Tampere University of Applied Sciences

Adoption of Generative Design in the Architecture Design Process

Revit and Dynamo

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ABSTRACT

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The architecture design process is a complex matter that involves many actors, and problems can emerge unexpectedly. Finding the most convenient and fast solutions is essential to diminish the risks during the rest of the project and to ensure long-term sustainability. The commissioner of this thesis is Raami Architects, a Tampere-based architecture firm with more than 20 years of working experience. Hospitals, daycare, urban planning, and residential and office buildings are among their projects. The company wished to venture into Generative Design (GD), having as tools Revit and Dynamo.

The thesis aims to determine the benefits and challenges of adopting GD as an aiding tool to complement the current traditional design process. The objectives followed to achieve the goals are: To contemplate the benefits and challenges of using GD, to recognize the most common problems that emerge during the architectural design process, to analyze the impact of GD on the current design process of Raami, to identify the type of projects and tasks that benefit from GD, to determine the resources necessary for the adoption of GD, and to study and experiment with Revit and Dynamo GD tools.

The theoretical background of the thesis consists of literature on the architectural design process and GD for the Architecture, Engineering, and Construction (AEC) industry. Qualitative surveys, one-on-one interviews, and the learning experience of the author were used as material for the research.

Based on the research, it was concluded that the adoption of GD as a tool in the design process at Raami may be beneficial. It was also concluded that GD should be used mainly in the early stage of complex projects and to solve problems that can be formulated mathematically. Identifying the type of problems GD can solve and knowing the possibilities, limitations, and when to use GD tools is essential to control the expectations of the designer. The research limitations were time-based. It would have been positive to analyze the experiences of other companies that have already adopted GD. It would have also been interesting to experiment with real architecture projects, but it was impossible due to the thesis schedule and the limitations on handling the tools.

Key words: generative design, design process, architecture, Dynamo, Revit, AI

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ABBREVIATIONS AND TERMS

AEC	Architecture Engineering Construction
AI	Artificial Intelligence
BIM	Building Information Modelling
GA	Genetic Algorithm
GD	Generative Design
GDP	Generative Design Phase
HVAC	Heating, Ventilation, and Air conditioning
MEP	Mechanical, Electrical, and Plumbing
POST-GDP	Post-Generative Design Phase
PRE-GDP	Pre-Generative Design Phase
QDA	Qualitative Data Analysis
ROI	Return On Investment
TPL	Textual Programming Language
VPL	Visual Programming Language
VR	Virtual Reality

1 INTRODUCTION

Artificial Intelligence (AI) holds the capacity to change how we live entirely. Computer algorithms are driving this change by performing complex tasks effectively and smartly. There has been a lot of study and experimentation in AI in Architecture, Engineering, and Construction (AEC), and industries are expecting that eventually, computers can address design problems on their own with less intervention from people (Exxactcorp 2022.) Automation and AI are being adopted and developed at an increasing rate, raising concerns about the potential displacement of many occupations and talents. Still, new technologies should not be taken as a threat but as an opportunity; automation and AI will change how people work, modernize job roles, and increase the effectiveness of human workers (Sharma 2022.)

Among the most popular technologies at the moment, Generative Design (GD) stands out because it brings to the architecture field a significant change in conceptualizing, designing, and building. Even though GD is not a brand-new concept, the increasing complexity in the design of architectural projects, the short deadlines, and the constant pressure on stakeholders make GD an exciting tool for companies to cope with wicked problems.

In this evolutionary context, architecture firms must constantly incorporate new tools to cope with large and complex projects and to stay ahead of their competitors. This thesis discusses the adoption of GD as an aiding tool of the traditional design process. It aims to identify the benefits, challenges, and possible uses of Revit and Dynamo GD tools in complex projects.

1.1 Objectives

The commissioner of this master's thesis is Raami Architects, the company where the author is employed. Raami is a growing architecture firm in Tampere that has gone from a three-person office to a studio of almost 40 architects. With over 20 years of experience, it is one of the most renowned hospital designers in Finland.

Among their projects, there are hospitals, daycare, urban planning, and residential and office building. Since being established in 2000, Raami has kept up with technological improvements, obtaining modern software and equipment for developing their projects. They use Revit, a Building Information Technology (BIM) software, and Virtual Reality (VR) for most of their design projects (Raami Arkkitehdit n.d.)

To avoid obsolescence and remain competitive, architecture companies must adopt emerging technologies. Therefore, at the beginning of 2021, the Raami office conducted a GD training given by Autodesk. In the class, workers needed to solve a given problem by setting aside the design process they use daily and applying a "Generative Design Mindset," a concept explained at the time by Autodesk professionals. The training was a theoretical example of how architects could use GD; experts did not show any demonstration with GD tools. When the training ended, the architects were satisfied and enthusiastic about the new learnings, but still, with many remaining questions in their minds. Later, Raami started to plan the adoption of GD in their office, but soon the topic was cut short because they realized that it was a very ambitious project requiring a lot of research time for its development. The desire of Raami to advance in the field of GD and the motivation of the author to explore GD tools encouraged the choice of the thesis topic.

This thesis aims to determine the benefits and challenges of adopting GD in architectural offices. The objectives of the thesis are: To contemplate the benefits and challenges of using GD, to recognize the most common problems that emerge during the architectural design process, to analyze the impact of GD on the current design process of Raami, to identify the type of projects and tasks that benefit from GD, to determine the resources necessary for the adoption of GD, and to study and experiment with Revit GD tool and Dynamo.

These objectives developed into the main research question: **What are the benefits and challenges of adopting Generative Design at Raami Architects?** Simultaneously, the following four questions derived from the central one:

- What are the most common problems architects face during the design process?
- How does GD impact the current design process of architects?
- What type of projects and tasks could benefit from the use of GD?
- What resources does Raami need to adopt GD?

1.2 Structure of the thesis

This thesis is divided into eight chapters: Introduction, Architectural design process and innovation, Generative Design, Generative Design tools for the AEC industry, Research methodology, Results, Recommendations, and Conclusion and future work.

Chapter 1, INTRODUCTION describes the research topic and its background. It contains relevant information such as case study, objectives, research questions, and structure to help the reader understand the idea of the whole thesis.

Chapter 2, ARCHITECTURAL DESIGN PROCESS AND INNOVATION explains the architectural design process, the most common problems that may arise during the procedure, and the need to innovate the design process due to the constant increment in the complexity of design problems.

Chapter 3, GENERATIVE DESIGN introduces GD as the central subject of the thesis, considering the role of the architect, benefits, challenges, potential uses of the tools, and sustainability.

Chapter 4, GENERATIVE DESIGN TOOLS FOR THE AEC INDUSTRY briefs the evolution of the AEC industry design tools. It expands on the GD tools and Visual Programming Language, explaining the Revit GD tool and Dynamo plug-in from the perspective of the author. It also includes information about the learning and experiments of the author.

Chapter 5, RESEARCH METHODOLOGY explains the methodology and methods used to gather and analyze the necessary data to answer the research questions. The data was collected through interviews, surveys, and literature review.

Chapter 6, RESULTS is the practical analysis of the data where the interview and surveys and exposed and interpreted by the author with the help of the literature and his own learning experience.

Chapter 7, RECOMMENDATIONS Based on the results, the author proposes a preparation framework for Raami that consists of a set of steps to organize and divide the responsibilities among the workers. The author also provides a workflow for anybody using Revit and Dynamo GD tools.

Chapter 8, CONCLUSIONS AND FUTURE WORK exposes the key findings, answers the research questions, sets research limitations, and advice on future research.

2 ARCHITECTURAL DESIGN PROCESS AND INNOVATION

This chapter explains the architectural design process, the most common issues that can emerge during the procedure, and the need to innovate the process of design due to the constant increment in the complexity of the design problems. The first part focuses on the structure of the design process and explains its phases. Next, some of the most common issues that arise during an architectural project are described. The last part cites the key concepts for an effective innovation in the AEC industry.

2.1 Architecture design process

Architecture plays an essential role in human well-being. Architects must contribute to enhancing the life quality of people and improving their living environments by designing sustainable and well-planned spaces. Making a good architectural design is a big challenge, and architects play a critical role in its success. The job of the architects is complex and diverse; they are the designers and the project managers, and they must follow legislation, make decisions, coordinate tasks, and negotiate with partners (Marsault 2018, 9.)

Moreover, architects work in a constantly changing environment, affected by new technologies, environmental problems, growing populations, and socio-economic crises. In this competitive industry, architects are pressured to adapt quickly to short design deadlines, tight budgets, and high technical requirements (Marsault 2018, 9-10.) To cope with these challenges, architects must have a clear and well-structured design process.

The architectural design process describes the steps of development of any construction project, and it is commonly divided into phases to provide the project with the necessary structure. Having a well-structured process leads the architect to define the periods for reviewing the project, organize the design information and tasks, and the billing intervals. Since construction is intricate, expensive, and subject to strict regulations, it is not advised to make changes to the architectural plans once the construction has begun. Therefore, the design process is crucial because it simplifies project management and provides explicit explanations of the design objective. The phases in this process relate to a specific range of problems, methods, documents, and participants and provide transparent and accurate information to lower risks that might cause expensive and unanticipated issues (Landau 2022, Shoshkes 1990, 10.) Considering sustainability during the design process and in the decision-making of each phase is crucial since those choices will impact the performance of the building over its remaining lifecycle (Feria & Amado 2019).

This thesis focuses mainly on complex projects, such as hospitals, that are the principal projects at Raami. According to Bengts (2020, 30), this type of project has the same structure but more complex challenges *at each phase*. Usually, in hospital projects, the phases need to be redesigned, and putting greater focus on the early stage is essential because it is where the direction of the entire service system is established. The design process of a typical architectural project usually involves the following phases (Figure 1):

FIGURE 1. Design process phases

Pre-Concept (Tarveselvitys, Hankesuunnittelu, and Suunnittelu): In this phase, the design team gathers information, starts planning the project, and produces some design options. This phase is divided into three stages:

- *Capture and preparation of the project (Tarveselvitys*) is when the workers must ensure they have thoroughly examined the project requirements, accuracy in the price, and potential risks. They also secure gathering sufficient information and counting on enough professionals for the team, including experts in the subject.
- *Start of the design process (Hankesuunnittelu),* when the design process starts, the architect needs to review the schedule of the project and ensure that the project and customer goals are aligned.

- *Design decision (Suunnittelun valmistelu)* is where the planning starts and must be ready before the beginning of the next phase. After completing this stage, the decision to start the project is a fact (Ekvall 2019, 9.)

Conceptual Design (Ehdotussuunnittelu): The design team ensures that they have gathered all the necessary information from the phase of pre-concept and checks if the data is accurate. They also list potential tasks and participate in the first design ideas (Ekvall 2019, 10-11.)

Schematic Design (Yleissuunnittelu): The primary design idea evolves into a more realistic design in this phase. It is also necessary to check the list of tasks and all the information gathered from the previous phases to share it with other potential designers. At this point, it is necessary to assess the security risks associated with the building and to confirm the resources for the development of the following phases (Ekvall 2019, 12-13.)

Detailed Design (Rakennuslupatehtävät and Toteutussuunnittelu): In this phase, the Schematic design evolves into more detailed drawings necessary for the following phases. This phase contains two stages:

- *Construction permit (Rakennuslupatehtävät)* is where all the documentation required for applying for the construction permit needs to be ready before the stage finishes. The documents are sent to be checked by the authorities.
- *Technical Design* (Toteutussuunnittelu) where the current design goes further and the architect prepares the required drawings and documents for the construction phase (Ekvall 2019, 14-15.)

Construction (Rakentamisen valmistelu and Rakentaminen): In this phase, the contractor follows the building schedule and the contract to organize his tasks. This phase has four stages:

- *Preparation of construction (Rakentamisen valmistelu)* aims *to* organize the construction, set the construction tasks, and finish the contract agreements. The outcome of the stage offers a construction decision and selects a potential contractor. At this point, the design team needs to ensure the drawings are correct and that the goal of the tendering offer is aligned with the one of the building projects.

- *Construction (Rakentaminen)* is a stage to ensure that the execution follows the contract; the design manager monitors the construction process. Additionally, they guarantee that the finished work meets the predetermined objectives. The design manager also carries out the supervision and inquiry duties asked by the authorities and the ones accord with the client.
- *Hand-over and closeout (Käyttöönotto)* is where the building contract is completed in its entirety. The contractor must fix any errors, and the general contractor must produce or collect the definitive certificates.
- *Warranty (Takuuaika)*, when the building is ready it begins the defects liability period, where the contractor must report and correct any error found on it (Ekvall 2019, 16-17.)

2.2 Design process problems

Design problems are part of the design process; there are easy ones that do not require a significant effort from the designer to solve, and wicked ones that need more attention. According to Rittle & Webber (1973, 160-167), most planning problems are wicked problems since they are difficult to understand and solve due to their conflicting objectives and social context. They are also difficult to define because fully understanding and finding potential solutions is an interconnected process. Wicked problems have specific characteristics. They do not have a clear solution; instead, the designer chooses the most suitable resolution he can come up with within the given time and budget. They have no correct or incorrect answers, there is no way to test the potential outcomes and no possibility of learning by trial and error. These problems are unique and might be regarded as a symptom of a more significant issue.

Designing a complex building is a process that involves many actors, a specific budget, tight deadlines, goals, and constraints, and no matter the type of project a designer is working on, most of them face the same challenges. This thesis looks at the issues that can emerge during the design process of complex architectural projects.

- **Project scope, schedule and budget** is a common struggle for designers. Throughout a project, the architect must follow strict goals, tight deadlines, and budgets, with the customer frequently in a hurry and given limited time to work on every possible solution and appropriate decision-making (Souza 2020). Scope, schedules, and budgets are intrinsically linked components, and it is practically difficult to modify one without altering the other two. However, solid project management software allows designers to consider these three project variables and make it easier to convert project budgets into corporate budgets in the short run (Denny 2016).
- **Communication** among designers and stakeholders is essential. In every project, clients play an integral role in the design process. However, regardless of the type or size of the project, the best clients are those who have a good understanding of the complexities of the design process and provide clear direction to the designer at the beginning of a project (Shoshkes 1990, 12). Frequently, the customer needs clarification on the desired outcome, or they may be ambiguous or unable to put their ideas into words (Easy Render n.d.). According to Brown (2001), simple failures to understand the other party at a verbal level stand alongside the baggage of agendas that virtually demands misunderstanding as a commercial negotiating tool. The leading designer must guarantee that the client completely comprehends the concepts and agrees that they satisfy their objectives.
- **Design goals and objective** are defined at the beginning of any architectural project. The design goals primarily correspond to the overall project aspirations, and the project objectives are the actions that support and help to achieve them. If goals and objectives are not well defined, the project participants will not know the direction of the project. Therefore, the role of the architect is to plan the best strategy to help set clear and concise goals (Pro Crew Software 2022.) In most projects, the design goals can differ between architects, clients, communities, and the construction

industry, even though it is possible to find commonalities to balance the situation (Wacht 2017).

- **Space layout** is one of the most significant duties of architects when designing a building. These floor plans are drawings that facilitate the understanding of the spaces of a building and collaborate to locate rooms and areas. They also contain rooms name, sizes, and limitations such as walls and floor. Space planning is a complex process with no precise resolution method. Meeting all the requirements that clients have is almost impossible (Dirk & Lobos 2010, 137.)
- **Sustainability** in architecture alludes to the utilization of ecologically friendly techniques and supplies during the construction of a building. Global warming, like public health and education crises, are wicked problems because there is no specific method to face them, and they are impossible to solve completely. The discussions about climate change, the local factors that dictate the consequences of climatic fluctuations, and the capacity of people to provide potential solutions require approaching climate change with a comprehensive and collaborative mindset looking for solutions that will last and benefit the future (Stony Brook University N.d.). Without help from architecture, it would be impossible to tackle the most pressing issues of the moment, such as guaranteeing economic vitality while assuring the equitable progress of societies and preserving the habitability of the planet (Finnish Government 2022, 9).

