects of the low performance of the façade design. One impact that explained in Chapter 1.1 is the poor indoor climate in the building. This impact contributes to the adverse effects on the inhabitants as they may incur the health issue and low productivity of work. Additionally, poor IEQ plays a significant role in the energy consumption of the building. Insufficient daylight and high quality of indoor thermal comfort demand more energy to support the HVAC system and more frequent maintenance of the system. As a consequence, this can cause a financial burden to the building owner (Omer, 2008).

Another impact of the façade design issue is a projected rework during the later phases, as explained in Chapter 3.2.1. This rework affects the project timeline and cost which requires extra labour in order to complete the project (Winch, 2010). The prolonging design period also impacts to the construction schedule that causes the dissatisfaction of the client and may result in project cost overrun.

3.2.4 Objective Tree

An objective tree is a tool for analysing the negative causes, core issues, and effects from the problem tree in Chapter 3.2.3 and turning them into positive targets to achieve. The expected results are set up based on the existing project causes. The core issue in the problem tree has turned into a project purpose and the overall objectives are a proposed result converted from the problem effects. (European Integration Office, 2011)

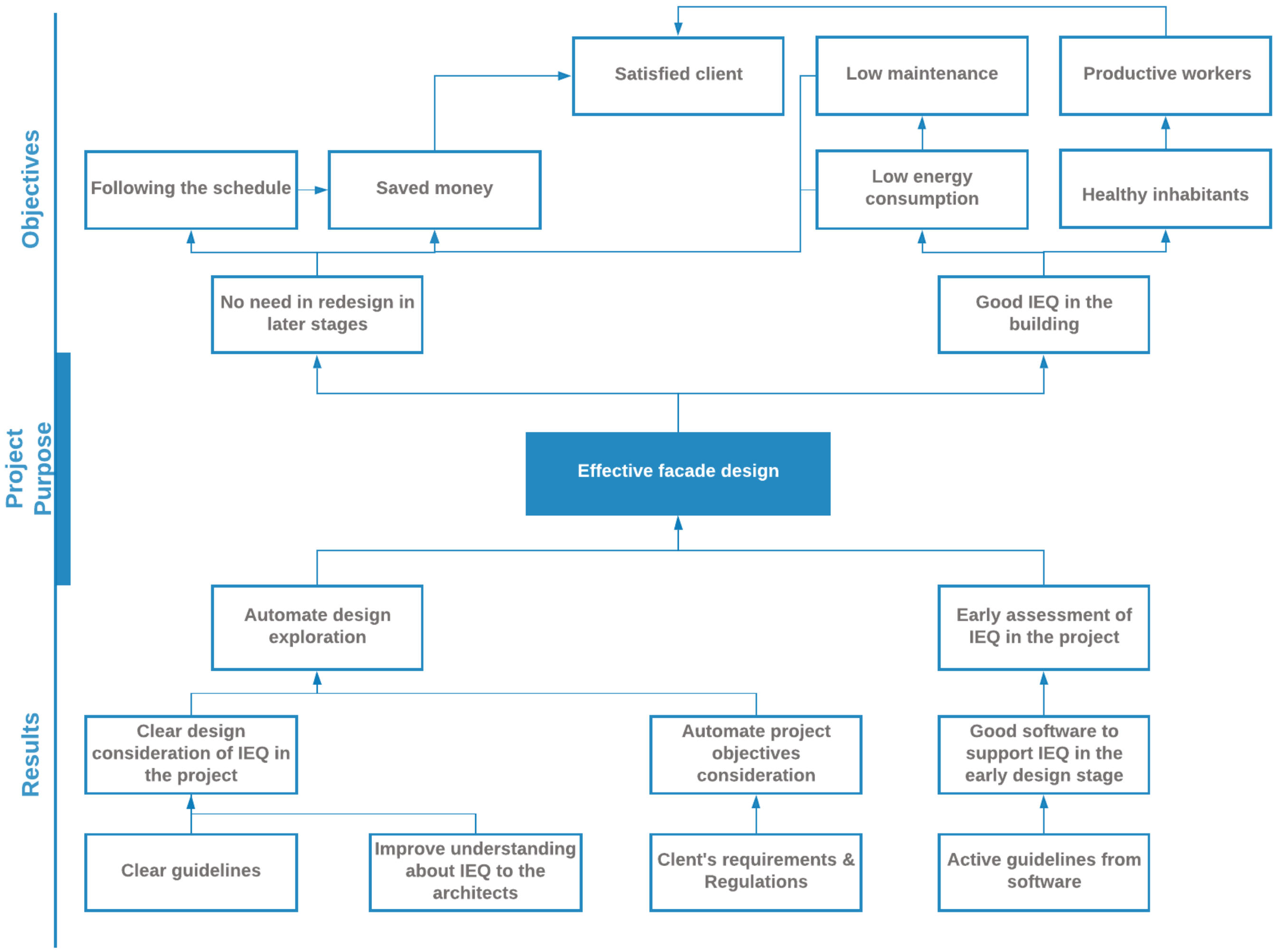


Figure 9 : The objective tree of an effective facade design.

The meaning of an effective façade design in this research refers to the designing process that can deliver the satisfaction of the project outcomes in terms of the high quality of IEQ and, reduce the flaws in the design since an early project stage. These results lead to the decrease of the iterative loops of the design revision, as illustrated in Figure 9. If the building can achieve a good quality of IEQ, this brings several benefits to the inhabitants and the building owner. Firstly, the issues related to health can be decreased and promotes the well-being of the residences. (Mujan *et al.*, 2019) As a result, the inhabitants can produce more productive work, which brings a financial benefit to the business owner. Another advantage of a good IEQ is the reduction of energy consumption. As explained in Chapter 1.1, the primary cause of high energy usage in the building is due to a poor IEQ. Thus, if the IEQ is improved with a proper building design, this will help to minimize the need for energy used in the HVAC systems. Additionally, to reduce the rework in the later project stages, a proper façade design solution is necessary since the initial design stage. As can be seen from Chapter 3.2.1, the result of a suitable design solution will reduce the risk of project time and cost overrun due to this rework which in turn, improves client satisfaction.

The results of the effective façade design specify that the architects can explore the design in a less complicated way and bring the assessment of an efficiency IEQ design to improve the building performance since the early project stage. To achieve an efficient design exploration, this requires a new process/tool that can reduce the manual work of the actors. This is because, with the less manual intervention in the design exploration process, the outcomes are based on the input data. These outcomes can guide the architects to consider each option based on their performance. As a result, this will enhance the design decision in regards to IEQ and bring the most suitable design options for the project. A further explanation of the performance-based design will be discussed in Chapter 4.2. Additionally, in order to implement the IEQ in the early assessment, a tool that supports interoperability and applicable to work with different levels of LOD is needed. The possible tool that supports these requirements is a visual programming tool which will be explained in Chapter 4.2.3.

All in all, it can be seen that in order to achieve an effective façade design, a new process/tool is needed. The process/tool that demands less human input to explore the façade design and incorporate the IEQ assessment within the design creation process is significant. In the next Chapters, the relevant principles and support theories of this process/tool will be discussed.

4 Literature review

In Figure 10 is shown the diagram which represents the content of the section. The review starts with the research problem area which is the IEQ problem. In order to solve the research problem, two methods have been studied. The first method is the typical building design method by means of BPS tools (red box) to analyse and improve design performance when the initial design has been proposed. The second method (green and blue) is focused on the performance-based design to generate the building design. By getting from top to the bottom, possible solution (blue), which includes all the before mentioned aspects, is introduced.

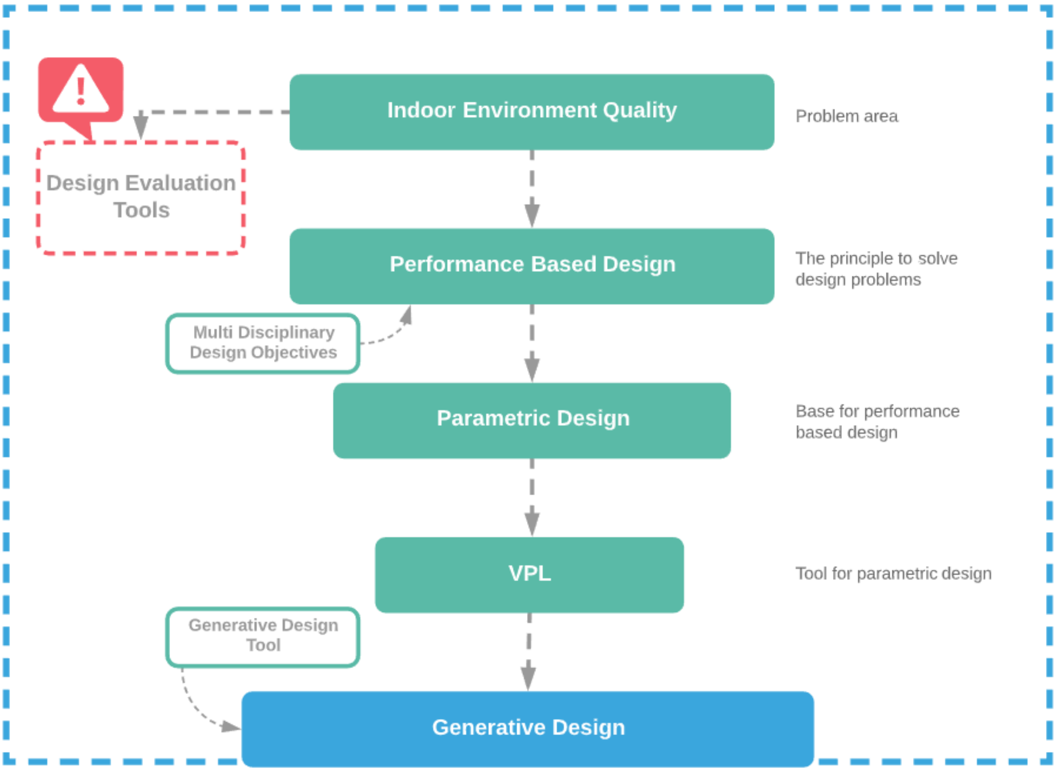


Figure 10: Readers guide starting with the problem area which is a more wide topic and narrowing down to specific things (green). The blue box represents a possible solution which is a method that includes the principle of the before mentioned aspects (green). The red dotted box shows the issues faced in the current workflow that would need to be solved.

4.1 Indoor Environment Quality

IEQ is formed by many aspects, such as humidity, air temperature, lighting, air quality, ventilation, acoustics, etc. All those factors can be divided into the four main groups for IEQ which are: indoor air quality, acoustics, thermal and visual comfort. (Wong, Mui and Hui, 2008) Indoor air quality can be influenced by human activities, construction materials, outdoor air, and ventilation. Acoustics takes into consideration the noise produced from outside (e.g. traffic) and inside (e.g. technical installations, reverberation, airborne sound) (REBUS, 2019). As it was mentioned in Chapter 1.5, the project is focused on the thermal, daylight and visual comfort factors, whereas thermal comfort is achieved by analysing temperature during summer and winter periods, avoidance of overheating and also implies ventilation (Oral, Yener and Bayazit, 2004). Daylight and visual comfort are interconnected, it is significant to consider the direct sunlight, daylight from outside and shading (overhangs, side fins, etc) (Konis, 2013).

In Denmark, to carry out a calculation about the indoor environment, such a tool as IV20[4] was developed. The purpose of this tool is to calculate the building's potential for a good indoor climate. For now, it is focused on the renovation of residential buildings, however, the overall aim is to use

[4] Indeklima Vurderingsværktøj - Indoor Climate Assessment Tool

IV20 also for new buildings of different types (REBUS, 2019). IV20 is represented in Excel format and it considers the four main IEQ groups mentioned above. In the end, it gives the results by showing the energy labelling from A-G scale and also the score for each of the four evaluation areas (REBUS, 2019).

4.1.1 Design evaluation tools

In the current design workflow to assess the indoor environment quality parameters or do design performance simulations, different methods can be used. Previously everything was calculated by means of traditional methods meanwhile nowadays more and more digital tools are being developed and implemented (Nielsen, 2005). Besides using traditional mathematical calculations for indoor environment quality there is modelling and analysis software. Modelling software is needed with the purpose to perform IEQ analysis and simulations such as energy analysis, sun analysis, heat loss/gain, etc. (Rocha, 2017) For modelling can be used Autodesk Revit, Rhinoceros 3D, SketchUp, etc. For analysis, there are many various possibilities depending on what is planned to be measured. Thus, for energy analysis, also considering thermal comfort, can be used Energy Plus, Design Builder, eQUEST, Be18 (Rocha, 2017). In regards to daylight, it can be a plug-in for Rhinoceros 3D - DIVA, Ladybug for Dynamo, BSim, Velux Daylight Visualizer.

In Denmark for indoor environment quality analysis is used BSim, also specifically for daylight analysis can be used VELUX Daylight Visualizer or Autodesk Revit (Nielsen, 2005). VELUX Daylight Visualizer (Figure 11) is used for daylighting analysis and design. Velux is an international company producing windows, skylights and corresponding attributes to those (blinds, roller shutters, etc.) The aim of VELUX Daylight Visualizer is to help the professionals achieve, predict and document necessary daylight in the buildings. The tool can be downloaded and the 3D model can either be imported in DWG, DXF, SKP or OBJ formats, or created in the program. It requires the user to give information about the 3D model (walls, floor, windows, doors, etc,), surfaces, furniture, and location. Basing on these factors, the tool will calculate and visualize daylight conditions. (Velux, 2016)

To analyse the IEQ in overall BSim (Figure 11) program can be used. By inserting necessary information about the building (location, materials) and installations (heating, ventilation, etc.) it will produce the results. For instance, for the annual temperature inside the building the program creates a graph which shows during which period the overheating can happen (Nielsen, 2005). BSim also can help with choosing HVAC systems and it is possible to examine various options with the purpose to achieve the desired indoor environment (Danish Building Research Institute, 2002).

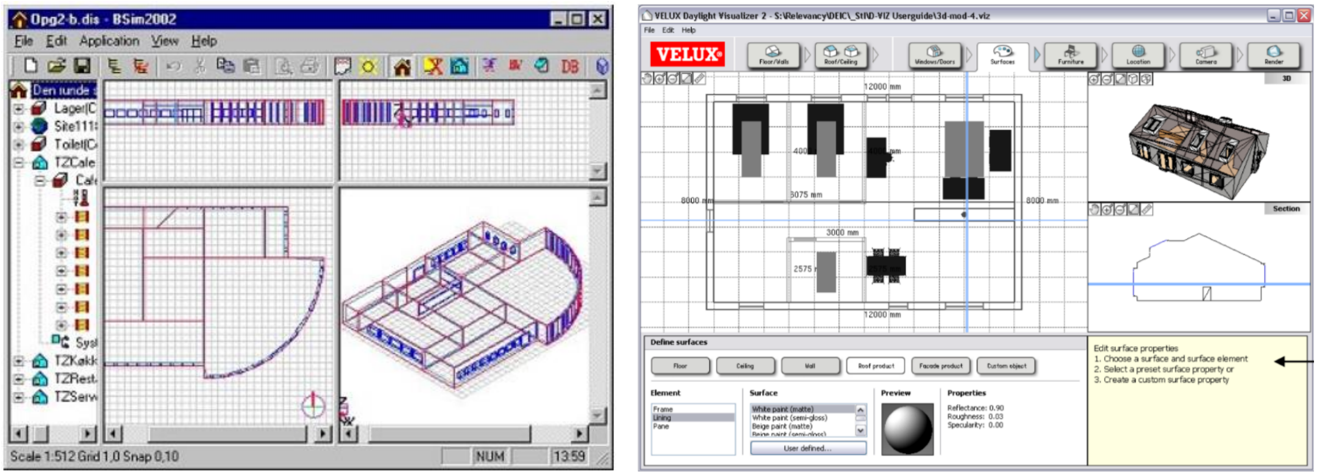


Figure 11: Bsim (left) and Velux Daylight Visualizer (right) user interfaces.

A simplified building simulation tool for the early design stage was developed by T.R. Nielsen (2005) to analyze building energy and thermal indoor environment. The tool was programmed in Matlab[5] and implemented in BuildingCalc. The calculations were compared with the results in BSim whereas they turned to be similar. However, the proposed calculation is made on an already created model, meaning that it can provide decision support but not drive the design.

The disadvantage of the above-mentioned tools is that they are not giving any feedback or guidelines on how to improve one or another factor but just presenting the result which must be estimated by an expert. In addition, as it was mentioned by (Nielsen, 2005) BSim can be used in a later design process as it requires information which is unknown at the initial design stage. Similarly, the Daylight Visualizer requires data about construction materials, window properties, etc. which is unknown at the initial design stage.

4.2 Performance-based design

Generally, in order to achieve the high quality of the building performance, the designers integrate BPS within the design process to analyze and investigate appropriate solutions that can improve the quality of the design outcomes (Chen, 2018). To proceed with the design, architects design buildings based on their experiences and inspirations (Winch, 2010). Hereafter, the building

[5] A programming platform for scientists and engineers (MATLAB, 2019).

drawings are transferred to the engineers that they will perform the analysis from BPS tools to simulate different scenarios, such as the analysis of building energy and IEQ. The engineers decide on the essential parameters of the building that have a high impact on its performance based on the analysis and inform the architects (Oduyemi and Okoroh, 2016).

However, the traditional design process for achieving a high quality of the building performance does not consider the essential parameters that have a high impact on the performance during the layout planning and building form generating (Anton and TĂnase, 2016). This process is instead making a small improvement in the overall performance of the building design as the analysis is occurred after the first building idea has been proposed. This process also has a few impacts on the architectural work while it will require a more increment of the engineering solution to investigate a practical approach that can improve the building performance. Additionally, if the required performances are a critical sensitive factor, this can impact the overall project development as the change of sensitive parameters may lead to the project re-design until it meets the requirement. (Anton and TĂnase, 2016)

Another aspect that considers the performance of the building is a factor that drives the creation of the building form. This aspect is known as the Pre-rationalization process, which is explained by (Anton and TĂnase, 2016) as a design process that considers variable rules and methods to create a building design. This aspect does not limit the operation of geometry creation to only the architect's vision, but the creation process can be based on the parameters and data that drive the design (Dino, 2012). Additionally, with the integration of the parametric design method, which will be further explained in Chapter 4.2.2, the building performance can be taken into consideration as an input parameter to generate a building geometry. The performance in regards to building sustainable factors, which are generally considered after the first building design proposal, can be incorporated in the design before the first formulation of the building form (Anton and TĂnase, 2016).

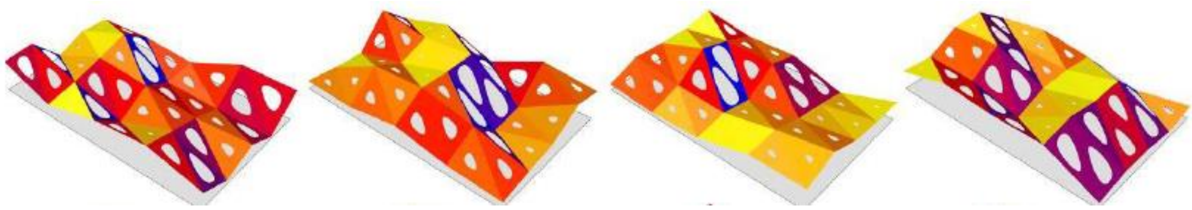


Figure 12 : Analysis results based on different building performances are presented on the geometries automatically in the design rationalization method (Anton and TĂnase, 2016).

Because the design rationalization brings the performance criteria for an input parameter to generate a building design, the building analysis applications are implemented in a different role from the traditional design method (Anton and TĂnase, 2016). The building analysis, in this case, performs itself as a key collaborator with the designers as it brings automatic results from the change of user-defined parametric inputs. The results are presented directly on the building geometry, which illustrates the performance of the building (Figure 12). The performance results are applied in a loop of design iteratively to define a set of rules that is suitable to create a building geometry based on the expected performance. (Anton and TĂnase, 2016)

As stated in (Anton and TĂnase, 2016) research, the design rationalization can be applied for building form-finding in regards to the energy usage and solar analysis of the building. The study made use of parametric modeling tools and extended plugins that can bring performance analysis to investigate the most suitable building form within the specific environmental conditions. This research also focuses on the optimization of a building form with several performance criteria by using the genetic algorithm to facilitate an exploration process. The finding of this research has concluded that design rationalization can encourage the design of the architectural form in the early stages while also promote the interdisciplinary collaboration for the different required performance.

The performance-based design demands a tool that can provide a direct link of the data connection between the different applications, which will be further explained in Chapter 4.2.3. Furthermore, the performance criteria always stem from multi-disciplinary actors who require different conditions of the building performance that can come with conflicts. This principle will be further addressed in Chapter 4.2.1. In the next Chapter, the roles of BPS tools in the current design process will be discussed to specify the problems and also investigate the possible solutions to support the design rationalization principle.

4.2.1 Performance-based design for multi-disciplinary design objectives

In every design project, it is inevitable to deal with various requirements from different actors. Especially when the project has to take the factors concerning IEQ into account, this demands the balancing of the importance of each factor to achieve the best outcome. This is because if such a factor is given more weight consideration than others, it can worsen the overall performance of the building. (Østergård, 2017). Thus, the principle of Multi-disciplinary Design Optimisation (MDO) should be taken into consideration. The MDO method allows different stakeholders to incorporate the required factors within the design process in order to enhance the design outcome corresponding to the various objectives needed. This technique illustrates an effective method to integrate expertise decisions during the design determination stage (Lin and Gerber, 2014).

The MDO can be done through a performance-based design method. As explained in the previous section about the integration of parametric design and BPS in a design rationalization, this process allows multiple actors to be in a part of the design analysis. The actors can determine the desired outcome along with the active feedback gaining from the analysis since the process of geometry creation. (Lin and Gerber, 2014) This process facilitates the designers to do the design exploration in order to investigate the most suitable option based on the multiple required performances of the IEQ as explained in Chapter 4.1 (Dino, 2012). The MDO also helps the designer to increase a set of design options that can be created and categorized corresponding to the different performance criteria (Lin and Gerber, 2014).

