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Parametric simulation as a tool for deep learning experience in Building science

Master's thesis in Sustainable Architecture
Supervisor: Francesco Goia
Co-supervisor: Gabriele Lobaccaro
May 2023

Master's thesis

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Abstract

A world in rapid change across several spheres demand buildings of an adaptability and resilience that make design projects and objectives more complex than ever (1). Solving these complex tasks require multidisciplinary teams with mutual understanding between members and each other's fields of expertise. Still, the comprehension and collaboration between architects and engineers are often superficial, and the utilization of potential revolutionising tools are too low. A key issue that keeps the gap open between the fields of architecture and building science is the complexity that lies within their interface. It is usually not a lack of willingness that stops either part from accommodate the other's desires in the design process. Rather, it is the overwhelming complexity of shifting their view from what they have been programmed to since their early years of studies, constantly focusing on finding the best solutions within their own discipline. The result being that the important aspects emerging between them stay unrevealed, and the potentially best solutions fail to appear.

This is what this thesis is trying to fix, with help from parametric simulation software. To bring out the potential benefits of a nurturing relationship between the two disciplines already from undergraduate level of education, a simulation model that visualize the impacts they have on each other is developed. The study investigates how parametric simulation can be used as a tool for deep learning experience in Building science. It demonstrates important steps in the development of a prototype, through planning, modelling, and closed beta testing. All three phases have provided useful experience, that can benefit both future development of the tool and similar software, the use of parametric simulation in education, and in turn help bridge the gap between architecture and building science.

Results of the thematic analysis performed on interview material from the closed beta testing show benefits of demonstrating emergent properties, visualizing interconnections and in general providing a holistic view to the complex subject. Answers from closed beta testing also show that most of the participants found the simulation model to have high potential as a tool for dealing with complexity in education. At the same time, feedback show that the prototype has some potential for improvement of the overall user experience, with ratings ranging it from "bad" to "very good". This is also a good representation of the experiences gained from planning and developing the prototype, which have provided useful reflections on both benefits and limitations of parametric simulation used as a tool for deep learning experience in building science.

Sammendrag

En verden i stadig endring på flere områder krever bygninger av en tilpasningsevne og motstandsdyktighet som gjør designprosjekter og deres mål mer komplekse enn noen gang (1). Å løse disse komplekse oppgavene krever tverrfaglige team med gjensidig forståelse mellom medlemmene og hverandres fagfelt. Likevel er forståelsen og samarbeidet mellom arkitekter og ingeniører ofte overfladisk, og utnyttelsen av potensielt revolusjonerende verktøy er for lav. Et sentralt tema som holder gapet åpent mellom fagfeltene arkitektur og bygningsfysikk er kompleksiteten av grensesnittet mellom dem. Det er vanligvis ikke mangel på vilje som hindrer noen av partene fra å imøtekomme den andres behov i designprosessen. Snarere er det den overveldende kompleksiteten ved å skifte sitt perspektiv fra det man har innstilt seg til helt siden de første studieårene, nemlig å hele tiden først og fremst fokusere på å finne de beste løsningene innenfor sin egen fagdisiplin. Resultatet er at de viktige aspektene som finnes i grensesnittet mellom dem forblir uavdekket, og de potensielt beste løsningene uteblir.

Det er denne utfordringen som forsøkes å løse i denne oppgaven, ved hjelp av parametrisk simulering. For å få frem de potensielle fordelene av et oppbyggende forhold mellom de to fagdisiplinene allerede fra bachelornivå, er det utviklet en simuleringsmodell som visualiserer virkningene de har på hverandre. Studien undersøker hvordan parametrisk simulering kan brukes som et verktøy for dyp læringserfaring i bygningsfysikk. Den demonstrerer viktige steg i utviklingen av en prototype, gjennom planlegging, modellering og lukket beta-testing. Alle tre fasene har gitt nyttige erfaringer, som kan komme til gode både for fremtidig utvikling av verktøyet og lignende programvare, for bruken av parametrisk simulering i utdanning, og i neste ledd bidra til å bringe fagfeltene arkitektur og bygningsfysikk tettere sammen.

Resultater av den tematiske analysen utført på intervjumateriale fra den lukkede beta-testingen viser fordeler ved å demonstrere emergerende egenskaper, visualisere sammenkoblinger og generelt gi et helhetlig syn på de komplekse temaene. Svarene fra lukket betatesting viser også at de fleste av deltakerne syntes at simuleringsmodellen hadde stort potensiale som et verktøy for å håndtere kompleksitet i utdanningssituasjoner. Samtidig viser tilbakemeldinger at prototypen har et visst forbedringspotensial når det gjelder den generelle brukeropplevelsen, med vurderinger som varierer fra «dårlig» til «veldig bra». Dette er også en god representasjon av erfaringene fra planlegging og utvikling av prototypen, som har gitt nyttige refleksjoner om både fordeler og begrensninger ved parametrisk simulering brukt som et verktøy for dyp læringserfaring i bygningsfysikk.

Preface

I would like to express my deepest gratitude to my main supervisor, Francesco Goia at the Department of Architecture and Technology, and my co-supervisor, Gabriele Lobaccaro at the Department of Civil and Environmental Engineering, both at the Norwegian University of Science and Technology (NTNU) in Trondheim, for the idea and opportunity to do this research. Thank you for your supportive and constructive guidance both when planning the simulation model and working on the project. Your knowledge and insight have been crucial.

I would also like to thank Yunbo Yang at the Department of Architecture and Technology at NTNU, for sharing her model of the ZEB Living Lab, which the geometry of the prototype developed in this thesis is based upon.

Thanks also to the rest of the staff at the master's programme in Sustainable Architecture at the Department of Architecture and Technology at NTNU, for providing useful feedback during presentations and discussions during the studies.

Furthermore, I would like to thank the students in the building science course in the 5-year master's degree programme in Architecture at the Department of Architecture and Technology at NTNU that participated in the closed beta testing of the prototype and provided important feedback through interviews.

Finally, I would like to thank my fellow students in the class for their indispensable friendship and social unity in the programme, to friends, family and my girlfriend Aurora for their valuable support, faith, and motivation throughout the project.

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List of Abbreviations

LCA	Life Cycle Assessment
NTNU	The Norwegian University of Science and Technology
PV	Photovoltaic
TEK17	Regulations on technical requirements for construction works (Byggteknisk forskrift)
ZEB	Zero Emission Building
ZEB-COM	Zero Emission Building in Construction, Operation and Materials
ZEB-O	Zero Emission Building in Operation

1 Introduction

This chapter gives an introduction to the research done for this thesis. Divided into three chapters, it starts by explaining the motivation for the tesis, followed by a problem description, where the research question is presented. The last subchapter presents the thesis outline.

1.1 Motivation

A world in rapid change across several spheres demand an adaptability and resilience of buildings that make design projects and objectives more complex than ever (1). The built environment must handle the strain of nature and climate change causing everything from heavy rainfall and strong winds to earthquakes, floods, and draughts. Pandemics and flexible workdays present a shift in use patterns of buildings, while digitalization and automation of industries around us are changing both the need for space and the way we work. Solving these complex tasks require multidisciplinary teams with mutual understanding between members and each other's fields of expertise. With a high-speed technological evolution in development of tools and software for simulation and design, the possibilities for collaborations and streamlining of processes are endless.

Still, the comprehension and collaboration between architects and engineers are often superficial, and the utilization of potential revolutionising tools are too low. Engineers often fail to appreciate the quality of innovative design beyond the most practical and feasible solutions. Architects, on the other side, often struggle to realize the importance of respecting physical principles and solid technical solutions. Both their aspirations are of great importance, but when competing against each other instead of working together, the most ground-breaking solutions for todays and tomorrow's world fail to appear.

A key issue that keeps the gap open between the fields of architecture and building science is the complexity that lies within their interface. It is usually not a lack of willingness that stops either part from accommodate the other's desires in the design process. Rather, it is the overwhelming complexity of shifting their view from what they have been programmed to since their early years of studies, constantly focusing on finding the best solutions within their own discipline. The result being that the important aspects emerging between them stay unrevealed, and the potentially best solutions loose.

This is what this thesis is trying to fix, with help from parametric simulation software. To bring out the potential benefits of a nurturing relationship between the two disciplines already from undergraduate level of education, a simulation model that visualize the impacts they have on each other will be planned, developed, and tested. Reflections of the experiences and results from all three phases can benefit both future development of the tool and similar software, the use of parametric simulation in education, and in turn help bridge the gap between architecture and building science.

1.2 Problem Description

A broad perspective on the problem area addressed in this thesis are the difficulties students face when trying to understand the content of a course with high complexity and interconnections between different fields of study. A common way of teaching complex subjects is to break them up in smaller pieces and present principles and details in each individual part from the ground up (2). Theory on innovative learning strategies suggest that there also can be benefits of using a more holistic approach (3). Moreover, digital tools and simulation software are widely used in education, but usually most for solving specific tasks and studying confined topics, often in graduate levels (4).

The aim of this thesis is to demonstrate how parametric simulation can be used as a tool for deep learning experience in building science, providing a more holistic view to the subject. As an example, a simulation model will be developed to visualize effects of design decisions on building physics parameters, like energy use and indoor comfort. The research question for the study is formulated as follows:

"How can parametric simulation software be used to develop an educational tool for helping students in building science handle complexity?"

To answer the research question, the thesis demonstrates important steps in the development of a prototype, through planning, modelling, and closed beta testing. All three phases will be discussed to provide useful experience about benefits and limitations of using parametric simulation software to model a tool for deep learning experience in building science. Through thematic analysis on feedback gathered from closed beta testing and interviews, it will be reflected on the potential of the tool to help students handle complexity in their course by using a holistic approach.

1.3 Thesis Outline

The following content of the thesis is structured like the outline in table 1.

Table 1: Outline for the rest of the thesis.

Chapter		**Description**
2	Background	Presents relevant theory.
3	Methodology	Describes the methodologies used to plan, model, and test the simulation model.
4	Results and Discussion	Presents and discusses results and findings of the development process, modelling, and testing of the simulation model.
5	Conclusion	Summarizes and concludes the work done for this thesis and proposes future work to be carried out.

2 Background

2.1 Literature Search Strategy

This thesis mostly revolves around the use of parametric simulation tools, building science and theory on pedagogy and complexity. Since the topics of parametric simulation and building science was mainly explored and used in practice, based on video-tutorials and related course content, theory of pedagogy and complexity was the main focus of the literature search. For this, search words such as "complex systems", "dealing with complexity" and "principles of complexity", "teaching methods" and "pedagogic principles" were used to search for literature in Oria and Google Scholar. When the theory of threshold concepts was discovered, this was investigated further together with characteristics such as "troublesome", "holistic", "transformative", "resilience" and "feedback loops". Some readings were discovered by following citations in the relevant papers. Some literature searches were also done on the principles of the methods used for conducting the research, such as beta testing, semi-structured interviews and thematic analysis.

2.2 Theory

This subchapter presents some of the most essential theory used, and how it is adapted, when conducting the study and answering the research question.

2.2.1 Pedagogic Strategies

Having an overview of the theory behind the most common pedagogic strategies for teaching complex systems was seen as a benefit when planning the simulation model. Both to find some potential tips on basic principles that could benefit the effect of the model as a learning tool, but also to have a clear view of benefits and limitations of the traditional methods that this project aims to challenge with its more holistic approach. Here, a brief introduction to both traditional and innovative pedagogic strategies are presented.

What most traditional pedagogic methods have in common is that they often have a strategy of dividing the subject into smaller pieces, which they address one part at the time. Usually, a set plan is made for guiding the students through all the material. The material often includes theory with explanations of important principles, examples, and demonstrations. Presenting the material to students is often done through lecture-based instruction or textbook-based learning. Here, the engagement is often small. An essential element in learning complex subjects is to also apply the knowledge they gain, which is why exercises and problem-solving activities are important parts of traditional pedagogy. To investigate what the students have learned, tests are often performed after each step, and a larger examination in the end. These traditional principles are well tested and solid methods of introducing knowledge to students, which they can apply to tasks they have trained at and evolve gradually (2, 5).

What can be considered more innovative strategies of pedagogy are the learner-centered approaches. These have often in common a higher focus on student interaction, leading to more engagement, critical thinking, and better problem-solving skills (3). The use of digital tools is well suited for this type of learner-centred approaches, as they often are more interactive than traditional media, and can easier visualize a more holistic view on the subject (6).

Even though digital tools and software can be used for demonstrations and modelling of ideas and concepts in traditional teaching methods as well, the focus is often still on single steps and tasks at the time (7). Innovative strategies on the other hand, might often lack the proper introduction of some important principles within the subject. However, the holistic view they provide can be effective when used in combination with traditional methods, for a deeper learning experience in complex subjects (8, 9, 10).

2.2.2 Complexity

As presented in the introduction chapter, the goal of this thesis is to demonstrate how parametric simulation software can be used to help students handle complexity in their field of study. What seems to be a natural way to start is to get more familiar with the concept of complexity. Complexity can be defined in many ways, and there are many different types of complex systems. What complex systems have in common is that they consist of multiple different elements that interact with each other based on rules. The complexity is the result of this interaction. Even simpler, a complex system can be defined as a collection of multiple different elements that share several connections to each other (11). To plan, develop and test the simulation model in this thesis in a way that demonstrates its potential to deal with complexity, an attempt was made to break down the theory and gather some key principles that illustrates aspects of the topic.