2.3 Innovation in the design process

Designing involves making decisions, and the secret to the success of a project is found in the design process and the end product (Shoshkes 1990, 8). According to Villagi & Nagy (2017, 3-4), architects usually base their decisions on heuristics, which means using old experiences to solve new problems. However, projects in the AEC industry are growing more extensive and complicated than in past decades, which calls for new organizational and technological abilities to help professionals to face them (Chihib et al. 2019). Therefore, innovation is a crucial success component for any company to accomplish growth and outpass its competitors.

Innovation is how business owners introduce changes as an opportunity to do a different business or introduce new products or services to stay ahead of the competitors. It is a discipline that is possible to learn and practice. Entrepreneurs must constantly search for sources for innovation and be aware of the symptoms that signal chances for good innovation. The key is to understand and implement the principles of effective innovation (Drucker 1985, 20.) This type of transformation may help firms gain better revenues, a higher brand value, and competitive differentiation. Even though the intrinsic novelty and unpredictable nature of genuine innovation conflict with the established cultures and procedures of many businesses, which makes innovation highly challenging for a company to achieve. Anyhow, organizations could achieve real innovation by mixing three critical components: toolsets, skillsets, and mindset. Depending on the working area and profession, **toolset, skillset, and mindset** may vary (Autodesk 2017, 1-3.):

Toolset: It is the equipment that any company possess to produce the goods, services, and experiences of their clients. The three essential tools are capture, cloud computing power, and manufacture. *Capture* means any tool dedicated to capturing the reality that allows bringing the existing world into a computable environment, such as drones or 3D models. *Cloud computing power* will enable businesses to incorporate cutting-edge computing in their designs. *Manufacture* means materializing the ideas the designers have in their minds through different methods and with the help of the necessary machinery (Autodesk 2017, 3-6.)

Skillset: These are the meta-skills required to innovate (Autodesk 2017, 1). Gathering the necessary skillset generally requires time, which will be spent training workers and, if necessary, hiring others who already have the desired skills. The required skillset are insight, design, and collaboration. *Insight* involves knowing for whom designers are working and why; it entails understanding the perspectives and objectives of their clients, what they are attempting to accomplish, and why they are doing it so that the outcome is expected. *Design* frequently makes the difference between an idea that fail and one that succeeds. Design tools are used to create models and prototypes and to evaluate and enhance performance. They are utilized to experiment with novel techniques and materials. *Collaboration*, as projects get more complex, the skills and expertise needed to manage the problems are not likely to be found in a single individual, so good cooperation can bring together the best combination of the people required to address the difficulties (Autodesk 2017, 8-14.)

Mindset: These are the varied mental models an organization has, ambient assumptions, and cultural beliefs (Autodesk 2017, 3). The most challenging part of innovation is to develop and keep the appropriate mental model. The innovation mindset needs separation, experimentation, and fascination. *Separation* is the distinction from the competition. If a company can successfully differentiate from competitors, it may enjoy substantial benefits such as higher pricing and margins, more market share, and significant brand value. There are two types of separation; sustaining innovation is about staying current, whereas breakthrough innovation is about breaking new ground. *Experimenting* is when a company attempts to accomplish anything completely novel, it is impossible to foresee what will occur, implying that individuals must try, fail, and try again to determine what is effective. *Fascinating* means getting out of the comfort zone and doing things that fascinate the clients of a company, which can be achieved with workers who are fascinated by their work (Autodesk 2017, 15-21.)

More about this topic is found in Section 3.2, Innovating with Generative Design, which describes the Toolset, Skillset and Mindset needed when adopting GD.

3 GENERATIVE DESIGN

This chapter introduces Generative Design, the main topic of the thesis. It explains the role of the architect in adopting GD, the benefits, challenges, and potential uses of this innovation, and how it impacts the sustainability of construction. The first part includes a brief history of GD, an explanation of the principal concept, and a definition of the GD phases. Next, it describes the toolset, skillset, and mindset necessary for Raami to face the adoption of GD. Later it expounds on the benefits, challenges, and possible uses of GD tools. Lastly, it explains how GD can impact the sustainability of a project.

3.1 What is Generative Design?

Among the most popular technologies of the moment, Generative Design (GD) stands out because it brings to the architecture field a significant change in conceptualizing, designing, and building. GD is not a brand-new concept; it originated around 1960 and has been used in the AEC industry for about 20 years (Follet & Knemeyer 2020.) New programming languages and tools started to appear in the late 1990s, and designers could now have aiding software. Later simplified version of GD emerged, but at that moment, its outcomes needed a lot of processing and analysis from the designer. By 2010, the capabilities of GD had been significantly developed, with considerably less need for human intervention (Li 2019.)

Generative Design is a revolutionary design process that allows architects to co-design with computers, discover unexpected, innovative ideas, and explore trade-offs between high-quality designs, project goals, and constraints (Villaggi et al. 2017, 13). According to Moret (2022), GD does not solve a whole project; instead, it provides tools to assist the designer in solving a specific problem within a project. GD allows the designer to analyze more solutions to a particular issue than a traditional process. In the conventional design method, developing few outcomes can take a considerable time; using a computer algorithm makes it possible to get tens to thousands of results in a short time (Moret 2022).

Any successful GD task begins with clear and exact comprehension of the design issue to solve (Matterlab n.d.). According to Villaggi & Nagy (2017, 5) the GD process is commonly divided into three phases (Figure 2): Firstly, the Pre-Generative Design Phase (PRE-GDP), where the designer gathers data, sets the goals of the project, defines constraints and requirements, and develops an evaluation criteria. Secondly, the Generative Design Phase (GDP), where the algorithm produces a set of solutions, evaluates them, and makes them evolve by creating a new set; each time this process is repeated, it is possible to find solutions closer to the goals already set by the designer. Finally, the Post-Generative Design Phase (POST-GDP) is where the designer chooses a design solution, integrates it into the project, and manually refines it.

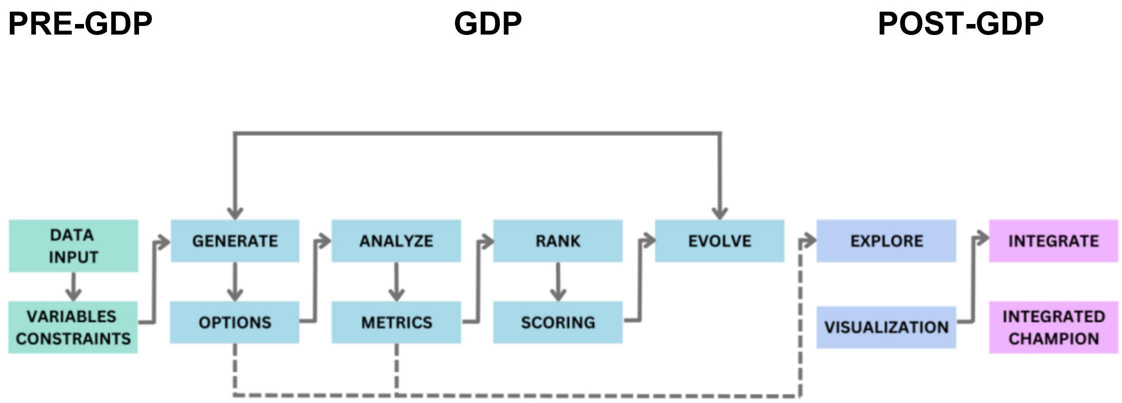

FIGURE 2. Generative Design workflow (Vermeulen 2020, modified)

In the PRE-GDP phase, as shown in Figure 3, the designer collects data from stakeholders and defines the task goals and constraints. The data will be input into the software as variables, constants, or other accepted formats such as unit inputs or files (Autodesk 2021.) **Variables** are flexible values that can vary when generating design solutions, and they can be adjusted to create different results (Graham 2020.) **Constants** are fixed values that remain the same regardless of the outcome (Autodesk 2021.) **Goals** are the project objectives that the designer wants to accomplish and enable the algorithm to evaluate or rank the overall quality of each solution produced (Graham 2020). The goals need to be precise, quantifiable, and measurable to enable the algorithm to evaluate the design options (Zesk 2019). When defining goals, the designer can decide whether to maximize or minimize each. Usually, there may be a contradiction between goals, but this is the perfect scenario for the optimization method to solve. **Constraints** are the limitations the solution must meet and prevent the algorithm from testing undesirable scenarios. If the study does not have constraints, the solutions may not be realistic (Autodesk 2021.)

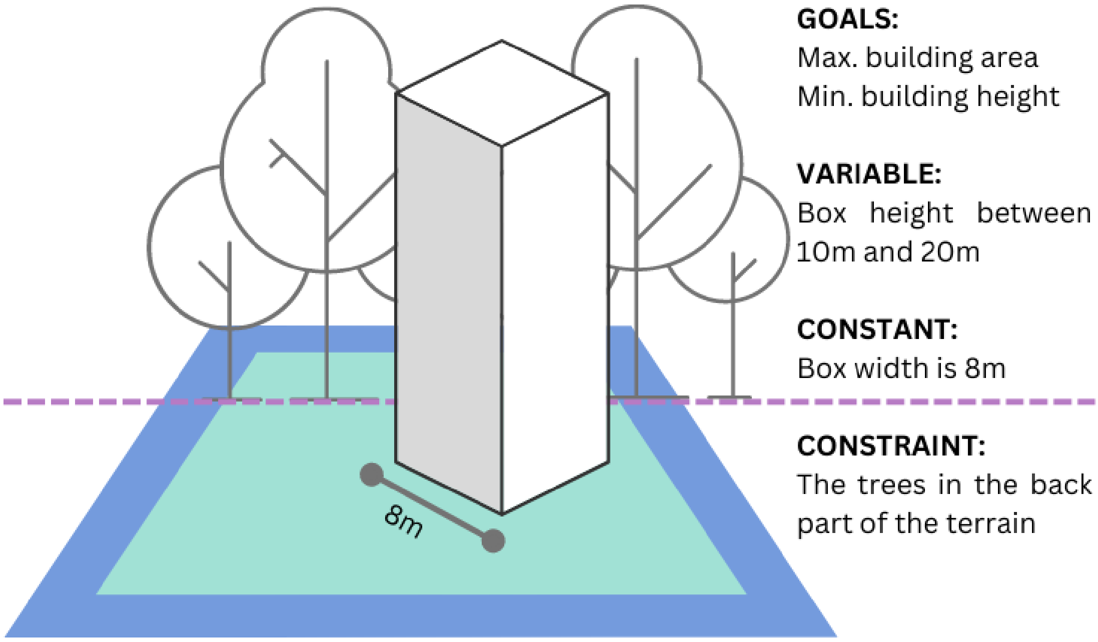

FIGURE 3. Example of a task Goals, Variables, Constants, and Constraints in the PRE-GDP

In the GDP phase, as shown in Figure 4, the computer does the work, and the results depend on the analysis method that the designer selects to process the algorithm. This thesis focuses on the use of the optimization method. The optimization method starts by **generating**, where the system uses the inputs previously set by the designer, and by running the algorithm, the computer generates the first population of design options. The next step is to **analyze** where the population of designs created in the preceding stage is now measured based on how effectively they meet the goals set by the designer. Then it is time to **rank**, where the alternatives are sorted or rated based on the previous analysis results. Finally, the last step is to **evolve**, where the algorithm will utilize the ranking of design alternatives, combine them and alter factors to determine which design options should develop further (Vermeulen 2020.) The generative design algorithm may explore a wide range of design possibilities over time, refining them to achieve a design objective (Graham 2020).

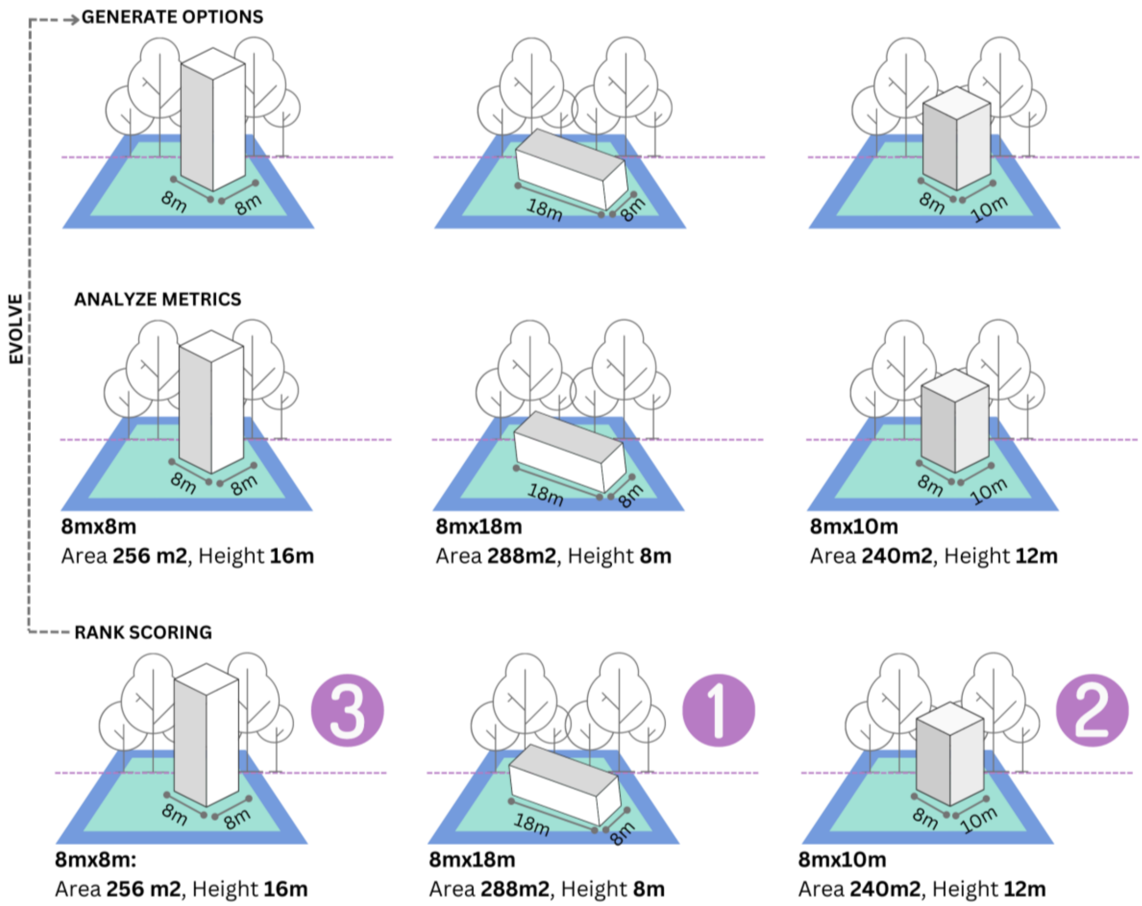

FIGURE 4.Example of Generating, Analyzing, Ranking and Evolving process in the GDP

In the POST-GD phase, the designer uses the navigation tools to explore the space and select the option more aligned with the objectives of the project. Then, the designer can integrate the solution into the project and manually refine it (Villaggi & Nagy 2017, 11.)

More about the GD phases is found in Section 4.2.1 Revit Generative Design tool and 4.3.1 Dynamo for Revit, where the process mentioned previously is explained from the GD tools perspective.