Some samples of the multidisciplinary design thinking that impact the building design are presented in the research conducted by (Hosseini *et al.*, 2019). Hosseini (2019) focuses on the use of performance-based design concerning the MDO for generating a kinetic façade based on the design criteria of the visual and thermal comfort. The research has concluded that by incorporating the MDO and parametric investigation, this brings a variety and opportunity for the design exploration of the building geometry to achieve the multiple requirements of the building performances.

However, only the performance-based design method is insufficient to bring the most effective outcomes for all stakeholders. There is a need for the proper process and artifact that can deliver the expected result corresponding to the performance criteria of the project. The further explanation of the process that incorporates the MDO and performance-based design will be further explained in Chapter 4.3.

4.2.2 Parametric design

Nowadays, most of the BIM platforms used for modelling, such as Autodesk Revit, Bentley Architecture, ArchiCAD, Tekla Structures, etc. are based on a parametric modelling system (Eastman, Liston and Wiley, 2018). The parametric design system is a principle to generate 3D geometry based on an algorithm. The algorithm is a set of rules that is created according to the semantic information or the user-defined criteria with the purpose to achieve the needed results (Milena and Ognen, 2011). The geometry created in the BIM platforms is a BIM model, which is a parametric object as the model performs based on parametric rules and contains semantic information of the building properties (Eastman, Liston and Wiley, 2018). However, the parametric object is not necessary to be the BIM model. The parametric object can perform according to the user-defined algorithm that may not incorporate semantic information of the building properties into the parametric object. This parametric object is often used to present a particular geometric entity for achieving specific project tasks by considering the whole project as a single object assembly. This is different from the BIM model which has its object functions that the users can select and assemble the different objects for solving the problem. (Boeykens, 2012)

In order to create parametric models, (Eastman, Liston and Wiley, 2018) explained that two significant principles can be applied. Firstly, parametric models can be generated from predefined parametric functions in BIM applications. In every BIM platform, predefined parametric objects are provided as a standard feature for the users. The reason for this provision is due to the standard conventions in the industry domains because architectural and engineering designs must comply with the standard practice. For example, the building parts and engineering systems, such as steel column and duct, are standard industrial products that are produced based on performance, safety, and usage. Thus, BIM applications provide these predefined parametric objects to facilitate designers to ensure the design quality according to this standard practice.

However, the predefined parametric geometry brings a negative impact in terms of limitations on design as they do not deliver certain design conditions to address specific project issues. Thus, the second principle, a user-defined parametric model is suggested by Eastman, Liston and Wiley (2008a) for solving a particular project condition. The user-defined parametric method allows users to define parametric objects manually based on user-defined parameters. This process starts by creating reference geometries in the BIM application or CAD software before importing it into the BIM platform. Afterward, these geometries are assigned to attributes and families corresponding to the BIM application manually. (Eastman, Liston and Wiley, 2018) The user-defined parametric objects offer more variation of the design in order to address specific design intents when comparing to the predefined parametric modelling. This method is applied in the design exploration process as the users are more open to investigating the suitable building geometries of the project. (Dino, 2012)

The importance of parametric design

There are various perspectives of the parametric design. One of the crucial aspects that underlies the necessity of the parametric design in the early design stage is the flexibility and the availability of parametric model adjustments (Davis, 2013). This perspective brings an impact not only for the architects but also for the engineers and the project owner. The reason for this is that the design changes in the early design stage can be done easily with less additional cost due to the flexibility of parametric models, this encourages the designers to be more comfortable to make changes in their design. This encouragement also reduces the conflict due to the ease of change when there is a project collaboration between different actors. As a result, it contributes to the improvement of project collaboration in the early design stage, which will, in turn, enhance a project decision in the later stages. Additionally, the improvement of project design decisions brings positive consequences to the project. Especially for the overall project cost as this improvement reduces project adjustments in the later phases, which are a stage that demands a higher cost of the design changing. (Davis, 2013)

Another aspect of the parametric design is that this method is practical for design exploration. (Davis, 2013) As the project design always comes with several problems that are not possible to compete with a single best solution, this requires the architects to investigate the most practical design option from various design solutions. In order to deliver the proper design alternative, the comparative design options are needed. Regarding the key characteristic of parametric models, the availability of design change allows the architects to explore many design options of the same parametric model. This approach facilitates the designers as there is no need to recreate a new model to make a design comparison. (Davis, 2013) Additionally, the parametric models also enable the architects to investigate other alternatives in a different design domain. By changing input parameters associated with specific design areas, such as shapes and materials, this can facilitate the designers to produce the new building models in a less time consuming and more efficient than a typical geometry creation method. (Dino, 2012)

Lastly, the parametric design offers an integration of a building performance analysis during the design investigation. The building analysis plug-ins (e.g. Ladybug, Honeybee), which are introduced in the following Chapter, can be incorporated into a design parameter in order to optimize building performance. (Hosseini *et al.*, 2019) Additionally, with the integration of the parametric model and building analysis tools, this brings an improvement of project coordination. The analytical feedbacks can be generated through this integration and presented on the parametric model. The stakeholders can utilize this analysis information from the model parameters for further analysis in their disciplines. (Dino, 2012)

Some of the use cases of the parametric design to improve the building performance in regards to IEQ was done by Lauridsen and Petersen (2014). This paper makes use of parametric design and an optimization algorithm to produce the designs based on the user required proposals which are the indoor temperature, daylight and energy efficiency of the building. The result presented that the use of the parametric solution and genetic algorithm give a variety of the design outcome in regards to the architectural design aspect. While in terms of performance, the results according to energy and thermal comfort can be achieved. To generate the design alternatives, there is no need to recreate the new models, this requires only the users to define the parametric input to change the architectural appearance.

4.2.3 Visual programming

As it was mentioned in Chapter 4.2.2 most of the modelling software is based on parametric modelling capabilities. The parametric operations can be extended by use of visual programming language (VPL), for instance, for Autodesk Revit such a tool as Dynamo was designed to expand the operations, drive the geometry creation by adding a level of associativity to be able to add driving parameters from external inputs, e.g. analysis and sensors (Kensek, 2014). For example, Kensek (2014) investigated if the data from environmental sensors could be sent to the 3D model with an aim to change it and, on the contrary, if the changes made in the 3D model can affect the physical model by means of actuators. The investigation was carried out by means of VPL (Dynamo) and the model was created in Revit.

Dynamo uses a visual programming language that is suitable for non-programmers and as it does not require detailed programming knowledge, it is intuitive and easier to be used (Preidel, Daum and Borrmann, 2017). The visual language is formal and with visual semantics and syntax (Dynamo BIM, 2018). The workspace is presented as a canvas where individual components (nodes) are placed and connected with wires by the users, which as a result create a script. The difference between VPLs is the level of granularity if, for instance, one node implies all the functions needed for a script or several nodes need to be used to achieve the same result (Dynamo BIM, 2018). VPL in digital construction is used for generative purposes or for checking/querying information on existing models (Beetz *et al.*, 2015). Several studies in the construction industry used VPL: Rahmani Asl (2014) implemented Dynamo to improve the energy performance of a building, Preidel (2017) based data retrieval from BIM models on VPL, Seghier (2017) assessed building envelope thermal performance using BIM and VPL, etc. As an alternative to Revit and Dynamo, Rhino 3D modelling tool can be used together with Grasshopper[6] visual programming tool or Marionette for Vectorworks (Preidel, Daum and Borrmann, 2017).

Nowadays the analysis tools are mostly standalone (e.g. BSim), meaning either a very low level of interoperability or even lack of it (Negendahl, 2015). That causes problems because in such a case architects and engineers work with different models and no direct feedback is available. In addition, often the calculations/analyses are not done on as detailed models as in the design tools because of BPS tools limitations (Negendahl, 2015). With the purpose to explore multiple design options based on required indoor environment quality parameters, Dynamo plug-ins need to be used. The plug-ins are *Ladybug* and *Honeybee* that aid designers to explore the performance of a parametric modelling

[6] Graphical algorithm editor (visual programming language) (Davidson, 2017)

environment (Knudsen, 2018). Originally these environmental plug-ins were used in Grasshopper but later adopted to Dynamo.

Ladybug allows users to carry out the following analyses: wind-rose, radiation-rose, shadow studies, sun path, view analysis. The analyses are done by importing weather files. Honeybee is able to perform building energy and daylighting simulations. (Wintour, 2016) The use of the above-mentioned tools: Revit, Dynamo and it's plug-ins provide a smooth interoperability process where the same model can be used both, for the design and IEQ analyses.

4.3 Generative design

As stated in Chapter 4.2.1, the design issues are multidimensional problems that require various expertise to contribute during the design process to bring the most satisfying outcome for the majority of project stakeholders (Anton and TĂnase, 2016). To achieve the MDO, the present design process cannot support this method. The reason for this is because it lacks performance integration to drive the design and the deficiency of integrating BPS tools to ensure the performance as previously stated in Chapter 1.1 and 3.2.3. Additionally, the traditional design method can produce only a few design options based on the designer experiences which leads to the IEQ problems as explained in Chapter 3.2.1 and 3.2.3. Thus, the parametric design exploration process or a generative design (GD) should be considered to address the multiple objective design problems.

The generative design (GD) is a process of a production system where the generation of the outcomes is created according to the design's logic or algorithm. The notion of the GD is based on a non-linear design method in which the design alternatives can be generated from various initial design generations as a morphogenetic process that brings new outcomes for every newly created generation (Agkathidis, 2016). The mechanisms that underlie the GD are the parametric design and performance-based design method that takes the performance criteria as a design logic to drive the geometry formulation as explained in Chapter 4.2.1. In order to proceed with the GD, this requires a computational tool or artifact that allows for the design exploration to produce design alternatives based on the criteria defined by the stakeholders. (Dino, 2012) With the computational capabilities, this can expand a set of design options in more complexity and variability than a manual design exploration depending on the defined algorithm from the designers (Agkathidis, 2016).

As the principle of the GD is the morphogenetic process, this employs the concept of natural evolution to the design approach. The results of natural evolution are production from successful developments that can adapt and fit to changing environments. This principle is applied to the architectural design of the GD method where it considers architecture as a form of artificial life evolution. This evolution is contributed by the iterative process of design and testing through computational tools and algorithms defined by the designers. (Frazer *et al.*, 2002) The process of GD consists of 4 elements (Figure 13) which are 1. The input of initial conditions and parameters 2. The algorithm for the geometric formulation or the generative mechanism 3. The outputs of the generation of the variants 4. The selection of the alternatives (Dino 2012).

These 4 steps of the GD start with the designers define the architectural concepts and project criteria from stakeholders as generative rule sets (1). These rule sets will be transformed into a genetic language (2) in a format of the computational script for the parametric design method to formulate the building geometries (3) which were described in Chapter 4.2.3. The geometries are created through the computational tools that are then evaluated based on their performance in simulated criteria set up as explained in Chapter 4.2.1. Within this stage (2) the designers can incorporate a genetic algorithm tool to automate the formulation of the building forms based on the multi-disciplinary design objectives, which will be further explained in Chapter 4.3.1. The last stage (4) of the process is the selection of the alternatives for further development in the next design generations. (Frazer *et al.*, 2002) (Dino, 2012) This GD process is continued iteratively as a cyclical process as can be seen in Figure 13 in which every loop of the new generation, the development of rules and scripts may require until the result meets the satisfaction criteria of the project requirements (Agkathidis, 2016).

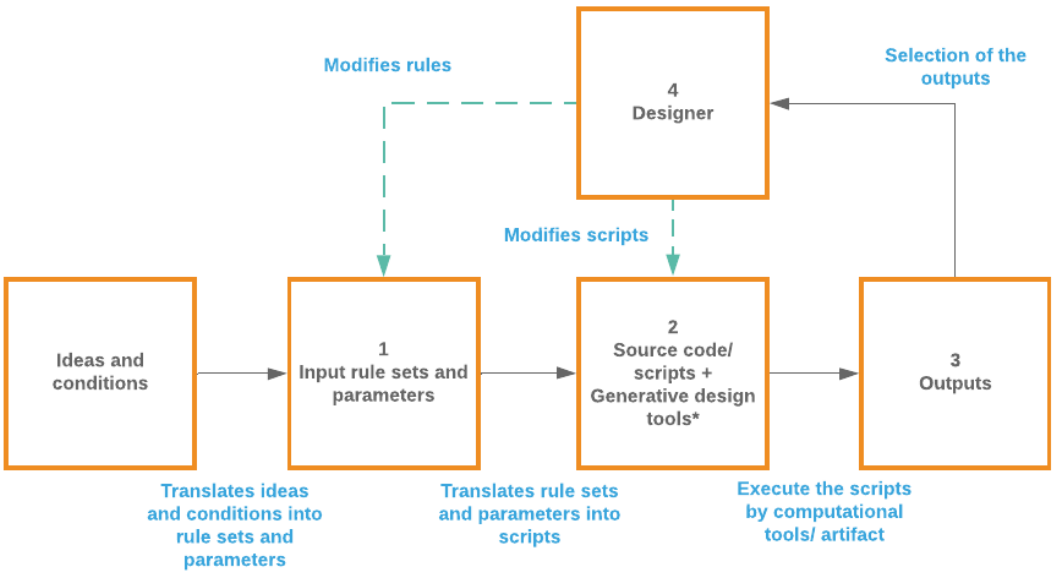


Figure 13 : The generative design process. The Figure is modified from (Bohnacker et al., 2012)

Several studies used GD to explore and design a sustainable building. For example, the research conducted by (Touloupaki and Theodosiou, 2017) applied the GD for the nearly Zero Energy Building by integrating energy simulation and geometric optimization based on genetic algorithm to explore the most effective design option. Another study from (Alfaris and Rashad, 2015) has implemented the GD within a specialist environment. The study showed that the GD can facilitate the professional decision as they can compare the design alternatives that lead to a better design outcome corresponding to the required environmental criteria.

4.3.1 Genetic algorithm

In order to do the design investigation, there is an artifact that can automate the design exploration that can produce the design alternatives based on the different required criteria. This artifact performs an iterative form-finding process by integrating the MDO principle to solve multi-objective problems. The iterative form-finding process can be executed through the genetic algorithm (GA). (Touloupaki and Theodosiou, 2017)

The GA is explained by (Holland, 2012) as a computational algorithm of gene evolution that uses a method of weighting and ranking to specify particular genes in the present generation for transferring into the next generation. This method applies the fitness matching of each individual population of the first generation to the objective criteria. If the fitness value of the objectives is matched to the geometric population, the process is stopped. But if the population does not fit the objective values, the evolutionary process of mutation and gene crossing continues. The mutation process occurs by the two or more individuals of the first generation that are chosen. By selecting the effective chromosomes of each individual that have a high fitness value to crossover and generate a new generation, this ensures that the new generation has a better fitness value than the previous generation.

In the AEC industry, there is various software that is used for genetic algorithm tools. For example, the Galapagos Evolutionary Solver, which is a plugin for Grasshopper, is the genetic algorithm tool used for optimization based on the GA method (Touloupaki and Theodosiou, 2017). In this research, Refinery, the genetic algorithm tool developed by Autodesk will be employed for the form-finding solution as this tool is an add-in of the VPL Dynamo (Autodesk Inc, 2019).

Refinery is a genetic algorithm tool that makes use of non dominated sorting genetic algorithm (NSGA-II) to proceed with the optimization function of the design exploration process. It also offers other methods to do the design exploration such as the randomize method, which generates a random mutation of the outcomes and the cross product method, which produces designs to all possible parameters of user-defined sampling size. (Walmsley, 2017)

4.3.1.1 Non dominated sorting genetic algorithm (NSGA-II)

Refinery is developed based on several methods to generate the outputs. One of the key features of the Refinery to solve the multi-objective problems is the optimization feature based on NSGA-II method (Walmsley, 2017). The NSGA-II method is a genetic algorithm (GA) that uses the non-dominated sorting and the crowding distance sorting solution to address the multi-objective problems from the multidisciplinary design actors as explained in Chapter 4.2.1. These 2 methods are a continuous process where the role of the non-dominated sorting method is used to categorize the populated geometries into the different ranking groups based on its performance, and the crowding distance sorting is applied for prioritizing the geometries within the group (Deb *et al.*, 2002).

The NSGA-II approach used the principle of Pareto optimality. However, as the Pareto optimality only considers the results that are not dominated by the others which sort at the front line (the red highlight based on the maximization values) in Figure 14, this requires various simulations from the individuals to generate different outcomes to fit into the multiple objectives. On the other hand, the NSGA-II considers not just only the individual at the frontier, but also the inferior ranking (the blue and yellow highlight in Figure 14) to produce the next generation which delivers a more variety of options due to supplementary parent generation in one single simulation. (Deb *et al.*, 2002)

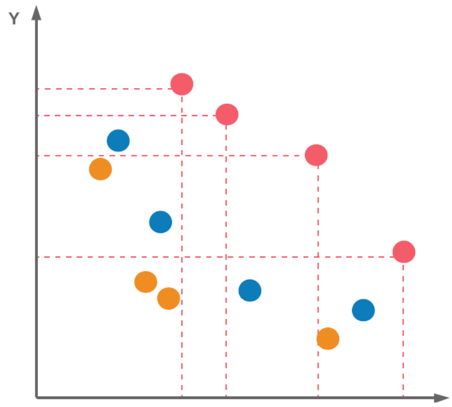


Figure 14 : The Pareto optimality considers only the frontier individuals (red) while NSGA-II takes other inferior individuals (blue and yellow) into account for generating the offspring generation. The Figure is modified from (Deb et al.*, 2002).*

Starting with the non-dominated sorting method, it uses the sorting system based on the domination ranking. This ranking is defined by the numbers that the individual can dominate the others and grouping into a sorting group. The order of the ranking refers to the performance quality of the individual. For instance, Figure 16 shows that the red dots can dominate the other 5 dots and have not been influenced by others that are grouped into the first rank for the best performance. The blue dots are dominated by the red dots but they can influence 1 dot of each individual that is categorized into the second rank for the intermediate performance. The yellow dots cannot dominate any dot and also be overshadowed by others that are sorted into the third place for the lowest performance. This sorting system can prioritize the performance of the individuals into a specific ranking group which facilitates the mutation process for the next generation. (Deb *et al.*, 2002)

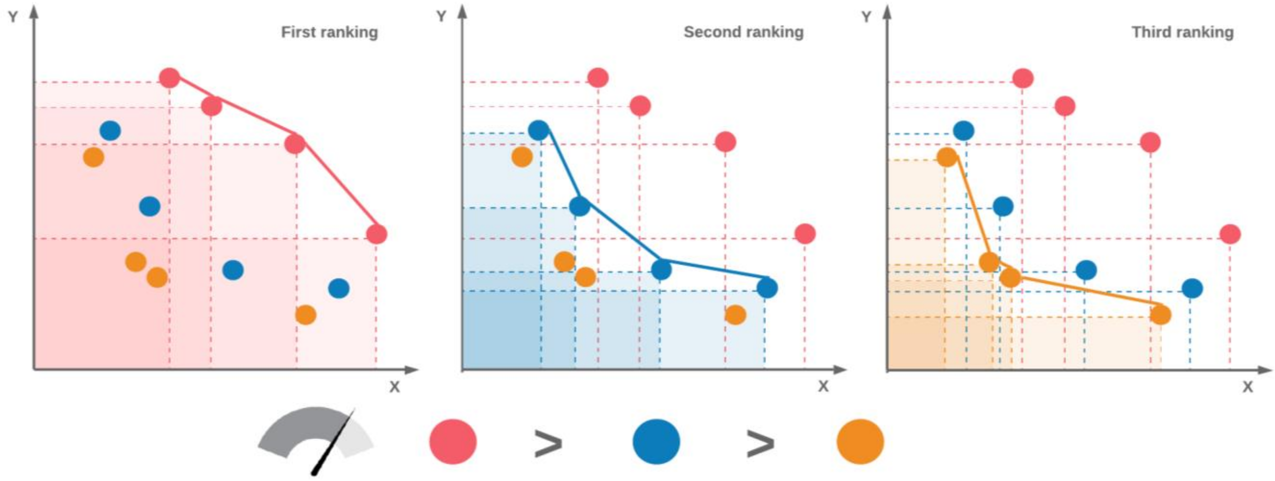


Figure 16 : The non-dominated sorting method categorizes individuals into the different sorting group depending on the level of influence to others. The Figure is modified from (Deb et al.*, 2002).*

After each individual is categorized into a different ranking based on the non-dominated sorting method, there is a need to prioritize the importance of the individual in the ranking. The crowding distance sorting is applied to give priority and variety to the individual. This variety of the parent generation is significant because it prevents the redundant result of the mutation. Thus, in order to maintain diversity, the location of the individuals should not be close to each other. This is because if the placement of the individuals is close to each other, the individuals will have the value of a similar gene. The crowding distance method measures the distance of the points by averaging. If the individual has far distance between the surrounding points, it gains high priority in the ranking group and vice versa for the average short distance surrounding points (Figure 15). (Deb *et al.*, 2002)

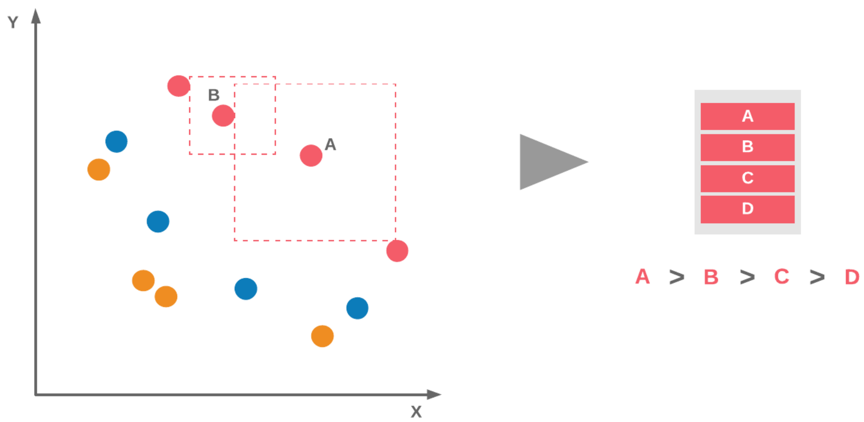


Figure 15 : The crowding distance sorting method prioritizes the individuals based on the average distance between the surroundings. The Figure is adjusted from (Deb et al.*, 2002).*

When the non-dominated sorting and the crowding distance sorting method are addressed, all the individuals can be ranked (Figure 17). The individuals that are within the population size (N) will be selected for the mutation process while the others will be rejected. These ensure that only the high quality of the individual that contains a high level of fitness genes will be selected for mutation. The mutation process will follow the principle of selecting and crossing genes from the genetic algorithm (GA) as explained in the previous Chapter. (Deb *et al.*, 2002) The internal genes that have a higher fitness value will cross over between individuals to mutate into the next generation as can be seen in Figure 17 (Holland, 2012). The mutation loops happen according to the number of generations defined by the designers or until the results meet the objective criteria (Walmsley, 2017).