The first concept found to be important for the understanding of complex systems is emergence. Emergence is behaviours or aspects of a system that result from the interconnections of elements and cannot be recognized by looking at them individually. Understanding and acknowledging emergence can help us appreciate that complex problems require holistic thinking and systemic approaches (12).

The next aspect included is non-linearity, which, as the term implies, is addressing the fact that relationships between elements of complex systems often are not linear. Sometimes the results of a decision can seem unexpected and confusing, as it deviates from the clear cause and effect that people often are used to and logically expect. Being able to understand and anticipate that the input and output of the system might not be in the same magnitude is important for handling complexity (13).

Another key phenomenon of complex systems are feedback loops. This can be described as the way output information is fed back into the system to reinforce positive feedback or regulate negative feedback. Since the process is intertwined, it is difficult to apply common reasoning of cause and effect to it, and the system must rather be investigated in a holistic view. If visualized and presented in a graspable way, it can help the understanding of patterns and break down complexity (14). In this thesis, the term is used in a slightly simpler way, referring to the feedback between parameters in the simulation model and the user making design decisions.

The last aspects chosen to include about complexity are adaptation and resilience. As unforeseen disruptions and disturbances can affect complex systems, they need to be able to adapt to variable surroundings and fit in with the connected elements. At the same time, they must keep their initial purpose to solve the task they were supposed to (15). Improving such a robustness can be beneficial when manoeuvring in complex situations.

Taking advantage of the qualities and principles explained above can be helpful when dealing with complex systems, to learn new connections and solve complex tasks. In this project they will first and foremost be used as discussion points for the simulation model's potential to help cope with complexity.

2.2.3 Threshold concepts

To supplement the general theory about complexity, another related topic that is useful for investigation of complex systems is threshold concepts. This is a term developed by Jan Meyer, Ray Land and colleagues to express a certain sort of transformative idea or concept within a discipline, that gets integrated in students' thinking. This can lead to new ways of approaching topics and is regarded powerful when it comes to learning and handling complexity. What can separate threshold concepts from other pedagogical concepts is that it involves a shift from how students are used to think of a subject to a new territory of interconnections that might be more difficult to understand at first. The advantage is that the new understanding also is deeper than before (16). In the same way as for the theory of complexity, the theory of threshold concepts is broken down in some key factors that will guide the evaluation of the simulation model's ability to solve its purpose. Different characteristics of threshold concepts have been developed, some of which the factors in this thesis are based on. However, some are interpreted slightly different when used in the analysis in this thesis, to relate better to the prototype modelled. The factors used in this thesis are listed in the following paragraphs.

The first factor decided to use is *transformative*, referred to as transformation in this thesis. This addresses the idea of a shift in the student's perception of a subject, like described about the concept already, and is the essential characteristic of a threshold concept (17).

Irreversible is the next factor. As the word suggests, this describes how threshold concepts give such a well-established understanding of a subject that it is unlikely to be forgotten, unless a proper attempt is made to unlearn it.

Another factor already mentioned when presenting threshold concepts is called *troublesome*, which speaks about the threshold concept's tendency to be initially challenging to grasp. In this thesis the aspect is referred to as difficulty. This initial difficulty can often be overwhelming to students, leading to confusion, frustration, loss of confidence and in the worst case giving up.

Integrative is another important aspect of threshold concepts. This looks at the ability to reveal interconnections and relationships between elements of a complex system. To follow the pattern of using nouns for the descriptions of factors in the thesis, this aspect is here called integration.

The last factor of threshold concepts considered in this thesis is called *bounded*. This involves the threshold concept's ability to illustrate the boundaries that are regarded essential for the field. In the analysis of this thesis, this is used to represent the simulation model's ability to provide a holistic view, which the factor is referred to in the thesis.

Recognizing and exploiting threshold concepts can have great benefits in education, both for students and educators. For students, being aware of threshold concepts can avoid complete loss of confidence when facing overwhelming tasks, by having the motivation of gaining a deeper understanding once grasped. For educators, the theory of threshold concepts can be powerful tools for designing curriculum and learning experiences, to bring out the pivotal understandings of how the discipline work (16).

3 Methods

This chapter presents how the study is approached to answer the research question. Divided into three subchapters, it explains how the simulation model was planned, modelled, and tested.

3.1 Simulation Model Planning

This subchapter explains the planning phase of the simulation model.

3.1.1 Simulation Model Objectives

The first step in software development is to identify the need that the tool is meant to solve (18). This is important for scoping the project and finding suitable solutions. As explained in the introduction, the overall goal of the tool developed for this thesis is to demonstrate how parametric simulation can be used as a tool for deep learning experience in building science. Specifically, the goal for the simulation model is to help students in undergraduate education handle complexity and understand the interconnections of architecture and building physics.

The scope of the model is to visualize effects of design decisions on building physics parameters, like energy use and indoor comfort.

The goal is not to learn students the specific details and calculations of topics in the course. This is still done in traditional ways, with lectures, calculation exercises, assignments etc. Instead, the model will aim to demonstrate how parametric simulation can be used as a tool for providing a more holistic view on the complex interconnections.

The goal is also not to teach students parametric simulation software. From a user's point of perspective, the model will therefore be developed to function as a black box, only displaying changeable input parameters and a selection of interconnected results of design and performance, in a holistic view.

As elaborated on in chapter 3.3.5, it is challenging to do research on students real understanding of a topic, especially within the scope of this thesis. Therefore, the goal will rather be to investigate how they respond to the model during testing, and to get their view on the simulation model's potential for helping them handle the complexity in their course.

To have a clear scope of the desired content and level of complexity to use for the simulation model, the students of two building science courses at NTNU were chosen as target audience. Both were undergraduate introduction courses, one belonging to the study programme of civil and environmental engineering, and the other to the programme of architecture. Apart for some variations, the syllabus of these two courses is overall quite similar. For planning of the simulation model in this thesis, the building science course in the programme of architecture is used as a basis for the scope of the specific focus and structure of its content. It was for this course the idea of the tool originated, by the course coordinating professor, Francesco Goia, who is also the main supervisor of this thesis.

The shape of the 3D geometry in the simulation model is based on the ZEB Living Lab at NTNU's campus *Gløshaugen* in Trondheim. This was done to make it more relatable to the students, compared to a simple box or some other design. At the same time, the ZEB Living Lab was found to be a good example of a suitable scope for the design, because of its size and possibilities for demonstrating design changes. However, other properties than the building form are not related to the ZEB Living Lab as designed or built in real life.

Figure 3.1: ZEB Living Lab at NTNU in Trondheim. Image source: Sintef, "ZEB Living Lab". Accessed via: https://www.sintef.no/laboratorier/living-lab/

3.1.2 Development Tools

The software Rhinoceros 3D and Grasshopper 3D will be used for the simulation modelling. In addition to standard components and functions for these programs, some plugins will be installed to access some additional components. The most important plugin for this model is Ladybug Tools, which among others include Ladybug features for climate data and Honeybee for energy simulations. To run energy simulations with Honeybee, Open Studio is also installed, including Energy Plus for energy simulations and Radiance for daylight simulations. To access some of the older components that will be useful for certain tasks, the Ladybug and Honeybee Legacy Plugin will be installed alongside the latest version of Ladybug Tools. Another plugin that will be installed is Bifocals, which displays the names of all components on the canvas and can be very useful when learning the software or new features for the first time.

3.1.3 Modelling Approach

The project was approached by getting an overview of the curriculum and complexity that the students were faced with, which the model was supposed to help them with. Since it was thought of as a clever principle to plan the tool in a modular way, the modular structure of the subject's content was applied to the planned outline of the simulation model.

Since the related building science course teaches the principles of all phenomena in a detailed bottom-up approach, not all the content was relevant to visualize in the simulation model. Focusing on a more holistic view of the subject, a lot of the detailed calculations taught in the subject would be happening in the background of the simulation model. Of course, some would argue that an important educational principle would be to present the background calculation as well (2). However, focusing on a more holistic approach is a choice that was made for this model. As mentioned in the problem statement, investigating the potential of this holistic view was part of the goal for the thesis.

When planning which parts of the subject to include in the simulation model, it was focused both on their importance in a broader perspective, and on the potential they would have to show impacts resulting from design changes. The considerations were made based on own prior knowledge, experience, and assumptions. Table 2 shows an outline of all the building physics phenomena and parameters from all five modules of the course that were planned to visualize in the simulation model. The considerations about importance and potential for visualization were also used to give priorities from 5 to 1 of which parameters were seen as most valuable to include. Chapter 3.2 briefly presents and discuss some parameters and connections considered for each module.

As chapter 4.1 and 4.2 will show, not all parameters in the plan were implemented in the prototype developed for the thesis. The colour coding of the priority numbers for each parameter shows which were included and not. Those marked in green are included and clearly relevant in both inputs and outputs of the user interface. Those marked in orange represent properties that are included in the simulation, but are either not made changeable among the input parameters, or are not particularly relevant to the visible output parameters. The parameters marked in red are left out of the prototype.

3.1.4 Simulation Model Outline

Table 2 presents an overview of the content planned to be included in the simulation model. Both the content and the modular division are based on the syllabus in the building science course which the tool is meant for.

Table 2: Simulation model outline.

Module	Category	Input parameters	Priority	Influence parameter/ Phenomena	Impact parameters	Output
1	Climate	Outdoor air temperature	5	Heat exchange Air infiltration Natural ventilation	Heating & cooling	Energy demand
		Outdoor relative humidity	3	Specific heat capacity Moisture transfer	Heating & cooling Ventilation	Energy demand Psychrometric chart
		Ground temperature	1	Heat exchange	Heating & cooling	Energy demand
		Wind	1	Air infiltration Convective heat transfer	Heating & cooling	Energy demand
		Sky radiation and ground radiation	2	Radiative heat exchange	Heating & cooling	Energy demand
		Solar radiation	4	Radiative heat exchange Daylight	Heating & cooling Artificial lighting Daylight	Energy demand Daylight
		Precipitation	1	Moisture intrusion	Vapor content	Mould growth Mechanical stress
	Orientation	Building axis relative to north	3	Conductive heat exchange Radiative heat exchange Daylight	Heating & cooling Daylight	Energy demand Daylight
	Local climate	Topography	2	Wind Solar radiation Background noise	Heating & cooling Daylight	Energy demand Daylight Acoustical comfort
		Surrounding elements	3			
2	Geometry	Size	4	Conductive heat exchange Radiative heat exchange Compactness	Heating & cooling Sound pressure level	Energy demand
		Roof angle	4			
		Envelope surface area	4			

	Thermal envelope construction	Thermal transmittance	5	Conductive heat exchange	Heating demand Cooling demand	Energy demand
	Thermal bridges	Linear heat loss coefficient	2	Conductive heat exchange	Heating & cooling Local thermal comfort Condensation	Energy demand Mould growth Mechanical stress
	Windows	Window to Wall ratio Glazing properties	5	Direct solar transmittance Direct visual transmittance G-value Thermal transmittance	Heating & cooling Local thermal comfort Condensation Daylight	Energy demand Daylight
	Shading	Type of shading devices	5			
3	Airtightness	Air Change per Hour (ACH)	2	Infiltration Exfiltration	Heating & cooling	Energy demand
	Ventilation	Airflow rate	2	Heat balance Mass balance	Heating & cooling Ventilation rate	Energy demand
	Thermal inertia	Thermal effusivity	3	Temperature Heating demand Cooling demand	Heating & cooling	Energy demand
	Boundary conditions	Building program	3	Set point temperature Activity level Occupancy Ventilation requirements	Heating & cooling Ventilation demand	Energy demand
4	Daylighting	Window distribution and placement	5	Illuminance level Luminance distribution Light distribution	Daylight Visual comfort	Daylight
	Shading	Type of shading devices	5			
5	Acoustics	Room dimensions	2	Echo Reverberation time Airborne sound transmission Impact sound transmission	Sound pressure level Reverberation	Acoustical comfort
		Room geometry	2			
		Material reflection	2			
		Material absorption	2			
		Material diffusion	2			

3.2 Simulation Model Content

This subchapter briefly presents some parameters and connections considered for each module of the simulation model, based on the five modules of the syllabus for the related building science course. This is mainly a description of the information presented in the outline in Table 2.

3.2.1 Module 1

The first module will mainly be about the impact of climate on the building's performance. The main categories within this module will be the climate itself, orientation, and microclimate.

The climate will be changeable by selection of location. This will determine all input parameters in the simulations, such as outdoor air temperature, outdoor relative humidity, ground temperature, wind, sky radiation and ground radiation, solar radiation, and precipitation. The most important input parameter in this category is the outdoor air temperature. This parameter will impact phenomena such as heat exchange, air infiltration and natural ventilation, which in turn impact heating and cooling demand. The result that will be displayed to the user is energy demand.

Another important input parameter is solar radiation. This parameter will impact daylight in addition to heating and cooling, and will also be displayed as results. The category of orientation will be changeable by adjusting the building axis relative to north. This input parameter will impact the same results as solar radiation.

The last category within the first module is local climate, or microclimate. Possible input parameters in this category will be topography, such as openness of the terrain, and surrounding elements, such as trees, and neighbouring buildings. These input parameters will probably be changeable through a list of options. They will impact both wind, solar radiation, and background noise. The visible results of impacts will be energy demand, daylight, and acoustical comfort.