3.2 Innovating with Generative Design

Innovation needs a lot of work, and true breakthrough innovation necessitates going beyond conventional wisdom and actively confronting it. It takes character and bravery of conviction to achieve this since it is a challenging task (Autodesk 2017, 24.) In architecture firms, innovation can be introducing new technology such as Generative Design. When adopting GD, the architect needs a specific toolset, to have some skills and learn new ones, and changes in the way they think about architectural problems, meaning changing their mindset. Therefore, the toolset, skillset, and mindset that make an architect transition from a traditional designer to a Generative Designer are mentioned below.

The **toolset** required for adopting GD is a Generative Design software, a visual programming plug-in, and cloud computing power.

The **skillset** required for a Generative Designer is: To be an architect or have a related design degree, excellent design abilities, visualization abilities such as drawing in two dimensions, 3D modeling and rendering, good communication abilities, knowledge of Visual Programming Language (VPL), and a basic or intermediate level in Textual Programming Language (TPL) is a plus (Matterlab n.d.) It also requires them to learn and understand the GD software he uses.

The **mindset** is the most critical and challenging aspect in transitioning from a Traditional Designer to a Generative Designer. The mindset evolution happens by shifting how designers think about a design problem and adapting their design process to the new design tools. Defining the new responsibilities of the designers is the most critical action for the success of the GD adoption. Some of the responsibilities of a Generative Designer are (Matterlab n.d.):

- **Identifying possible GD problems:** The designer should consider specific problem characteristics that make them ideal for using GD. When checking the problem aspects, the designer should consider: Ensuring that the issue is relevant for the company size, framing issues to allow for reuse in many projects, and ensuring that the GD team can handle the complexity of the problem. The identification also requires that the designer fully understands the problem and can formulate it mathematically; this means that, for example, he can express the goals in numbers.

- **Developing a workflow:** Creating a workflow deals with the fundamentals and practical aspects of GD. The designer would develop the actual process and the relationships between variables, outcomes, and assessment criteria. Therefore, he needs VPL skills to create workflows within that environment.
- **Evaluation:** For evaluating, someone outside the GD team would be a better choice because they can be more impartial in evaluating how valuable, relevant, and efficient the GD workflows and scripts are.
- **Other considerations:** When architects introduce GD in their design process, they should consider some things to avoid getting overwhelmed. Before tackling more significant and complex issues, start with easier and smaller ones. Try to divide complex problems into simpler and more general ones to reuse the same workflow later in other projects. Set an expected duration and budget for each problem you want to tackle; this helps determine which issues will yield the greatest return on investment (ROI) as well as those worth solving first. Make sure that people understand what generative design is for and how it may assist; it is crucial to control expectations and know its limitations while discussing its possibilities. The problems must be well defined; if the inputs of the study are limited, the tool will not be able to give a diversity of outcomes. Lastly, the designer must have precise goals to assess and a strategic way to determine which design solution is good.

3.3 Benefits and challenges

The literature ponders the benefits of GD in the AEC industry. Despite being increasingly common in architecture, GD has advantages and disadvantages (Infurnia 2020). Knowing the limitations of the GD tools brings reality to the expectations of the designer. GD tools may be used for typical design challenges with no unique obvious answer; these types of wicked problems usually have several solutions, difficult interconnections, and contradicting objectives. On the other hand, GD tools should not be used to solve simple problems as it would be

a waste of time and effort (Matterlab n.d.) Using GD can give more control over the project because it forces the designer to think about the problem from a new perspective. In this process, instead of solving the given problem, the architect manipulates the system that will solve the issue for him by adjusting objectives, variables, and constraints (Moret 2022).
Generative Design can also increase the number of design iterations (outcomes) and allow the designer to explore them and select the best; accessing more designs supported with analytical data makes it possible for the designer to make optimal design decisions (Slowey 2020.) Saving time can be another significant benefit of incorporating GD in the workflow; the iterations that the computer produces are done quickly, something that would be impossible for a human being (Stainer 2021). Simultaneously, reducing time in making alternatives can lower costs and free up time for designers to focus on helping the client in the process of decision-making (Slowey 2020). From the point of view of improving the long-term sustainability of the building, GD can be significantly helpful; the tool can help the designer make more sustainable decisions regarding building location, lighting, sunlight, and waste reduction (Moret 2022). According to Slowey (2020) architects can work straightly with clients and make them part of adjusting variables and examining outcomes, which would help improve communication. These tools can also help to understand and define the project goals and enhance the creativity of the architect.

However, the use of GD can also have its drawbacks. It is easy to demonstrate that generative design is feasible, but it is far more challenging to demonstrate its value; shifting from the real world to the solution space is extremely difficult (Davis 2020, Zesk 2019). Davis (2020) states that GD will fail because of technical and human grounds. In his article, Davis lists six reasons for said failure; It is usually forgotten that when using GD, the designer is also responsible for developing the generative script from scratch, an arduous task that can be costly and time-consuming. Quantity does not mean quality; when getting hundreds of outcomes, just a few are likely good. Filtering, comparing, and selecting the best solutions is tedious. The metrics used in GD to rank the iterations are usually not the most relevant to a project. The design process is not linear; the designer usually goes back and forth to get a result; instead, GD is a linear process where the scripts do not have such flexibility to face significant changes. Software companies in other working fields than AEC are not using GD, meaning there is no clear future perspective for the technology.

In different articles, Ramanauskas (2020) and Allen (2020) agreed that even though the paper of Davis has a logical foundation, GD is a relatively new and growing tool in the AEC industry intended to co-work with the designer during the design process. According to Slowey (2020), the projects that gain more from the use of GD are those that have similarities from project to project because to invest in developing an algorithm; the problem must be significant and shared in several projects.

3.4 Potential uses

GD has a wide range of uses that focuses mainly on the Pre-Concept phase of the design process when things are not well defined and can provide the most significant value. Decision-making at that point of the project is critical because any decision will positively or negatively affect the rest of the design process and even after the building is constructed.

According to Moret (2022), GD can be used to improve building sustainability in the following tasks: Optimize the pavement placement to generate less waste, design a building mass according to solar incidence and site surroundings, place a ready design idea on the terrain according to the better orientation and sunlight and distribute lights in a room optimally to reduce the number of light fixtures and increase the amount of light. In their article, Schwartz et al. (2021, 404) added other possible uses, such as: Reducing the total cost of structural components and optimizing the heating, ventilation, and air conditioning (HVAC) systems by reducing the usage of energy and life cycle costs associated with heating and increasing overall indoor comfort, find optimal building geometry to lower their costs and environmental implications, reduce the life cycle costs and environmental effects of new or renovation projects, optimize layouts to cut costs, improve energy and lighting effectiveness, improve the visual appeal and structural integrity. Finally, in a research done through the GD Dynamo forum (2022), designers claim to have used GD for distribution line routing, design of process plants, neighborhood design, parking lot layout, solar and offshore wind farms layout, profiles of roads, laboratory buildings, water treatment plants, airport runways, equipment layout, interior design, and building facades. It should be noted that the creation of scripts for the uses mentioned above varies in difficulty, some of which can be highly complex.

Some of the already mentioned uses have been implemented in real projects such as Project Rediscover, which utilizes GD to design the Autodesk office in Toronto. This project used GD to define the office floorplan layout. It included numerous restrictions such as the room size, the number of facilities, shared spaces, and set placements for mechanical areas. The goals set by the designers were a mix of quantitative and qualitative components of human life. The GD procedure lets the designer investigate varied designs (Walmsley 2017,4.)

3.5 Generative Design and sustainability

Sustainable construction is spreading worldwide, mainly since it was adopted as a compliance standard for constructing new buildings in significant economies all around the world (Schwartz, Raslan, Korolija & Mumovic 2021, 401). Building environmental performance is improved due to a sophisticated design process that incorporates passive and active design methods and considers several building factors, such as the building shape, geometry characteristics, and working systems (Schwartz et al. 2021, 402). Increasing the sustainability performance of a building is still tricky because designers tend to have short design deadlines, tight budgets, and persistent demands from the stakeholders. The pressure for fast and good results can lead to costly errors throughout the project, such as: Raising the budget, lengthening the design and construction times, and negatively impacting the long-term sustainability of the building.

In recent years, interest in computer-based design research has grown, and automating complex repetitive processes begins to be based on computational capacity. Modern computational methods like GD significantly impact the process and results of architectural design. Automated computational design is predicted to grow as computers become more affordable and powerful and visual programming tools are more often adopted (Schwartz et al. 2021, 402.) GD is not just part of the design process; it is also a new possibility for companies to achieve sustainability goals. In complex projects, there are usually many constrain and requirements, and most of the time they have overlapping interests. Generative Design uses those constraints and needs to get plenty of solutions that match the goals set by the designer; this translates to more sustainable possible solutions (Haley 2022.)

4 GENERATIVE DESIGN TOOLS FOR THE AEC INDUSTRY

This chapter briefly introduces the evolution of design software and then delves into GD and Visual Programming Language (VPL) tools. It shortly describes tools such as CAD and BIM, and then it expands into Revit GD and Dynamo, considering the learnings and experiments of the author.

4.1 Evolution of design software

The AEC industry uses computational tools to understand the project from different perspectives such as design, structure, energy efficiency, possible costs, and construction. Old tools used for this purpose usually needed manual work that, in the long run, ended with outdated data, costly errors, and many hours of ineffective work (Cohn 2007,3.) Naturally, it was not uncommon that the constructed building was far away from the initial concept designed by the architect (Shah n.d.).

In 1960, CAD was introduced and was a revolutionary software that impacted many industries, including architecture. Its main benefit was the time saved from continuously hand-drawing in the different phases of the design process. This technology remained an aiding tool for many years, rarely employed in the conception of the design, but finally, it got the opportunity to displace the manual sketches. At that moment, CAD had invaded design academies and became one more subject like many others. (Shah n.d.). The transition to CAD led to a more efficient and collaborative design process, improved technical documentation, and increased the urge for more significant buildings as their creation was easier (Barreto 2016.)

Even though CAD was a great innovation, in the last years, CAD has been swiftly surpassed by BIM, which provides model analysis and visualization in real-time that is more suitable for the AEC industry (Hood 2018.) Therefore, many companies introduced Building Information Modeling (BIM) for creating and managing their projects. BIM is a collaborative working methodology that gathers extensive project data in a single model. In addition to 2D and 3D drawings, it handles information such as building materials, costs, and performance. It also produces the necessary documentation and can help make essential design decisions (Cohn 2007,3.) Many software emerged around BIM technology, such as Revit, Archicad, Plannerly, and Revizto, among others.

Design problems are becoming more complex, and to handle that difficulty and provide people with more creative solutions, companies such as Raami need to adopt new technologies to complement BIM software. The need arises from the short design deadlines, tight budgets, persistent demands of the stakeholders, and awareness for long-term sustainability. The pressure for fast and good results, added to the short time to solve problems efficiently, can lead to costly errors. According to Udeze (2021), recent years have seen the rise of Artificial Intelligence (AI), which has created new opportunities for iterating the design process while utilizing technology. Algorithms are increasingly capable of self-solving complex issues rather than merely simplifying routine chores. Adopting GD as a supporting tool within the design process could help to cope with some design issues.

Most of the AEC software suppliers provide some type of GD. Some are integrated into the software, but most are plug-ins that must be purchased separately. Even though this thesis focuses mainly on the Revit GD tool, here are some other GD options:

- TestFit is a software developed for architects. It does not generate multiple outcomes; instead, it produces one choice based on the designer-provided parameters, which can then be edited with manual tools. The software does not require creating scripts; it helps the worker reduce time in their first concept proposal and allows them to export the idea to BIM software (Karthick 2021.)
- Digital Blue Foam is a software developed for architects, among others, and used mainly in the Pre-Concept phase of a project. The benefit of this tool over others is its commitment to sustainability across the board. The software also enables real-time collaboration with other stakeholders over a single model, no coding skills are necessary, and it allows integration with other BIM software (Karthick 2021.)

- Delve is a software developed for architects and other industries. Usually, it is mainly used in the Pre-Concept phase, but it could also be applied at any project stage. It gives the user design options while considering variables/factors under four main categories: Program, Design objectives, life quality, and financial result (Karthick 2021.)
- Rhino and Grasshopper is a popular GD tool within the AEC industry. It is easy to use and quite flexible, allowing designers to create iterative designs (Nagy 2017.)
- Revit Generative Design tool and Dynamo enable users to examine, assess, and design by setting design goals and producing outcomes that match the project objectives. This tool requires Dynamo GD scripts to work. (Matterlab n.d.).

This thesis focuses on Revit and Dynamo as GD tools since they are the primary design software used at Raami Architects.

4.1.1 Revit Generative Design tool

The first time Autodesk introduced some GD tools for architecture was in 2016 with Project Fractal, allowing users to automate design options. A few years later, in 2018, Fractal evolved to Project Refinery Beta; the difference between them is that in the new version, the designer could set goals and achieve them by optimizing. Since the release of Revit Architecture 2021, the old Project Refinery has become Generative Design in Revit. Now, the tool does not require a separate installation and is integrated into the Revit interface to access from the Manage tab directly (Fronte Boa 2020.) This research uses the GD tool from Revit Architecture 2023.

The GD tool has different analytic methods to process the scripts and generate solutions (Matterlab n.d.). There exist four methods:Randomize, Space Evenly, Like This, and Optimize. **Randomize** is a simple method that does not need to set goals. This method uses random values in the variables and constraints to generate arbitrary designs within those parameters. This study is adequate when exploring a wide range of potential solutions without having a definite goal

(Graham 2020). **Space Evenly** method does not need to set goals. This method uses variables and constraints and generates every possible solution testing against each other the values assigned to the inputs. This study is also adequate when exploring a wide range of potential solutions without having a definite goal (Graham 2020). **Like This** method does not need to set goals, and it is mainly used to refine an already accepted design solution. In this method, it is necessary to define the variables the algorithm can modify when processing. The outcomes will be generated by adjusting the variables within 20% under or above the values already set. This method works best when knowing that the solution is nearing the final design outcome (Graham 2020). **Optimize** is the most complex method and enables the designer to produce and develop a wide range of design alternatives to improve the results based on one or more objective design goals. This thesis focuses mainly on the optimization method.

As explained in Section 3.1, the GD process is divided into three phases: Pre-Generative Design Phase (Pre-GDP), Generative Design Phase (GDP), and Post-Generative Design Phase (Post-GDP). These phases can also be described through the GD tool. Next, the author explains the phases of the GD when applied to the Revit GD tool based on her own learning experience.

The Revit GD tool is found under the Manage tab, and it contains two buttons; Create Study and Explore Outcomes (Figure 5)

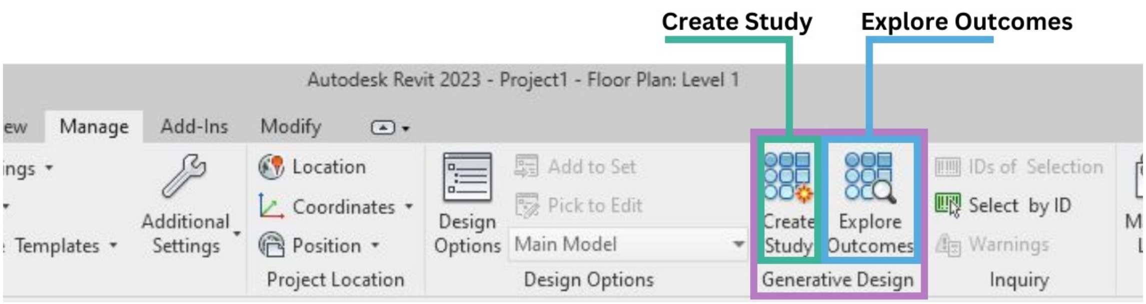

FIGURE 5. Generative Design in Manage tab

Pre-GDP process starts by creating a study (Figure 6). By default, Revit has five basic study types that serve different purposes; Grid Object Placement, Maximize Windows Views, Randomize Object Placement, Stepped Grid Object Placement, and Three Box Massing. The content may look different in each study type. Common to all the studies, the designer can define the study name and an analysis method and check for issues. In the Optimize analytic method, the designer can input goals, constraints, variables, and constants. Once all the values are set is time to press Generate.