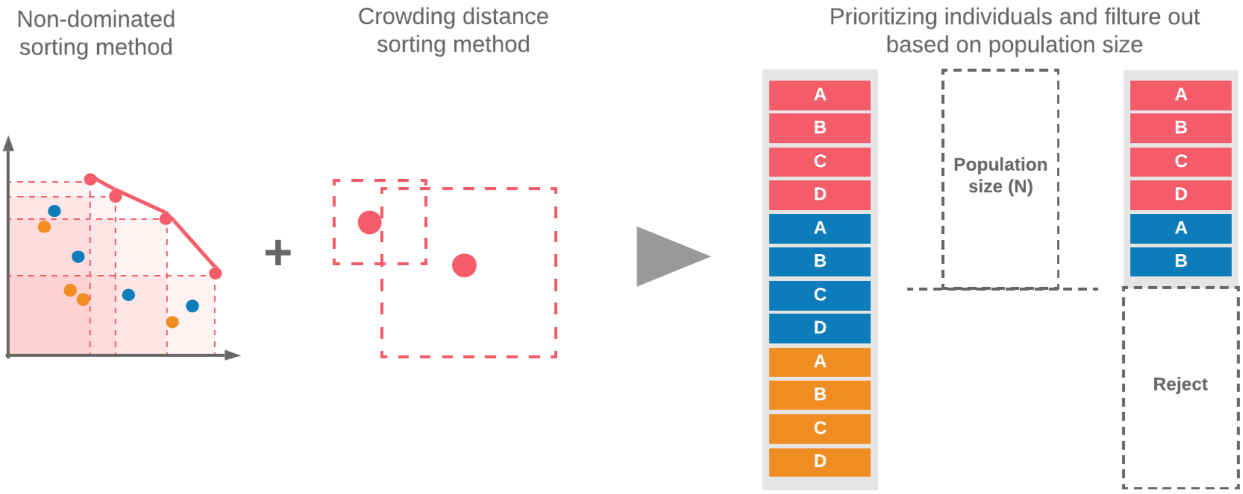


Figure 17 : All the individuals are ranked according to the non-dominated and crowding distance methods and are filtured the options that are not in the population size. The Figure is created based on (Deb et al., 2002)

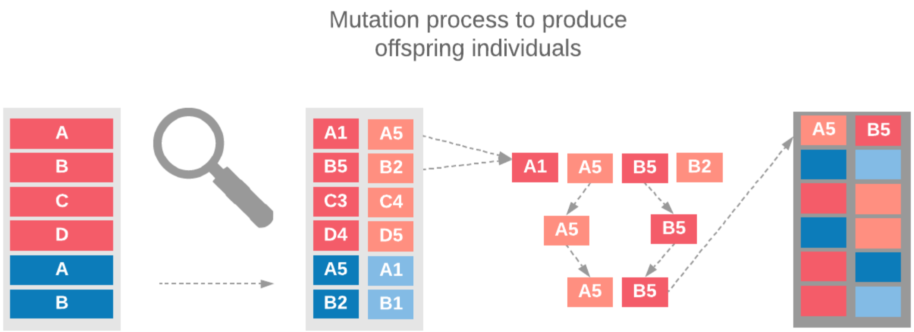


Figure 18 : The GA of crossover and mutation inspired by (Holland, 2012)

In order to elucidate the process of NSGA-II, the authors have created Figure 19 to explain how the NSGA-II works within the Refinery according to (Deb *et al.*, 2002) and (Walmsley, 2017). The process starts by Refinery populating the first population geometries in a double size (2N) based on the framework defined by Dynamo. These geometries are sorted according to the non-dominated sorting and the crowding distance sorting method. The generated geometries that are not within the population size defined by the users will be rejected. Only the geometries within the defined population range (N) are selected for further mutation process. The mutation produces the equal size of offspring (N) to the parent (N) in the next generation. The process repeats until the objectives have been met or the generation loop has been achieved.

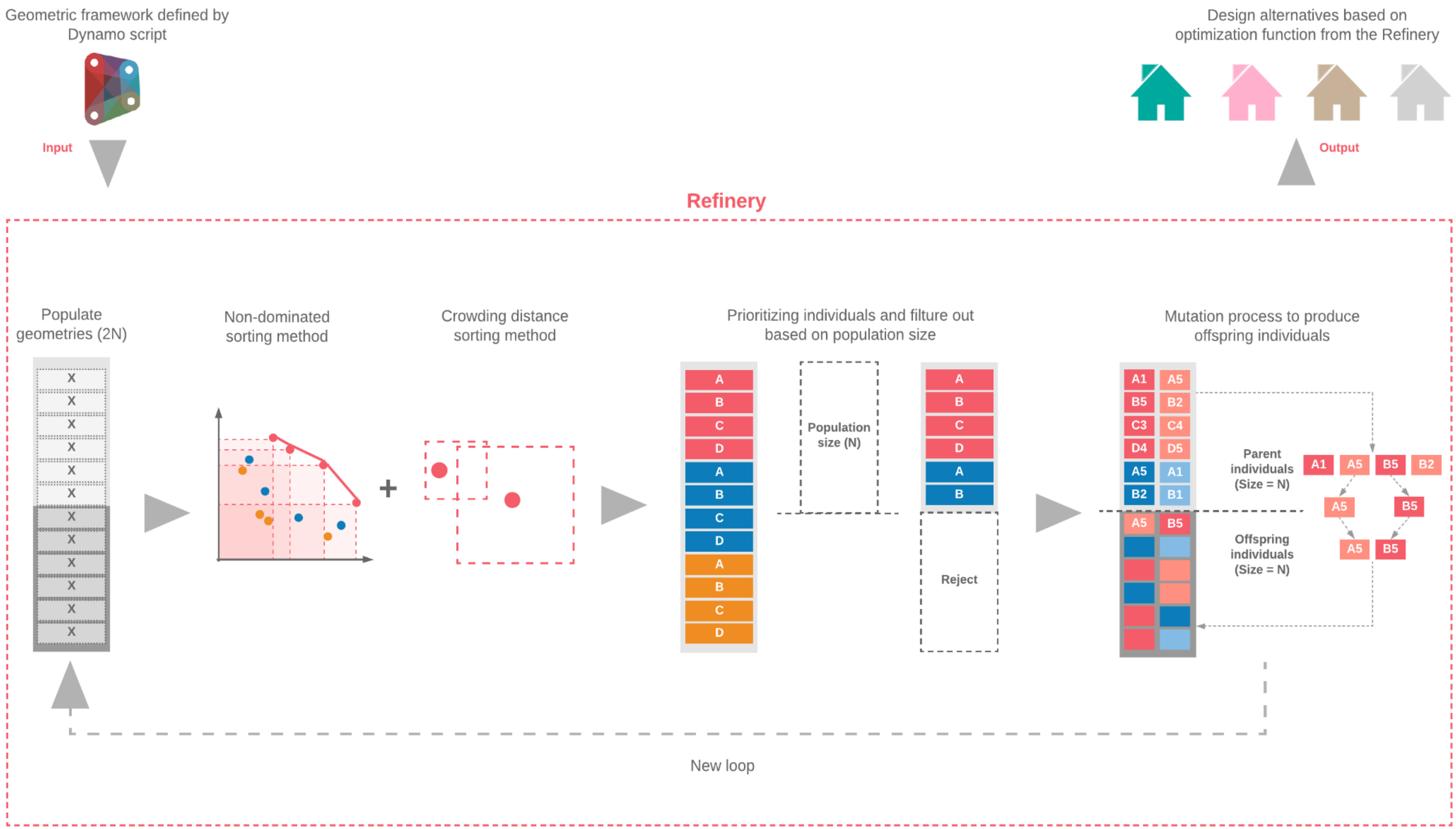


Figure 19 : The operation of the Refinery based on NSGA-II principle.

5 Final problem formulation

The Problem Analysis and Literature Review parts were investigated on the basis of the initial problem formulation which is presented as following in Chapter 1.4:

"How IEQ can be improved during the initial design stage, before first performance simulations?"

By means of root cause analysis chapter the issues, faced nowadays during the initial design stage in regards to IEQ factors, were analysed. The biggest problem is the gap in collaboration between two important actors: architect and engineer. Each of them is an expert in a particular area that is why they have different viewpoints on a construction project. The architect at the initial design stage has a bit more power than the IEQ engineer because the architect is the one who creates the building from scratch. Engineer here works as an assistant who gives only some guidelines that need to be fulfilled to reach the IEQ requirements (Negendahl, 2015). In the case of misunderstandings, the iterative process of changing the design can take a long time and delay the project. Furthermore, the current initial design process does not consider different design options as the architect creates only a few options based on their experiences. In addition, during the literature review, in Chapter 4.2.1, it was investigated that the current design process cannot solve multi-objective design problems and balance the significance of different factors as it is not the design rationalization method.

Another problem that was investigated during the literature review is that currently used BPS tools do not provide any feedback to the users meaning that the changes are made based on the actor's experience. The BPS tools are used when the initial design is finished and cannot be integrated to actually drive the design. In addition, most of the BPS tools are intended to be used in later phases as they require more detailed information about a building. Also because of the inability of BPS tools to handle complex geometry and lack of interoperability, rework might appear. From the literature review and the samples presented above, it can be concluded that GD can be applied to solve the research problem.

Above mentioned problems lead to the final problem formulation which is:

"How can the use of generative design improve the initial design stage with regards to IEQ?"

Furthermore, the following sub-questions should be considered while processing the problem:

- When and how should the implementation of generative design happen?
- How does the collaboration between an architect and an engineer change?

6 Problem processing

The following section presents the considerations, tools and proposed solution(s), particularly for this project.

6.1 Considered IEQ factors

To achieve the necessary IEQ at the initial design stage, IV20 is analysed with the purpose to consider the parameters needed for daylight, visual and thermal comfort. The parameters are sorted out depending if relevant information is known at the initial stage or if it requires further development of the project. It might be that the values of some of the parameters will be calculated in the later stages, but the minimum requirements are indicated in e.g. Building Regulations, which can already be taken into consideration. Thus, for daylight and visual comfort such parameters as glazing area, location, orientation are important (Carlucci *et al.*, 2015) as the rooms have to have sufficient daylight to be well lit (Hansen, 2015).

Thermal comfort is influenced by air temperature, humidity level, airspeed, activity level, amount of clothing, sunlight, etc. (Oral, Yener and Bayazit, 2004). It is difficult to calculate and analyse all the parameters at the initial design stage that is why it was decided to analyse only sunlight for thermal comfort. By getting sunlight for a long amount of time, it raises the risk of overheating in the building, especially in the summer (Habibi, 2017). Thus, limitations for direct sunlight getting through the windows can be applied and the framework can be generated, also overhangs and side fins are taken into consideration (Konis, 2013).

In the project, basing on IV20, the visual comfort is treated as a good view for the inhabitants/workers. In the tool, it is required to indicate if it is possible to see green areas, sky if anything interrupts the view, etc. (REBUS, 2019). Thus, the objective of the output is to maximize the areas facing a particular viewpoint determined by the user. For daylight comfort, maximization of daylight in the rooms is the aim (Oral, Yener and Bayazit, 2004), for instance, in Denmark sun does not shine often and it is getting dark fast during the autumn-winter season (Weather Atlas, 2018). That is why, at that time many people get depressed because of lack of sunlight (Power, 2018). Furthermore, providing an appropriate amount of daylight can help to save building energy by using less artificial lighting (Ochoa *et al.*, 2012).

All in all, the three factors are dependent on the window's glazing and shading part that is why some conflicts might appear. For instance, if for daylight the maximization of window area is required, it can cause trouble in regards to sunlight as more of it will get into the building. At that point overhangs and fins can be used but they can block the viewpoint. To solve the issues, the digital tool should be implemented as it has the ability to analyse and generate various design options by balancing the factors.

6.2 Proposed solution in implementation

According to the literature review chapter, the authors have explained the potential of the generative design to solve the project issue. The computational tools that the authors select to work in the GD are the VPL, Dynamo to create the parametric geometry, and Refinery to automate the design exploration. The scope of work will focus on only the process of the parametric design exploration according to the GD principle to investigate the most suitable design outcomes as a framework for the designers for further project development. The method of selection of the design alternatives will be omitted as the proposed process of this research gives autonomy for the designer to decide on the selection criteria for the next design generation. The further explanation of the new work process will be stated in Chapter 6.3.1 and 6.3.2.

As this project focuses on the design exploration of the building facade, the building mass will be first created by the architects according to their concept as explained in Chapter 3.2.1. Because the mass model is created in Revit, Dynamo will be implemented to create façade geometry based on parametric design and external inputs that will lead to the generative design. In Figure 20 is presented an IDEF0 functional model that represents the input, control(s), mechanism(s) and output for the scripts that need to be made to generate the design. Thus, the *mechanism* for the scripts is the Dynamo tool which gives an opportunity to create scripts using VPL. The *input* is a Revit mass model and parameters added by a user. The *control* of the scripts is performance criteria which are the guidelines architects get from the engineer (IEQ) or the regulations and, the design objectives are based on the performance criteria that the architects expect to achieve but also depend on the architectural idea. For instance, even if in the guidelines it is indicated that there must not be overheating, the architect, depending on a design idea, can minimize or maximize the glazing area of the building but still fulfilling the requirements by e.g. placing overhangs. The *output* of the process is the geometric framework of the building facade defined by Dynamo which is used to explore the design as it is described further.

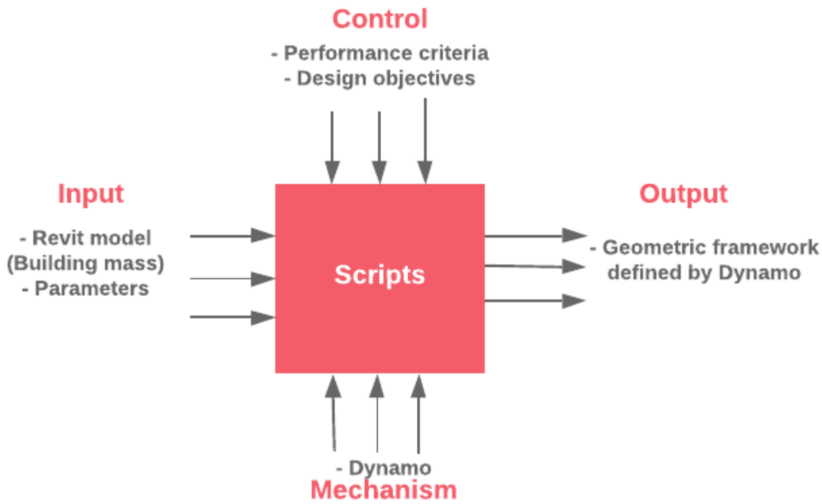


Figure 20 : IDEF0 for creating scripts

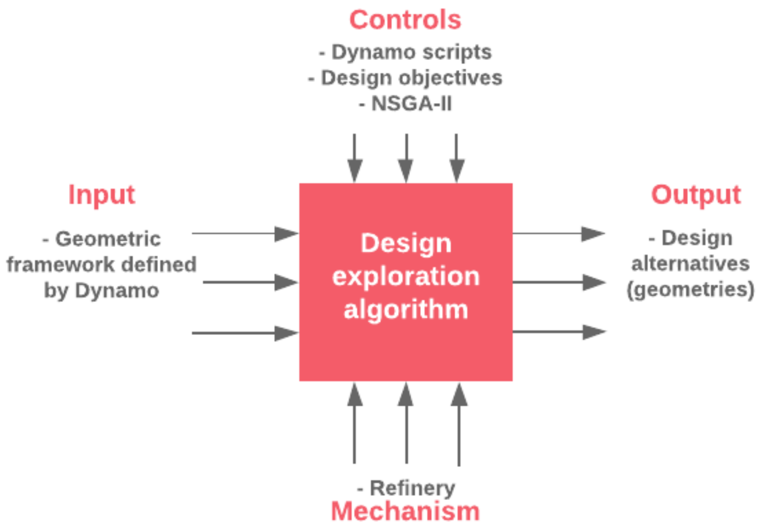


Figure 21 : IDEF0 for design exploration algorithm by Refinery.

To carry out the form-finding, the Refinery is needed to be paired with the Dynamo graph (Figure 20). Figure 21 above illustrates the functional models of the design exploration algorithm that is operated by the Refinery (*mechanism*). The *input* is the geometric framework defined by Dynamo in which Refinery will populate the geometries based on the specified variables in Dynamo. The *control* of this algorithm is the Dynamo graph which indicates the logic to generate the geometries, the design objectives which are the target outcomes defined by the users, and NSGA-II which is the method of design mutation for optimization. The *output* is the design alternatives according to the defined objectives from the users. In order to clarify how the Dynamo and Refinery work together for the geometric form generating and finding within the generative design process (GD), the authors have created Figure 22 to illustrate these tools for an overview. In this research, the optimization method based on NSGA-II is selected to solve the multiple design objectives.

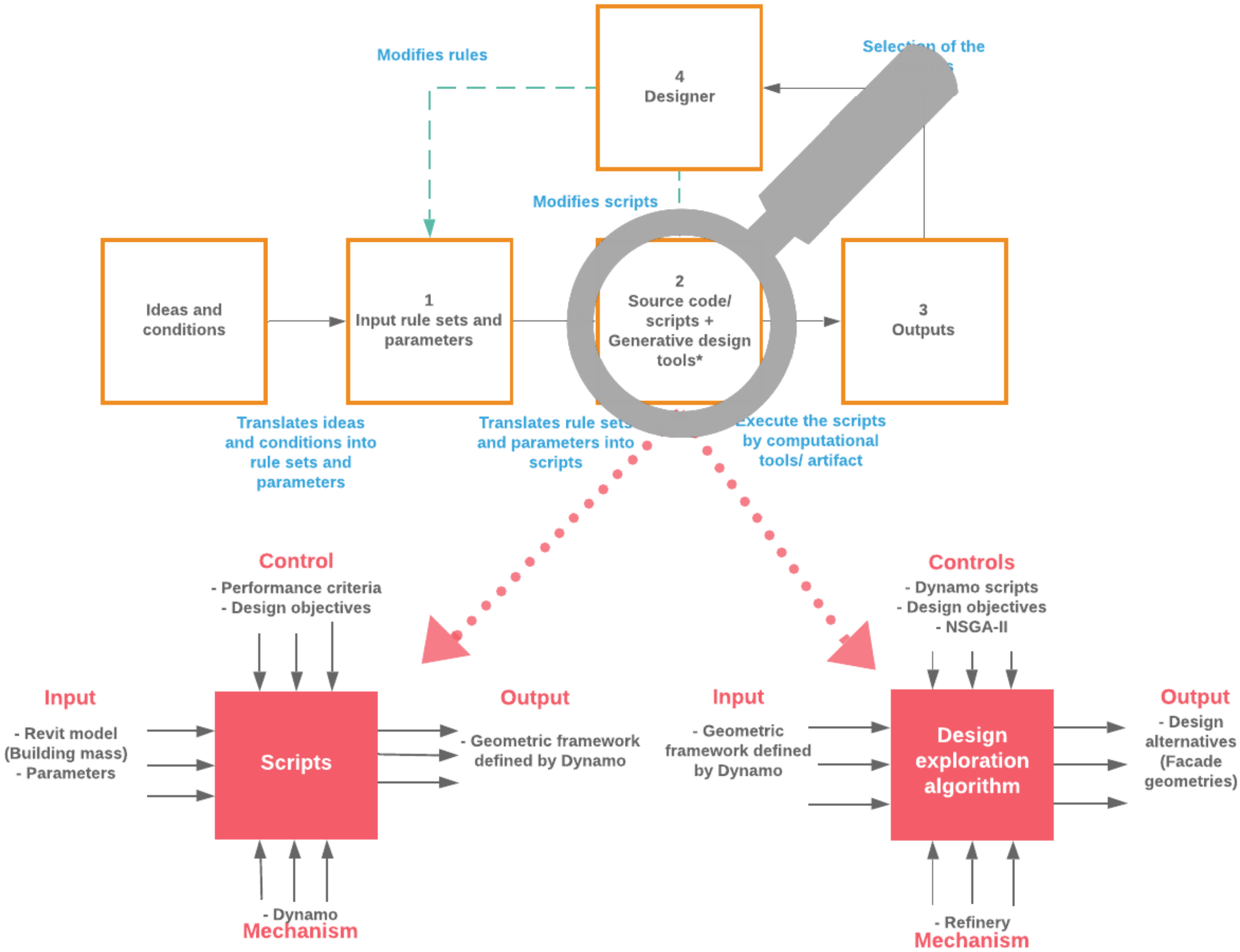


Figure 22 : The overview of Dynamo and Refinery within the GD.

6.3 Prototype development

6.3.1 Storyboard

For the prototype development, storyboards (Figures 23, 24) were created to define the vision of interaction of actors and a new way of work (Holtzblatt and Beyer, 2014). They consist of six steps showing how the collaboration between an architect and IEQ engineer happens and can be improved.

Chapter 1.1 and Chapter 3.1.1 present that both architect and engineer are important actors at the initial design stage, they have high interest and influence but different requirements (1). Literature and interviews showed that because of two different areas of specialization there is a risk of misunderstandings (2), for instance, the requirements from an engineer can be interpreted in a different way by an architect. Architects are responsible for the design of the building and might have many ideas at the same time and, what would be beneficial to have, is the framework that can serve as a start point for the design development (3). The framework would be based on IEQ factors whereas nowadays it is the other way around, firstly design is made and then it is checked by means of BPS tools described in Chapter 4.1.1.