3.2.2 Module 2

The second module will be mainly about the building envelope. The main categories within this module will be the geometry, thermal envelope constructions, thermal bridges, windows, and shading.

The geometry will be changeable by selection of size of floor area, roof angle and envelope surface area, through the shape of the building. These parameters will impact both conductive and radiative heat exchange and the compactness factor, which might will be displayed, together with the resulting energy demand.

The next category is thermal envelope construction, with thermal transmittance as the most important changeable input parameter. This will be controlled either directly with the u-value, or more in detail by construction properties such as heat conductivity, thickness, and specific heat capacity of materials. The thermal transmittance will impact the heating and cooling and show results on energy demand.

The category of thermal bridges will have the input parameter of linear heat loss coefficient, impacting conductive heat exchange, and showing results on energy demand. A more advanced feature could be to also show thermal bridges illustrated in 2D, with results of potential condensation risk.

The category for windows in this module will have window to wall ratio and glazing properties as input parameters. This and the category for comparing different types of shading will impact phenomena such as direct solar transmittance, direct visual transmittance, g-value and thermal transmittance. The visible results will be energy demand and daylight.

3.2.3 Module 3

The third module will be mainly about heat and mass balance in the building. The main categories within this module will be airtightness, ventilation, thermal inertia and boundary conditions, such as type of building, equipment, occupancy etc.

For the categories of airtightness and ventilation, the air change per hour and airflow rate could be adjustable, ultimately impacting energy demand.

The same goes for the category of thermal inertia, where input parameters could be surface materials of varying thermal effusivity. This feature could also show indoor temperature to demonstrate its impact on setback strategies.

3.2.4 Module 4

The next module will be mainly about daylight. The main categories within this module will be windows and shading, with changeable input parameters representing window to wall ratio, window distribution and placement, and types of shading. This will impact parameters such as illuminance level, light and luminance distribution, and glare. This can be visualized through advanced daylight simulations and possibly glare analysis.

With this module being closely interconnected to the impact on energy use, these results would also be presented. Since windows and shading are included in module 2 as well, the control units could be more or less the same. The difference would be mostly in the results, where module 2 focuses mainly on energy demand, while module 4 goes more in depth on daylighting. However, some key results should be visualized from both at the same time, since these interconnections are important parts of what the model aims to visualize.

3.2.5 Module 5

The final module will be about acoustics. This has only one category, where the input parameters will be room dimensions, room geometry, material reflection, material absorption and material diffusion of walls, ceilings, and surfaces. These impact both echo, reverberation time, airborne sound transmission and impact sound transmission, which in turn show results on acoustical comfort in the form of sound pressure level and reverberation. Different methods can be explored for simulation of acoustics from indoor sources and for simulation of outdoor noise, with varying construction materials. Even though there are interesting relationships between the potential input parameters mentioned for acoustics and design decisions in other modules, that could be useful to demonstrate the effect of, the topic of acoustics is not regarded as the most essential aspect to visualize in this thesis. To scope out a realistic plan for the tool being developed in this thesis, module 5 will therefore be left out in the first prototype, represented by a low priority in table 2.

3.3 Closed Beta Testing

The first step taken to answer the research question was to demonstrate how the tool could be modelled using parametric simulation software. Since the goal of the tool is to help students handle the complexity in their course, a natural second step is to investigate how effective the model is in solving this task. A good way of doing this is to perform closed beta testing with the target audience for the tool. This will both bring discussion points about the tool's potential for breaking down complexity and illustrate an important step in the software development process, that provide useful feedback on user experience. This chapter will present the methods of the closed beta testing used for the empirical study in this thesis.

3.3.1 Participants

As mentioned already, the target audience for the simulation model is students in undergraduate building physics courses. It was for one of these courses the idea of the tool originated, by the course coordinating professor who is also the main supervisor of this thesis, Francesco Goia. The students in his course are therefore a natural target audience for closed beta testing and interviews about the simulation model.

This is a mandatory introduction course held in the first year, second semester of the five-year master's programme in architecture at NTNU in Trondheim. Other courses in the first year of the programme are mainly focusing on form and colour, aesthetics, philosophism, creativity, as well as some mechanics, loads and structure. The building physics course gives them in introduction to theory, principles and calculations of phenomena and topics such as those presented in table 2. However, they have not yet been subjected to energy simulation and modelling of performance using software. Nor have they started using computer aided design much for their architecture projects. The students are in other words quite newbies when it comes to the use of simulation software through the studies. For many of the first-year students, the closest previous experience they have to the simulation model being tested in this project are software used in maths and science courses in upper secondary school, and any games or modelling software tried on their spare time.

To recruit participants, a presentation of the research project was given to the students during the first 15 minutes of a lecture in the building physics course, three days before the day of the testing. The testing was performed during learning assistance hours for the course, in the studio rooms where many of the students would be around anyway, studying building physics or working on other projects. Because of this, the timing of the information and recruitment presentation is assumed to have been effective, even though three days in advance may seem like a short notice. Notifying the students earlier could have risked them forgetting about the testing, since they had no obligation to it. Even though participating was voluntary, in a period where exams were closing in, it was assumed that at least some students would be interested enough to take the time to test the model. After all, the content is designed to be relevant to their specific course. To spark interest for participation, the presentation also tried to communicate the benefits the concerning topics could have later in their studies and career. Participation in the testing could both help them see the importance of a focus on the interconnection between design choices and building physics, give them an introduction to energy modelling and parametric design software, and give them a peak into the work of a master's thesis in a related study programme.

Less than ten students, about 30% of the class, attended the lecture where the presentation of the research project was held. Still, there were more than enough students present in the studio on the day of the testing, since this is where a lot of them usually sit to study and work on projects. A total of nine students tested the model and gave feedback in interviews afterwards. Number of students available for testing and interviews was not a limiting factor for the number of participants. The time that it took with testing, interviewing, and completing the notes between each round, meant that the workday was over when nine students had been interviewed. More students would probably have participated another day if necessary. However, nine participants were considered enough, as the initial goal was around eight to ten. Furthermore, the feedback collected at that time had been varied, but started to get repetitive. Since the goal was to gather qualitative feedback rather than quantitative data, it was seen as unnecessary to collect more answers most likely quite similar to others. However, when investigating the trends of opinions in the thematic analysis explained in chapter 3.3.5, a larger group of participants would without a doubt have made the results more reliable.

3.3.2 Procedure

As mentioned, the testing and interviews were performed in the first-year students' studio rooms. The students present on the day of the testing were studying and working on projects by themselves and in groups. Students who seemed like they were not too busy or focused on a task were approached and asked if they wanted to test the simulation model and be interviewed about it afterwards. Some of them had been in the lecture where the research project was presented three days earlier, while others heard about it for the first time that day. They were all informed that the experiment was anonymous, as no personal data would be collected. Everyone who was approached was willing to take part in the experiment and seemed to be interested in trying the simulation model.

A laptop with the model files and all necessary software installed was brought around in the studio for the students to test the simulation model. In this way, there were no need for the students to do any preparations, like installing all the right software and setting up the viewports in Rhino and Grasshopper. This is regarded as crucial for the participation in the testing of the prototype in this project.

Once the laptop was set up for testing, the student was given a brief introduction to the control panels of changeable input parameters and where the different results would be displayed. They then spent some time with the model themselves, trying out its functions. Since each input change require some runtime to be executed, it can take up to a few seconds from the command is given by the user to an impact in the results are visible. For this reason, not all possible changes were tried by every student. The focus was on letting them try all main types of inputs and design changes. For example, there is not much added value in trying to change every single option for the window placements in all orientations. What is most important is that they see the impact that window placement in general has compared to changing the climate, geometry, or construction properties.

Another goal was for everyone to try the different types of control unit operators, as this is one of the main design choices to be made when it comes to the user interface. A perhaps even more important factor regarding the user interface is the display of results. For this reason, a collection of different diagrams, charts, 3D geometry and a table were displayed in different viewports in Rhino. The students had the ability to choose which results to look at but were also guided to some degree to understand the layout of where the impact of their design changes would show. This could have an impact on their experience of the tool, especially when it comes to questions regarding the user interface and visualization of results. However, the guidance was mostly just repetition of information that had already been given in the introduction before they started exploring the model themselves. When participants needed some guidance to navigate in the results, this was also part of the impression of how well the model functioned to its purpose. Of course, all impact on the research from guidance on how to navigate the model could have been avoided by recording a video tutorial with an introduction instead. Since the goal of the experiment was to gather feedback on the potential of the model, and not to measure its exact effect on the students learning, the method of guiding participants and noting their struggles with the tool was considered reliable.

3.3.3 Data Collection

After the student had spent some time with the simulation model and tested all its most important features, we went on with the interview. These were conducted as semi-structured interviews with each individual student. Two of the interviews were conducted in focus groups with two and three students at the time. However, the questions were the same as in the individual semi-structured interviews. The style of the dialog was also quite similar, only with more answers and discussion to each question.

A list of questions was prepared, but some of the phrasing and order was adapted to the dialog in each interview. The questions are divided into the topics of complexity and user experience. The following list presents all the questions and explanations that were prepared in advance and used as a basis for the interviews.

Complexity

- "Do you think this tool has potential for improving students' general ability to handle complexity, regarding the interconnection of building science and architecture?"
- "How does this model affect your ability to see a holistic view of the course and understand how the various parts affect each other? "
- "Do you think you learn best when you have great or little freedom of choice to change elements in the model?"
    - "For example, do you prefer to be able to adjust many parameters for the same element, such as the windows and sun shading, or to concentrate on fewer or only one parameter at a time, such as climate and orientation?"
- "How do you think using this model can contribute to collaboration with others on complex tasks?"

User experience

- "For adjusting parameters in the model, you have tried both dial button, number sliders, on-or-off buttons, and drop-down lists with either single values or complete value sets."
    - "Which adjustment method did you find most intuitive or appropriate for the operation it was supposed to perform?"
- "Among the visualization methods you have seen in the model, there are displays of results both in the form of tables, bar charts, balance charts, graphs, colouring of the 3D model and colour maps on the floor plan of the model."
    - "Which visualization method do you think best brought out the results it was supposed to show?"
- "Which visualization method did you find most difficult to understand?"

- "Is there anything you would like to highlight as good about the model?"
    - "What did you like the best? "
- "Is there anything you would like to point out as bad or challenging about the model?"
    - "What did you like the least?"

As mentioned, the goals of the interviews were both to bring discussion points about the tool's potential for breaking down complexity, and to illustrate an important step in the software development process, that provide useful feedback on user experience. This should again help answer the research question. The questions in the first topic were therefore formulated in such a way that the answers could be analysed based on theory about complexity in learning described in chapter 2. The questions in the second topic were formulated in a way that could provide feedback about user experience, which would be useful for further development of the tool. Since the two topics are related to each other, some answers were expected to be beneficial for both purposes when analysed.

The answers were written down in the form of notes during the interviews, which were cleaned up right after each interview. At this point, the responses were still fresh in mind, and could be properly transcribed. All participants were given a number based on the order they were interviewed in, to separate them later in the process. The participants in the focus groups were given two-digit numbers that represented the order of their interview while at the same time separated them from the other members of the focus group. The numbers of the nine participants from the six interviews or focus groups are thereby 1.1, 1.2, 1.3, 2, 3, 4, 5.1, 5.2 and 6. Using numbers that represented the order of the interviews made it easier to remember and keep track of the responses.

When only writing notes by hand during interviews, there is always a risk of information bias or missing some nuances (19). Recording the answers would have eliminated this risk. The main reason why audio recording was not used in this study it that it is classified as personal data, which require an application to Norwegian Centre of Research Data (NSD) at least a month before collecting it (20). Since the plan earlier in the project was to collect feedback from the closed beta testing using a survey, this application was not sent before it was too late. No application is required for interviews where anonymous answers are written down without any personal or recognizable data, which is how the data collection was done in this thesis (21). Even though it was not as verbatim as a recording, noting the data by hand was also considered a well-suited method for collecting data in this experiment. This allowed the answers to be slightly filtered for what was known to be relevant, and capturing the overall expressions that the participants gave when testing the tool, rather than just transcribing word by word from a recording.

3.3.4 Research Design

Even though the phrasing and order of questions varied in each interview, it was always stressed to avoid research bias. The questions were therefore phrased unambiguous, while at the same time not leading. However, the circumstances could still entail a risk of research bias, like social desirability bias (19). For example, the only reason why some students said they were a little bit hesitant to participate when approached, was that they did not feel very confident in their building science competence. When they were told that this was no problem for using the tool, and that it was fully anonymous, they wanted to join anyway. However, the fact that they were asked questions that might reveal some of their level of knowledge in their field of study, could have influenced the way they answered in some parts. One effort made to avoid this was to phrase the questions indirectly. For example, they were asked how they thought other students in their situation in general would experience the simulation model, not how they as individuals experienced it.

The fact that they were asked questions about a simulation model made by the person who were interviewing them could also have led them to answer more polite or in a way that would present them in socially acceptable terms. Of course, they seemed to understand that the study aimed at getting genuine feedback, but the setting could still entail a risk of some information bias (19).

An option that was considered for the data collection was to let the participants answer a survey after testing the model. This would have been more effective in eliminating research bias and misinterpretations when writing down the answers. However, this would also remove the ability to ask follow-up questions and gather more nuanced elaborated answers. This qualitative feedback served the purpose of the testing better than a quantitative survey would have and is more in line with the common practice for beta testing in software development (18).