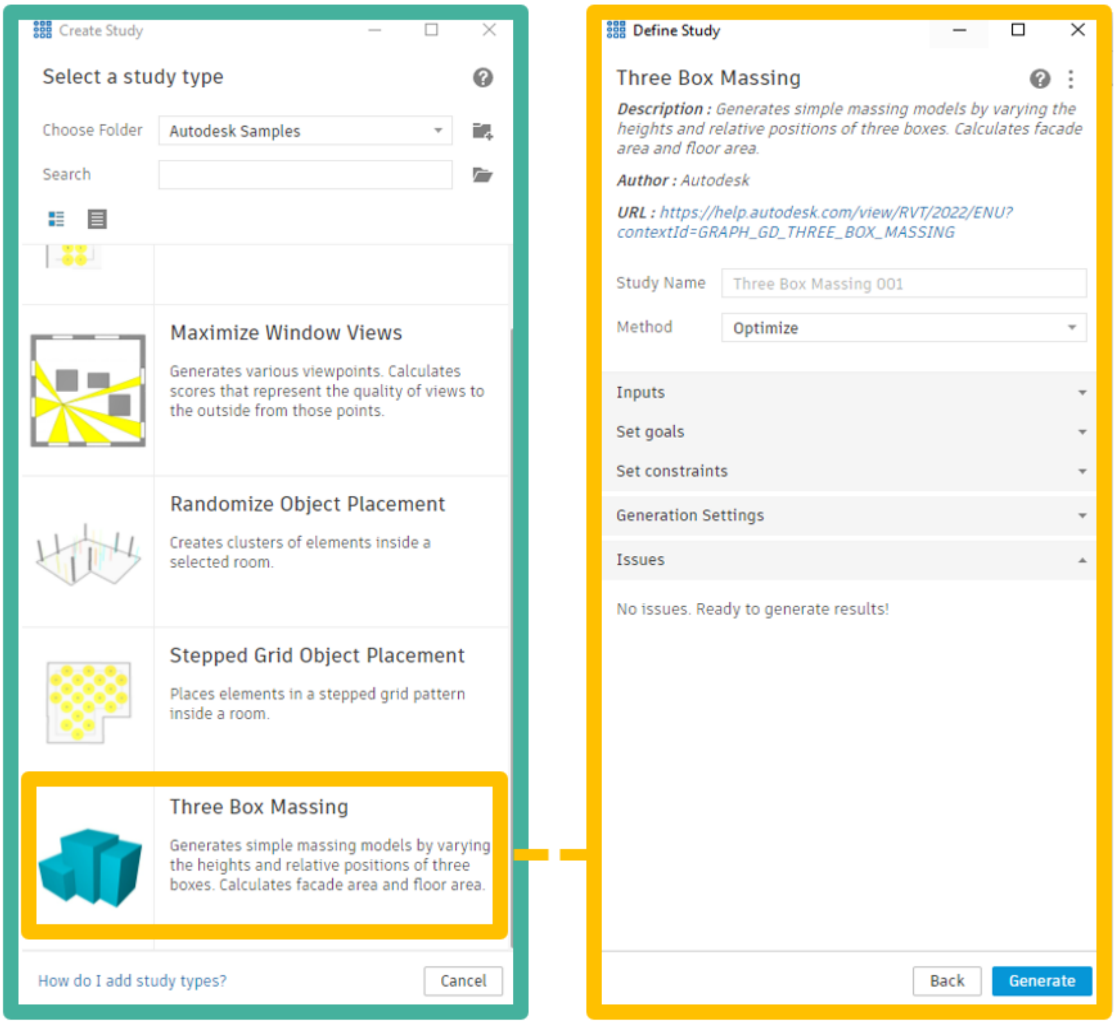

FIGURE 6. Create Study and Three Box Massing Study example

The GDP process begins by pressing the Generate button, which runs the study through the chosen method and creates the design solutions. The computer carries out this phase while the designer waits for the results.

Post-GDP is when the design solutions are ready. They appear in the Explore Outcomes window, which can also be accessed from the Manage tab. This is a navigation space that helps the designer filter and selects the best design solution. On the left side of the exploration window, there is a list with all the studies previously created, and over that list, there is a search bar where the designer can filter the list by study type. In the middle section, the individual solutions are shown in 3D, but it is also possible to change the visualization mode to a list of results. Under the solutions, there is a chart of outcomes that allows the designer to make an analysis and compare the options; the graphic can be changed according to personal needs. On the right side, there are the values and details of the currently selected solution. Finally, there is a button called **Create Revit Elements** that allows the creation of the chosen option directly to Revit (Figure 7).

FIGURE 7. Example of the Three Box Massing Study Explore Outcomes window

4.2 Visual Programming Language

Using BIM in the design process allows designers to validate the information of the model in real-time, which is beneficial for identifying and evaluating trade-offs more efficiently (Zhang et al. 2016). This contributes to the prediction of construction performance and helps to make decisions during the different phases. Technological advances have allowed the automation of some of the tasks involved in the design process by using VPL (Mota Veras de Carvalho et al. 2021.)

Figure 8 shows that VPL is an image-based language defined by visual objects composed of nodes and connectors (Mota Veras de Carvalho et al. 2021). Using VPL tools can bring many benefits: It provides the designer with programming capabilities without requiring learning any specific coding language. It improves the productivity of the workers and the overall project time by allowing them to make modifications in real-time. It helps designers access data by importing and exporting it from BIM to Excel and another way around. It enables the automation of repetitive and tedious tasks by creating different types of scripts. And finally, it allows architects to create multiple design iterations through the use of scripts that are essential for some GD tools to work (Verma 2022.) According to Verma (2022), the three most used VPL tools in the AEC industry are:

- *Grasshopper* is a quite popular VPL plug-in. It is a reasonably mature program that has been available for many years and is compatible with Rhino software.
- *Param-O* is a built-in tool that can be used within the Archicad interface and does not require writing a script.
- *Dynamo* is a VPL tool that allows architects to create scripts, and it is used with Revit.

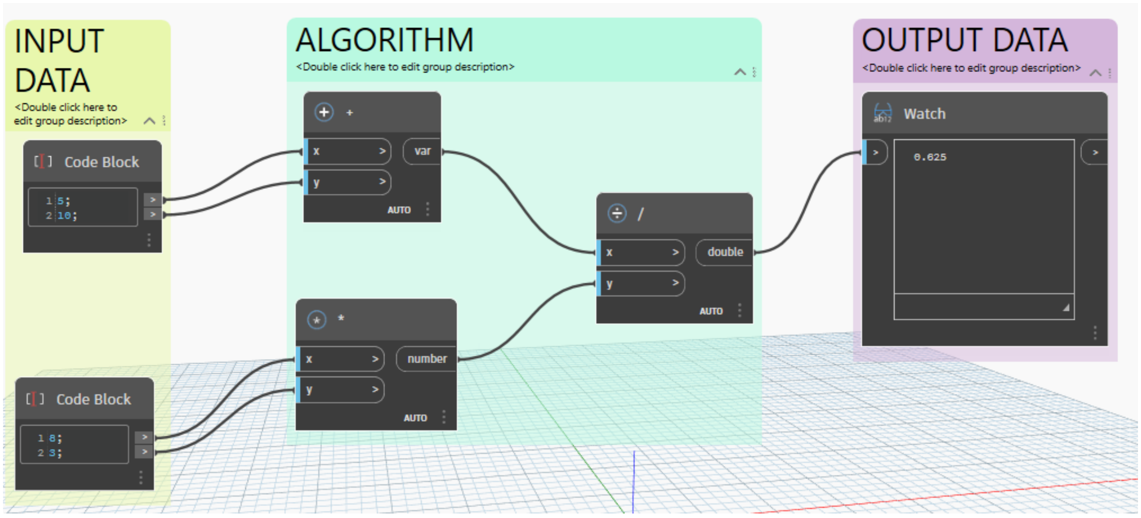

FIGURE 8. Example of a VPL script structure using Dynamo

4.2.1 Dynamo for Revit

Dynamo is an open-source visual programming environment for Revit that requires no previous programming knowledge. Dynamo allows the user to design visual logic that manipulates how data is handled in Revit. (Dunn 2022). Many things can be done with Dynamo and Revit, such as model, automating repetitive tasks, minimizing errors, exporting data to a spreadsheet, etc. (Arch Daily 2020).

Designing is about the relationship between shapes, colors, and textures. To design, the designer usually starts with a concept (input), follows a series of steps (algorithm), and finally gets the result (output) without realizing he is working as algorithms do. VPL works in this same way, but without the need to write codes; instead, the user connects prefabricated nodes to create an algorithm (Modelab n.d.) An algorithm can be defined as "A set of instructions that typically help to solve a problem" (Matterlab n.d.) (Figure 9)

FIGURE 9. Input, algorithm, output (Modelab n.d., modified)

Dynamo GD scripts follow the same logic shown in Figure 8 but are way more complex than when automating tasks with Dynamo. As described in Section 4.2.1, the Revit GD tool comes with a few studies by default, but it is necessary to create scripts from scratch for more complex issues. All the studies are defined with a Dynamo script; without Dynamo, the GD tool would not exist. From the Create Study window, there is an edit button in the right-down corner of every study to access any of the scripts (Figure 10).

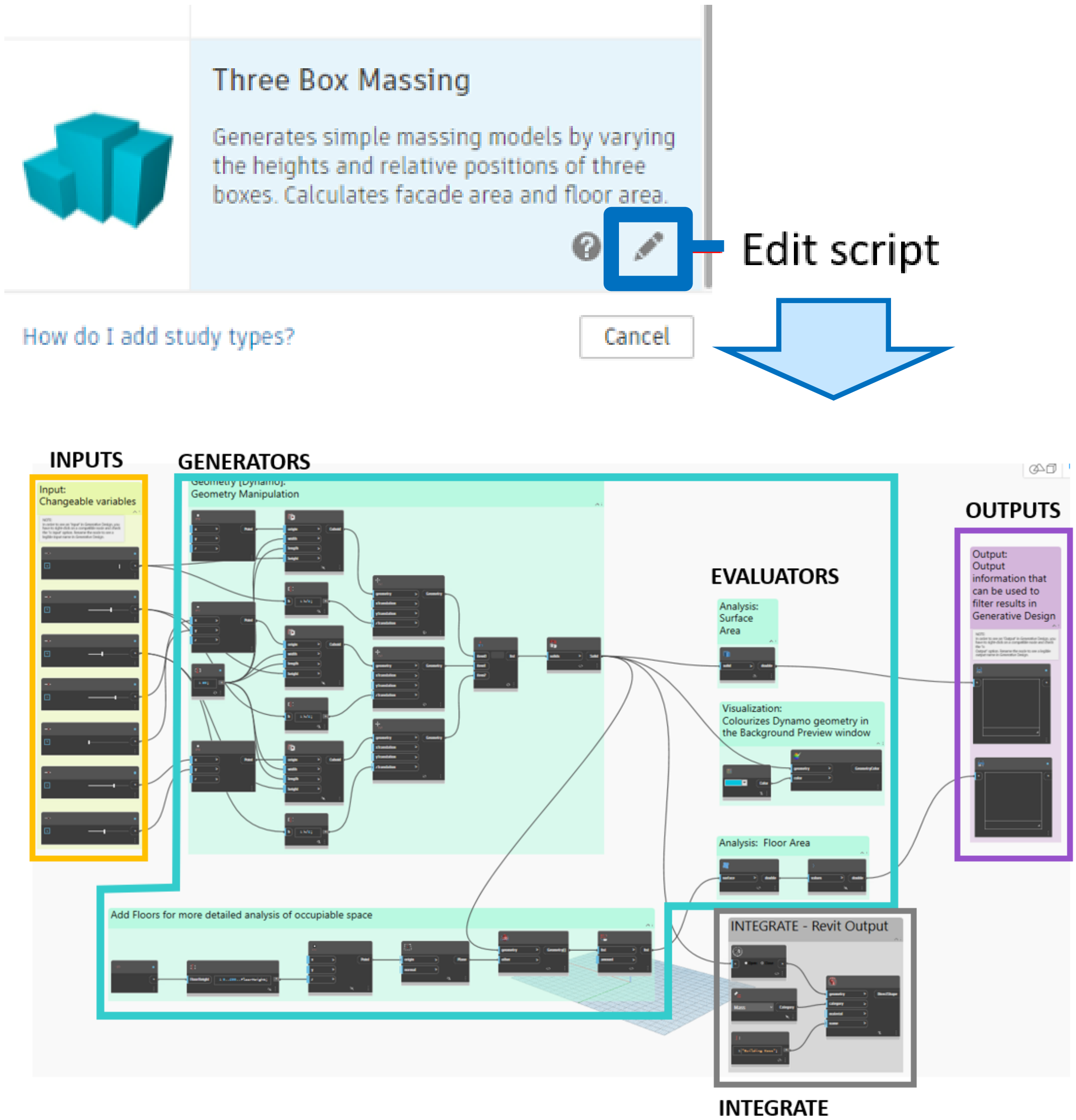

FIGURE 10. Example of the Dynamo Three Box Massing script

The Pre-GDP is the data that can be input in the GD tool studies; these inputs are first defined in Dynamo (Figure 11). If some change in the inputs is done in the script, that will be immediately reflected in the GD tool. The inputs in Dynamo are usually number slider, integer slider, Boolean, or Revit selection nodes, and it is necessary to set them as input.