Figure 23: Storyboard showing the collaboration gap between an architect and engineer (1-2), and possible solution for the problem (3).

As investigated in the Analysis part, there is a gap in collaboration between an architect and an engineer. In Chapter 4.2.1 is mentioned that there are multiple requirements needed to be fulfilled for the building design, for instance, glazing area and daylight comfort, overhangs and sunlight (4). Chapter 6.1 explains that three factors in this project are taken into consideration and the balance among requirements should be found, thus MDO method can be used to improve the design outcome. To develop a framework that could support the engineer's requirements and at the same time give the architect the possibility to influence the project, the generative design presented in Chapter 4.3 can be applied. By means of GD, multiple factors can be considered and a lot of options can be generated. By choosing the most suitable one basing on IEQ factors, the architect will get the framework of the façade design (5). The GD needs a computational tool to produce the parametric design to generate 3D geometry as written in Chapter 4.2.2. Parametric design serves as a base for GD, the parametric models can be changed easily and give the possibility to explore many design options. As a result, the framework which ensures the quality of the end result can be developed further (6). can be developed further (6).

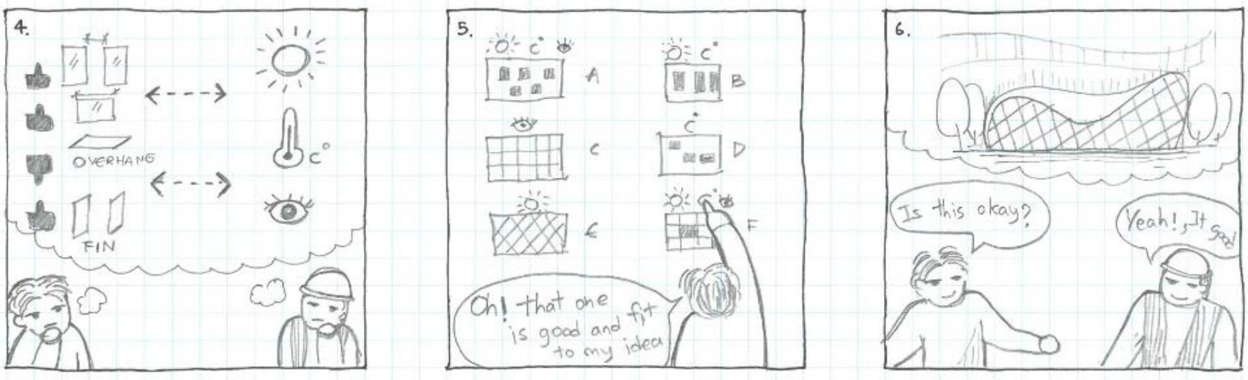


Figure 24: Storyboards showing new workflow by implementing GD.

6.3.2 New process proposal

According to the explanation in Chapter 6.2 and 6.3.1, this project proposes a new process of the initial design phase and to explain it - Business Process Model and Notation (BPMN) diagram is used. BPMN is a standardized graphical language for modelling workflows (Beetz *et al.*, 2015).

In Figure 25 is presented the workflow of the initial design phase including five actors: architect, IEQ engineer, BIM modeler, project manager and the client. The process starts with the client requesting a construction project (1.1) whereas the brief (1.2) is made by a project manager (PM) and a setup meeting (1.3) is carried out to introduce and discuss the project with the architect and IEQ engineer. Based on the client IEQ demands, the engineer has to create the guidelines with objectives of IEQ factors for the architect (1.4). When the guidelines are received by the architect (1.5), he/she can start creating a form of future building (1.6). The architect sketches and creates a digital 3D mass model of a building in collaboration with the BIM modeler (1.7). As soon as the model is received by an architect (1.8), the developed script is applied for the façade design exploration. The process starts with project parameter adjustment (1.9), by completing this part script starts running and the results of the IEQ factors are presented (1.10). With the purpose to analyse all the possible options and optimize the design, the architect launches the Refinery tool (1.11), described in Chapter 4.3.1. Refinery presents the result in a graph showing which factors are fulfilled less or more, that is why it is important for the architect and IEQ engineer to have a meeting here (1.12) to decide on the most suitable option. The meeting can be omitted if, for instance, the priority of the factors is mentioned in the guidelines. In such a case, the architect can choose the option by himself basing on the guidelines. Further, knowing the framework, the architect starts developing it (1.13) by making sketches and creating the digital model (1.14). During this process, the BIM modeler is also involved (1.14) as he/she has better skills in digital modelling (Eastman, Liston and Wiley, 2018). When the model is completed (1.15), the next step is a presentation of the initial design to the client (1.16). By approving (1.17) the results, the project can move to the next phase (1.19) but if the client is not satisfied, the project has to be rechecked. Here, based on the client's comments the recheck can start at different steps. For example, if the client is not satisfied with the indoor climate results, the rework has to be done from creating objectives and guidelines for an architect (1.4) but if the client is dissatisfied with the design of the facades and would like e.g. to remove overhangs, the rework should start at the project parameters adjustment (1.9).

All in all, the new process incorporates the building analysis to drive the design. Comparing to the existing workflow by means of Refinery all the possible options of the design are considered and optimized. Thus, the risk of having problems with IEQ in the next phases is lowered.

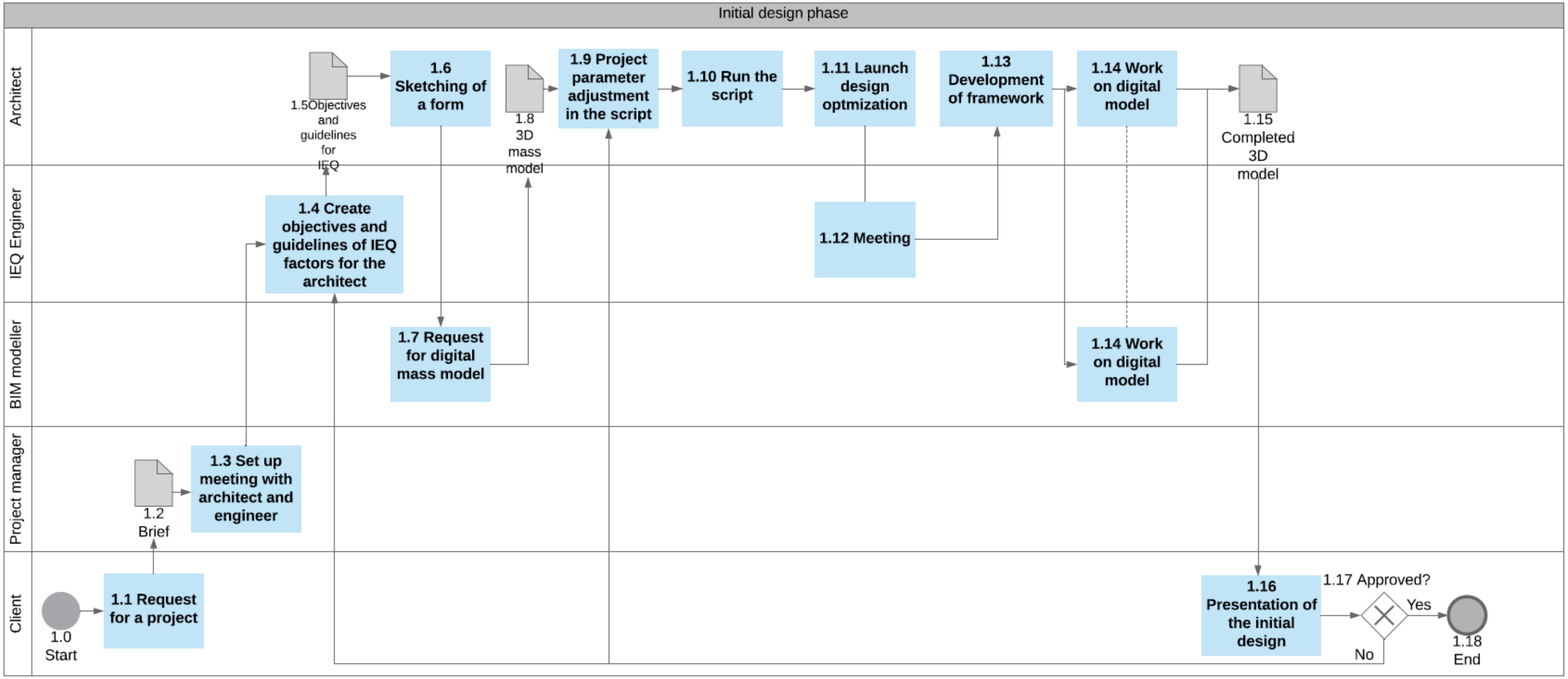


Figure 25: BPMN for the initial design process including the process of generative design, Appendix 6.

6.3.3 User environment design

In Chapter 6.2 the authors explained that generative design will be used to propose a new way of the initial façade design process. Figure 22 illustrates the overall process of GD with four steps including the functional models that represent the tools: Dynamo and Refinery. Further, the storyboards in Chapter 6.3.1 describe the scenarios and sequence of the proposed method. To further develop the solution, User Environment Design (UED) can help to understand the components necessary for it. The UED shows each part of the system: how to use the tool, which functions are available, how to achieve needed results (Holtzblatt and Beyer, 2014), it is a structure of actions, objects, and attributes (Foley and Sukaviriya, 1995).

The diagram in Figure 26 was made to serve as UED for this project. As explained in Chapter 6.3.2, firstly, the architect has to have the project objective parameters (yellow) from the IEQ engineer. Afterward, the mass model (grey) is created in Revit and connected to Dynamo with the purpose of seeing the façade design changes, as described in Chapter 6.2. The project objective parameters will be addressed to define what are the goals for each factor and what are the relevant parameters to achieve those goals. These parameters impact the actors who will be responsible for determining and deciding on the parameters to generate the facade geometries as explained in Chapter 6.3.1. The decision of the project parameters (green) is based on the goals of the project objective parameters (yellow) corresponding to the IEQ criteria as explained in Chapter 6.1. The geometry (blue) is formulated based on the inserted project parameters to carry out the analysis. Afterward, the core part of the script factors & analysis (red) executes the operation and presents the performance results (purple). Consequently, when the script is completed, the generation of the design can be carried out in Refinery (grey).

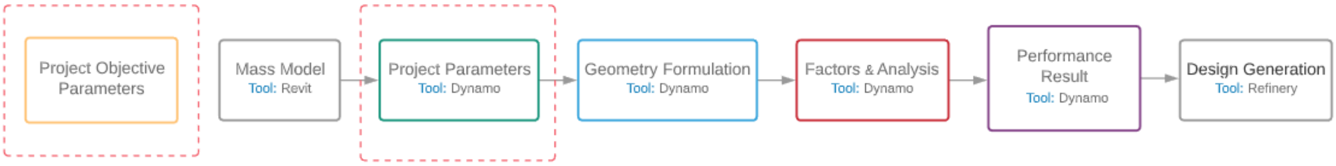


Figure 26: The overview of the user environment design (UED) to create the script

After design generation, the program will present design alternatives for the facades based on set up criteria, thus achieving the framework for an architect described in Chapter 6.3.1.

6.3.3.1 Project objective parameters

In Chapter 6.1 were analysed and indicated the three IEQ factors that are considered in the project: daylight, visual and thermal comfort. Each of the three factors has a particular objective; however, all of them are depended on glazing parts (windows) (Oral, Yener and Bayazit, 2004). For visual comfort, there is chosen a specific viewpoint by the user that should be visible from a window, that is why the glazing area is considered. In addition, overhangs and fins have to be taken into account as they can block the view. The influence of thermal comfort stems from many factors, but because of the scope of the project, it was decided to take sunlight into consideration. It was chosen because sunlight getting into a building can raise the probability of having overheating (Habibi, 2017). Even though Denmark does not have a lot of sunshine (Weather Atlas, 2018), still in the summer, it can have an impact on IEQ (Habibi, 2017). Thus, by setting up a particular time, it is possible to limit direct sunlight into a building, also through overhangs and fins (Seghier *et al.*, 2017). Both factors are connected with the glazing parts, which also means that the daylight is getting in through that (Oral, Yener and Bayazit, 2004). Daylight is vital for human well-being and energy savings in the building (Habibi, 2017). Further, Table 1 sums up the purposes for each factor, whereas for daylight, the objective is to increase the area of the glazing part to get more natural light. For visual comfort, it is the area of windows with an ability to see a particular point chosen by a user. And for sunlight, the objective is to limit the hours of the sunlight getting into the building to lower the risk of overheating.

Table 1: Three IEQ factors are considered in the project, whereas all of them are achieved through window elements. Each IEQ factor has its objective measured in a particular unit.

Project objective parameters	
IEQ factors	**Objective**
Daylight	Increase daylight getting into the building by considering the glazed area (m^2).
Visual comfort	Ability to see a particular point out of the window by considering the glazing area facing that point (m^2).
Thermal comfort → Sunlight	Limit sunlight getting into the building at a particular period to reduce the risk of overheating (h/day).

6.3.3.2 Project parameters

After the analysis of the project objectives, the determination of the relevant project parameters that correspond to the goals is necessary. There are 3 different types of project parameters, which are 1. The user-defined parameters, 2. The project parameters of the building mass, 3. The project parameters of the environmental conditions. These 3 types of parameters affect the building performance in different ways and also impact the level of involvement of the users to decide on the façade elements of the design outcomes.

Starting with the *user-defined parameters*, these parameters give autonomy to the users to decide on which façade elements will be taken into account for analysis and generate the geometry, as explained in section 6.3.1. The user-defined parameters stem from the related façade elements that can impact the 3 main factors from the section mentioned above. The category of the façade elements consist of 2 central systems, which are the glazing system and shading system (Piraccini, 2018). For the glazing system, the proportion of glazing, glazing orientation and properties have a high effect on the 3 main project objectives. For the shading system, the façade elements such as window overhang and louvers can reduce the solar radiation that impacts the building, which in turn, improves the indoor thermal comfort. (Piraccini, 2018) The testing of the design parameters was done by Østergård (2017) in his Ph.D. research to investigate the sensitive design parameters according to energy demand, thermal comfort, and daylight of a particular building. The investigation revealed that besides the glazing properties, e.g. g-value, the window sizes, and shading elements can have a strong influence on the building performance according to the interested factors.

The next design parameters are the *project parameters of the building mass*. These parameters are fixed parameters in which the users cannot define the value of it in the script. The reason for this is because these parameters derive from a building mass and surrounding buildings proposed by the architects since building layout design. The importance of the building mass parameters is that it underlies the framework for creating the façade. The architect gave the information such as building height and width, the distance from floor to floor, the building location and orientation since the formulation of the building mass. This information underlies the basic framework of the script to generate the façade geometries on top of the selected building mass.

The last parameters are the *project parameters of the environmental condition*. According to those mentioned above, the thermal comfort factor requires information about the date, time and location. The users provide this information manually and set up in the script. To specify the location and the sun path, this demands a weather file[7] for an indication. This necessary information of the weather conditions will be used for the analysis of the façade geometries corresponding to the project objectives.

To conclude the project parameters, the authors have created Table 2 to illustrate the necessary project parameters for generating the building façade.

[7] The weather file or EnergyPlus Weather file (.epw) is a file format that contains weather data of a specific location. The weather data that is stored in the weather file can be domestic recorded data of a particular year or multiple years. (EnergyPlus, 2019)

Table 2: The table presents the necessary project parameters to create the facade geometries.

<table>
<tr><th colspan="3">Project parameters</th></tr>
<tr><th>User-defined parameter</th><th>Project parameter of the building mass</th><th>Project parameter of the weather condition</th></tr>
<tr><td>Glazing system:
- Glazing proportions</td><td rowspan="2">- Building sizes (width and height)
- Building levels
- Surrounding masses</td><td rowspan="2">- Date and Time
- Weather Data of the specific location</td></tr>
<tr><td>Shading system:
- Window overhang dimensions</td></tr>
</table>

6.3.3.3 Final user environment design

Based on the explanation of the implementation of generative design in Chapter 6.2, there are 2 user environment designs (UED) that are involved in the process (Figure 27). The first UED defines the structure and framework to generate the façade geometry according to the performance-based design principle (Chapter 4.2) which is done through the Dynamo script. The second UED is the explanation of the Refinery's features that has the function to automate the design exploration and optimization based on the genetic algorithm (NSGA-II). These 2 UEDs are a coordinated function as the first UED underlies the framework of the second UED for the geometric exploration. To begin with the first UED (Dynamo), the structure of it is based on the GD principle. It has the project parameters as the design input to produce the design outputs according to the project objective parameters. This UED consists of 4 main areas (Figure 27), which are 1. Project parameters (green), 2. Geometry formulation (blue), 3. Factors and analyses (red), 4. Performance result (purple). These 4 main areas underlie the operation of the Dynamo script which requires different actors to interact and define the parameters as explained in Chapter 6.3.1, 6.3.3.1 and 6.3.3.2.

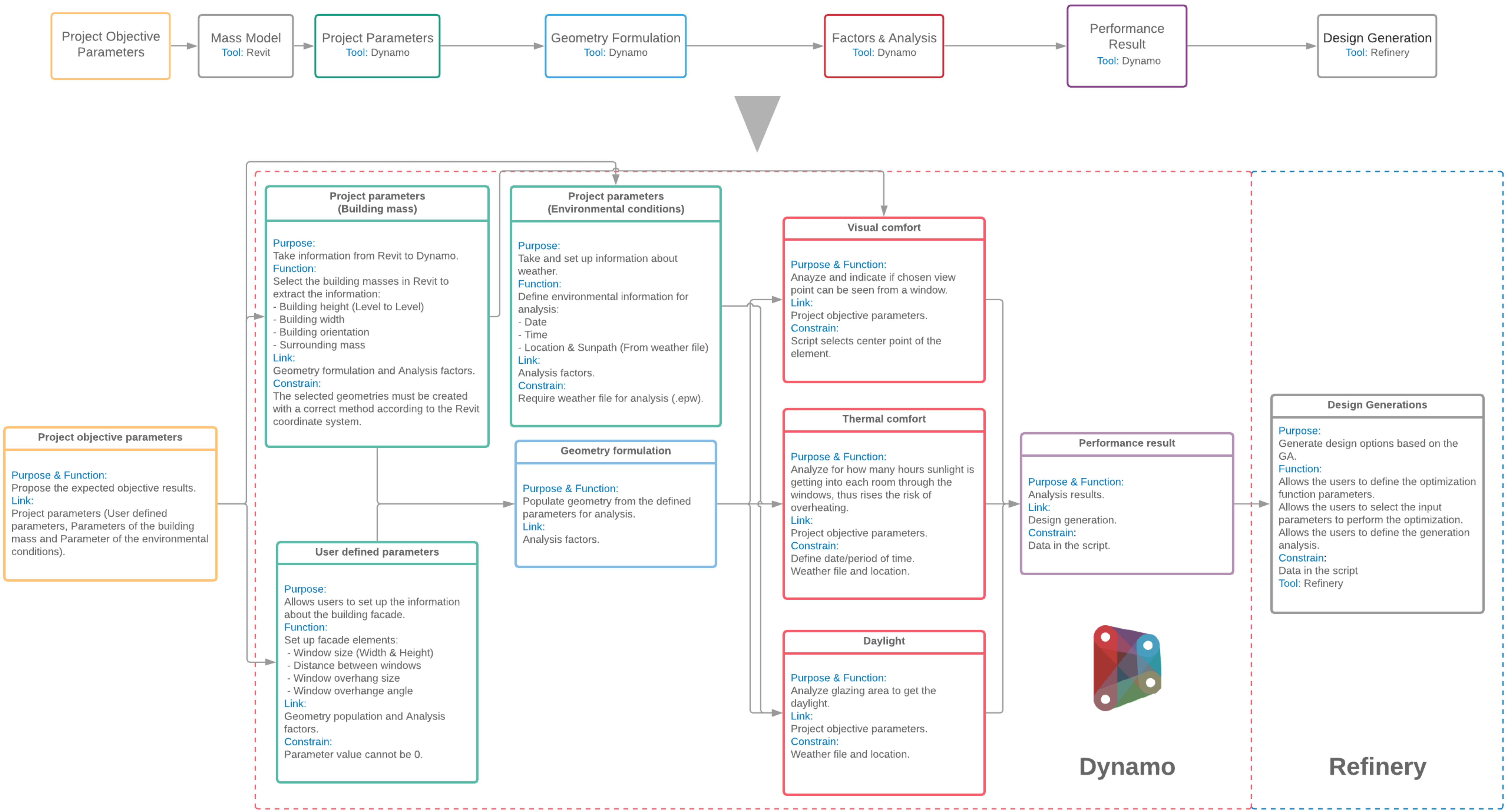


Figure 27 : The user environment designs (UED) of the Dynamo script and Refinery.

Starting with the project parameters area (green), this area consists of 3 sub-focus areas that require the architect to set up all the parameter values. The first sub-focus area is the user-defined parameters to allow the users to give information about the expected façade design. The function in this sub-focus area demands the users to decide on the façade elements (glazing and shading systems) and the dimension of the faced elements, as explained in the previous section, to generate the façade geometries. The constraint of this sub-area is that all the values of the user-defined parameters (window size, the distance between windows overhang size and angle) cannot be "0" as it can cause the problem in the script due to no value to create geometries. The next sub-area of the project parameters is the project parameters of the building mass. The purpose of this sub-area is to collect the information, i.e., building height, width and orientation from Revit to Dynamo. In this sub-area, the user must select the main building mass and relevant surroundings that can impact the façades while generating the design. The last sub-area is the area that corresponds to the environmental conditions. This sub-area requires the user to set up the information on the analysis period and select the weather file as mentioned in the previous section. This information connects to the thermal factor that can impact the performance results of the facade.

The next part of the first UED (Dynamo) is the area of the computational operation to create the geometry based on the project parameter inputs (user-defined parameters and project parameters of the building mass) and analyze the geometry according to the project objective parameters (blue and red in Figure 27). Starting with the geometry formulation, the function of this area is the operation of the script to generate the façade geometries. The Dynamo script will populate the base geometry for analysis in the next area. The generated geometry in this area is not the outcome but performs itself as a starter geometry for the analysis. The analysis area in the next section performs the analysis based on the project objectives. The analyses happen under the 3 factors which are the visual comfort, thermal comfort and daylight, to examine the performance of the starter geometry. The output of this area is the performance values and the result of the geometries that can achieve the conditions of the 3 factors from Chapter 6.3.3.1. The constraints of the analysis area are based on the defined information of the project parameters of the environmental conditions and the project parameter of the building mass.