3.3.5 Data Analysis

When all beta testing and interviews were done, the answers were analysed to find out what they meant for the research questions. The first goal of the closed beta testing was to find the participants' view on the tool's potential for helping students to deal with the complexity in the building science course. The second goal was to gather feedback on user experience of the content and user interface.

The answers were examined by performing a thematic analysis. A thematic analysis can be efficient for analysing qualitative data, as it is a flexible and accessible way of finding out people's views, opinions, and experiences. The process used for the thematic analysis was inspired by the six steps developed by Braun and Clarke, which involves, familiarisation, coding, generating themes, reviewing themes, defining and naming themes, and writing up the results (22).

The first step of the thematic analysis was to get familiar with the data. This came quite natural during the process of collecting, cleaning up and transcribing, and translating the answers from Norwegian to English. With only nine participants, in seven semi-structured interviews and two focus groups, remembering the main impressions from the interviews was manageable. In combination with the notes that were cleaned up and transcribed after each interview, this preserved a reliable impression of the expressions of each participant during testing and interviews.

Having such a clear image of the answers made it possible to use a latent approach when interpretating the data, reading into the subtext of the transcribed sentences to bring out the underlying meaning of the answers. Even though an approach like this can have a high risk of observer bias (23), it was necessary to do some more detailed interpretation of the answers to find out what it meant in for the research questions. This was done by highlighting words and phrases of the transcribed data and linking it with tags that tell something about the meaning. In a thematic analysis, this is called coding the data (22).

The codes used to bring out the meaning of the data were based on the theory of complexity and threshold concepts, as well as some important aspects of the user experience. To minimize the risk of missing nuances in the data, a wide range of codes were used. The three topics of complexity, threshold concepts and user experience were used as broader themes that the codes would support. All codes are listed and explained below. The goal was that these codes would bring out results and discussion points about the prototype's potential effectiveness as a tool for breaking down the complexity in the subject and provide some typical beta testing feedback that could be useful for further development.

While feedback about user interface and general experience of the tool can easily be collected through beta testing, it is more challenging to gather results of how the tool achieves its goals of helping students handle complexity. Both because it is hard to quantify complexity itself, and because measuring the students' knowledge and understanding is difficult to do in a reliable way (24).

Even if the time and scope of the project would have allowed for the students' understanding to be measured through tests before and after using the model, comparing results between different participants would have been problematic, since students' ability to learn in general and from different methods are highly individual. This is why the goal is rather to demonstrate the tool's potential, not actual effect, as a learning tool for increased understanding and handling of complexity.

The following list presents all final codes within each theme used for the thematic analysis, with a description of what each code refers to, based on theory which have been simplified and adapted to the prototype:

Complexity

1. **General potential:** View on potential for improving general ability to handle complexity.
2. **Collaboration:** View on potential for positive impact on collaboration on complex tasks.
3. **Emergence:** View on potential for demonstrating new aspects emerging from connected elements.
4. **Non-linearity:** View on potential for demonstrating variable relations between input and output.
5. **Feedback loops:** View on potential for providing feedback on effect of design changes.
6. **Adaptation:** View on potential for correcting previous misconceptions.

Threshold Concepts

7. **Transformation:** View on potential for changing the students' perception of a subject or phenomena.
8. **Integration:** View on potential for revealing new interconnections.
9. **Irreversibility:** View on potential for giving understandings that cannot be reverted from.
10. **Difficulty:** View on potential for avoiding overwhelming or troublesome experience in the start.
11. **Holistic view:** View on potential for demonstrating a holistic view and the boundaries of the field.

User Experience

12. **Flexibility:** Opinion on freedom of choice to change properties of elements in the model.

13. **Control units:** Opinion on method for adjusting input parameters found to be most intuitive.
14. **Results:** Opinion on suitable number of results displayed at the time.
15. **Good visualization:** Opinion on method for visualizing results found to be most effective.
16. **Bad visualization:** Opinion on method for visualizing results found to be least effective.
17. **Simulation time:** Opinion on problem of simulation time resulting in lag when changing parameters.
18. **Level of complexity:** Opinion on level of complexity of the content.
19. **Sustainability:** Potential for helping students make design choices that are good for sustainable buildings.
20. **Overall user experience:** Impression of each participant's opinion of overall user experience based on their expressions in testing and interviews.

Starting out with some preconceived themes and expecting to find them in the answers is called a deductive approach. This is almost by definition a more biased way of coding the data than an inductive approach, which lets the answers decide the themes (25). To bring out some results that could help answering the research question however, it was necessary to look for opinions related to the key characteristics and principles of the theory. An inductive approach to the thematic analysis of this data would not necessarily lead to very different codes and results, as the topics and questions of the interviews were anyway formulated to give answers to these themes. A few codes were also added along the way, to supplement the predetermined codes when found relevant as the text were went through.

For each code, all the transcribed answers from each interview were read through manually to find connections between the code and the meaning of the text. Relevant words and phrases were highlighted with a colour matching the code. The transcribed and highlighted answers from all interviews are attached in appendix 2. For each time a code was found in an answer, the participant's number was registered in the table in appendix 3, which was used as an overview. If participants talked about something related to the same code more than one time throughout the interview, each case was registered, but only once for each question.

To provide some more information about the highlighted word's meaning in the text, it was categorised into one of five options for the particular code. These categories were set up as a scale from one to five, representing properties that varied slightly depending on the code. For all codes in the themes of complexity and threshold concepts, the categories represented the participants' view on the prototype's potential for succeeding within the aspect of the code. Their view on these potentials were categorized on a scale from "very high" to "very low". The same participant could be registered with views in different ends of the scale for the same code if their answers to different questions were interpreted this way. Like the coding in general, the selection of category was done based on the subtext of the answers as they were written and recollected from the interviews. It is important to note that the codes and categories here are mainly considering the participant's view on the potential of the prototype, even if not always explicitly formulated this way in the transcripts. The interpretation of their view is often formed by their feedback on the specific prototype that they tested. This is why participants sometimes could be registered with views in different ends of the scale for the same code.

For the theme of user experience, the categories represented a wider variation of topics, usually related to the participant's opinion of certain features. For example, the code called "control units" categorizes answers based on which types of control units in the simulation model the students found to be most intuitive for its purpose. If the participants answered multiple options in a code like this, all would be registered. Some of the categories were adjusted along the way, to fit better with their purpose.

Because there is a limited number of highlighting colours available, some codes share the same one. These are codes that fit within the same category or would anyway be relevant to each other. For example, the codes for flexibility, results and level of complexity can sometimes be relevant to the same words and phrases and are all sharing the dark grey highlighting. However, highlighted words and phrases are still only registered for the specific relevant code. The last code, for "overall user experience", does not have a colour, as it has no specific connections highlighted in the text. This is interpreted based on the total impressions each participant gave through expressions during testing and interviews.

When all connections to the codes had been highlighted and registered for all interviews, the names and descriptions of all codes were reviewed to make sure they represented the data accurately. For example, the code for visualization of results was split up in one code for visualization methods found to be good and one for methods found to be bad. This was because enough data were found for both codes, which both were regarded as useful results for further development.

The last step of the thematic analysis is to present the results, which can be found in chapter 4.3. There, the frequency and meaning of the reported codes within all three themes are described. This is based on the theory, the construction of the prototype and the description of each code listed in chapter 3.3.5. In chapter 4.3, main findings of the results are also discussed to answer the research question.

4 Results and Discussion

Like the methodology chapter, the results and discussions of this thesis are divided in three subchapters. The first one presents some of the experiences obtained from the process of learning how to use the parametric simulation software and developing the prototype of the simulation model. The second subchapter explains how the prototype was modelled and discuss how it could have been done differently. The last subchapter presents the results of the thematic analysis performed on answers from interviews during the closed beta testing. Since all subchapters are highly relevant to each other, parallels are drawn, and references made between them during parts of the discussions.

4.1 Development Process

In this subchapter, some of the key experiences from the development of the prototype are shared, and explanations are given for deviations from the plan presented in chapter 3.2.

The process of developing a prototype of the tool has underlined the importance of a good plan, clear goals and objectives, early user involvement, an outline of the planned content, and beta testing with feedback of user experience. Modelling the prototype with very little prior experience in parametric simulation has proven to be a steep learning curve. When time and resources are limited, the ability to narrow down the scope, while still achieving the desired results, are crucial to be able to complete.

Modelling the prototype has also shown that following the plan for made in the beginning is not always as practicable to construct technically, especially when dealing with topics of high complexity and many interconnections. Because of challenges met in the development process, there is not necessarily a direct link between which parameters are given a high priority for including in the model and what ended up being included in the prototype, like the simulation model outline in table 2 shows. These challenges were mainly regarding the modelling itself. For example, finding a set-up of components that function together the way they are supposed to can be hard enough as it is for a new beginner, without worrying about how to make it fit into the predetermined complex structure of interconnections between content and modules. Instead, solutions sometimes had to be made strictly based on what was found to be a feasible way to solve a single task, despite not fitting in exactly to the modular set-up planned in the planning phase. However, the parameters coloured green in table 2 are developed, and the ones in orange are included in the background. All the modelled content will be presented in chapter 4.2, together with discussions of why they were solved the way they were, limitations, and potential improvements.

As the results of the closed beta testing uncovered, the user experience of the tool has potential for improvement. The development could probably have benefitted from earlier user involvement, by conducting an initial survey before planning and constructing the model. This could have led to a more fitting level of complexity in the content. Initially, such a survey was meant to be conducted. The reason why it was never done, was that it was difficult to know what to ask the students about before having a clear enough idea of how the model would be designed, as the trial and error during development took a lot of time. However, when looking at this thesis as part of a larger project of developing the tool, the closed beta testing performed here can be regarded as a useful early stage exploration of the concept before potentially putting more time and resources into the development over a longer time period.

4.2 Prototype Modelling

This subchapter explains how the prototype of the simulation model was constructed in Grasshopper. Some limitations and benefits of the resulting solutions are stated, and potential improvements and alternatives are discussed.

Figure 4.1 shows an overview of the entire Grasshopper file canvas where the simulation model is set up. For the presentation of all operations, the canvas is divided into 14 main groups of components, as displayed in figure 4.1 and named in table 3. In the next parts, the build-up and function of each group is explained together with zoomed in figures and screenshots of relevant results visualized in the Rhino scene.

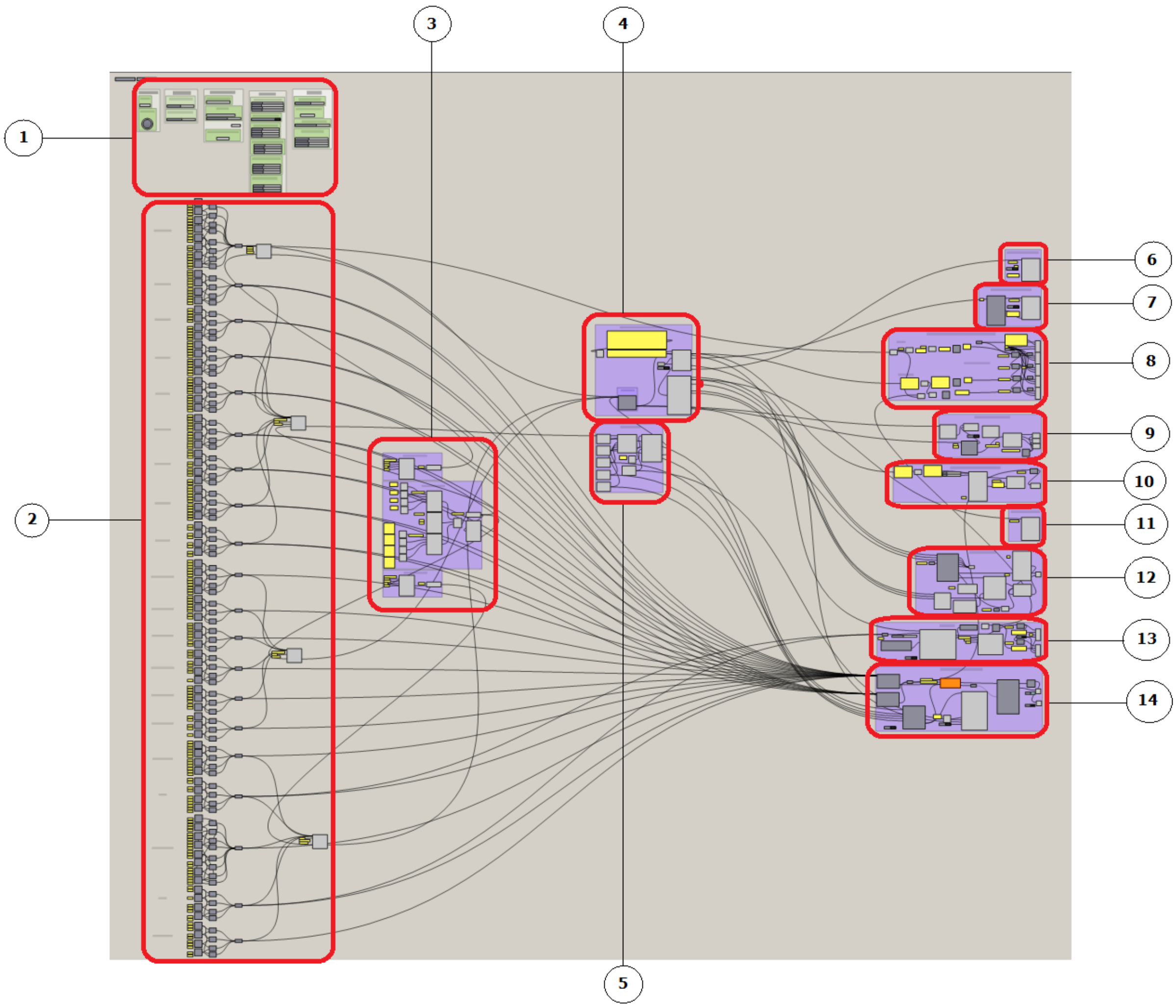

Figure 4.1: Overview of Grasshopper canvas showing the background operations of the simulation model.