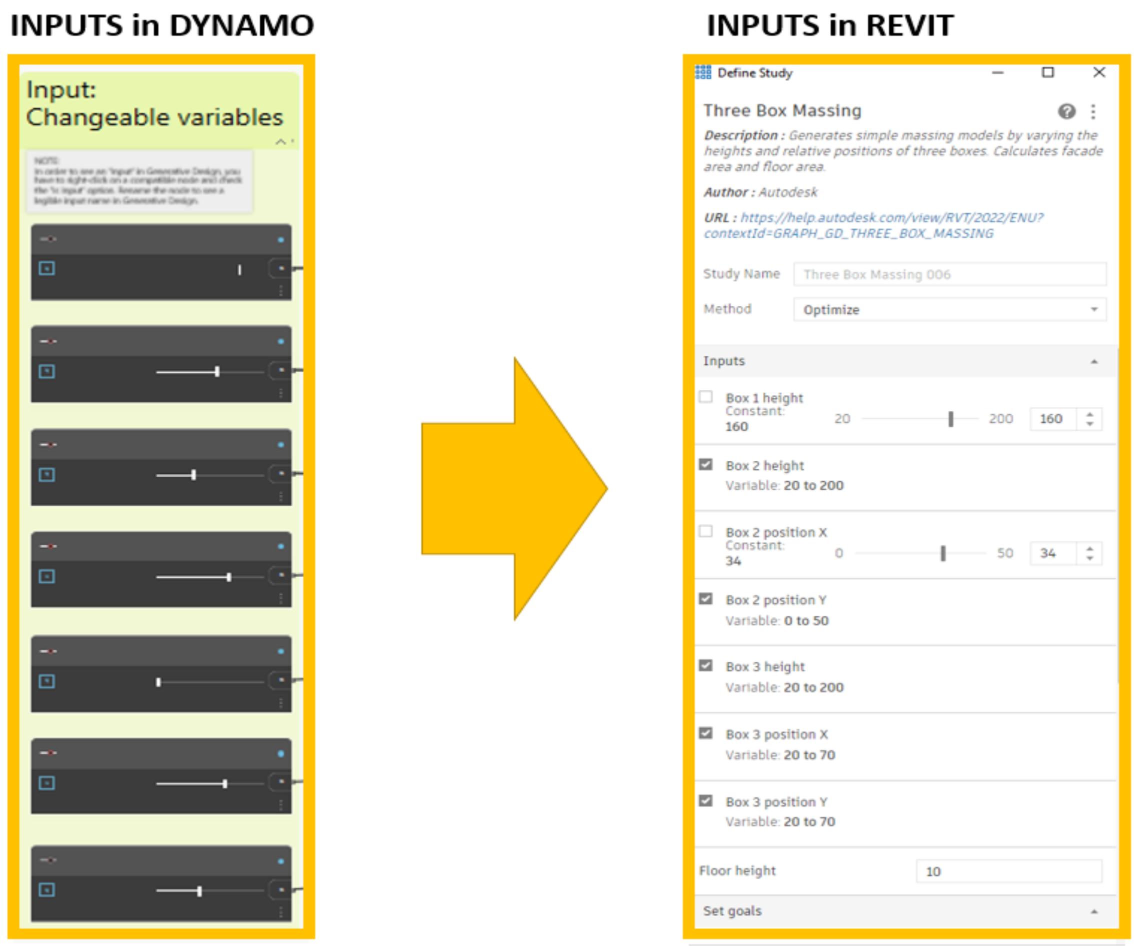

FIGURE 11. Same inputs in Dynamo script and Revit GD tool

The GDP is when the algorithm works to generate the design solutions. As opposed to what occurs when using the Revit GD tool, where the designer is waiting for the results, in Dynamo, who creates this part of the script, is doing the most arduous and complex work. The typical parts of this phase include Generators, Evaluators, and Solvers (Figure 12).

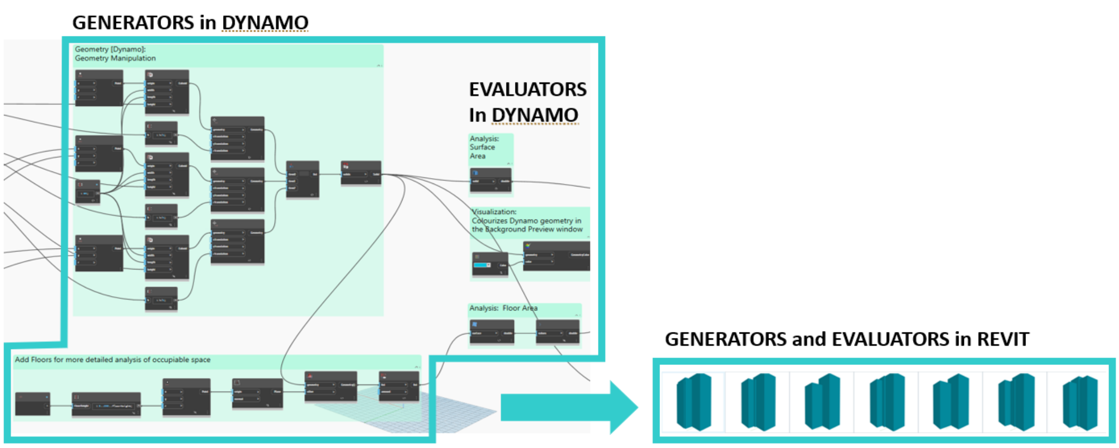

FIGURE 12. Generators and Evaluators in Dynamo and Revit

Generators are the logical route to create new possible alternatives. The Generator uses the input values and generates options according to them. If the designer modifies the values, the Generator node/s makes new alternatives. **Evaluators** use the generated outcomes to evaluate what are the best choices based on the objectives. **Solvers** can automatically and continuously run a script with generators and evaluators. This type usually has the challenge of defining the problem in a manner that is easy to understand for the Solver. Therefore, the inputs need to be as precise as possible. The Solvers utilize several methods to process the script differently. These methods are the already mentioned Randomize, Space Evenly, Optimize, and Like This (Matterlab n.d.).

4.3 Author's learnings and experiments with Revit GD and Dynamo

The author studied Revit GD and Dynamo for many months without previous knowledge of the tools. The exact duration of the learning process is unknown because the learning sessions were spread unevenly over several months. The author calculated an estimated 170 hours to gather knowledge and practice of the tools through the self-learning method by taking online courses, following tutorials, hearing videos, researching forums, reading written material, and experimenting.

The learning curve was very different for each of the tools learned. On the one hand, Revit GD is simple to understand and use, despite there are certain GD-specific concepts that the designer should become familiar with:

- Methods: Understanding the four different methods by which a computer can process the algorithm is essential to know which one to select on each occasion according to the needs of the task.
- Goals, constraints, variables, and constants: These concepts are required when working with GD, and most of them can be adjusted within the Revit GD tool environment. Even though sometimes they can be found with different names, knowing the difference between them helps the worker to make modifications depending on their needs.
- Number of solutions, Population Size, Generations, and Seed: These concepts are part of the generation settings and differ depending on the

selected method. The number of solutions is the number of results the designer wants after running the script. The population is the set of results the designer gets after running the script; the population size refers to the number of design options the set of results will contain. The generations refer to how many times the algorithm will run and evolve the population. Each time the algorithm runs, a population with new design options is created. The seed tells the algorithm where to start from. It is mainly used to get different results; if the designer has run the study and does not get the desired outcomes, changing the seed can help to get new ones.

- Learning to use the Explore Outcomes window is quite important because this is a navigation space that allows the designer to choose the best design outcome. Many filter options can be used to understand the results better.

On the other hand, the author claims that learning the basics of the Dynamo plug-in can take a considerably short time, but it may take many years of practice and study for a designer to master it. It should also be noted that the Dynamo scripts for automating tasks differ in complexity from the ones needed for GD, the last ones being more difficult to figure out and solve. When planning the workflow for a GD script is also essential to think about the best way to set the project goals, constraints, variables, and constants in the graph. This type of script also requires excellent handling of Dynamo geometry, and having TPL skills is an extra benefit. While experimenting with GD scripts, the author finds out some vital things to remember when working with these types of graphs:

- The script must be set as Generative Design type to work in Revit. DynaExtensions→ Graph Status→ Generative Design.
- **Data.Gate:** In almost all the GD scripts, it is necessary to have Data.Gate node that controls the flow between elements in the script and Revit (Figure 13). When the Data.Gate is set as open; the data goes through and creates elements in Revit automatically; when it is set as close, no elements will be made in Revit automatically. The Data.Gate node is strictly connected to the Create Revit Elements button in the Revit GD tool.

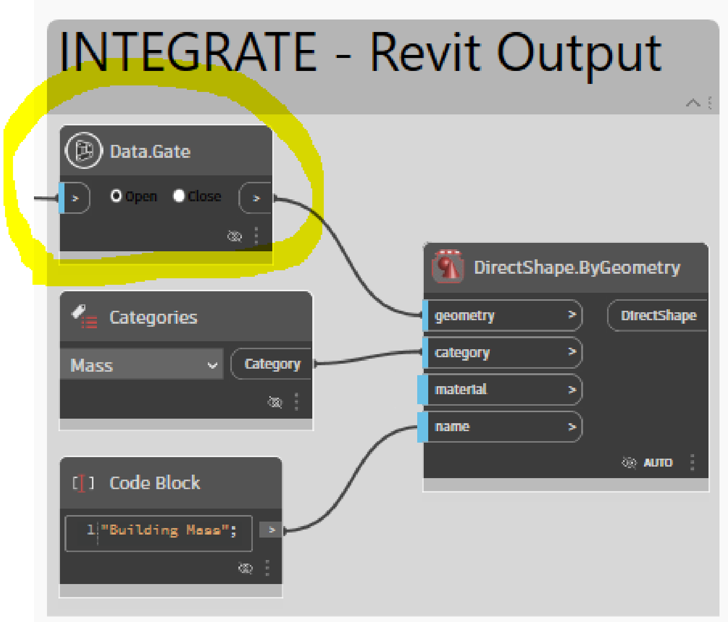

FIGURE 13. Data.Gate set as Open

- **Inputs** The nodes accepted as inputs are Number slider, Integer slider, Boolean, and Revit selection nodes. For an input to be visible in the Revit GD tool, it needs to be set as Input.
- **Output** The nodes accepted as outputs are Watch nodes and math operation nodes and they need to be set as Output.
- **Data.Remember:** When using selection nodes to access Revit elements, the process can be quite heavy. This node helps Dynamo to store Revit data for later use and makes the script work faster (Figure 14).

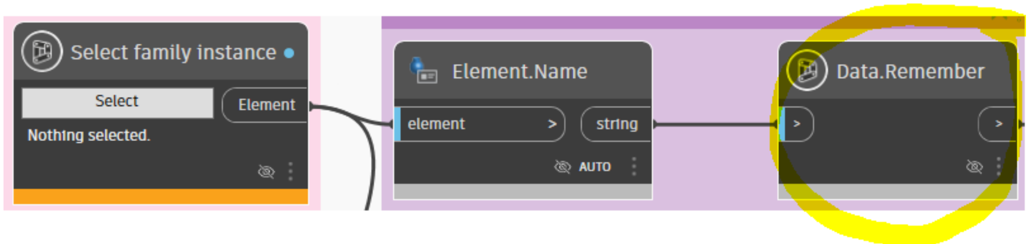

FIGURE14. Data.Remember node

- **Masses:** If the script is intended to work with masses is essential to check Revit Visibility and Setting and set them as visible before creating Revit Elements. In Revit, masses are off by default.
- **Grouping nodes:** Grouping nodes organizes the script and makes it easier to identify the function that each node fulfills in the graph.

- **Freeze nodes**: Freezing nodes when working in a script help to avoid affecting Revit each time the designer presses Run.
- **Debug**: Debug constantly debugs because having nodes with errors is not good in the long run.

Lastly, the author finds fear mentioning that there were some technical issues in the Revit GD tool and Dynamo that made the learning process a bit tedious and challenging. The author states that the problems are understandable since the tools are in constant development and that the solutions for the issues can often be found in Autodesk help and Dynamo forum (Knowledge Autodesk, n.d.; DynamoBim, n.d.)

5 RESEARCH METHODOLOGY

This chapter discusses the research methodology and methods used to collect data for the thesis. It explains the purpose of the interview and inquiries at Raami and how that data has been managed. Finally, it explains the method selected to analyze the collected information.

5.1 Qualitative research method

A research methodology is an overarching concept that will guide the study; it is also considered the entire strategy for researching the topic and involves thinking about restrictions, challenges, and ethical decisions within the investigation. The research methods are the available instruments that collect data, such as interviews, surveys, experiments, etc. (Dawson 2009, 14.) This research employs a case study methodology with qualitative research methods to evaluate the assumptions, perspectives, and resources in adopting GD.

A case study is a research methodology that allows authors to investigate phenomena in depth within a specific context and by using numerous data sources. A case study presumes a relativist ontology, where an objective truth does not exist; the perception of reality reflects what human being generates in the world. It also has a subjective epistemology, where authors consider that knowledge can have different interpretations and, therefore, is not objective (Rashid et al. 2019.)

Qualitative research focuses on the analysis of specific cases on their temporal and spatial individuality, beginning with the expressions and behaviors of people in their surroundings (Flick 2014, 21). Some methods used to collect data in qualitative research are in-depth interviews and surveys.

This research methodology of this paper and methods were chosen based on the central research question. A case study was necessary to get an overall view of the current situation of Raami; its resources, design processes, and expectations set the starting point for adopting GD. The qualitative method was the appropriate selection because this research required getting more profound responses rather than large volumes of superficial answers.

5.2 Data collection

In this paper, the data remains anonymous. Any personal data collected is only available to the interviewer, the thesis supervisors, and evaluators, who process it only if it is necessary for the thesis to be accepted. No data was recorded, and any written personal research data will be destroyed once the research has been concluded. The data was collected through a qualitative research method using in-depth interviews, surveys, learning and experiments, and literature review. The collected data was divided into primary and secondary data.

5.2.1 Primary Data

Primary data is information created for the first time by the author via personal initiative and experience to meet his study challenge. The investigator is in complete control and charge of the data collection. Numerous techniques can be used to gather the data, including surveys, observations, physical examinations, postal questionnaires, questionnaires completed and sent by enumerators, in-person, telephone, and online interviews, focus groups, and case studies (Surbhi 2020.) Open-ended questions are used in qualitative surveys to generate lengthy written answers and get the experiences and opinions of the interviewee. As they aid in identifying early themes or concerns to be explored more profoundly in the study subsequently, surveys are frequently a helpful intro to interviews or focus groups. Surveys can be utilized iteratively, changing and being adjusted as the research continues (Deakin University Library n.d.)

For this thesis, the primary data was collected through in-depth interviews, surveys, learning, and experiments. One interview and two surveys were done within the Raami Architects office. The decision to interview and survey a total of three workers was made because precise answers were sought that could be answered by a few people.

The purpose of the interview was to get an overview of the current situation of the Raami, its resources, and expectations about the GD to set the starting point for potential adoption. The interview lasted more than one hour and was done online through Teams. Soon after, messages with open questions were exchanged to clarify things about the previous conversation.

Two people answered the surveys to reveal data about the challenges during their design process and pre-conceptions of the workers about GD. The survey had eight questions and were sent through Teams; after receiving the answers, messages were exchanged to add some information about the topic.

As already discussed in Section 4.3, Author's learnings and experiments with Revit GD and Dynamo; the author studied the tools and carried out experiments over many months to get a realistic perspective of GD. In the process, the author evaluated the learning curve, the difficulty level, technical issues, overall benefits, change of mindset, and potential adoption steps. The author learned Dynamo basics and experimented with GD scripts by the self-learning method of making online courses, following tutorials, hearing videos, researching forums, reading written material, and experimenting.

5.2.2 Secondary data

Secondary data refers to information that has already been gathered and documented by any source other than the user. It is a kind of data easily accessible and compiled from various sources, including censuses, government publications, internal organizational records, books, journal articles, websites, reports, and more (Surbhi 2020.)

This thesis gathers secondary data from a literature review that was used mainly to support the data analysis and was collected using Google as a search engine and other research content tools such as Andor, Research Gate, Theseus, and

Internet archives. The keywords used to find information were: Artificial Intelligence for architects, new technologies for architects, Generative Design, Generative Design for architecture, Generative Design for Revit, Dynamo, optimization, architectural design process, and BIM. From the results, titles unrelated to architecture were discarded, except for some exciting texts discussing GD as a general concept. Then the introduction or abstract of every thesis, article, or book was read, thus filtering the most appropriate for the central topic of this paper.

5.3 Data analysis method

The data gathered for this research was analyzed through a Qualitative Data Analysis (QDA) . In this method, the author must read and filter the most critical data, organize it by topic, search for relevant connections between the data, and finally make interpretations and conclusions (Warren 2020)

In this thesis, the interview, and surveys provided information about the state of GD at Raami, the pre-conceptions and expectations of the employees about the same subject, and data about the current design process that architects use. The literature review and the learning and experiments defined the basis for the benefits and challenges of adopting GD in architecture offices. With the research questions in mind, the literature review and the learning and experiments supported the analysis of the interview, and surveys. They gave a framework for the adoption of GD in architecture firms.