The last area of the first UED (Dynamo) is the performance result which illustrates the analysis outcomes of the generated geometry. The constraints of this area are the same as previous ones because this area requires the operation from the earlier parts to create the output. The link area that connects to this focus area is another UED for the design generations which performs in the Refinery.

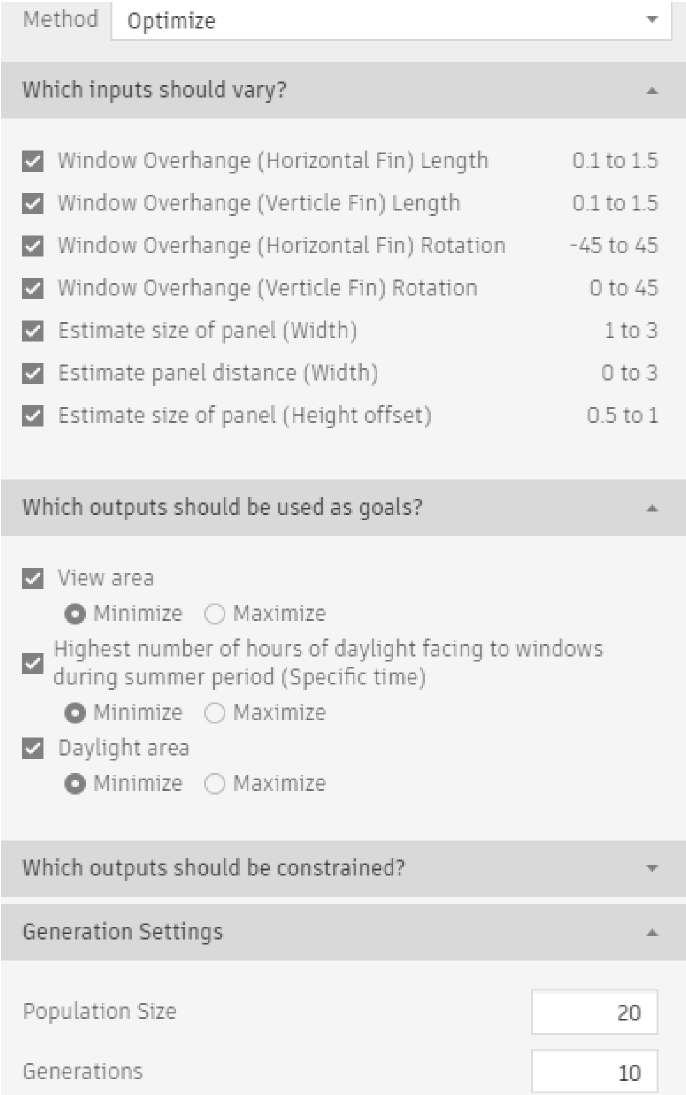


Figure 28 : The provided features in Refinery.

The second UED (Refinery) represents the system structure of the Refinery features where the users can select and operate different functions from the provided features. The purpose of Refinery is to generate design alternatives based on the GA (NSGA-II) as explained in Chapter 4.3.1.1. The provided features of Refinery allow the users to decide on the expected performance results (maximization/minimization). Refinery operates this optimization according to the logical structure of the Dynamo script and NSGA-II which can be seen in Figure 28. The users can set up the number of design generations and decide on the project parameters that should be taken into account for processing the GA to produce the design alternatives.

6.3.4 Scripts development

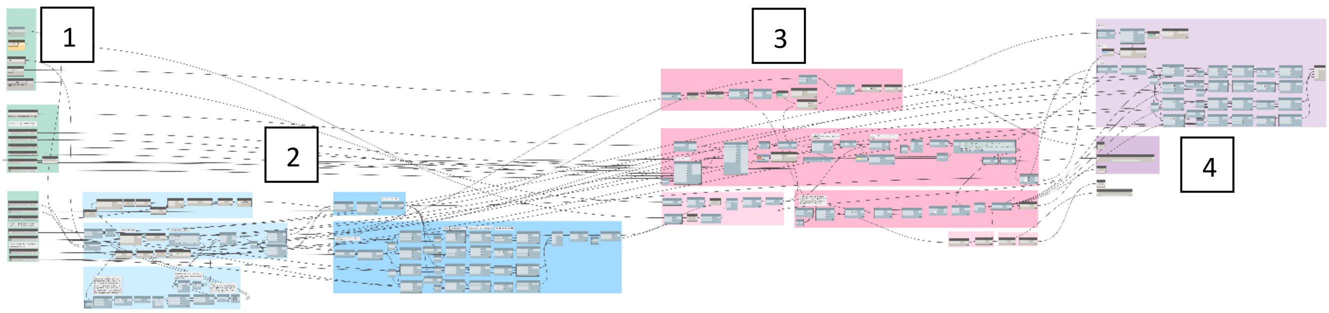


Figure 29 : The overview of the Dynamo script consists of 4 main sections which are 1. Project parameters (green) 2. Geometry formulation (blue) 3. Factors and analyses (red) 4. Project objective parameters (purple). The detailed script can be seen in Appendix 7.

From the explanation of the user environment design (UED) in Chapter 6.3.3.3, the proposed UED underlies the structure of the Dynamo script. The functions of the script consist of 4 main sections following the UED of the Dynamo script and applying similar colors for grouping the functions of the script (Figure 29). The first section of the script (1) consists of the 3 node groups of the project parameters (Figure 30). The first node group is the "User-defined parameters". This node group contains the slider nodes from the node "Number slider" that allows the users to adjust the value to create the façade geometries. Most of the information in this subgroup is fed to the node group "Window panels (Generator)" and "Window overhang (Generator)" in section 2 – Geometry formulation. The second node group is the "Project parameters (Environmental conditions)". This node group brings information about the date, time and location for the analysis to the node group "Thermal analysis" in section 3 – Factors and analyses. In this node group, the "File Path" node is employed to take information from the weather file as explained in Chapter 6.3.3.3. The last node group of the project parameters is designed for extracting data from the Revit models. The nodes "Select Faces", "Select Model Elements" and "Categories" are applied to select the building surfaces, elements and level respectively from the Revit models.

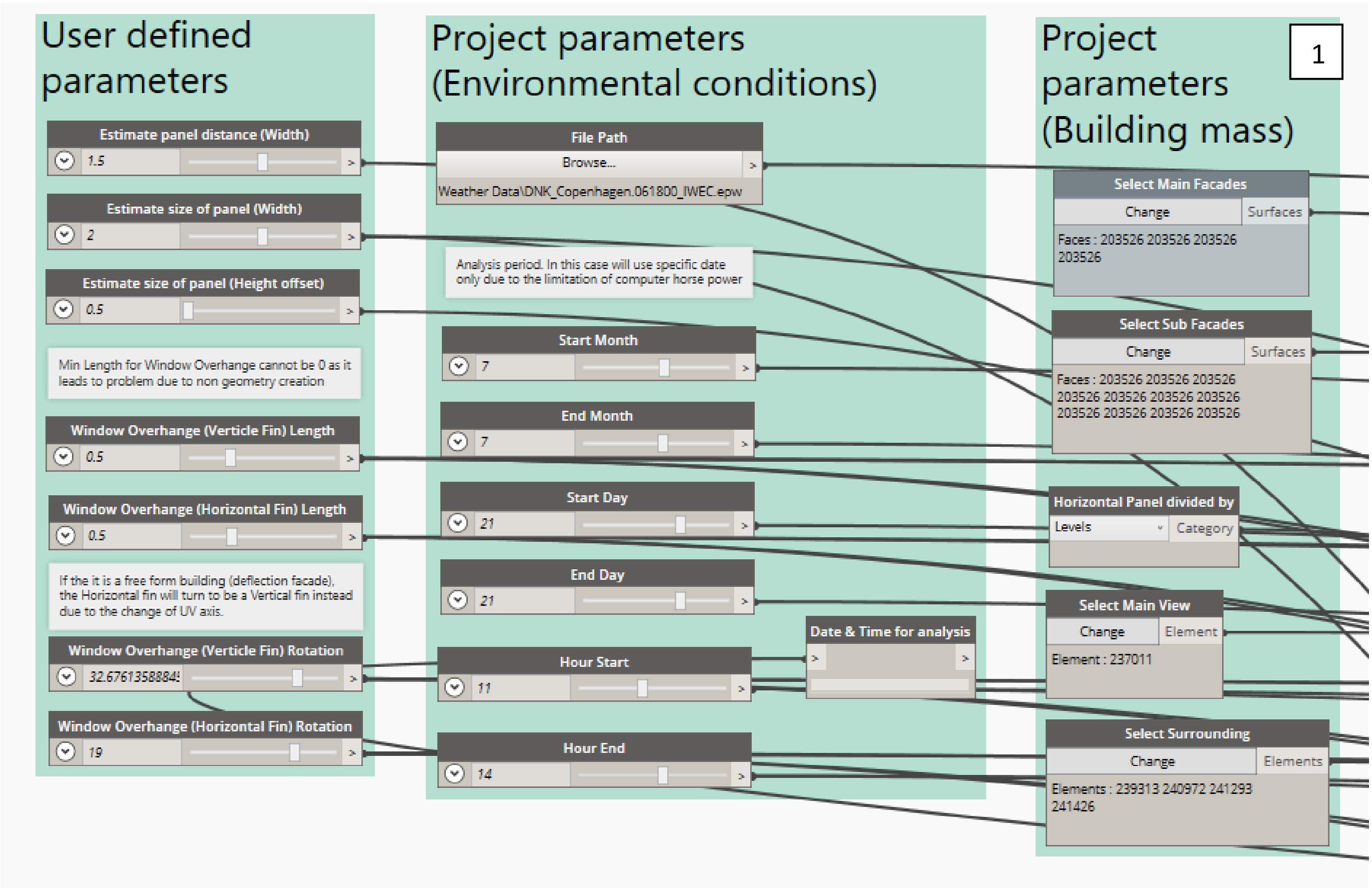


Figure 30 : The 3 node groups of the project parameters which are the node groups of the user-defined parameters (A), project parameter of the environmental condition (B) and project parameters of the building mass (C) perform the operation to assign the value to the façade geometry (A), assign information for IEQ analysis (B) and extract information from the Revit model (C) respectively.

The second section of the script (2) performs the operation to generate the façade geometries as explained in Chapter 6.3.3.3. This section demands 2 processes which are 2.1. Extracting the information from the Revit model and structuring the reference outlines for creating the geometries (Figure 30), 2.2 Creating the façade geometries based on the reference outlines. Starting with the first operation (2.1), the node group "Extract and create reference panels" that consists of the Dynamo nodes and Dynamo packages are used to extract the information of the Revit mass model. In this node group, the node "Surface.GetIsoline" is employed to define the reference line of an associated axis of the selected model surfaces. This node requires the input values 0 or 1 to define the U – V axis. These axes are important because the reference line on these axes is used as a base for dividing the selected surfaces into the panels. In order to give value to this node, the node group "Check façade planarity" is created. This node group checks that the selected surfaces are a plane surface or diagonal surface as these 2 types of the surface have a different value of the U and V axis. The node group performs the surface planarity inspection by checking the alignment of the 4 points of the surface corner. If the 4 points are aligned, this means that this surface is a plane surface, if not, it is a diagonal surface. The plane surface gives a return value at 1 (V axis) and the diagonal surface at 0 (U axis) for the horizontal reference line (Figure 32) by using the Python script to return the value. When the horizontal reference line (top) is defined by the given value, the next step is to analyze the total segment division of the surface perimeter to create the panels. To find the division of line segment, this can be done by the "Code Block" node with a mathematical formula. The total numbers of the horizontal line segments stem from the division of the defined horizontal line (top) of the surface divided by the expected panel width from the user-defined parameters section. The total vertical segments can be taken out from the vertical surface perimeter and are divided by the overall level of the selected building mass. These 2 numbers of the horizontal and vertical segments feed into the node "Panel.PanelQuad" to create grid segments which are used as a reference for generating the panel geometries (Figure 32).

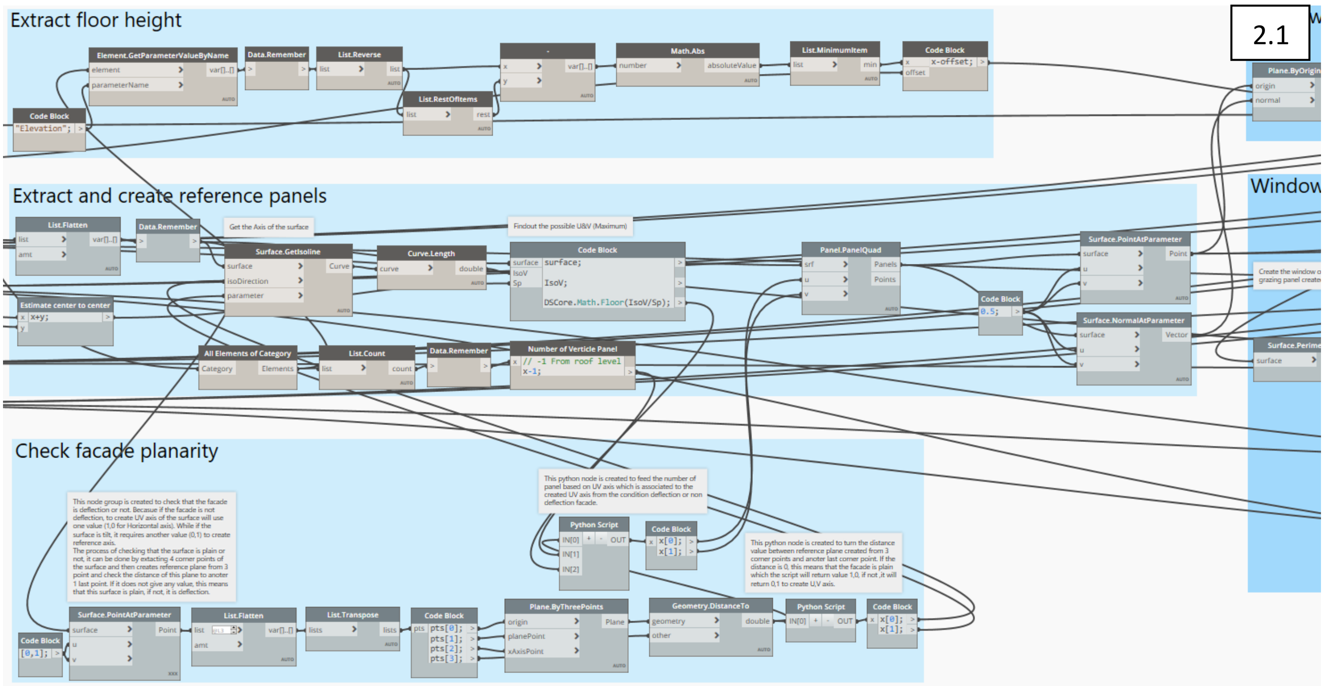


Figure 31 : The section 2.1 of the script consists of the node groups A. Extract and create reference panels B. Check façade planarity C. Extract floor height. These node groups are used for extracting the information from the Revit model and structure the reference outlines for creating the facade geometries. In order to proceed the the reference outlines creation, this requires the façade planarity checking (B) that will check the U and V coordinate axis for the main horizontal reference line. Afterward, the reference segments are created from the User defined parameters (Estimate size of panel and Estimate panel distance) that will define the horizontal segments and the node group Extract floor height (C) for the vertical segments.

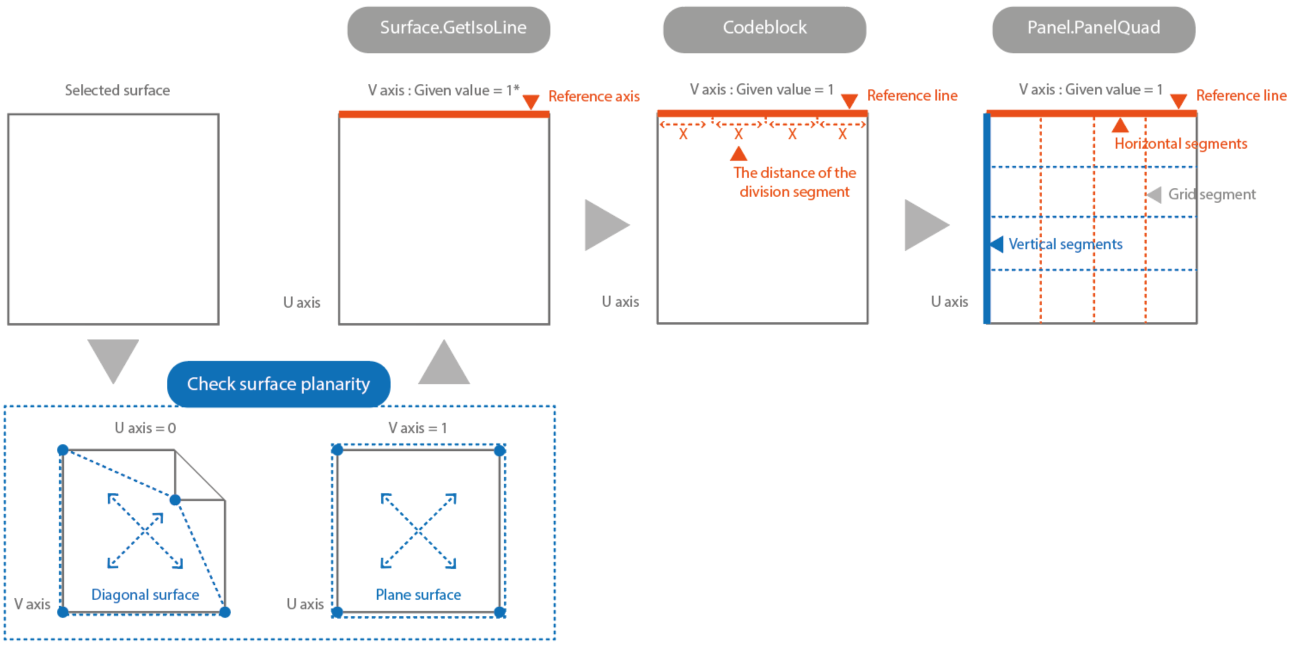


Figure 32 : The diagram explains the function of the nodes “Surface.GetIsoLine”, “Codeblock”, “Panel.PanelQuad” and the node group “Check surface planarity”.

After the creation of the grid segment reference, the next section (2.2) (Figure 33) is to generate the panel geometries from this reference. Firstly, the node "Surface.PointAtParameter" is used to define the center points of every grid segment (Figure 34). These center points are a reference point for the node "Rectangle.ByWidthLength" which is equipped to generate the window panels according to the User-defined parameters. Hereafter, the perimeter of the generated panels is applied to structure the window overhang. To generate the window overhang, there is a need to define the hinge point for rotation and the extrusion direction of the window overhang. For the hinge point, the node "Curve.PlaneAtParameter" is used. This node demands an indication of the baseline for the hinge point which can be done by the node "PolyCurve.CurveAtIndex". The output of this node is the base plane, which is an input of the node "Geometry.Rotate". In regards to the extrusion direction, the node "Surface.NormalAtParameter" is used for generating the vector direction. This vector outcome is fed as an input of the node "Curve.Extrude" which allows the users to define the extrude distances of the overhang geometry.

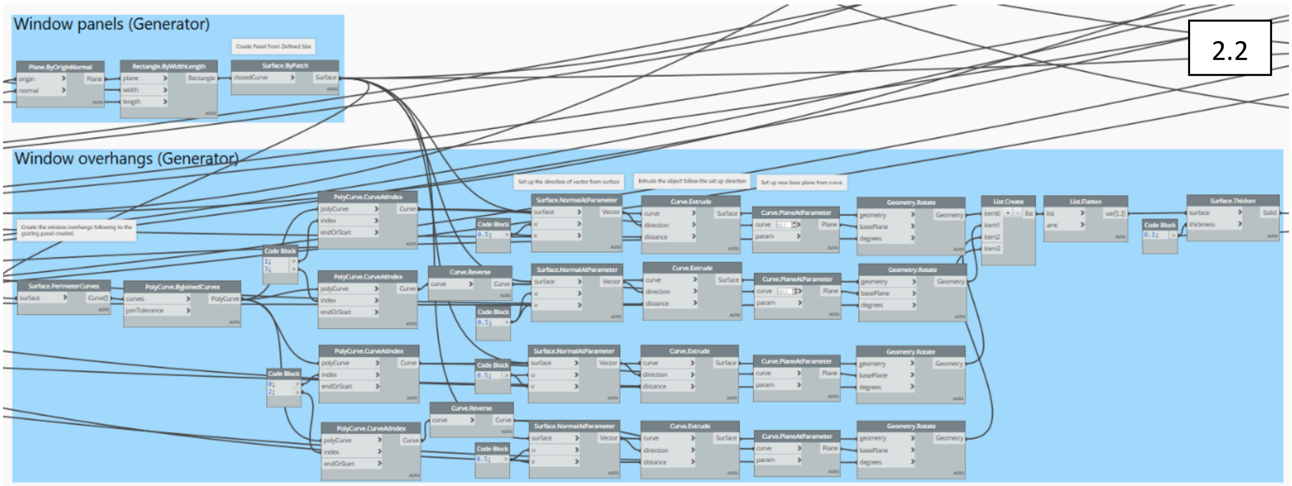


Figure 33 : The node group to create the window geometries based on the grid segment reference (2.1). To generate the geometry, this requires the information from the node group User define parameters in the section 1 to defie the size and proportion of the façade geometry.