Table 3: Overview of numbers in figure 4.1 paired with background operations.

Group	Function
1	Control panels
2	Composition of geometry points and surfaces
3	Construction properties
4	Climate data and Energy+ simulation
5	Window and shading properties
6	Monthly energy balance diagram
7	Monthly heating load intensity diagram
8	Table of annual energy intensity and benchmark values
9	Daylight simulation
10	3D visualization of geometry coloured based on total energy intensity
11	Dry bulb temperature graph
12	Psychrometric chart
13	PV energy production simulation
14	3D wireframe visualization of geometry with windows and shading

4.2.1 Control panels

In the prototype of the simulation model, the changes to design and input parameters of the building are made in the Grasshopper canvas. As presented in figure 4.1, this is the same place as all other components for the simulation are located. However, the control panels for the changeable input parameters are the only components supposed to be touched by users. In a further development into a black box tool, this is the part that would be visible in the user interface, while the rest of the components in figure 4.1 would be hidden.

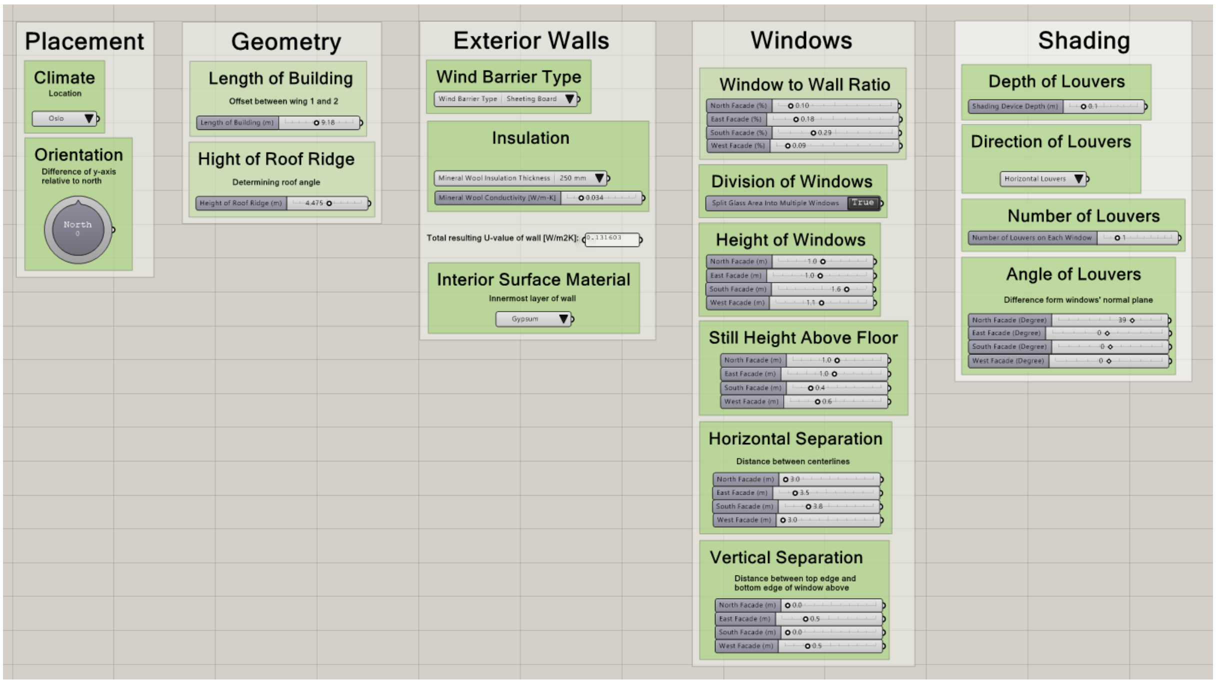

Figure 4.2: The control panels for all variable input parameters changeable by the user are gathered in the top corner of the Grasshopper file.

The control panels for all variable input parameters changeable by the user are gathered in the top corner of the Grasshopper file.

Even though the control units look like they are disconnected, they are in fact connected to their respective operations in the rest of the canvas. The wires are just hidden to minimize confusion among users of what to focus on, and to achieve an experience more like a black box. To improve the user interface, each type of changeable input is grouped and given a background colour, a heading, and a short description of what it controls. On top of that, the inputs affecting the same type of parameters are grouped in a parent category, corresponding to categories of some of the certain modules in the plan presented in table 2. These categories are examples of what could have been used as separate viewports in a further developed version.

Of course, additional input parameters could also have been made changeable to users, as suggested in the planning phase in chapter 3.2. However, the ones shown here represent a wide variation of both features and types of control units, which were considered useful to test in terms of user experience and potential for breaking down complexity. To make sure all types were tested by all participants, the number of changeable parameters were limited, to avoid some being overlooked. Therefore, the aim for the prototype was a balanced number of changeable input parameters. Feedback from the closed beta testing, however, suggests that the prototype might even have too many options in one place. Some suggested that dividing the content into multiple pages, with even more limited input parameters and output results, could have been beneficial. Several participants also wished that the content was divided into different levels of complexity, enabling them to choose what they feel they are ready to engage in.

These ideas are all possibilities to consider for the future development of the tool and are quite in line with the original plan of dividing the content in modules and categories, presented in chapter 3.1 and 3.2. It must be reflected on what it would mean to the idea of a holistic approach if the content were to be divided too much, but a combination could probably be a good solution. For example, could the design and total energy demand always be visible, while input parameters and detailed results vary according to the specific parameters being explored at the time.

When using the simulation model in the prototype, the Rhino scene is best set up with a composition of multiple viewports, showing at least one view of the design and one view of the resulting performance. In this way, results on different aspects can be visualized at the same time, to clearly show the relation between design decisions and results.

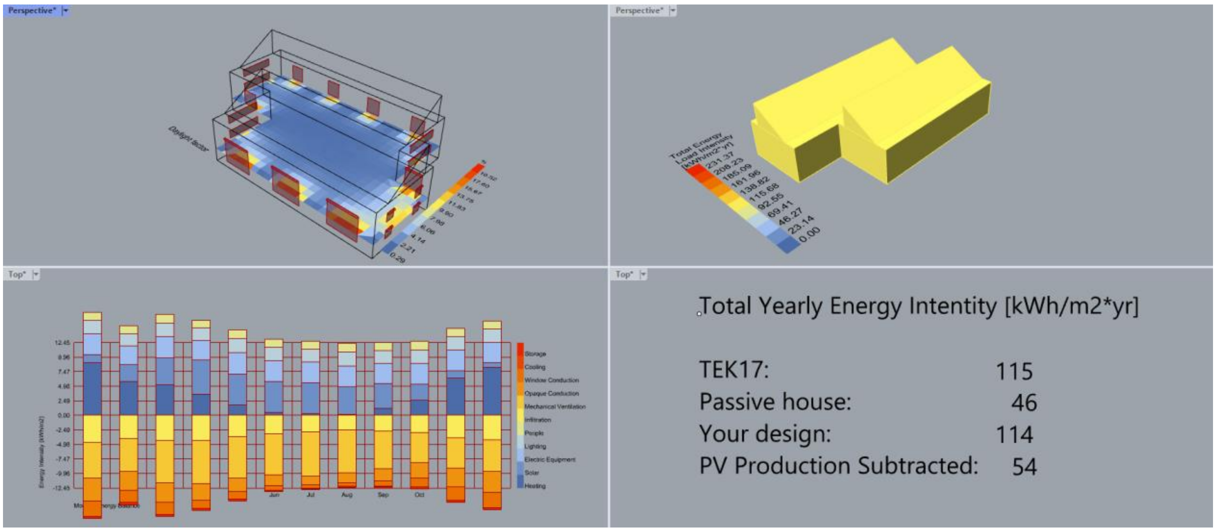

Figure 4.3: Viewport in Rhino showing a wireframe of the building with window design, a 3D model coloured based on results of total annual energy intensity, a monthly energy balance chart, and a table of total annual energy intensity benchmarks.

4.2.2 Composition of geometry

There are several ways of constructing Rhino geometry in Grasshopper. In this model the geometry consists of surfaces constructed by lines constructed by points. The reason why this method was chosen is that it enables the geometry to be changed by moving the points connected to the relevant surfaces. In this way, the design of the building shape could be changed by the user and impact the simulations performed on it. Even though all points of the geometry could have been movable using this set up, the changeable options were limited to one façade extrusion and the height of the roof ridge. These two options were considered representable for important aspects of the design changes, while still keeping the building recognizable. For example, the position of the façade in accordance with the others impact the floor area, and thereby compactness of the building. Adjusting the height of the roof ridge also impact the solar irradiation.

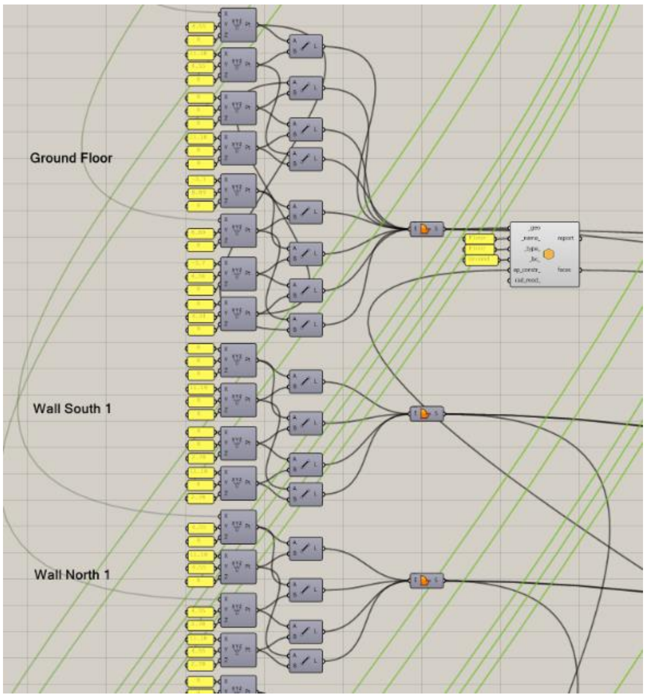

Figure 4.4: Composition of points, lines and surfaces, forming the geometry.

4.2.3 Construction Properties

Construction properties in grasshopper can be decided using complete generic construction sets or constructing them from scratch material by material. To demonstrate the impact of changing insulation thickness and thermal conductivity in the exterior walls, a custom construction was set up in this model.

From a pedagogical point of view, an important aspect for the students' understanding could have been to show the calculations being performed by the model in the background, before reaching the results displayed in Rhino. It can be argued that this early in their education, it could have been important to understand how the calculations are performed, instead of only focusing on performance optimization. However, this is a choice that must be made between a high level of detail in calculations or a more holistic view (2).

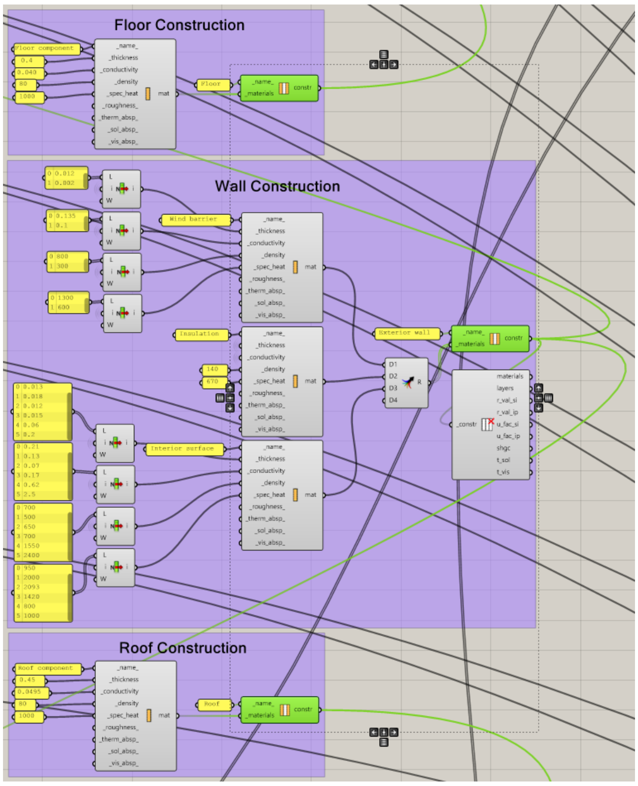

Figure 4.5: Construction properties.

An option of enabling more detailed input changes is demonstrated for the exterior wall construction properties. Here both the insulation conductivity and thickness can be changed by the user, resulting in a variable thermal transmittance. This is then displayed both in the form of total u-value and the resulting energy demand and demonstrates the non-linear relationship between insulation thickness and the resulting effect. An alternative method for deciding exterior wall properties could have been to only enable changes of the total u-value directly. This would have been more in line with the other changeable input parameters in the model. However, to investigate the effect of a more detailed calculation option as well, this was tried for one of the parameters.