6 RESULTS

This chapter presents the findings derived from the data collection. The analysis was made with the data collected in the interview and surveys and based on the literature review. First, the current design process used at Raami for complex buildings and its design phases is described. Then the resources regarding toolset, skillset, and mindset of Raami are examined. Lastly, a link is sought between the problems that arise in the design process and the potential uses of GD to identify tasks that could benefit from the use of GD tools.

6.1 Impact of the GD adoption in the current Design Process

A survey about the design process at Raami was done on one person within the company. The questionnaire was intended to understand the design process in the office to see how the potential adoption of GD could impact it. The answers defined the current design process in the office, the importance of decision-making, and the role of the architect in a project.

The **first** question was based on the design phases of a project defined by the literature review. The idea was to determine whether Raami Architects followed those same design phases or used different project stages.

1. Do you agree that most of the projects at Raami office, independently of their complexity, have the following design phases?
- Pre-Concept (Tarveselvitys, Hankesuunnittelu and Suunnittelun valmistelu)
- Conceptual Design (Ehdotussuunnittelu)
- Schematic Design (Yleissuunnittelu)
- Detailed Design (Rakennuslupatehtävät and Toteutussuunnittelu)
- Construction (Rakentamisen valmistely and Rakentaminen)
If you disagree, please explain the project design phases used at Raami.

The respondent agreed that these same phases are followed at Raami.

2. The **second** question aimed to define if there is some difference in the design process and design phases in more complex projects such as hospitals.

Do you agree that in complex projects such as hospitals, the same phases are respected but with more difficulties in each one of the phases?
If you disagree, please explain why and the differences in the phases when working on complex projects.

The respondent agreed that the phases in complex projects are the same and stated that the main difference is that in complex buildings the most important in every phase is to give more alternative solutions and strive to facilitate the decision making.

The **third** question was intended to know the approximate timeframe for each design phase in complex projects.

3. Please estimate how long each phase lasts in complex projects. If you agree with the phases in question one, you can mention them. If you disagreed with the phases in question one, please use the phases you wrote in question two. Please mention the phases and put an approximate time for each one. (For example: Phase xx lasts between 4 and 6 weeks)

The respondent answered that the Pre-Concept (Tarveselvitys, Hankesuunnittelu and Suunnittelun valmistelu) could last from 3-8 months, the Conceptual Design (Ehdotussuunnittelu) from 5-7 months, the Schematic Design (Yleissuunnittelu) from 2-4 months, the Detailed Design (Rakennuslupatehtävät and Toteutussuunnittelu) from 8-16 months and the Construction (Rakentamisen valmistelu and Rakentaminen) from 28-80 months.

The **fourth** question aimed to know which of the phases in complex projects was the most important and decisive when making decisions.

4. Do you agree that in hospital projects, the decisions made in the Pre-Concept phase are the most important for the development and lifecycle of the building? If you agree, please explain why the Pre-Concept phase is the most important. If *you disagree, explain why. Please tell which phase you consider more important and why.*

The respondent agreed that the Pre-Concept phase is the most important because decisions such as the size of the building and its basic functionality are taken in that stage.

These answers revealed that the design process of any architectural project at Raami consists of five phases with different lengths, as shown in Table 1. Raami uses the same design phases when working on complex projects such as hospitals or schools. It was also stated that the Pre-Concept is the most critical phase considering the type of decisions taken in that stage. GD is a tool that performs better in the early stage of a project helping the designer to make critical decisions.

TABLE 1. Design process phases and timeframe

DESIGN PHASE	TIMEFRAME
PRE-CONCEPT	3-8 months
CONCEPTUAL DESIGN	5-7 months
SCHEMATIC DESIGN	2-4 months
DETAILED DESIGN	8-16 months
CONSTRUCTION	28-80 months

6.2 Toolset, skillset, and mindset

An interview and a follow-up survey about the resources at Raami were done to one person within the company. The interview aimed to know the situation of Raami regarding the adoption of GD. The questionnaire was intended to understand what toolset, skillset and mindset the workers already have, and which ones need to obtain to adopt Generative Design effectively. The toolset, skillsets and mindset required for the adoption of GD have been determined by the literature review and compared with the skills of Raami workers.

The **first,** and **second** questions aimed to identify what software and VPL tools the company already has that could be used in the implementation of GD.

1. Which software that can be used for Generative Design is available at the office?

- *Revit*
- *Rhino*
- *Other*

2. Which Visual Programming Language (VPL) tools are available at the office?

- *Dynamo*
- *Grasshopper*
- *Param-O*
- *Other*

The respondent answered that Raami counts with Revit and Dynamo with a license for every worker and that the Rhino and Grasshopper license can be renewed if necessary, but at the moment, it is not in use. The interview reflected that the primary design software of the office is Revit, and that Dynamo is currently used for automating repetitive tasks. Therefore, the research explored the adoption of GD within the Revit software and the Dynamo plug-in (Table 2).

TABLE 2. Toolset required to adopt GD and Toolset at Raami

TOOLSET	RAAMI TOOLSET	RESULTS
CLOUD COMPUTING POWER	Unknown	More information is needed
GD SOFTWARE	Revit as the primary design software of the office and with a license for every worker. Rhino's license can be renewed if necessary.	The company software for Generative Design is Revit-
VPL SOFTWARE	Dynamo currently used for automating tasks. Grasshopper's license can be renewed if necessary.	As the GD software is Revit, Dynamo must be the VPL plug-in.

From the **third** to the **eighth** question aimed to know if there are workers with VPL, TPL, and Revit GD tool skills in the office and if so, what is their knowledge level.

3. How many workers have VPL skills at the office?

- *0*
- *1-2*
- *3-5*
- *6-10*

4. If there are workers with VPL skills, what is their general knowledge level? Point from 1 to 5, being 1 little experience and 5 extensive experience.

5. How many workers have Textual Programming Language (TPL) tool skills at the office?

- *0*
- *1-2*
- *3-5*
- *6-10*

6. If there are workers with TPL tools skills, what is their general knowledge level? Point from 1 to 5, being 1 little experience and 5 extensive experience.

7. How many workers have Revit GD tool skills at the office?

- *0*
- *1-2*
- *3-5*
- *6-10*

8. If there are workers with Revit GD tools skills, what is their general knowledge level? Point from 1 to 5, being 1 little experience and 5 extensive experience.

The respondent answer that there are between three and five workers with VPL skills, no worker with TLP skills, and one to two workers with GD tool skills. The average level for VPL is of is advanced beginner (2), and for GD tool is beginner (1). The results shows that Raami count with the necessary tools, but they are missing the amount of VPL, TPL and Revit GD tool skills (Table 3).

TABLE 3. Skillset required to adopt GD and skillset at Raami

SKILLSET	RAAMI SKILLSET	RESULTS
ARCHITECT OR SIMILAR DEGREE	The workers are architects or have a competent degree.	Skill already adopted
DESIGN ABILITIES	The workers have design skills to varying degrees.	Skill already adopted
VISUAL ABILITIES	The workers have communication skills to varying degrees.	Skill already adopted
COMMUNICATION ABILITIES	The workers have communication skills to varying degrees.	Skill already adopted
VPL (DYNAMO)	Between three and five workers have a beginner level on VPL.	Skill to reinforce or adopt
TPL (PYTHON FOR DYNAMO)	No worker have TPL skill.	Skill to adopt
REVIT GD TOOL	Between one to two workers have a beginner level on Revit GD tool.	Skill to reinforce or adopt

The **ninth** question aimed to identify workers that worked before with GD tool. Studying and working with GD helps to make the necessary mindset change and start thinking about design problems from another perspective.

9. According to your knowledge, have some worker/s been working in practice with any Generative Design tool? If so, please explain how many workers, which means and experience level.

The respondent answered that no worker had previous experience in GD, but in the interview was mentioned that workers have had an introductory class in GD that focused on the change of mindset when working with these types of tools.

Although Raami have had a training in GD, the practice is essential. As the literature suggested, using GD is necessary to get a GD mindset, which can be achieved by defining new responsibilities for architects. The key responsibilities are: Identifying possible GD problems, developing a GD workflow, and evaluating the workflows. The results show that most of the architects at Raami can act as evaluators because they have the knowledge and criteria to know if the outcomes are correct. On the other hand, no architect in the office has enough experience in GD to identify the problems to solve with GD tools quickly. There is no worker with the necessary skills to develop a GD workflow (Table 4).

TABLE 4. Mindset required to adopt GD and the mindset at Raami

ARCHITECT ROLE	RAAMI ROLES	RESULTS
IDENTIFY POSSIBLE GD DESIGN PROBLEMS	There is no architect that could clearly identify problems that could be solved with GD	New role to adopt
DEVELOP GD WORKFLOW	There is no architect that could clearly develop a GD workflow	New role to adopt
EVALUATE THE GD WORKFLOW	Many of the Raami architects have the knowledge and criteria to evaluate if a workflow and its outcomes are good or not.	Skill already adopted

6.3 Design problems and GD solutions

Two architects within Raami answered a survey about the problems that arise during the design process of complex buildings. The questionnaire was intended to find out which issues commonly arise during the design process of a complex project to establish which could be solved with the help of GD tools. The literature helped to identify other problems that were not mentioned as a result of the survey but that is also common during the development of an architectural project.

The architects were asked to focus in one specific project to answer the questionnaire. The **first** and **second** questions aimed to understand the project goals.

1. What were the primary goals for the project?
2. Did you achieve all the project goals? Which ones did you not?

The respondents had different goals for each project. One of the main goals was to ensure that design tools and the planning guidance worked seamlessly. The other project was a new extension of an existing hospital building, and the goal was to extend the logistic and personnel connections to the old part. In both cases, the project goals were accomplished.

These goals refer to a too-large problem, indeed to a whole building project. For GD to be able to solve some of the project tasks, the problems must be divided into smaller issues, and the designer must define goals for each one. The design problem must be formulated mathematically, and its goals must be precise, quantifiable, and measurable, so that the algorithm can process them.

The **third, fourth** and **fifth** questions aimed to recognize the obstacles that emerged during the design process and also to know if the same type of errors are repeated in other projects.

3. What are the design obstacles you faced during the project?
4. Are these same obstacles repeated in other projects?

5. During the design process, have you encountered wicked problems that are difficult to solve? Give an example.

The respondents answered that the obstacles in their projects were: Human connections, getting useful meetings with designers and clients, change within user groups, goals set by the users, presenting the needs for the design, HVAC needing more space, connections between the operations unit and other areas, and Revit tools. They both confirm that these same issues are usually present in other projects.

All the issues identified in the projects have a different nature; some have to do with stakeholders and communication, others are design problems, and the last are technical ones. The literature identified other obstacles or difficulties when designing, which can be complemented with the ones reported by Raami architects. These problems are the scope, schedule, and budget, communication between stakeholders and designers, design goals and objectives, building space layout design, and coping with sustainability. Developing a GD workflow requires different resources, so identifying common issues in many projects is the key to knowing if it is worth creating the GD script.

The **sixth** question aims to understand if the workers think the use of GD tools could help the to cope with some design issues.

6. Which of these tasks do you think could have had better outcomes by using GD? Buildings location and orientation, Building mass, Room type optimization, Workspace layout, Façade design, Parking lot layout, Playground layout, Interior design.

The respondents believed that GD could help them get better outcomes in some of the design tasks of a project, even though the literature also identified others assignments that could be solved with GD tools (Table 5).

TABLE 5. Tasks people believe GD can solve.

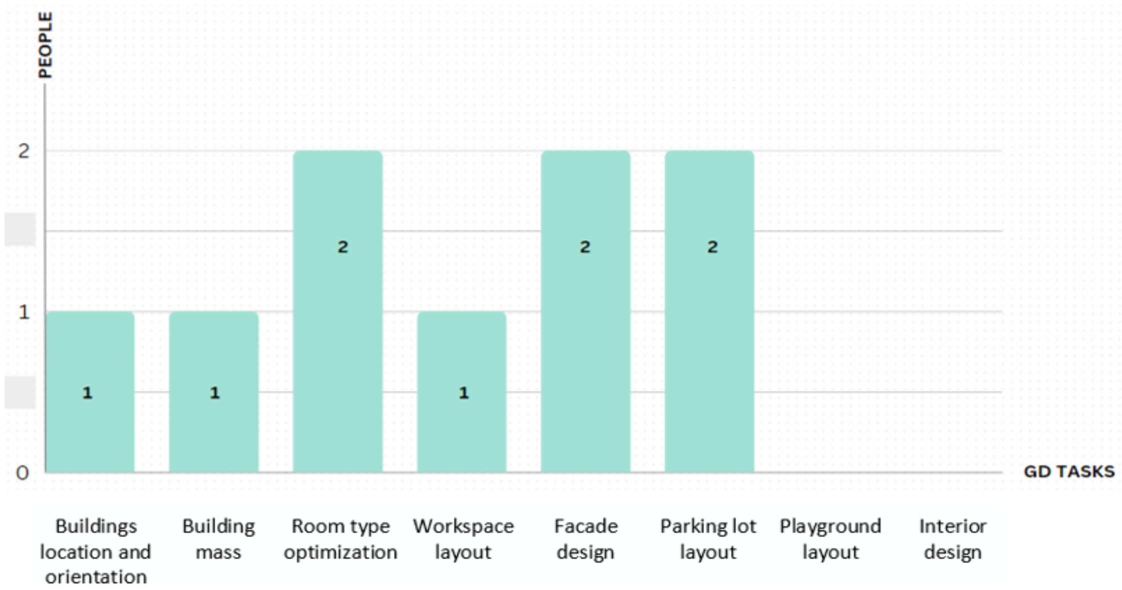

Table 6 link the problems that arise in the design process and the potential uses of GD to identify tasks that could benefit from the use of GD tools.

TABLE 6. Design problems and GD solutions

DESIGN PROBLEM	RAAMI DESIGN PROBLEM	GD USES	RESULTS
SCHEDULE AND BUDGET Tight deadlines and budgets wit limited time for decision-making	-	• Reduce the total cost of structural components. • Reduce the life cycle costs and environmental effects of new or renovation projects.	
COMMUNICATION customer frequently may be ambiguous or unable to put their ideas into words. The designer must guarantee that the client comprehends the concepts	• Human connections. • Getting useful meetings with designers and clients. • Presenting the needs for the design	• Find optimal building geometry to lower their costs and environmental implications. • Improve the visual appeal and structural integrity • Facade design • Interior design (Optimizing the placement of tables in break rooms, cafeterias, restaurants/ designing furniture)	
GOALS AND OBJECTIVES In most projects, the design goals can differ between architects, clients, communities, and the construction industry	• Change within user groups. • Users' goals.	• Most of the GD uses help to achieve the overall goals and objectives of a project	
SPACE LAYOUT It is a task where meeting all the clients' requirements is complex. These floor plans are drawings that make it possible to understand the space of a building and locate rooms and areas.	• Presenting the needs for the design. • Connections between the operations unit and other areas.	• Parking lot layout • Playground layout • Room type optimization • Workspace layout	Most of the GD tasks that have been identified solve one or more problem categories.
SUSTAINABILITY Is a wicked problem almost impossible to solve completely.	• HVAC needing more space.	• Optimize the pavement and tiles placement to generate less waste. • Design a building mass according to solar incidence and site surroundings. • Distribute lights in a room optimally to reduce the number of light fixtures and increase the amount of light. • Optimize the (HVAC) systems by reducing the usage of energy and life cycle costs associated with heating and increasing overall indoor comfort. • Find optimal building geometry to lower their costs and environmental implications. • Reduce the life cycle costs and environmental effects of new or renovation projects. • Building location and orientation • Placement of sprinklers	

7 RECOMMENDATIONS

The recommendations aim to facilitate the potential adoption of Generative Design with Autodesk tools at the Raami office, but any other company in the AEC industry can also consider the same suggestions. To adopt GD, Raami must thoroughly understand the purpose of the innovation, its benefits, and its challenges. It also must consider the necessary resources and be aware of the impact on the design process and in the role of the architect.