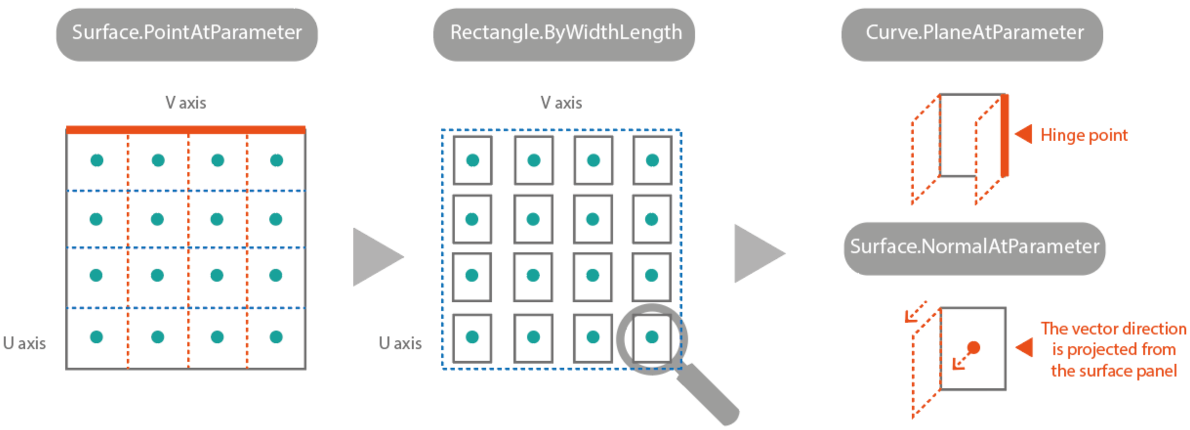


Figure 34 : The diagram explains the function of the nodes "Surface.PointAtParameter", "Rectangle.ByWidthLength", "Curve.PlaneAtParameter" and "Surface.NormalAtParameter".

The next section of the script is the analysis section (Figure 36). This section consists of the node groups for visual, thermal and daylight analysis, as explained in Chapter 6.3.3.1 and 6.3.3.3. Starting with the visual node group, in order to check the panels that can have a good view, this requires a projection of the defined viewpoint to the panels. To proceed with this task, the users have to select the element viewpoint from the Revit model for projection. After the users select the viewpoint element, the node “Solid.Centroid” is used to define the centroid point. Hereafter, to create the projection line of the viewpoint to the panel, the node “Line.By.StartPoint.EndPoint” is employed to develop the line from the centroid point to the center of the panels (Figure 35). When the lines are created, the nodes “List.FilterByBoolMask” and “Geometry.DoesIntersect” are used to filter the panels that are blocked by the surrounding buildings and the generated overhangs. The next node group is the node group for thermal analysis. According to the explanation in Chapter 6.3.3.1, the measurement of the thermal comfort will be based on the total hours of the sunlight that faces to the panels. In order to estimate the total hours, the node “SunPath” from the ladybug is applied. This node generates the sun path simulation based on the project parameters of the weather condition. When the sun path has already been generated, the node “Line.By.StartPoint.EndPoint” is equipped to create the projection lines (Figure 35) following by the nodes “List.FilterByBoolMask” and “Geometry.DoesIntersect” to filter the projection lines that are obstructed by the geometries. Afterward, the lines that can project to the panels are counted the total hours by the node “Math.Sum” as each projection line represents 1 hour of the sunlight. After this stage, the panels that gain sunlight hours over the defined period are eliminated by the node “List.FiltureByBoolMask”. The last analysis is the analysis of daylight from the total area of the window panels that can achieve the conditions from the view and thermal analyses. The node group of this part performs the operation to union the panel areas and presents in the project objective parameters.

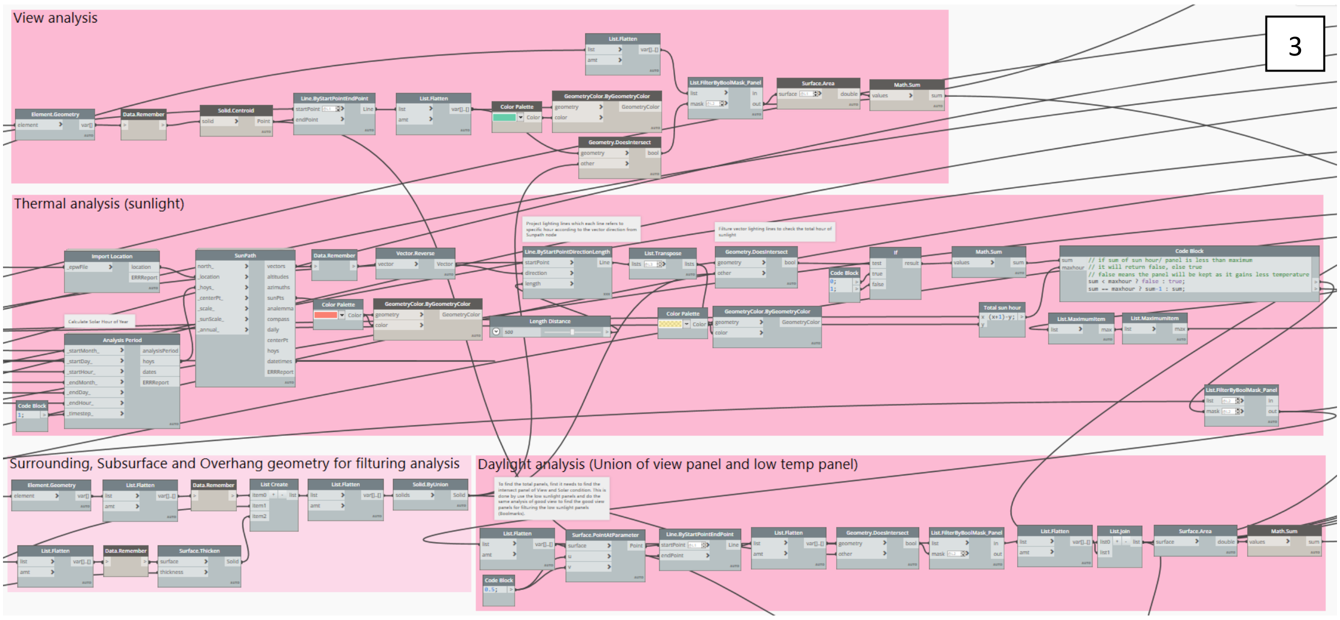


Figure 35 : The node groups for visual, therml and daylight analysis. These node groups demand the information from the project parameters of the environmental conditions and building mass from the first section to generate the analysis. The complete script can be seen in in Appendix 7.

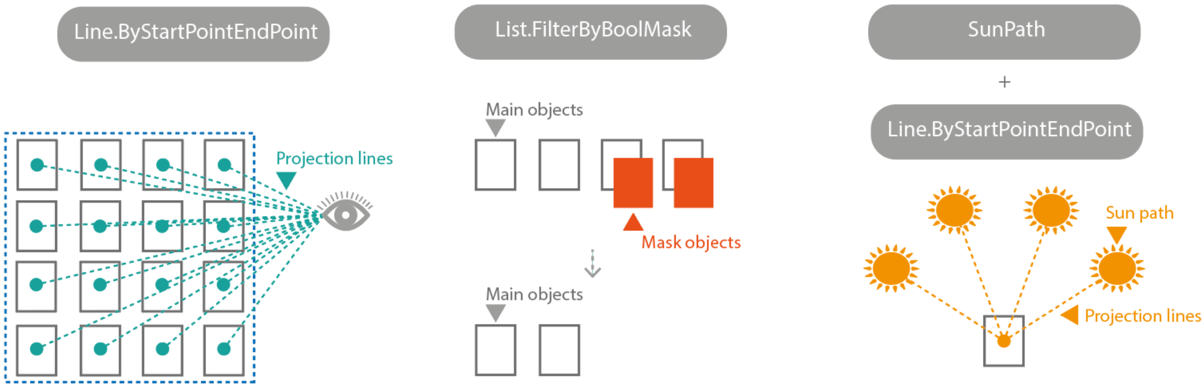


Figure 36 : The diagram explains the function of the nodes "Line.By.StartPoint.EndPoint", "List.FilterByBoolMask" and "SunPath".

The last section of the script is the node groups for presenting the outcomes of the analyses and the final façade geometries (Figure 37). To display the results, the node "Watch" is equipped. This node is used for the optimization in Refinery which demands the users to specify as "Is Output" function. The last node group is the "Final model presentation" which the main feature is to display the final façade geometries (Figure 38). In this node group, the node "GeometryColor.ByGeometryColor" is employed to present the geometry in color. However, in order to present the final shading geometries, the authors have to recreate these elements based on the last glazing panels. The reason for this is because the result of the analyses gives the new glazing panels, which are not the same geometries as the previously generated panels in the node group "Window panel (Generators)". These new panels cannot use for filtering the already created geometries due to the structural change of the list. As a consequence, this requires a new set of nodes to generate the shading geometries according to these final panels.

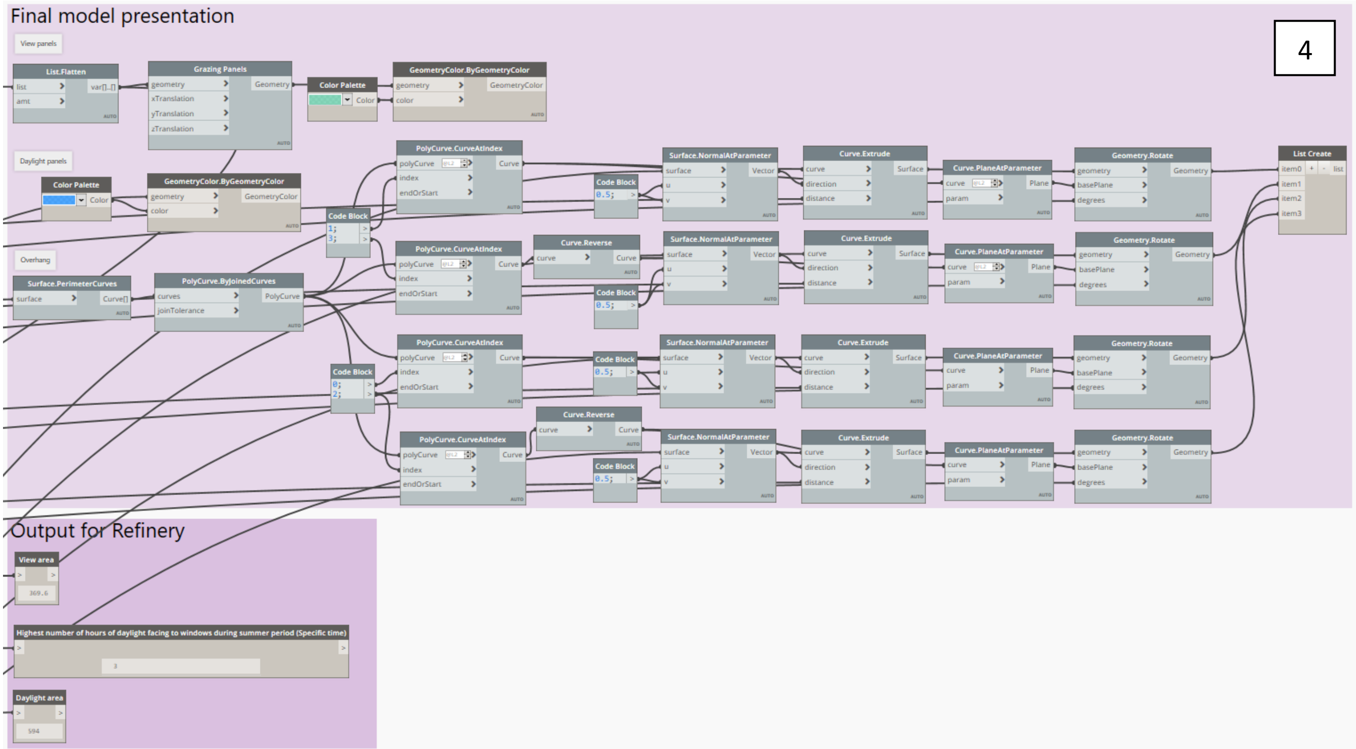
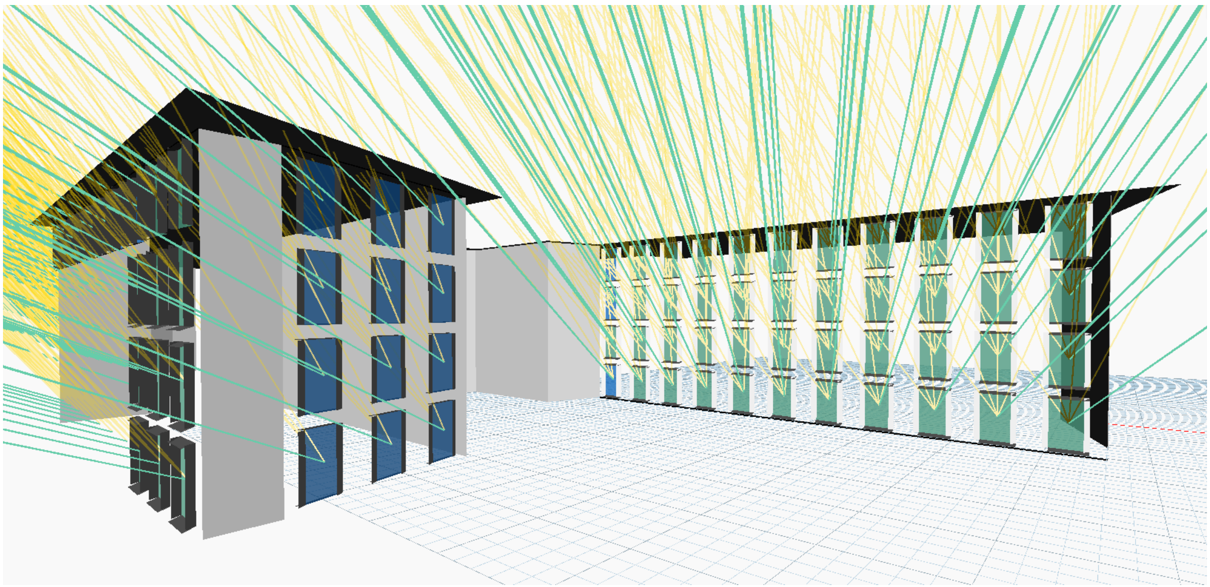


Figure 37 : The node groups to present the final geometries and performance results. These node groups have the function to display the performance outcomes and the final geometry. The performance outcomes are also be used in Refinery to decide on the optimization function of the expected project performances. The complete script can be seen in in Appendix 7.



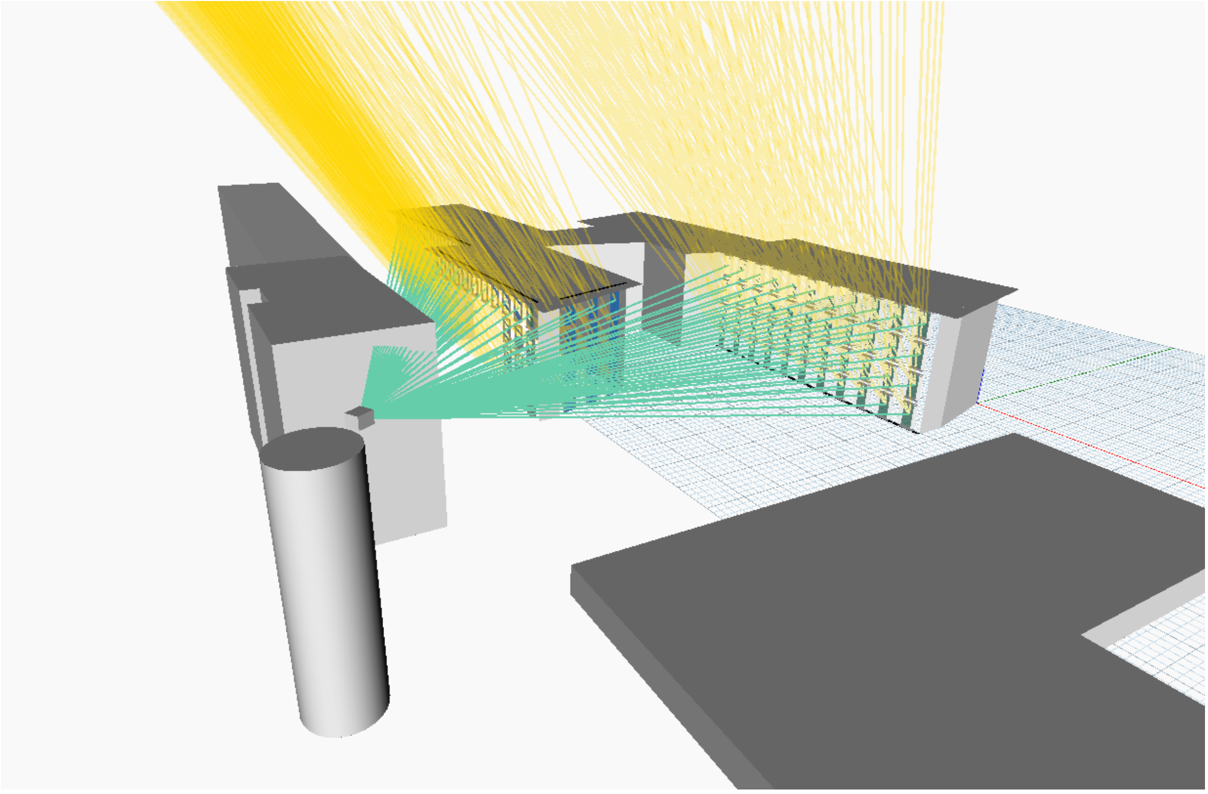


Figure 38 : The final facade geometries with the analyses of the view (green) and sunlight (yellow).

6.3.5 Results

After the script execution, the next stage is to run Refinery for design exploration and optimization. As explained in Chapter 6.3.3.3, the users decide on the maximization/minimization of the performance outcomes in regards to project objective parameters. In this project, as the goals are to optimize the IEQ performance, the view area and daylight were set up for maximization while the minimization was for the sunlight hours. According to the generation settings, the population size and the entire generations were decided to be at 12 and 8, respectively. The explanation about the population size and total generation will be discussed in Chapter 6.5.

The generated results from Refinery suggested that 5 options should be taken into account (Figure 39). Among these 5 options, there is 1 option that delivers the most productive performance. This option can minimize the sunlight hour to 2 hours and maximize the total window areas to gain the view and daylight in a certain environment. This option illustrates that the length of window overhangs (horizontal) has the most impact on the performance outcomes. With the span of 1 meter and the rotation angle at 4 degrees, this can block most of the sunlight of the specified period. On the other hand, the fins (vertical overhang) have less impact on the sunshine and view.

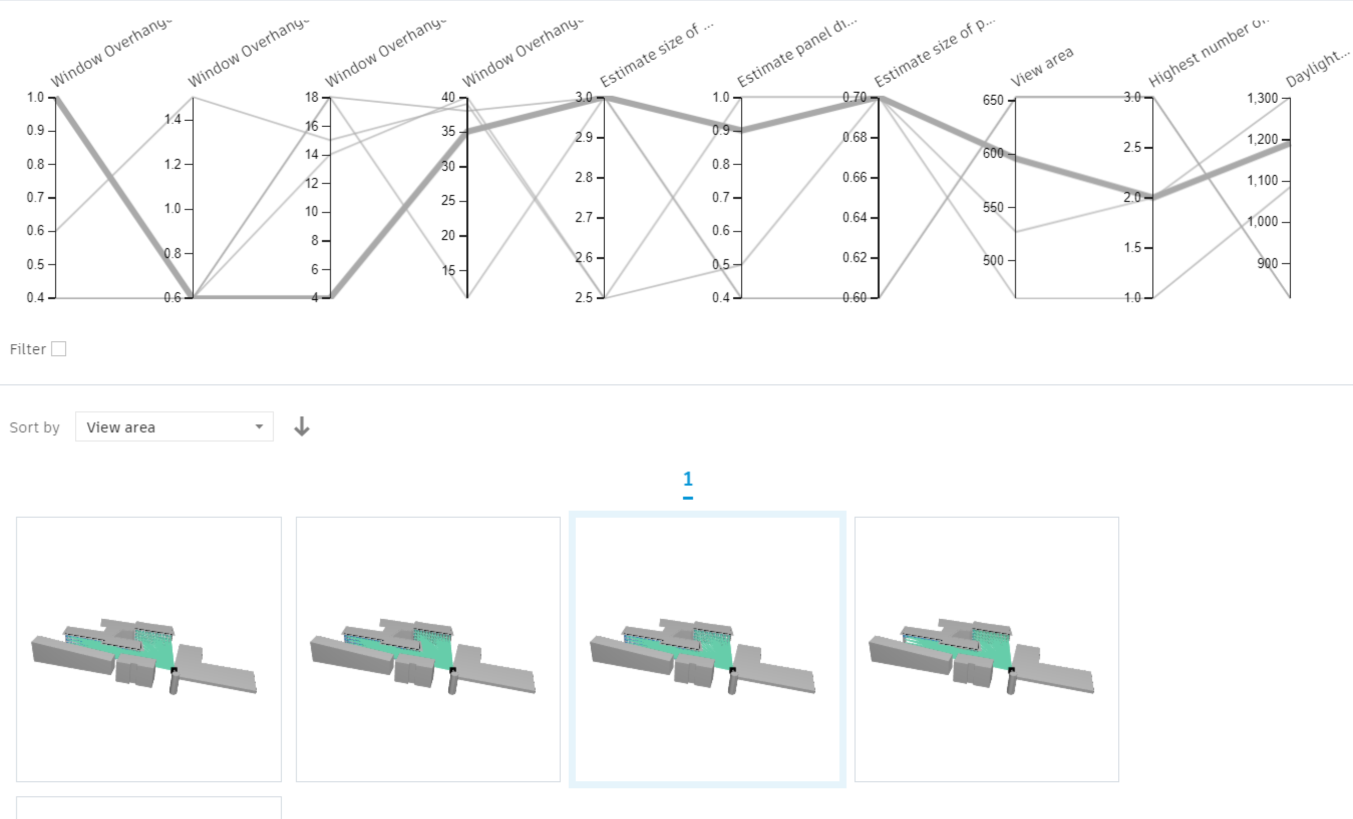


Figure 39 : The design alternatives based on the optimization function from Refinery.

6.4 Validation

During the project, the authors run the script several times with the purpose to see what results are achieved while changing *population* and *generation* numbers (Figure 28). It must be noticed that the higher the number gets, the longer it takes to generate the design for Refinery. Authors started with a population of 8 and a generation of 2 and at that time it took approximately 1 hour for the computer to generate. While the population size was 12 and generation 8, it took around 4-5 hours and, when those numbers were increased, the program got stuck.