4.2.4 Climate data and Energy Plus Simulation

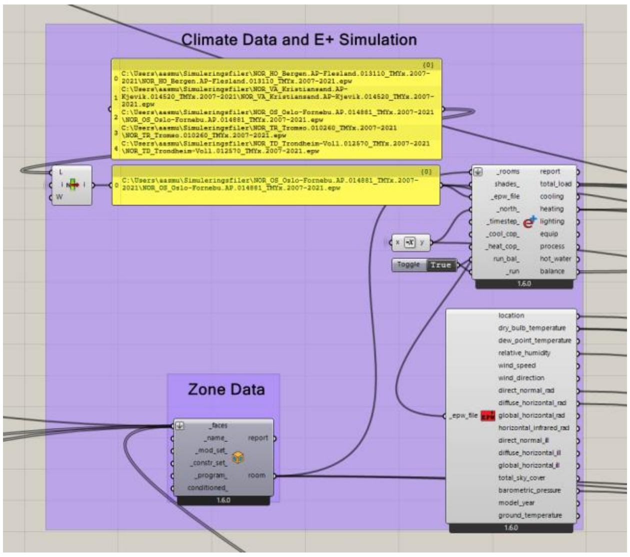

Figure 4.6: Climate data and Energy Plus simulation.

The climate data used for the simulations are stored in EPW-files, which needs to be downloaded to the user's computer. The yellow panel in figure 4.6 lists the file addresses of the stored climate files for the locations that can be chosen by the user in the control panel in figure 4.2. This information must be updated to the file address on the user's computer when setting up the tool. To avoid this operation, it would also have been possible to use a component that downloads EPW-files from the web on command from the user. This enables them to choose whichever location and climate they want. The reason why a limited group of predetermined location options were used in the prototype, was to avoid the students testing it having to take the extra step of downloading EPW-files.

When all data about the design of the building is gathered in a zone component, this in inputted together with the climate data into the simulation component, which is the one that in turn provides the results being displayed. For the prototype, it is used a component that runs a quick and simple version of an energy plus simulation. Since heating, ventilation and air conditioning systems are not considered in this model, there is no need for running more advanced simulations through Open Studio. To visualize the connections scoped out in the prototype, the energy demand is sufficient, and there is no need to take the efficiency of heating and cooling systems into account.

What is prioritized higher here, is quick simulations. The simulation time of a few seconds creates a lag that can be a little annoying when trying to demonstrate how design changes impact the building's performance in building physics parameters. This is especially an issue when using number sliders to change input parameters, as the model then runs the simulation for several values in the steps between the original and the new setting. Getting rid of this lag would make the interaction more seamless, which in turn could improve the model's quality. To do this, however, would require either a very fast computer, or the simulations for all value steps to be pre-run, stored and reloaded when commanded by the user. The first option is unrealistic, as the undergraduate students that the model targets are mainly using their private computers for their studies, which cannot be expected to be powerful enough. The second option would be feasible but require competence and resources necessary for setting up a system for storage and reload of pre-simulated results. In addition, it would take a lot of time to perform the pre-simulations themselves. The main drawback with this is that it would reduce the flexibility of the tool a lot, if only pre-simulated combinations were available in the input options. With the aim of visualizing changes of multiple parameters on the same results, the possible combinations would very quick become enormous with a high level of flexibility.

To expand the level of flexibility in a model with pre-simulated design settings, another option could be to connect the model to an online database. This could store a larger number of pre-simulated design settings than what would be suitable for an offline version. An issue with this is that loading pre-run simulations from an online database would take more time than loading from an offline database downloaded to the computer. This could again have a bad effect on the user experience. However, if the lag is shorter than the one that is caused by real time simulations, an online database could be a good solution. This would both improve the user experience by making the input changes visible directly, and at the same time maintain a large level of flexibility in available input options.

4.2.5 Window and Shading Properties

Together with the building shape, changing the windows and shading devices are the only options available in the prototype for deciding the visible design. This is done with the help of components that adds glazing and shading devices to inputted facades of the building, based on commands for the configurations. The changeable configurations in the prototype are the ones represented by the control panels shown in figure 4.2. For the windows, this includes window to wall ratio, division of windows, height of windows, still height above floor, horizontal separations, and vertical separations. Even though windows cannot be completely customized using this method, it allows for quite a large range of variations. For the shading, the available options are whether to have horizontal or vertical louvers, as well as depth, number, and angle of louvers.

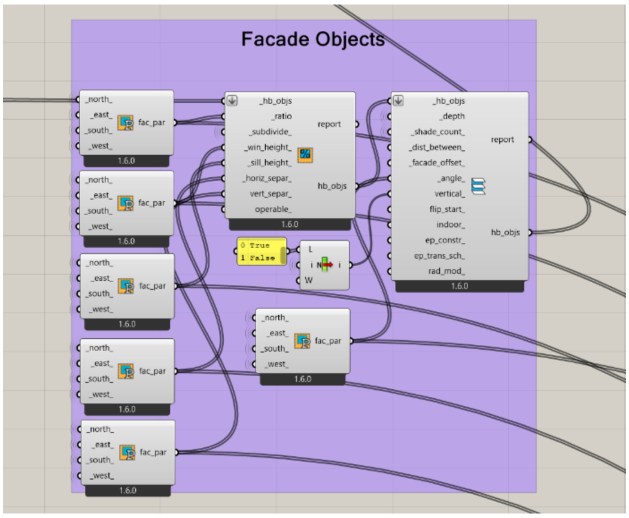

Figure 4.7: Assigning design-choices for windows and shading.

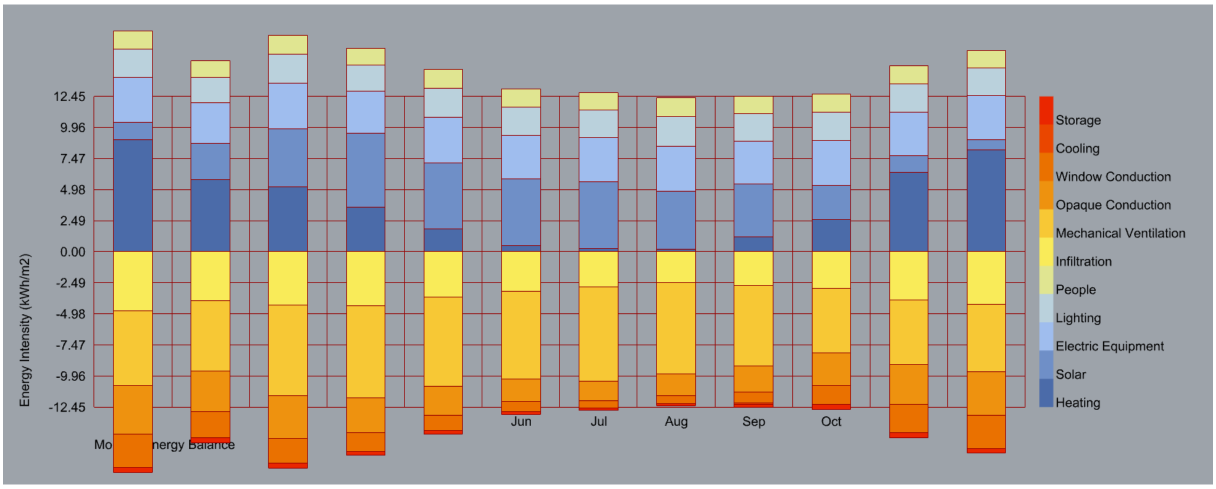

Figure 4.8: Display of the monthly energy balance diagram.

4.2.6 Monthly Energy Balance

A small but obvious potential for improvement is adjusting the height interval of the diagram so that the labels on the x-axis does not get covered by columns when their values exceed the limit. Creating better diagrams is in general a potential for improvement of the tool. Despite being registered among the two favourite visualization methods in the thematic analysis of the feedback from the closed beta testing, some participants requested improvements to the diagrams, among other things. Ideas that were shared were for example to either let the diagrams pop out and be displayed in separate windows, or to construct the whole tool as a webpage. These ideas are well in line with some of the thoughts for potential further development of the tool. Among the multiple different plugins available for Grasshopper, some are meant for the purposes of improving the visualization of diagrams based on results produced in from simulations.

For the prototype in this thesis, however, the focus is mainly on demonstrating the potential of the software. Because of the limited time available and experience with the software when starting on the thesis, the goal was never to create a visually perfect tool. Therefore, setting up the diagram for the monthly energy balance in the prototype requires very little effort once the data from the simulation is ready, as shown in figure 4.9. The text panels connected to the monthly chart component all include optional information for point of location in the Rhino scene, extruding the height and naming it.

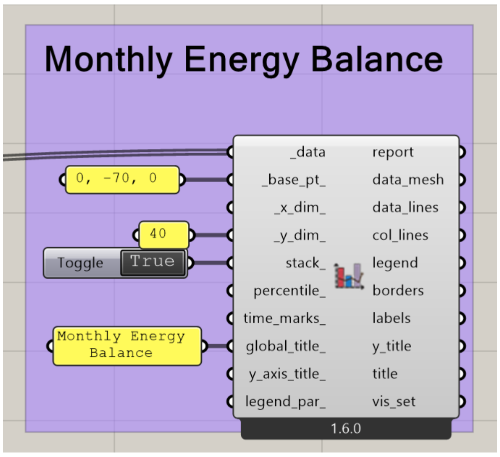

Figure 4.9: Component for monthly energy balance.

4.2.7 Monthly Heating Load Intensity

The monthly heating load intensity is displayed in a clear and simple bar chart diagram, which might be easier for some students to read than the monthly energy balance, where there are a lot more information gathered. As results from the closed beta testing show, many students found the prototype in general to have a bit too high levels of complexity in its content, and too many changeable inputs and visible results. In this respect, results like this simple monthly heating load intensity might be better.

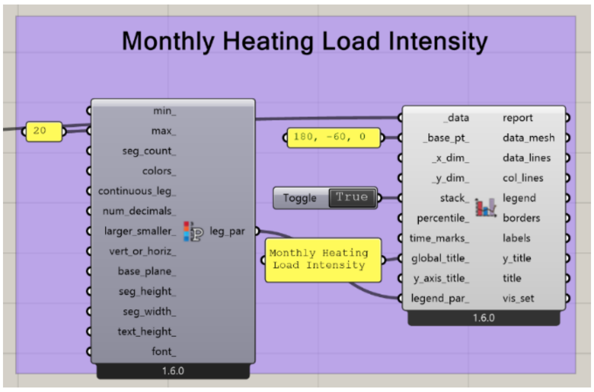

Figure 4.10: Setting up the diagram for the monthly heating load intensity.

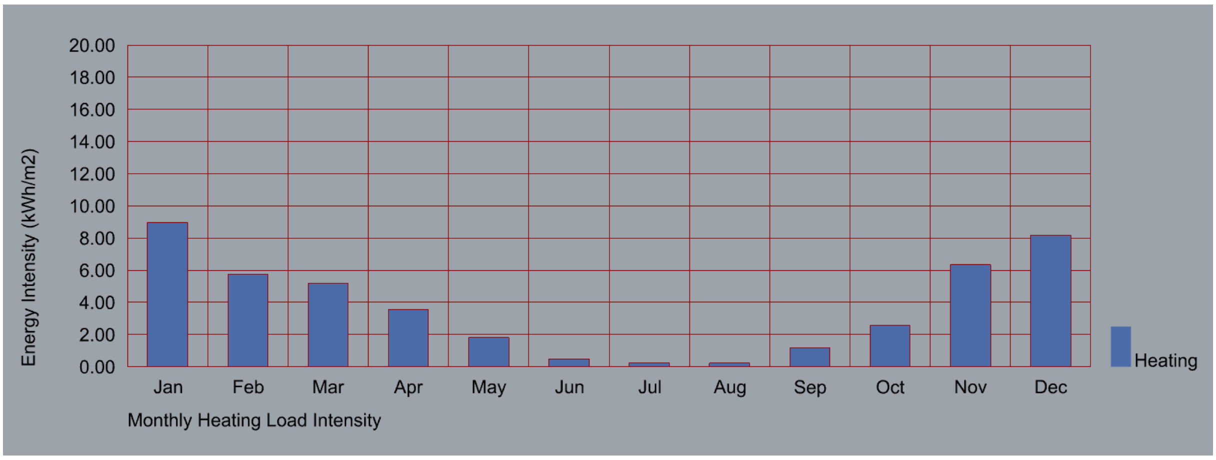

Figure 4.11: The monthly heating load intensity is displayed in a column diagram.

4.2.8 Table of Annual Energy Intensity

Missing a relation to the results gotten from calculations is a common challenge for students in many subjects, with architecture and building science certainly not being exceptions. Not knowing what to do with the results they arrive at when doing calculation exercises have been reported as frustrating during some interviews in the closed beta testing. An example is shown with the following citation "(…) If you calculate it manually, you only get a number that you often don't know what to do with. You don't know if the results are good or bad, or how much impact different design decisions have compared to others. (…)" (interview 4, Appendix 2)

A good solution to this is to provide some relevant benchmark values that the results can be compared against. In the prototype, a table of the total annual energy intensity for the designed building is listed together with benchmark values for the requirements in TEK17 and an example of a number for energy intensity on passive house level. The number used as an example in figure 4.12 is not necessarily a correct energy intensity for a house according to the passive house standard used in Europe. Rather, it is to be regarded as a demonstration of a more ambitious goal for the performance of the design.