According to the author the benefits of adopting GD are:

- Reduces the time and costs of finding an optimal solution by quickly providing the designer with many solutions.
- It frees up time for the designer to focus on helping the clients in the decision-making process by reducing the time of some of the tasks of the Pre-Concept phase.
- It improves the creativity of the designers by getting a broad set of solutions impossible to get without the help of the computer.
- It helps the designer make better and more sustainable decisions by providing design options that count with analytical data.
- It improves the communication between the designer and client when working with the GD tool; they can modify settings, get immediate results, and evaluate the options together.
- It improves building sustainability by reducing waste or optimizing the use of natural sunlight, among others.
- It helps the company keep ahead by adopting new technology.

At the same time, it poses the following challenges:

- Identify the correct design problems to solve needs from an excellent understanding of the problem and generative design workflow.
- Training the workers to acquire the necessary skills takes time and effort.
- Creating GD scripts requires good experience in using Dynamo. The level of skills required depends on the difficulty of the problem to be solved.
- Technical errors that can arise from both Revit and Dynamo.

The author suggests utilizing GD as an aiding tool to complement the traditional design process instead of as a design process itself. The tool must be used cautiously and only when deemed necessary, and it is primarily intended to solve complex problems that are difficult to solve and has contradictory requirements. GD tools work better with issues belonging to the Pre-Concept phase. Even though there is no strict rule about this, the designer can also experiment with issues found in other phases. To cope with the potential adoption of GD, the author proposes a set of steps for Raami to organize and divide the responsibilities within the workers, and a GD workflow that can be used as a starting point in the implementation.

7.1 Raami's preparation framework for the adoption of GD

The author proposes the following preparation framework for Raami to adopt GD. The framework proposes the division of the responsibilities into three groups that must collaborate with each other to succeed in the adoption of Generative Design. The groups are Raami management, the GD team, and the other architects (Figure 15).

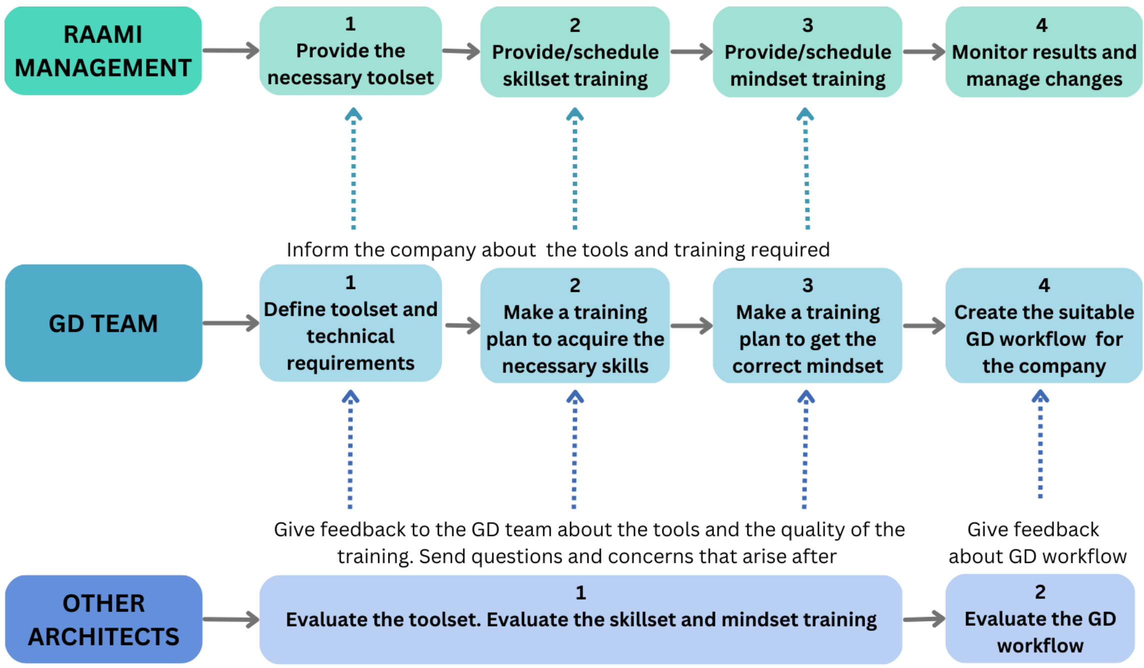

FIGURE 15. Preparation framework for Raami to adopt GD

The **GD team** should comprise workers with some knowledge of GD tools. An expert on the subject could be hired to speed up the process if necessary. This team is the first organizer of the adoption; they first define the tools and technical requirements and then make a training plan to acquire the necessary skills and the correct mindset. When this information is ready, they must inform the Raami management so they can provide the tools and schedule the training. As a starting point for defining tools and training, the author states that Raami already counts on Revit and Dynamo as their GD tools, even though verifying the cloud computing power of the firm would be advisable. Regarding skills, the workers have the ones related to their profession as design and visualization abilities. However, they still need to acquire or improve the ones associated with GD, such as the use Revit GD tool, Dynamo, and Iron Python. The author suggests incorporating training in the Revit GD tool destinated for every worker in the office and VPL ones mainly for the members of the GD team. It is not recommended to include training about TPL at the beginning until the workers have a better understanding and experience with Dynamo. The GD team is also responsible for creating the GD workflow.

Raami management acts as a provider and controller in implementing Generative Design. They get the information from the GD team about the necessary toolsets and training; with that knowledge, they can provide the tools and schedule the training. Once the teaching has started, the GD workflow is ready, and some projects start to include GD in their design process, Raami management must monitor the overall benefits and challenges and gives feedback to the GD team and other project members. Based on the information collected, they can decide whether to continue or stop the implementation of GD.

The **other architects** act as evaluators. They are responsible for evaluating the quality of the training, gathering questions and concerns about the tools, assessing the GD workflow, and giving feedback to the GD team. The other architects also participate in some tasks of the GD workflow.

7.2 Workflow when using Revit and Dynamo as GD tool

The author suggests a workflow for anybody using Revit and Dynamo GD tools, which begins by identifying the problem and ends with an overall evaluation of the process. The workflow is divided into four major parts (Figure 16): **A)** Identify the problem, **B)** Create the Dynamo GD script, **C)** Create a new study in the Revit GD tool, and **D)** Evaluate the overall process. Parts **A)**, **C)**, and **D),** are tasks that can be done by members of the GD team and other architects, being part **D)** preferably done by other architects than the ones of the GD team, so the evaluator is different from the creator. Part **B)** is a task intended mainly for members of the GD team.

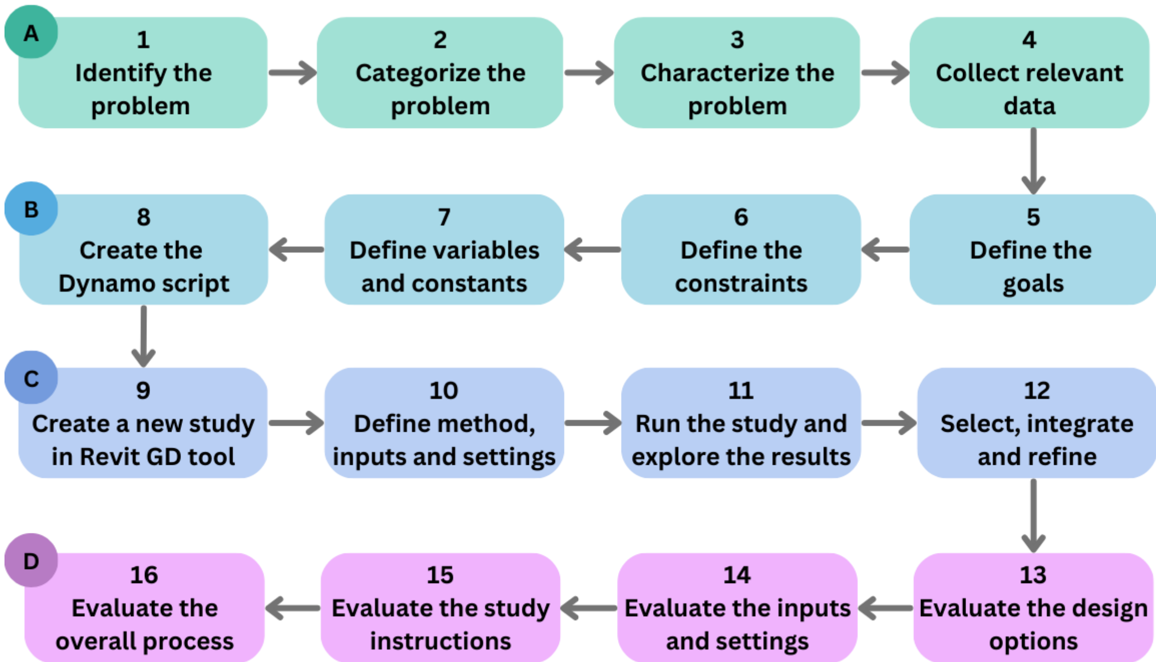

FIGURE 16. Suggested workflow to follow when working with GD tools

A) *Identify the problem:* Identifying the design problems that could be solved with the help of GD tools requires fully understanding the problem and having a structure that let the designer be methodical in the identification of issues. The first part is divided into four steps that go from 1 to 4 and helps to ensure that the problem is appropriate. Step 1 is to *Identify the problem*; in this step, the designer may ask himself what the problem is and clearly explain every part for a better understanding. Step 2 is *Categorize the problem*; this help organizes issues by category and makes it easier to identify problems that may belong to the same type and, therefore, may need similar solutions. Step 3 is *Characterize the* *problem*; by asking several questions, the designer can know if the problem has the essential requirements to be solved with GD tools. Step 4 is *Collect relevant data*; once the designer knows the problem is a potential candidate for the GD tools, he must collect all the relevant information that could help in the development of the Dynamo GD script. Figure 17 shows an example based on the author's experience experimenting with GD tools and aims to help better understand the GD workflow steps.

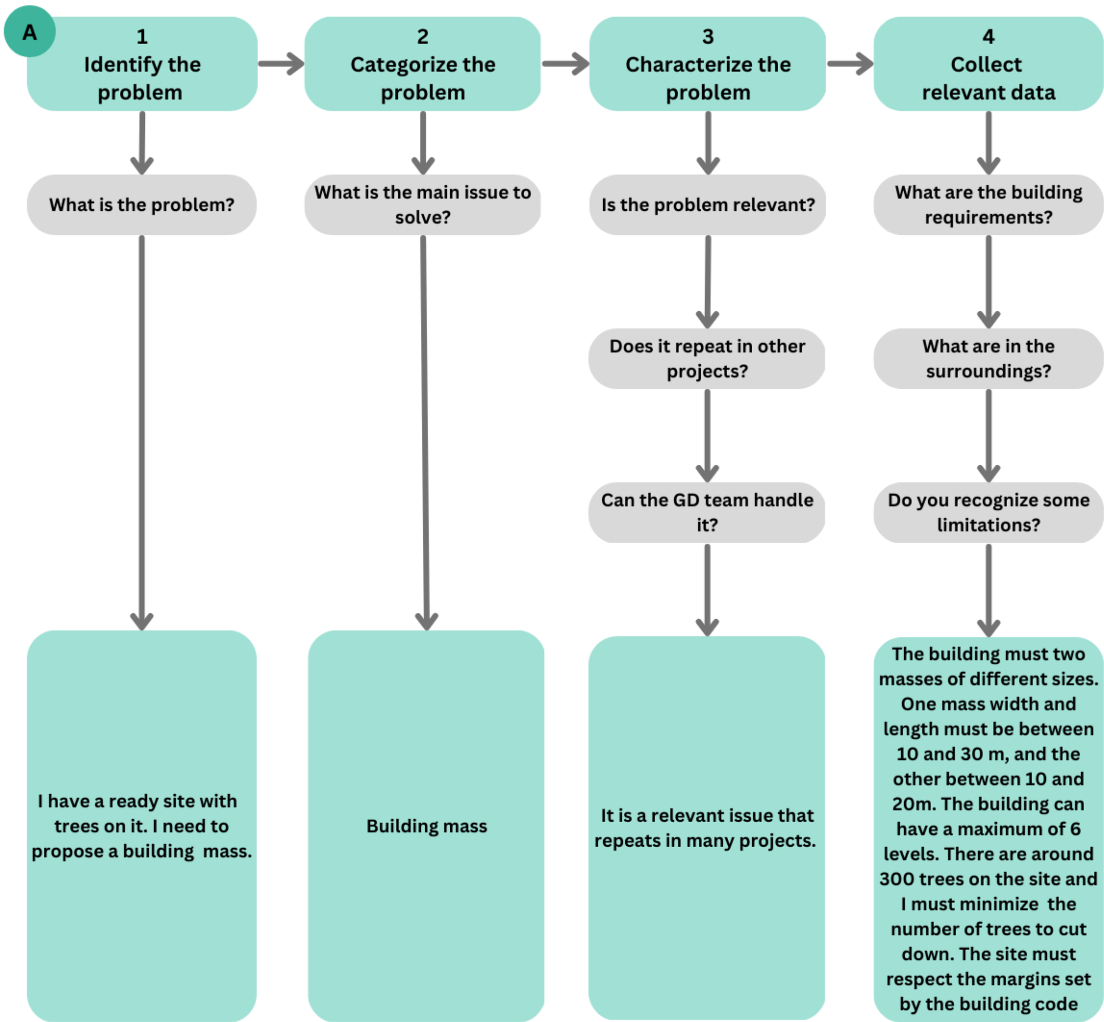

FIGURE 17. Suggested steps to follow to identify a GD problem

B) *Create the Dynamo Script:* Creating the GD script in Dynamo varies in complexity, depending on the issue it is trying to solve. The more comprehension of the problem and the more experience with Dynamo, the easier to decide whether the approach should be modifying an old script or starting from scratch. This part aims to break down the problem and find the most appropriate way to express it mathematically (Figure 18). Step 5 is *Define the goals*; when defining goals, is important to assure that they are precise, quantifiable, and measurable. The optimization method allows having multiple goals that can be minimized or maximized. Step 6 is *Define the constraints;* when defining constraints, it must consider any limitation to prevent the algorithm from testing unwanted scenarios. Step 7 is *Define variables and constants*; the script starts with a set of inputs that may be adjustable or fixed values. Step 8 is *Create the GD script for Revit GD tool*; the creation of the script starts in step five; at this point, the designer may continue working on it and testing it until it is ready. Once the script is finished, the designer must create short instructions for anybody to use. Some drawbacks may appear when working on a Dynamo script; when there is no clear path to move forward, the author suggests visiting the Dynamo forum or Autodesk help page.