Furthermore, the authors set up an interview with three Building Energy Design (BED) students from Aalborg University to receive some feedback on the work done (Appendix 5) which is summed up further in this chapter. In the future, they can work as IEQ engineers and the authors introduced them to the new way of work by implementing the generative design. As the process is focused on the initial design phase, they were asked if it would be possible to eliminate the use of BPS tools during that phase. However, the script was created with a simple assessment of the IEQ factors, the analysis is insufficient and less reliable than the use of the BPS tools. Also, to make the building legal and constructible BPS tools cannot be eliminated.

The interviewees mentioned that it is good to automate the process that could make the initial design process faster and reduce some big mistakes in the future. Moreover, the students suggested that as only basic calculations are made during the initial phase, all of it can be automated but the script (algorithm) must be able to adapt to different cases.

Considering automation, it is still significant to have real communication and collaboration between the actors as the more they communicate, the better results can be achieved. However, as mentioned by one of the interviewees, based on his experience, the architects have a very low understanding of the engineering part and do a lot of random things. Thus, helping architects understand more in the engineering field by giving them an alternative framework can help to improve collaboration.

All in all, the feedback about the proposed method of the initial design from BED students was positive. Such a process helps the architect and engineer to improve collaboration, eliminate a lot of mistakes in further development and make the process faster overall.

6.5 Discussion

In this chapter, the issues and considerations faced during the project work are discussed. The purpose is to highlight important aspects that could influence the workflow.

Coordinates

The digital process starts by creating a mass model, as mentioned previously, the mass model for this project was made in Revit. The problem experienced while the script was run is that the elements: windows, fins and overhangs were facing inside the building (Figure 41) on some of the walls. To fix the problem, the coordinates of the mass walls were checked in Revit whereas the issue

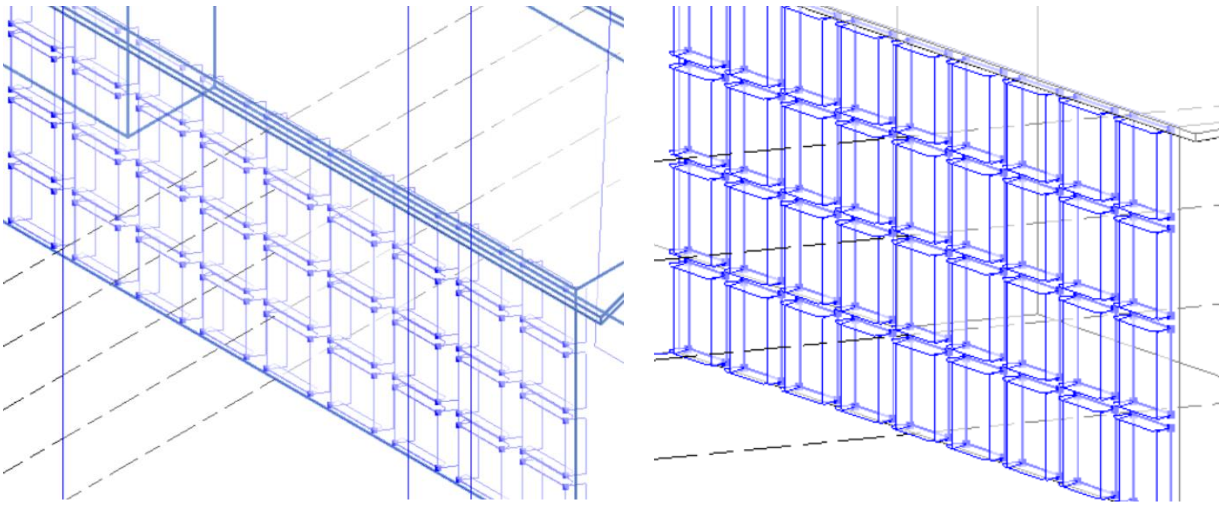


Figure 40: Facade with elements when the script was run. Because of wrong mass wall coordinates in Revit the elements are facing inside the building (1st picture), after the issue was fixed elements started facing outside (2nd picture).

was found. In Figure 40 is shown that the coordinates are facing inside and, as Revit does not allow just to flip the element, the wall had to be redrawn. Afterward, the coordinates started facing outside and the issue was fixed. Such a problem might appear because of a random sequence of the wall lines while creating the first mass model, whereas the second model was drawn clockwise line by line.

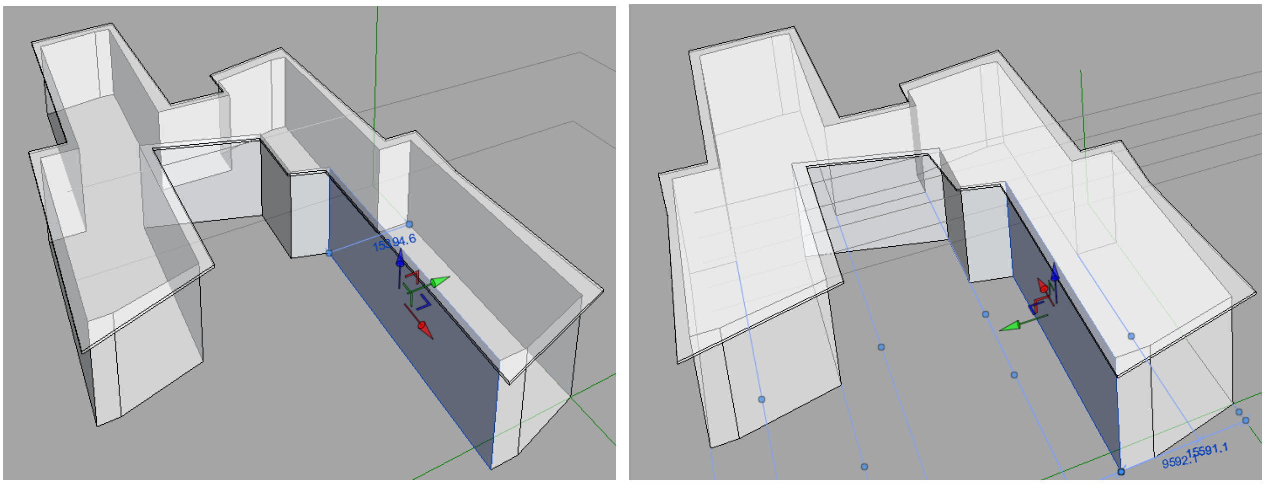


Figure 41: The issue discovered in Revit that coordinates are facing inside the building (1st picture), after redrawing the mass wall coordinates are facing outside (2nd picture).

Population sizes and number of generations

The population sizes and the number of generations have a significant impact on the performance results when performing the GA optimization. Thus, there is a question in which conditions have a stronger influence on the performance results and what is the suitable value for each condition to perform the GA.

To investigate these problems, Vrajitoru (2000) conducted experiments to study the issues. The testing was set up in control conditions and the number of generations multiplied by the population size is at 80 for all tests. The research reveals that comparing population sizes and the number of generations, the population sizes have a more significant impact on the performance results. The reason for this is because there is a higher possibility of finding the effective performance gene for optimization when the population sizes are big. However, the number of generations is also essential. This is because when the population sizes are large, it requires a more mutation process for crossover and filters only the high-performance genes for the next generation (Gotshall and Rylander, 2000).

According to the suitable values of the population sizes and number of generations, the authors decided to use the population sizes at 12 with 8 design generations. The reason for this is because, with the higher input values, it demands more time to produce the outcomes. Especially when the input values are over the given values, the operation was failed when it proceeded into the generation 4 and 5.

Ladybug and Honeybee issues

When doing a performance analysis by using the Dynamo package – Ladybug and Honeybee, there is a possibility to perform the solar irradiation analysis (LLC, 2019). This analysis gives the information in regards to thermal comfort which is the requirement of the IEQ criteria. However, this package has an issue with the node “Honeybee Surface” which is a node to give a building property to a geometry surface for analysis. One of the reasons this node cannot be used in Dynamo is due to the lack of support from the developer. In every new version of the Dynamo builds, there is an update of the features and issues fixed (Autodesk, 2019). The custom packages, which are created by various developers, are generally made for a specific version of the Dynamo build. The developer of the Ladybug and Honeybee packages has stopped the development since 2018 (Figure 42), while the authors use the Dynamo build 2.0.3 which was created in 2019. Thus, there is a possibility that some of the nodes may be incompatible with operating in this Dynamo version, which in turn, gives the error operation of the node script.

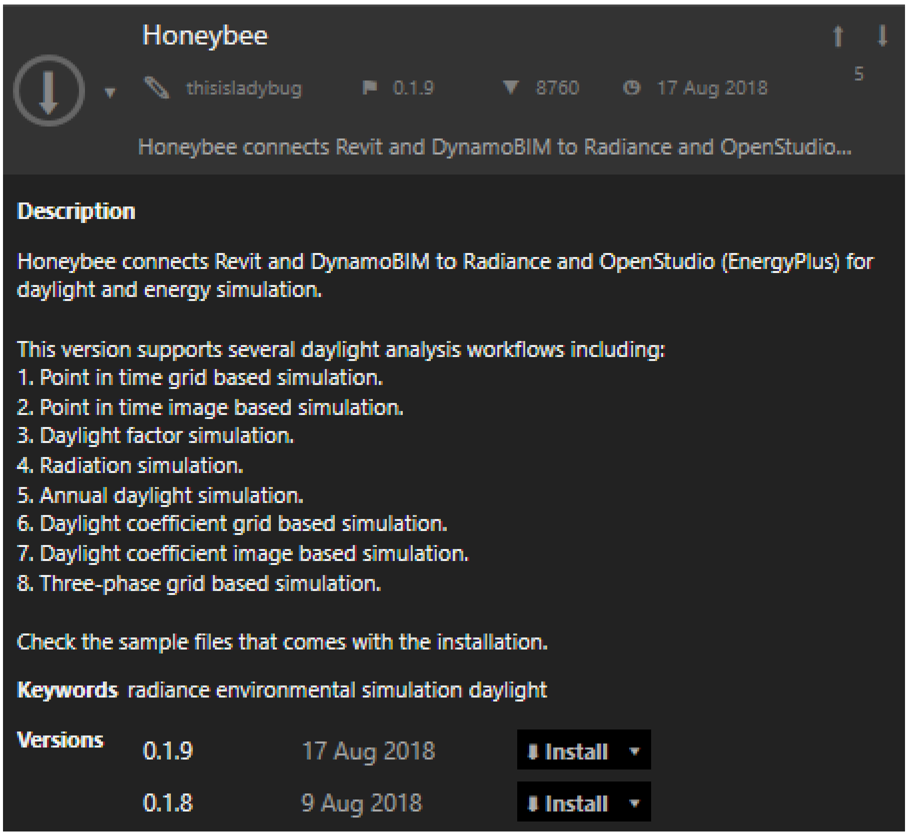


Figure 42 : The Dynamo package Honeybee show the last update at 17 August 2018.

Additionally, one of the significant issues when using the Ladybug and Honeybee packages is the problem with the amount of generated information. As the authors decide to perform the thermal analysis based on the gaining sunlight hours, this analysis has created 560 of the line geometry (Figure 43). This amount of geometries causes an overload of project information. This problem leads to an error when performing the design exploration in Refinery, especially when specifying the high value of populations and generations as explained in Chapter 6.3.5.

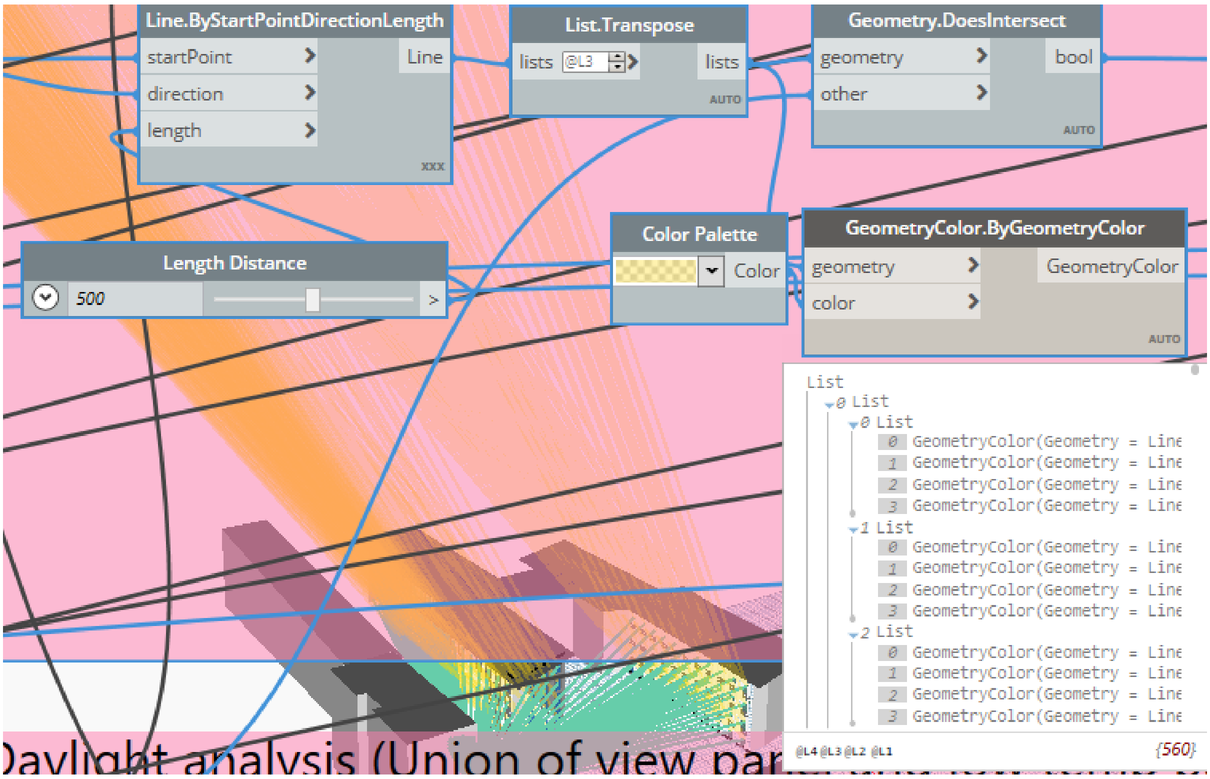


Figure 43 : By doing the sun hours analysis, this method generates 560 of the line projection geometries that cause a heavy load of file size and error of the design exploration in Refinery.

Parametric model to BIM model

According to the proposed solution in this research, the final model generated by Dynamo and Refinery is a parametric model. The question comes if there are any other methods besides Dynamo and Refinery to do the design exploration? And what is the benefit of using Dynamo and Refinery?

In order to do the design exploration, various researches such as “Integrating Indoor Climate, Daylight and Energy Simulations in Parametric Models and Performance-Based Design” (Lauridsen and Petersen, 2014) and “Energy performance optimization as a generative design tool for nearly zero energy buildings” (Touloupaki and Theodosiou, 2017) performed the design exploration with the parametric modeling tool and genetic algorithm tool - Rhinoceroes and Galapagos. The generated results are a parametric model, which is the same model type as this research result. However, there is a clear benefit of using Dynamo and Refinery regarding the BIM approach.

As Dynamo is an add-in product of the Autodesk Revit software, this program can transfer the information between the BIM model to other file formats as explained in Chapter 4.2.3. It can also be used to assign the BIM model families to the generated parametric model which will turn the parametric model into the BIM model as stated in Chapter 4.2.2. In order to proceed with this process, the users can use node "AdaptiveComponent.ByPoint" (Figure 44) in Dynamo to assign the families

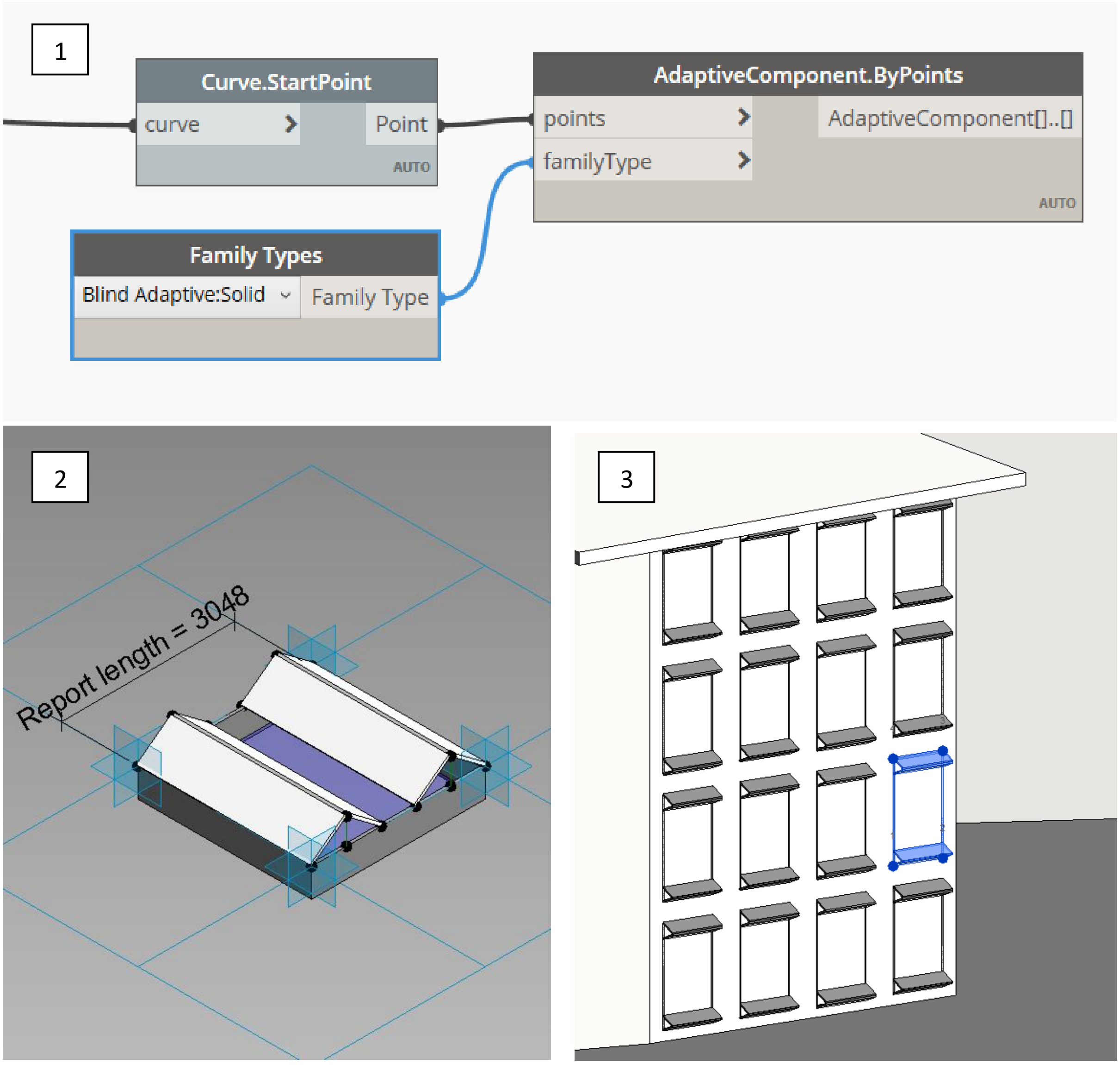


Figure 44 : The node "AdaptiveComponent.ByPoints (1) is used to assigned the family type (2) into the reference parametric model which will generate this family for a BIM model in Revit environment (3).

into the parametric geometry. This node will return the selected Revit families into the reference point of the generated parametric model. The result of this process is the created BIM model in Revit software as can be seen in Figure 44.

Architect's and engineer's role

The idea of this project is to propose a new procedure during the initial design with the purpose to consider IEQ as early as possible. The process is done by means of generative design which influences the architect's role. The generative design process is built in a way that the human is encoding some of his work that needs to be done or generated (Dino, 2012). Thus, the idea is not to eliminate architects but to give them some framework for further façade design. Such a framework will be able to make the design process easier, improve collaboration between an architect and IEQ and consider multi-disciplinary objectives as described in Chapter 6.3.1. Thus, there is a higher probability of eliminating many mistakes in further phases and making the general process faster. By taking a mass model and applying the script with parameters adjusted by an architect based on the guidelines from IEQ engineer, it will generate a number of building facades where an architect in collaboration with the engineer can choose the most suitable one. Thus, selecting an exact façade design can be a framework for further design development. Such a process does not eliminate any actors but makes the design process more comfortable and more efficient.

Comparison of buildings

The project was applied for an existing building located in Aalborg that is why it would be interesting to compare the real building and new proposed framework, however it cannot be done reliably. The reason for that is unawareness about the existing building's indoor environment quality aspects, what was wished to be achieved by the client and how the building operates nowadays in regards to IEQ. It can be seen that the windows do not have overhangs or fins and placed similar to the proposed framework. However, the windows in the existing building have a width of 1412mm and the distance between is 2188mm but in this project, during the script run, 2000mm window width and 1500mm distance between windows were considered. The results presented in Chapter 6.3.5 are including overhangs and fins, thus after optimization, the program suggests to leave all of the windows at the facades as overhangs and fins protect the building from sunlight.

Additionally, the authors run the script by removing overhangs and fins. In such a case, after the optimization Refinery proposed to remove most of the windows from the South façade due to sunlight. Again, that happened because of the limitations of sunlight for getting inside for no more than 3h/day however it is unknown which aims have the real project.

7 Conclusion

The final problem formulation is described in Chapter 5 and is stated as following:

"How can the use of generative design improve the initial design stage with regards to IEQ?"

Furthermore, the following sub-questions were considered while processing the problem:

- When and how should the implementation of generative design happen?
- How does the collaboration between an architect and an engineer change?

In order to successfully answer the given problem formulation and sub-questions, the research was conducted. By analysing the existing workflow of the initial design phase and collaboration between an architect and IEQ engineer in Chapter 3, it was investigated that because of different fields of specialization it can be difficult to understand and interpret for an architect the IEQ guidelines from an engineer. To improve the collaboration, performance-based design for Multi-disciplinary Design Objectives was taken into account which serves as a base for generative design. MDO is significant in this process as many IEQ factors have to be analysed; however, this project is scoped only to the three explained in Chapter 6.1. Generative design in this research is achieved through VPL – Dynamo and optimization tool – Refinery.