Total Yearly Energy Intentity [kWh/m2*yr]	
TEK17:	115
Passive house:	46
Your design:	114
PV Production Subtracted:	54

Figure 4.12: Table of the total annual energy intensity for the designed building and benchmark values.

In addition, a number for the net energy intensity of the designed building is showed. This uses the total energy intensity from the Energy Plus calculation, and subtracts the energy simulated to be produced in the PV energy analysis. What could have made this number even more interesting is to highlight it as the difference form ZEB-O level, by changing the description. This could have an even more motivating effect on the students, making them explore all available options in a strive to design the most energy efficient building possible. Even though such an energy optimization of the design is not necessarily the goal of the architecture and building science education at this level, it could have a positive effect on the way the students perceive and understand the complexity and interconnection within the fields of study.

There are multiple aspects within the theory of complexity and threshold concepts that could be affected by using energy optimization as a method for helping students handle complexity by focusing on the totality of the topics. Among the factors investigated in this study, three that can be mentioned are emergence, transformation, and holistic view. These are all used as codes in the thematic analysis of the interviews during the closed beta testing, for highlighting students' responses interpreted as a views on the simulation model's potential for helping them to handle complexity. Explanations to how some of these aspects can be connected to this optimization approach are given in chapter 4.3.

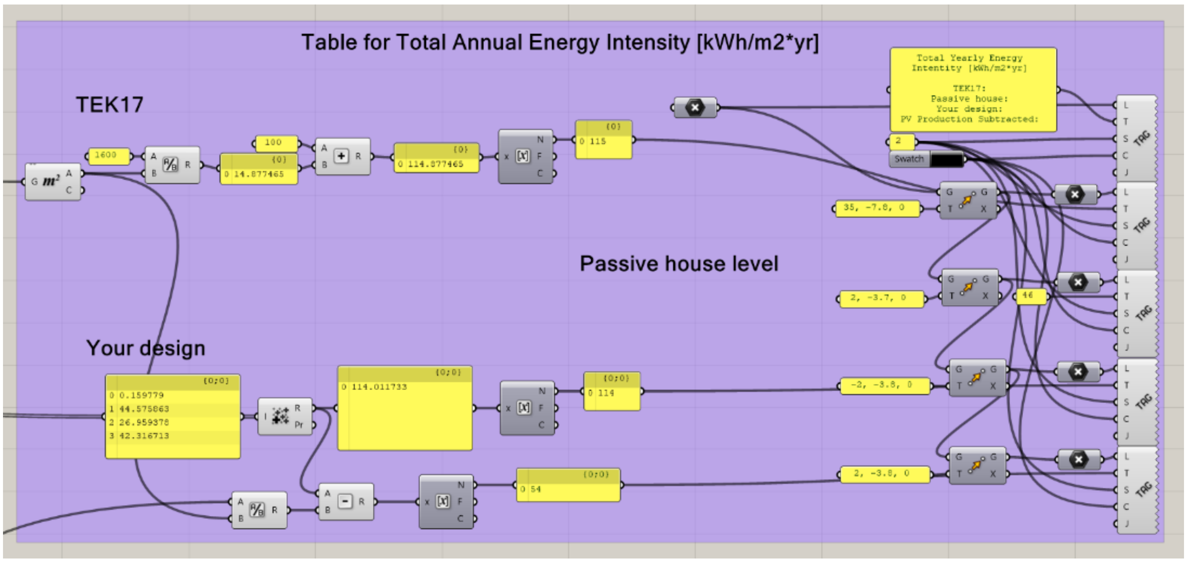

Figure 4.13: Construction of the table for annual energy intensity and benchmark values.

A possible further development of this could be to include calculations for the design's impact on emissions of CO2-equivalents, by performing Life Cycle Assessments (LCA) on the construction and materials required. In this way, the table of benchmark values for energy intensity could be expanded with comparisons against levels for more comprehensive ZEB classifications, such as ZEB-COM. This would have given the students the opportunity to explore combined considerations of both energy use, energy production and material use when striving to design buildings that reach a certain level of climate impact. This again, could potentially open new emergent aspects between the elements, give them a holistic view on the field, and transform the way they perceive the topics.

4.2.9 Daylight Simulation

For the daylight simulation, only the daylight factor was calculated. This simple option was chosen mainly to minimize simulation time, while still demonstrating some of the designs impact on daylight in the building. To demonstrate the impact on daylight of the building's orientation, one would have to set up more advanced simulations. This would also enable considerations of shading by surrounding elements, like buildings and vegetation. However, this might lead to longer simulation time. In the prototype, the daylight factor calculation is the operation that involves the longest wait, compared to the energy simulation. The fact that the simulation window also opens during the calculation, can be a bit annoying when adjusting parameters for windows and shading. Possible options for reducing simulation time have been discussed in chapter 4.2.4 but is not explored further in this thesis. This is something that potentially can be explored further in future work.

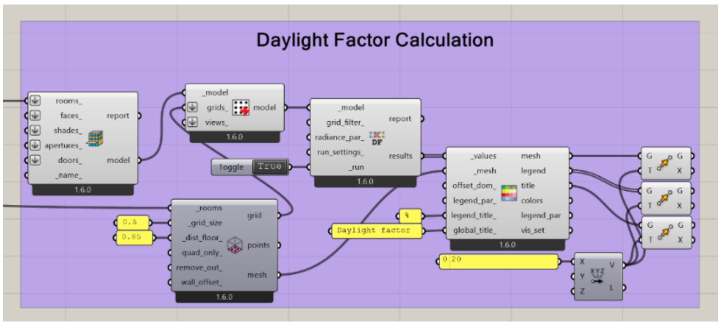

Figure 4.15: Set up for performing and visualizing the daylight simulation.

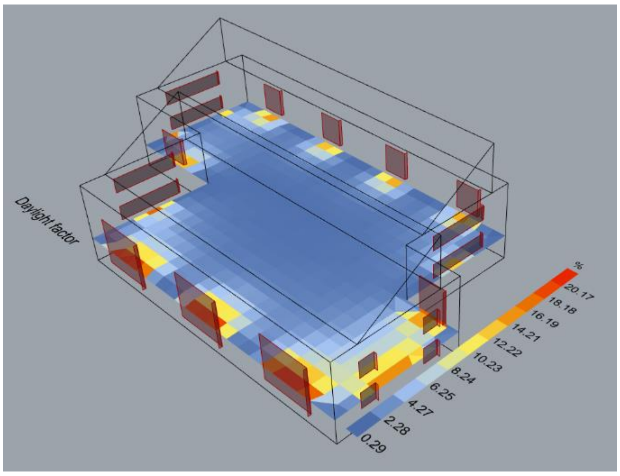

Figure 4.14: Results of daylight factor simulation visualized on the floor plan of a 3D wireframe of the designed building.

4.2.10 Coloured 3D Visualization

Since the aim of the simulation model is to help students break down complexity by visualizing impacts of design decisions in building physics parameters, the way results are visualized is an important topic for the project. For example, by creating visualization of the 3D geometry coloured by results of simulations. In the prototype, the colour on the 3D geometry is based on the number for total energy load intensity per year [kWh/m2*year]. Like displayed in the table in figure 4.12, this number is compared to requirements in TEK17. A design resulting in a total energy load intensity around the same level as TEK17 will be visualized in yellow. Higher energy loads will turn the colour towards red, while lower numbers will turn towards blue.

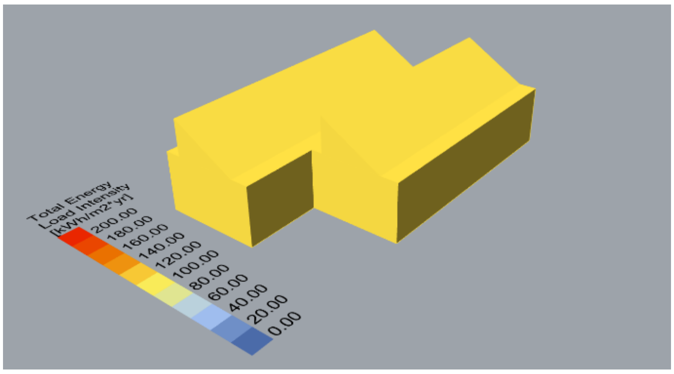

Figure 4.16: 3D Geometry coloured based on results.

Using coloured 3D geometry to visualize results was anticipated to have a positive effect on the user's ability to interpret the meaning of results related to the buildings energy performance, as it removes the traditional separation between design and results. Feedback from the closed beta testing imply that this hypothesis was correct. Coloured 3D geometry is voted the favourite visualization method and mentioned positively for the ability to see connections multiple times. One could always argue that the success of this visualization is just as much due to the use of colours to show the difference between good and bad results. However, as answers from the beta testing suggests that an important aspect is also the close connection between design and results that parametric simulation modelling enables. The following interview citation supports this "I like that it is using the actual house. Normally, it can be difficult to connect design and graphs" (Interview 1, Appendix 2).

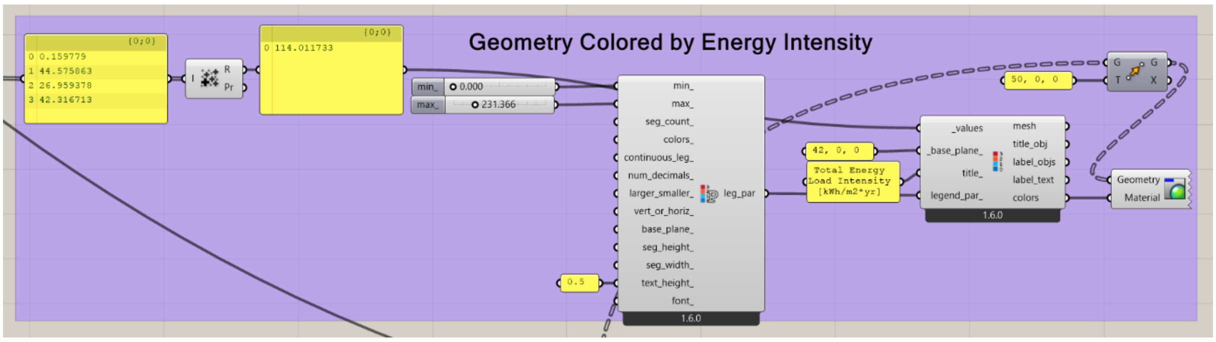

Figure 4.17: Setting up 3D Geometry coloured based on results.

4.2.11 Dry Bulb Temperature

The dry bulb temperature data is retrieved from the climate file and displayed in a graph, using a monthly energy diagram component. As reflected by the simple operation required for retrieving and visualizing the information, this feature obviously does not show any explicit interconnection with architecture or building science. Still, it is highly relevant, as one of the most important climatic factors to consider in building design. Since it with its simple set up method can be considered free content, it was included as an option among the visualized results in Rhino. When changing the location, it can be interesting for users to see the changes in energy performance in relation to changes in temperatures.

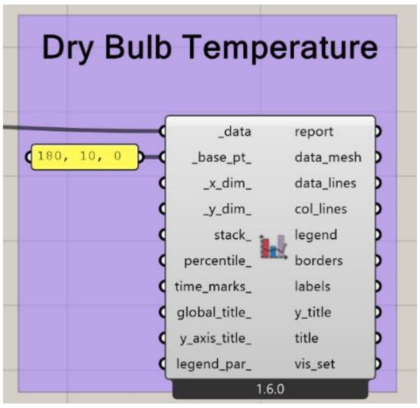

Figure 4.18: Component for dry bulb temperature.

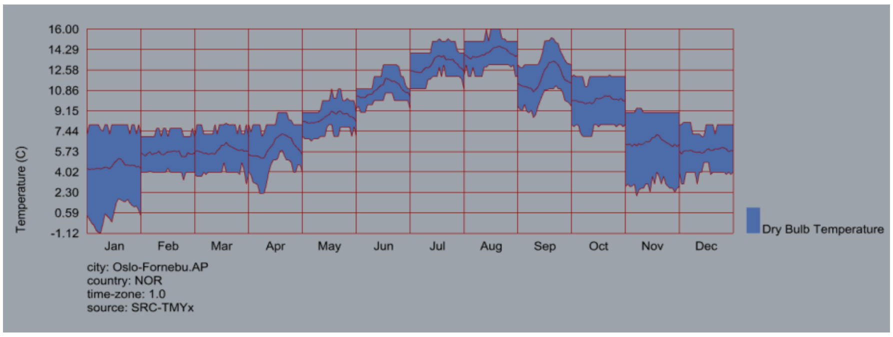

Figure 4.19: Dry bulb temperature displayed in graph.

4.2.12 Psychrometric Chart

Another climatic result chosen to include as an optional exploration in the Rhino scene is a psychrometric chart. However, since it was lacking some information about the meaning of the results, it was not the most useful. Even for the participants who were a little bit familiar with a chart like this, it was impossible to read any meaningful results from it without any information about the data and areas. Providing some more information would maybe have enabled some students to get something meaningful out of the chart. Still, it would most likely have been too advanced for the entry level of the tool, as some feedback suggests that the content of the model is a bit too advanced.