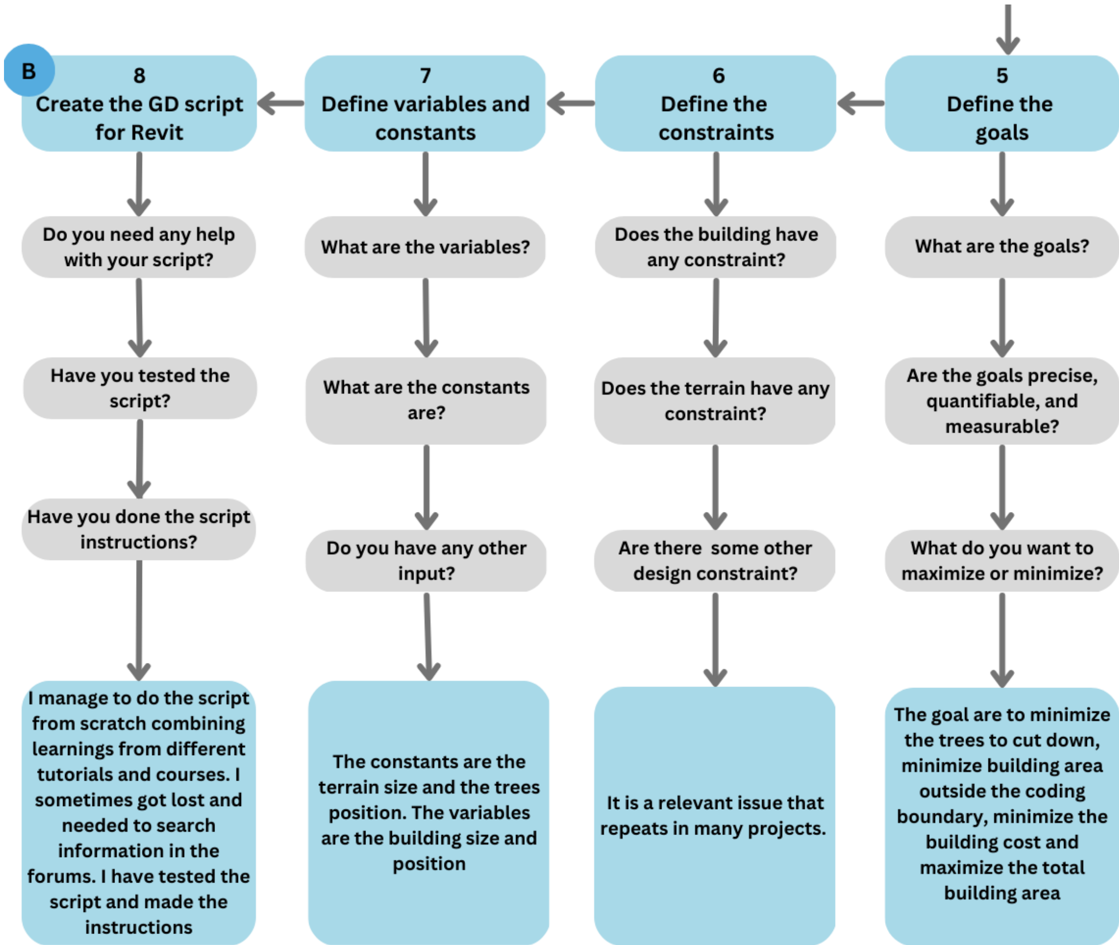

FIGURE 18. Suggested steps to follow to create a GD script with Dynamo

C) *Create a new study in Revit GD tool:* Once the script is done and tested in Dynamo, it can be used in any project that requires it (Figure 19). Step 9 is *Create a new study in Revit GD tool*; once the script is ready and saved correctly, the designer must make sure he has the instructions with relevant information and that when he opens it as a study from the Revit GD tool, there are no visible warnings. Step 10 is *Define method, inputs, and settings*; when creating a new study, the designer must select the method for which he wants the algorithm to be processed. Although this thesis focuses on the Optimize method, the designer can use any of the other three if the project requires it. Then is time to adjust the inputs and generation settings of the study. Step 11 is *Run the study and explore the results*; when everything has been set up, the designer can run the study and wait for outcomes. Sometimes when running a study, some errors occur, so the instructions should consider the most common errors that can happen when running a study. Step 12 is *Select, integrate and refine the option*; when the results are ready, the designer can explore the results, compare the graphics and data to select the best option. Once the option is selected, it can be created in the Revit project and manually refined by the designer.

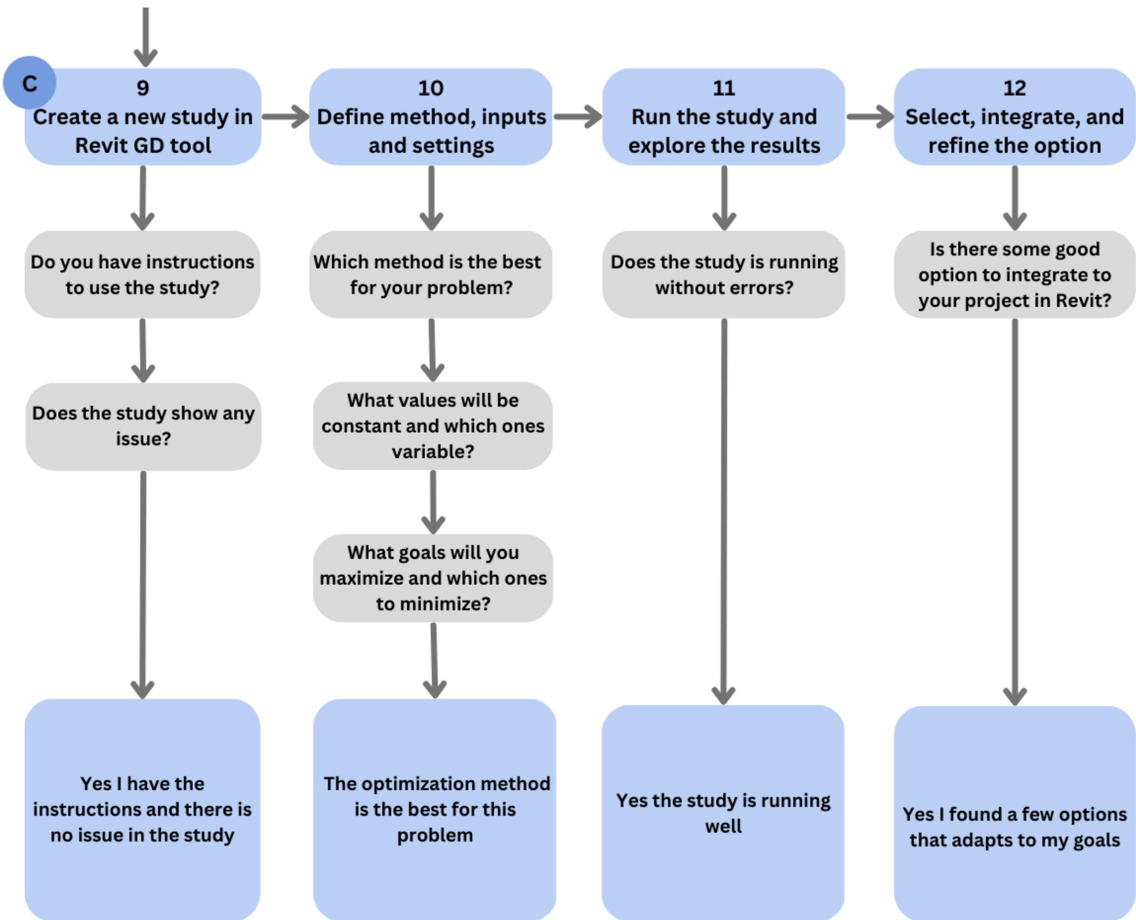

FIGURE 19. Suggested steps to follow to create a new study with Revit GD tool

D) *Evaluate the overall process:* When the GD process has finished, and the tool is not used anymore, it is advisable to evaluate the whole process (Figure 20).

The evaluation is essential for the GD team to know if the scripts they create are good or need modifications. Step 13 is to *Evaluate the design options*; the first thing to do after using the tool is to evaluate the results, so asking some questions is an excellent idea to determine whether the results were as good as expected. It is also advisable to calculate the time it took for the designer to use the tools, get the results, and select one option, to know how much time is being saved in creating solutions. Step 14 is *Evaluate the inputs and settings*; when evaluating the inputs that can be adjusted in the tool, it is essential to recognize if they have proper names and the flexibility the designer needs. Step 15 is *Evaluate the study instructions*; when using a new study, it is a good idea to have accurate instructions with relevant information about the possibilities and limitations of that script. The instructions must be clear and easy to understand. Step 16 is *Evaluate the overall process*; this is the last evaluation, and any question, concern, or suggestion that emerges from the process needs to be noted and sent to the GD team for review (Figure 20).

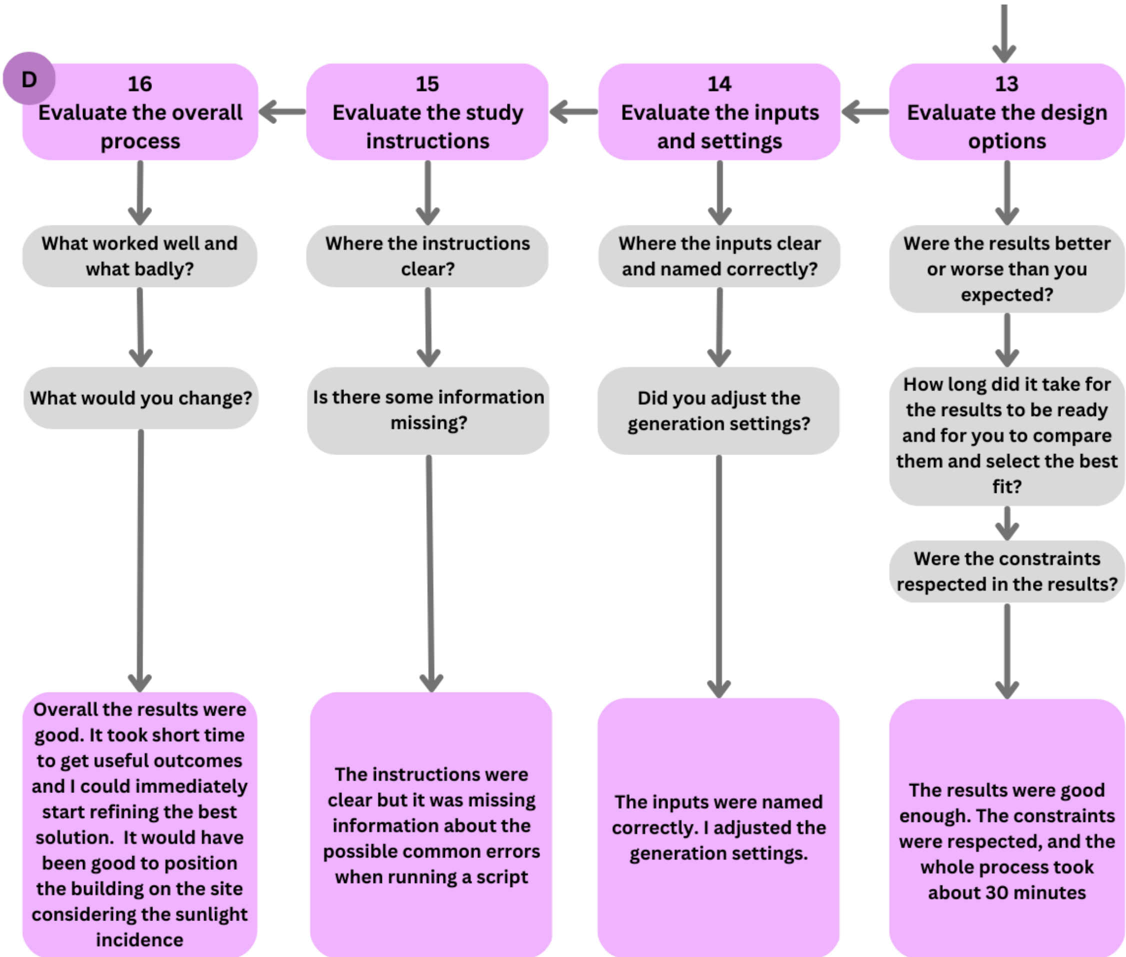

FIGURE 22. Suggested steps to follow to evaluate the overall process

The GD workflow already presented in Figure 16 is the one that the author suggests using as starting point. It can be modified depending on the needs that emerge during the adoption process. The sample questions are just a guide that can also be adjusted depending on the requirements of the script. Those are the questions the author had while creating the script “Building mass and trees.” The script was made from scratch by mixing knowledge from different tutorials, courses, and the own learnings of the author. The script created by the researcher author is confidential material for the use of Raami.

8 CONCLUSIONS AND FUTURE WORK

This thesis investigated the benefits and challenges of adopting Generative Design in architectural companies, especially Raami. The paper employed a case study methodology with qualitative research methods to evaluate the assumptions, perspectives, and resources in adopting GD. The data was collected through a literature review, in-depth interviews, surveys, learning, and experiments. It was decided to interview and survey three workers because the data needed were specific and only required a few people to answer. The data was analyzed through the Qualitative Data Analysis (QDA) method by reading, filtering, and organizing the data to find interesting connections between and make conclusions. The data was also analyzed and compared with the literature review.

The research identified how introducing GD as an aiding tool would impact the traditional design process at Raami and the architect's role. Then it recognized the most common problems that arise when developing a project and how GD could help to solve some of the issues. It investigated the Revit GD tool and Dynamo plug-in to understand the GD from practical use. Finally, the author provided a preparation framework for Raami to adopt GD and a kickstart workflow to follow when working with GD tools. The key findings of this thesis are outlined below.

1) The main research question of the thesis was: **What are the benefits and challenges of adopting Generative Design in Raami Architects?** The results have shown that the main benefits are reducing the time and cost of solving some design tasks, improving communication with the clients, helping the decision-making process, enhancing the creativity of the designer, improving buildings sustainability, and helping companies to keep ahead of competitors. On the other hand, the challenges are the difficulties in identifying the correct problems to solve, the time required to train workers and make GD scripts, and the possible technical errors that can arise from the Revit and GD tools. Considering the benefits and challenges, companies as Raami must carefully plan the adoption of GD so that it is manageable and can be easily integrated with its traditional design process.

2) The rest of the research questions were:

- What are the most common problems architects face during the design process?
- How does GD impact in the current design process of architects?
- What type of projects and tasks could benefit from the use of GD?
- What resources does Raami need to adopt GD?

To answer the above questions, the author conducted one interview and two surveys. In the analysis, the author recognized issues that emerged during the design process and linked them with the tasks that GD tools could help to solve. At the same time, it was possible to identify the resources necessary for adopting GD in the AEC industry, compare them with the ones that Raami already has, and deduce which resources to incorporate or strengthen. Based on the Results, the author provided Raami with a preparation framework for the adoption of GD and a kickstart workflow for anybody using Revit and Dynamo GD tools. The **preparation framework** proposed the division of responsibilities into three teams: Raami management, the GD team, and Other architects. The teams must work collaboratively, aiming to define, provide and evaluate a set of tools and training necessary for implementing GD. The **workflow** proposed a set of steps that include participants of the GD Team and Other architects' participants and aims to identify potential design problems that could be solved with GD, create the GD script, apply GD in real projects, and evaluate the whole workflow. The author also provided an example to better understand the GD workflow.

The limitations of this thesis are mainly time-based. Gathering data about the experiences of other companies when adopting GD would have been enriching for the overall proposal. Another of the limitations was the handling of tools. The author learned from scratch the Revit GD tool and Dynamo, and due to a tight schedule for practicing, the level acquired was not enough to master them, an essential requirement for high-quality experiments. Applying the GD learnings to an actual project would have given more understanding of the tools' practical use and allowed the detection of more uses, benefits, and challenges.

As this thesis has focused mainly on the Revit GD tool and Dynamo, it is suitable to investigate further the use of Textual Programming Language for Dynamo, which is considered an advantage when working on GD scripts and other types of automation tasks. Also, considering the various GD tools that exist for the AEC industry, it would be interesting to study all the tools available on the market, compare their benefits, challenges, and potential uses and define which would be the most suitable to solve architectural design problems.

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