To develop the prototype, storyboards were created which serve as a foundation for a new idea. Afterward, the new process is shown through BPMN in Chapter 6.3.2, whereas it considers only the initial design phase and such actors as the client, project manager, BIM modeler, IEQ engineer and the architect. BPMN shows that the proposed method does not intend to eliminate any actor in the workflow but improve the collaboration between the architect and IEQ engineer. Through implementing the generative design (steps 1.10-1.11 in BMPN, Figure 25) the architect can achieve the MDO approach and as a result, a framework is generated by a computer tool. As such a framework already takes into consideration IEQ factors and runs optimization, it eliminates many mistakes in further phases. The generative design step is helping the actors to achieve better results but still, human involvement is needed.

There was developed a script explained in Chapter 6.3.4 for three IEQ factors. The Dynamo script and use of optimization tool Refinery is the generative design process. The script requires manual input that is precisely described in Chapter 6.3.4, that the architect is responsible for. The use of generative design is not limiting the architect in the design process because the mass model is created independently, and after optimization, a framework for the architect is given. The framework is showing, for instance, where the windows should and should not be placed to reach the IEQ goal and, by following the suggestions, the probability of fulfilling IEQ demands in further phases is increasing.

Summing up, this research shows that generative design can be used in the initial design stage. By building the script in accordance with the indoor environment quality factors and applying an optimization tool afterward, a framework for the façade design can be generated. This framework intends to serve as a base for the façade design. By following it, the probability of fulfilling IEQ demands, eliminating some of the mistakes and getting the project done faster is rising.

7.1 Perspectives

In this report, the authors used the Dynamo package Honeybee and Ladybug to perform the IEQ analysis. This package requires the information outside the Revit program, such as building location and weather conditions from the weather file, as explained in Chapter 6.3.3.2. However, this information already provided in Revit since the architect generated the mass model. Dynamo can extract the information i.e. building location and sun location without the need for the additional package. But, Dynamo lacks the feature to take the information of the sun path period, sunlight direction and solar irradiance which is the essential data for the analysis. Thus, the authors suggest it would be beneficial if Dynamo can utilize this information from the Revit model without the need for additional packages. This would help to minimize the file size due to the less input of information.

Moreover, as the project performs the IEQ analysis based on the simplified information due to the limitation of the project timeline, this causes to the less reliable of the project outcomes. Thus, the authors suggest that the analysis should be performed according to the complete information which will give a better result of the project. The daylight analysis, for example, should be based on the daylight factor that demands information about illuminance. Also for thermal comfort, this requires various information to be taken into consideration such as external temperature, internal temperature and the source of factors to generate the most accurate outcome for the analysis.

Lastly, the authors can see the potential of implementing the generative design to enhance the design quality in the initial design stage. This method does not limit to only the IEQ factors but it can be applied for other cases that demand a design exploration of the building performances. The issue would lie to the lack of scripting skills among professionals (both an architect and an engineer) and the perception of the design method. As the generative design is a rationalization design process that demands logical thinking to create a system for the design exploration, this has changed the way of the design method where the creativity has to be translated into the computer language. This process looks for the objectives and measurements rather than aesthetic and personal preferences. It has changed the design perception which requires a transformation and education to the designers.

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8.1 List of Figures

9 Appendix

Appendix 1 – Interview guide for an engineer

Appendix 2 – Interview with Nanna Dyrup Svane (engineer)

Appendix 3 – Interview guide for an architect

Appendix 4 – Interview with Tima Bagheri (architect)

Appendix 5 – Interview with Building Energy Design students

Appendix 6 – Business Process Model and Notation

Appendix 7 – Overall script

Appendix 1 - Interview guide for an engineer

These sample questions were used for the interviews

Topic/area	Reflections (What do we want to know?)	Interview questions (Which questions are asked?)
General about interviewees	Educational background and experiences.	- Could you please tell us a bit about yourself, your education and what you do for the company you work in?
Current design process in the company	How new buildings are designed.	- Could you please tell us who is involved in the initial phases of the building design? - How they decide how the building should look like? What are the major factors? - How long does the process take? - Which tools are used? (Paper & pencil, Revit/AutoCAD etc.) - Do you incorporate parametric design in your design process? - What means "Parametric design" in your opinion?
Sustainability (Indoor thermal comfort, visual comfort, daylight)	How those factors are considered while designing a building and at which stage.	- At which stage indoor environment quality is considered/calculated? - Is it a good phase to consider it? - Does such a late consideration causes any problems? (design, financial, planning) - How do you decide on the importance of IEQ, how do you give the priority to those different criteria? - Which part of the building is crucial for indoor environment quality?
Tools used for building energy analysis	What tools are used in a particular company.	- Which tools do you use to analyze building performance? - At which stage do you use those tools? - Do you find those tools useful and efficient? - Who is responsible for those calculations/analyses?
Generative design	To know if the company is familiar with it.	- Have you heard/Do you know what is generative design? *If yes:* - Have you ever tried to use it in your company? What did you do? How was the result? - Do you think it can be beneficial?

Parameters for generative design method	Which parameters would make sense to use to achieve better results	- While designing a façade, which parameters you are most concerned and how do you decide on that?

Appendix 2 – Transcription form the interview with Nanna Dyrup Svane

12.09.2019, Aalborg

Authors: We would like to know your background and experiences?

Nanna: My name is Nanna. I am a civil engineer and I finished education in 2012 from Aalborg and Aarhus University. I work here (MOE) ever since within the department of special competences, energy calculations, indoor climate calculations, sustainability, DGNB consultant and auditor. I can certify buildings within the sustainability standard. And just a few months ago, I started an industrial Ph.D. study with the collaboration between Aalborg University and MOE where I work mainly in the indoor energy climate calculations e.g. how to make it more efficient. I also work with the façade solution.

Authors: The authors explain the project details and the initial problem background of it.

Authors: What we are trying to investigate the problem background on how the industry works? How the engineer and architect work in the company? Does MOE have the same working system in every branch? (The authors also asked about the implementation of generative design works from the graduated Ph.D. student Torben Ostergard who works at MOE)

Nanna: Yes, we have the same system and we also use the tools (generative design projects from Torben) in Copenhagen. And my Ph.D. is the further development of Torben's Ph.D. project. Torben worked in the multi-energy programming and my Ph.D. concerns in the indoor climate calculations. It is the same method but chooses different program.

Authors: Could you please tell us for the current design process in MOE company, who involve in the initial design phase, how the building is actually designed from scratch?

Nanna: Designing a building is so complicated. So many involved parties. The architect, the building owner, the entrepreneur, engineers, the many kinds of engineers like structure, HVAC, energy. It is difficult and complicated to collaborate when you have so many people. Usually, it starts with a start-up meeting and I could be a kind of engineer who participates in the meeting. I work as indoor sustainability engineer and usually talk to the architect. It would be like a meeting where you discuss what does the building owner want. Cause that is the primary target. Like what does he wants, goals and visions for this building? Then the architects make some sketched based on that and I will give him some guidelines on how to reach the energy targets and indoor climate. Such as percentages of glass. I expect them to produce 40-50% of glass. It is before even they have a model.

It is true in what you said before that it is some time a kind of iterative that we get a drawing from the architect and say no it is not enough. We ask something differently and architect make another drawing. Of course, it is a process between partners. But architects and engineers think differently, they have to do their job and we have to do our job. It is a process. We have a meeting where we discuss what is the goal and then architect make some sketches.

Authors: We would like to ask about the standard of IEQ that you use?

Nanna: It depends on which kinds of building. Such as office building, we use 1752DS, building regulations.

Authors: What means parametric design in your opinion, do you incorporate parametric design in your process?

Nanna: We do. We always make different variations in our simulations. But that is what my Ph.D. concern. It is the method of how you make parametric design much easier and faster. We do not do it enough as it is right now.

Authors: We would like to know the tool that you use for creating a model and facade?

Nanna: Mainly creating a façade is the architect job. We just guide them.

Authors: How do you decide on the indoor environment quality, the priority to different criteria when you start designing the building also checking the design from them?

Nanna: First is the regulation that must comply with. And normally building owner will tell us which class of energy and an indoor environment that we wish to have like A, B or C. C is the lowest you can accept. Normally, they choose B or A. Depending on which kind of building, for the hospital you have to pick A for indoor climate. Basically, it depends on the owner, what does he want and try to get that, that how we work, we try to make the building that the owner wants.

Authors: This means it quite variable depending on the project to project.

Nanna: It is the same method as if the owner requires indoor environment-class A, this means we need more air in the room for example. It is more difficult to get.

Authors: How do you prioritize the criteria of indoor environment quality (Thermal, Visual, Ventilation, and Noise)?

Nanna: Normally, you have the regulation, it is difficult enough to reach those requirements. So that normally the goal. We have to fulfill all, we cannot say one is more important than others.

Authors: In which phase do you usually calculating energy performances and IEQ?

Nanna: After the architect made the first model.

Authors: Which tools do you use?

Nanna: We use BSim and we give some guideline for the architect to create model for this.

Authors: Do you find this tool is useful?

Nanna: It could be more efficient. That is a part of my Ph.D. Basically, we use BSim because it fits the Danish standard. And other programs are not, that is why we use BSim.

Authors: What about BE18, do you know that tool?

Nanna: Yeข, but that is for energy, BSim is for IEQ.

Authors: And you are responsible for that calculation?

Nanna: Yes, my department.

Authors: Have you actually heard about generative design?

Nanna: Yes.

Authors: Have you use that in your company, what is the result?

Nanna: I haven't used it myself, I have read a lot of articles about it and following the Ph.D. works.

Authors: Do the architects use Rhino and Grasshopper to create the facade?

Nanna: I am not sure, but in Denmark, we have separately architects and engineers, other countries architect and engineer work in the same company where is more common to use generative façade. I don't tell the architect how the façade should look like, that is not my job, but I tell them how we can make small change in his façade in order to comply with the requirements.

Authors: Do you think that generative design can be beneficial in the construction industry?

Nanna: I think it is good approach to find a sustainable solution. The way you ensure the good indoor climate, the daylight and so on. I thought that creating a façade that you know fulfill requirements also I see the dilemma in building energy design.

Nanna also suggest about interviewing an architect about how they design a façade.

Appendix 3 - Interview guide for an architect

These sample questions were used for the interviews with architect

The scope focuses on the building façade design based on the performance of an indoor climate factors.

Topic/area	Reflections (What do we want to know?)	Interview questions (Which questions are asked?)
General about interviewees	Educational background and experiences.	- Could you please tell us a bit about yourself, your education and what you do for the company you work in? Ans
Current design process in the company	How new buildings are designed.	- Could you please tell us who is involved in the initial phases of the building facade design? Ans - Can you briefly explain about the design process step by step starting from when you have already got a design brief to send the first drawings/model to an engineer for performance evaluation? Ans - From the previous question, how do you design the façade, when it happens, how you decide the building facade should look like? What are the major factors? Ans - Which tools are used? (Paper & pencil, Revit/AutoCAD etc.) Ans

Sustainability (Indoor thermal comfort, visual comfort, daylight)	How those factors are considered while designing a building and at which stage.	- At which stage indoor environment quality (IEQ) is considered/calculated? Ans - How do you decide on the importance of IEQ, how do you give the priority to those different criteria when you do a façade design? Ans
Tools used for building energy analysis	What tools are used in a particular company.	- Which tools do you use to analyze building performance? - At which stage do you use those tools? - Do you responsible for those calculations/analyses? Ans (If you do not involve within this part, can you tell me who take responsible for this)
Generative design	To know if the company is familiar with it.	- Have you heard/Do you know what is generative design? *If yes:* - Have you ever tried to use it in your company? What did you do? How was the result? Ans

Appendix 4 – Interview with Tima Bagheri (architect)

Interview guide used for the project.

These sample questions were used for the interviews with architect

The scope focuses on the building façade design based on the performance of an indoor climate factors.

Topic/area	Reflections (What do we want to know?)	Interview questions (Which questions are asked?)
General about interviewees	Educational background and experiences.	- Could you please tell us a bit about yourself, your education and what you do for the company you work in? Answer I am an architect with almost 6 years of experience in building industry. I am mostly doing 3D modeling, concept developing, drawing and the visualization.
Current design process in the company	How new buildings are designed.	- Could you please tell us who is involved in the initial phases of the building facade design? Ans I think, architects are mostly in charge with façade designing at the initial phases. - Can you briefly explain about the design process step by step starting from when you have already got a design brief and till sending the first drawings/model to an engineer for performance evaluation? Ans The first step is context and case study, next step is concept developing and making the first sketches of the design ideas, then build the design model. Also should have some ideas about how it should be constructed and draw the technical plans and details. - From the previous question, how do you design the façade, when it happens, how

		you decide the building facade should look like? What are the major factors? Ans At first, I try to see some samples of the ideal façade designing around the world, (which are similar to my case), then make a conclusion about these different ideas and adding the specific factors and criteria which I should consider in my case to make the unique design of my façade. - Which tools are used? (Paper & pencil, Revit/AutoCAD etc.) Ans At the first stage paper and pencil but as the idea is developing, software like Revit and Auto Cad should be used.
Sustainability (Indoor thermal comfort, visual comfort, daylight)	How those factors are considered while designing a building and at which stage.	- At which stage indoor environment quality (IEQ) is considered/calculated? Ans At the initial phase - How do you decide on the importance of IEQ, how do you give the priority to those different criteria when you do a façade design? Ans Based on our context/case study we can decide which criteria are the most important ones.
Tools used for building energy analysis	What tools are used in a particular company.	- Which tools do you use to analyze building performance? - At which stage do you use those tools? - Do you responsible for those calculations/analyses?

		Ans (If you are not involve within this part, can you tell me who takes responsibility for this) I am not involved in this part, maybe building constructors and civil engineers are in charge with it.
Generative design	To know if the company is familiar with it.	- Have you heard/Do you know what is generative design? *If yes:* - Have you ever tried to use it in your company? What did you do? How was the result? Ans

Appendix 5 - Interview with Buildign Energy Design students:

Karolina Poczobutt, **Attila Kopanyi**, **Lajos Adam Pallagi.**

Date: 22.11.19 12:00

Authors: *intro about the thesis, new proposal of initial design process. Explanation about factors.*

BED: When you consider sunlight does it depend on orientation of the building, like you have windows on South, what about windows on West, East...because the sun will be there in a different time.

Authors: Have not considered this issue. *Explanation continues.* Do you have any question?

BED: How does it calculate the thermal comfort?

Authors: *Explanation of limitations.*

BED: Did you take into account global horizontal radiation, direct (on horizontal surfaces) ?

Authors: Have not considered that, also about the angle.

BED: It is not a coincidence that we use BPS tools, they asses dynamically the comfort. In your case it is more simple assessment but it can be also assessed in a more difficult ways. For the start it is good that they can optimize it automatically but I would not say you can eliminate the BPS tools. It is not only about comfort but also about energy, it is connected to everything – the façade design. So there is still need for BPS tools because they asess the whole thing but at initial stage it ok to have what you propose.

Authors: You alewady answered the first question: Do you think after the new process (when the model is generated by means of script based on IEQ factors) the use of BPS tools is still necessary for you?

Basically you say that there is still need for BPS tools after optimization? So, checking the model again in BPS, the project can move to the next phase?

BED: I do not have big experience in the real projects. But BPS are definetely needed, the question if they really need it at the initial design phase. But BPS assess energy and also thermal comfort. Because in your case it is very simplified, if it is not simplified then you already create BPS tool. Also to make the building legal you need the approximation of atmospheric comfort in the building.

Authors: Does the automation process improve the collaboration between architect and IEQ engineer?

BED: Yeah, I guess it would make it easier if there would be an automated process to check. Also important not to forget the energy engineer cause it is very much connected with the facades. It is good to have automation but still you cannot eliminate certain amount of iterativity.

Authors: The next question: Is there is any IEQ factor at the initial design process that cannot be automated?

BED: Difficult to say, so you would automate the work of engineers basically but you cannot know what type of indoor furniture they choose, clothing, type of windows...because of the early phase. The type of window also affects the acoustics. The engineer is not just someone who checks if everything is okay, before proposing something he/she has to think and I do not think human intelligence can totally omitted but the automation just makes it easier.

But as you are talking only about initial phase, actually there we do not make very complicated calculations/analyses we do some math and physics, it also depends when exactly the initial design stops. But I think at the initial everything can be automated. But the algorithm can become so complicated because it is needed to be used and able to adapt to many different cases.

Theoretically it can be automated as it is based on calculations but then the inputs always change. And you cannot eliminate the engineer's work because you need to set up the calculations somehow.

Lets say you created everything and then one person has to click one button and that is it - > Revit can become as a BPS tool but not dynamic but simple.

But I do not think that usually the Revit models contain all the information that is required for analyses. Could be but they usually do not. In the future I think what they will try to do, also if I look at the MOE, they are trying to make communication or the data transfer between BPS tools and Revit. They are trying to do it more easier, they are not trying to incorporate scripts in Revit or make BPS tool out of Revit but improve interoperability between tools. For them the goal is to have the optimized design, they will run all the cases and choose the best.

Authors: That is actually the next question: Is it good to automate the optimization process?

BED: Yeah, of course. It can be tricky to set it up and also the person has to be able to evaluate it later. I think it is nice, you can make many simulations, many designs, that is useful. MOE is investing a lot of money in it.

Authors: And the last question What advantages and disadvantages brings the new process for IEQ engineer?

BED: It is a big advantage if the architect could understand the engineers demands. I had some experience as engineer and needed to collaborate with architects (as structural engineer) and I could see that architects had low understand of static and structure and they do a lot of random things, they believe it is so nice and fancy but when I need to calculate that, too way complicated. So if architects would understand more it improves the collaboration. Also advantage is (depending when the initial design phase ends) it is quite easy to make the initial analyses and enough to present for the client, but later it probably will get more and more complicated in further phases. So that could also reduce some big changes in further phases.

Generally the tools that can automate IEQ analyses is a good idea.

It probably eliminates a lot of mistakes in the later phases. And makes the process faster in general.

Just a concern – it is a problem for us when we need to use a lot of programs so it is nicer if we would get one program where we can do from the initial until the end. There are usually a lot of programs while exporting files...

But then you would have one big model for everyone and it is going to be very heavy! So there is basically always discussion about it.

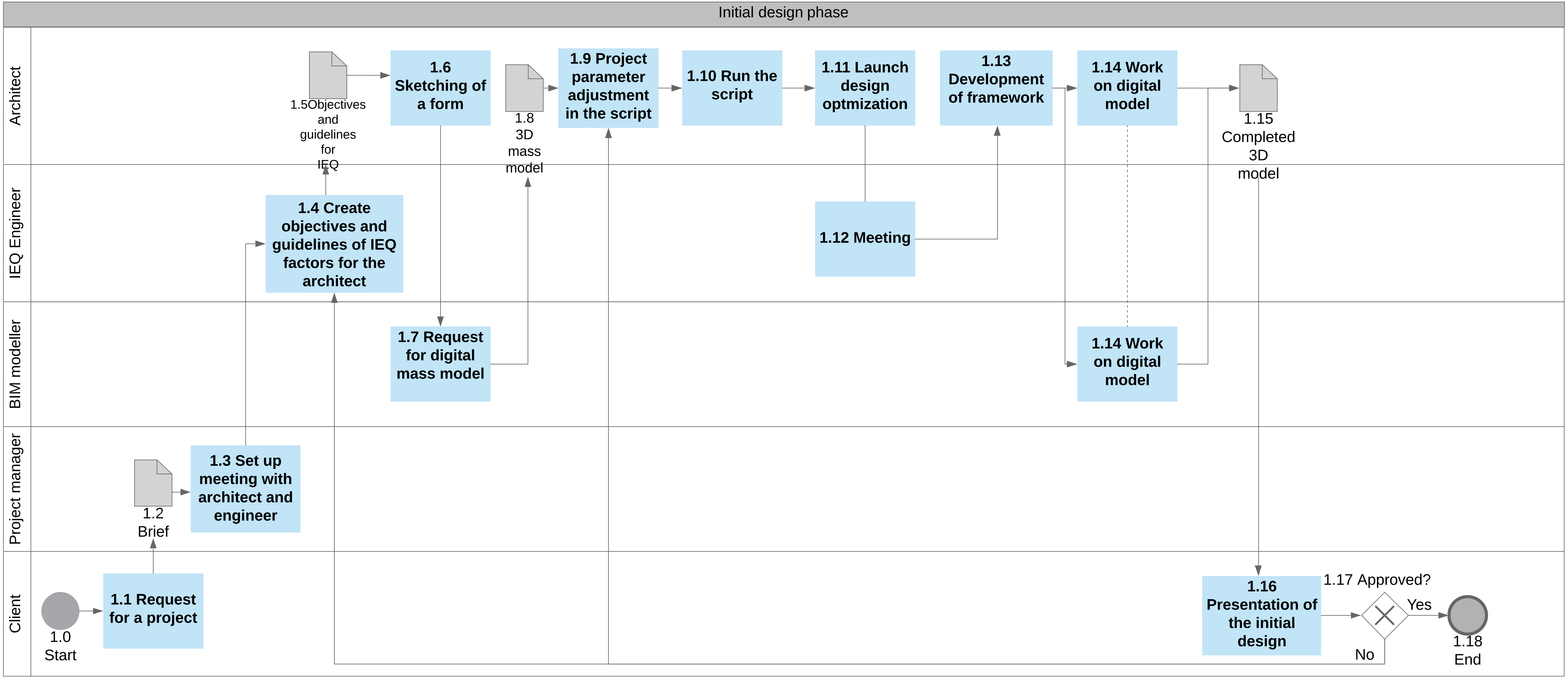
Authors: About communication – does the dialog is still important between architect and engineer when such an automation is implemented?

BED: Yes, it is still most important thing. At the certain point they still need to speak.

They still need to discuss the results of the assessment before it goes to the further stage.

If they are working together through the whole project then it is a good idea to communicate. Based on my experience it is nicer, the more you can communicate the better.

Appendix 6 - Business Process Model and Notation



Appendix 7 - Overall script