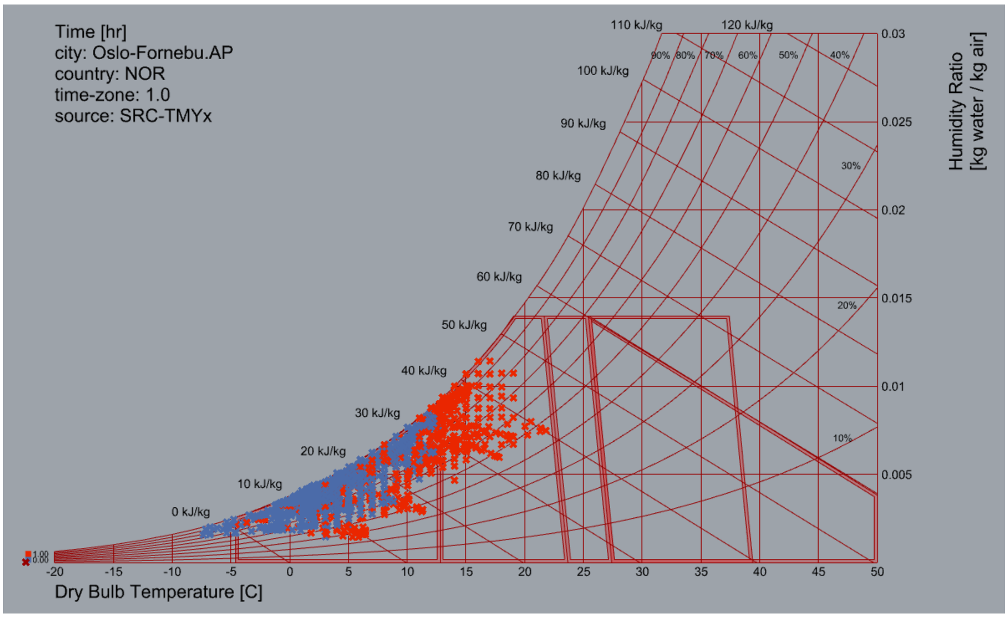

Figure 4.20: Display of the psychrometric chart.

A risk associated with including too advanced content like this is that the users get overwhelmed by the initial complexity, which might even make them give up before they have made a proper attempt at understanding other more manageable parts.

An interesting feature could have been to visualize examples of passive strategies suitable for the climate in the chosen location. Exactly how this would best be designed for the tool is not answered in this thesis, much less how it would be modelled or set up technically. One option could be visualizing relevant passive strategies in the form of principle sketches. Another option, taking more advantage of the possibilities

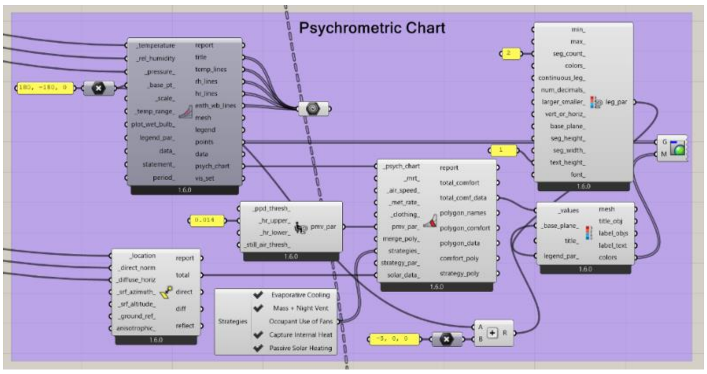

Figure 4.21: Components for constructing the psychrometric chart.

of parametric simulation modelling, could be to suggest design changes in the geometry. However, this would be quite comprehensive, unless the geometry were to have very little flexibility.

4.2.13 PV Energy Production

To demonstrate the impact of the building shape and the roof angle on solar irradiation and potential photovoltaic energy production, a PV analysis was included in the simulation model. This connection can lead to enthusiasm among users, as many students in general often have an interest in topics that can have an impact on climate and sustainability. This assertion can be supported by some of the registrations about views on the tool's potential for positive impact on climate and sustainability.

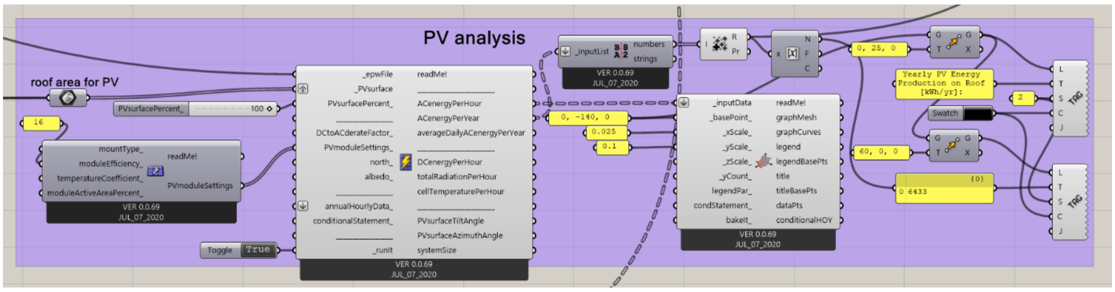

Figure 4.22: Setting up analysis of PV energy production.

As confirmed by some of the participants in the closed beta testing, displaying the results of the PV energy production in two different colour graphs can lead to confusion among the users. Despite the potential good effect of illustrating this feature, it was one of the visualizations that most participants struggled to understand. The following citation illustrates the issue well "Solar energy production was a bit difficult to read at first glance. It was also a bit difficult to see what the result was for. Whether it was energy use or energy production, as well as what the difference between the two diagrams for each of the roof surfaces is. When you know it, it makes sense, but could have been explained" (Interview 4, Appendix 2).

The confusion of two apparently similar graphs is first and foremost a matter of presentation of results that is easy to improve, even by simply adding some more text description for each of them. The general difficulty to understand the results might require more creative visualization methods but could also be improved by clearer text or highlighting the number for total energy production. As a concept, the dilemma of buildings shading their own surfaces and reducing PV-production potential is interesting to demonstrate, as it represents an emergent aspect of building form and PV-energy.

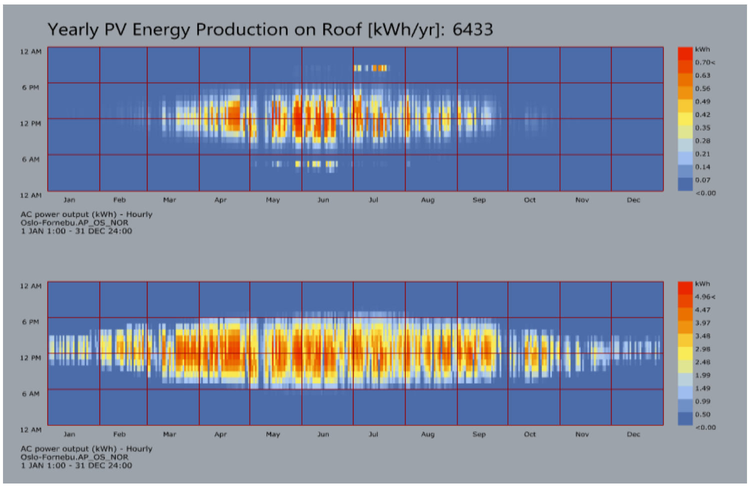

Figure 4.23: Visualization of the potential PV Energy Production.

4.2.14 3D Wireframe Visualization

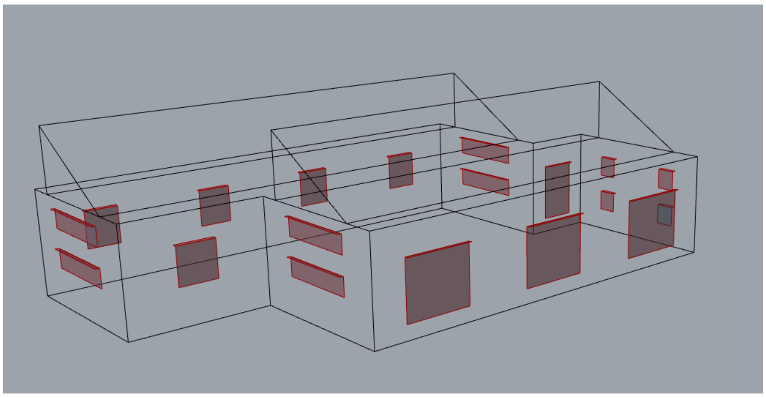

Figure 4.24: 3D wireframe visualization.

To visualize the window and shading design configurated by users in the control panel, a 3D wireframe of the building was displayed in Rhino. The visualization of wireframes instead of coloured surfaces was chosen here to be able to also see the windows on the other side of the building. As shown in figure 4.24, this also makes it possible to see the results of the daylight factor simulation on the floorplan at the same time, like in figure 4.14. Using coloured envelope surfaces with a higher transparency would have led to the same goal, but with more disturbance of the visualized results.

In the prototype, the 3D wireframe is visualized using the older Ladybug and Honeybee Legacy components, because the new component for adding glazing to a surface was unable to connect with the visualization component. This visualization was therefore modelled alongside the input of windows and shading in energy and daylight calculations, based on values from the same changeable control panels. The properties of the components for adding windows and shading louvers to faces were for the most part corresponding between the old and new versions, making them controllable by the same inputs, and providing corresponding visualization and result data. The exception is the Boolean toggle for deciding whether to split the glass area to multiple windows or not, which were opposite between the two versions. This was solved by flipping the Boolean values for the input of the Legacy component, using a list item selector.

Even though this problem was feasible to work around, and the core of it might have been some other mistake, it demonstrates an issue of combability between different versions of components. Problems and bugs like these are frequently fixed through updates in the software community but is something that must be expected when working with planning and development of software.

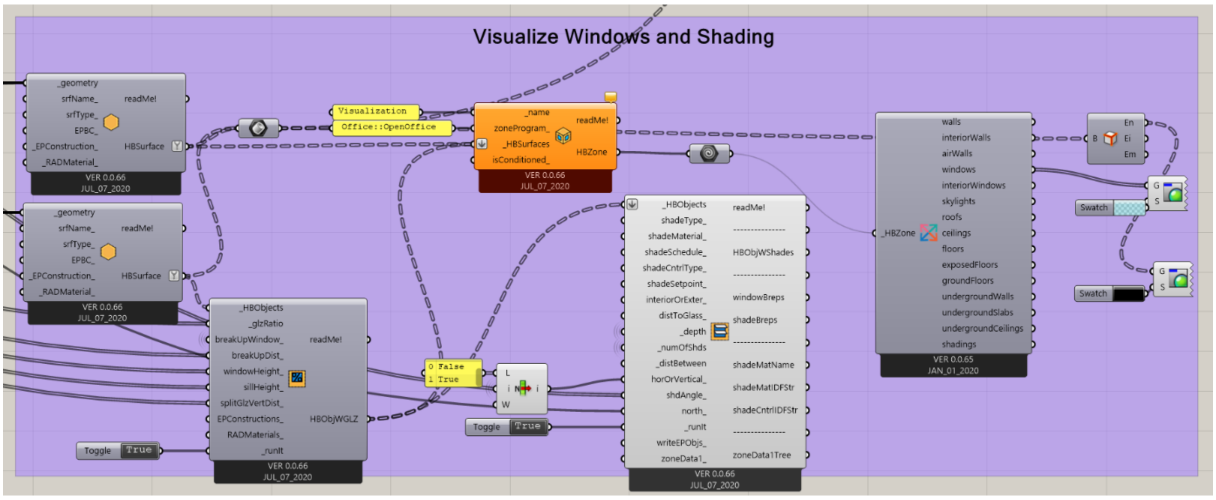

Figure 4.25: Setting up 3D wireframe visualization with windows and shading.

4.3 Closed Beta Testing

This subchapter presents the results of the thematic analysis of the data gathered from the closed beta testing, where the participants were interviewed about their view on the simulation model's potential as a tool for handling complexity in the course. The three main themes for the data are complexity, threshold concepts and user experience. Codes within these themes are presented for each theme below. All the codes used for the thematic analysis and a recap of their meaning are listed in subchapters, together with a description of the results presented in the figures. The results are interpreted and discussed in relation to results and reflections of the modelled prototype in chapter 4.2. Transcriptions with highlighted codes and the table for overview of the codes are attached in appendix 2 and appendix 3, respectively.

4.3.1 Complexity

This theme goes straight to the point of the result question, trying to find out the students view on the model's potential for helping them handle complexity. As described in chapter 3.3.5, the codes used in the thematic analysis are based on theory presented in chapter 2.

4.3.1.1 **General potential**

- View on potential for improving general ability to handle complexity.

For this first code used to interpret answers, one single vote has been registered for each participant, despite not all of them being connected explicitly to a highlighted word or phrase in the transcribed text. Instead, this code is judged based on the overall expression that each participant gave during testing and interview. As explained in chapter 3.3, the context and overall impression have been part of the consideration for all of the coding. However, the exception of giving one vote for all participants in this first category, is made to have a clear vote of the general opinions on the tool's potential for helping to break down complexity. Since all other codes within the themes of complexity and threshold concepts also feed relevant data to this code, the results are based on a large foundation, and are regarded reliable. As figure 4.26 show, the vast majority of the participants found the simulation model to have high or very high potential as a tool for dealing with complexity in education, while one vote is in the medium category.

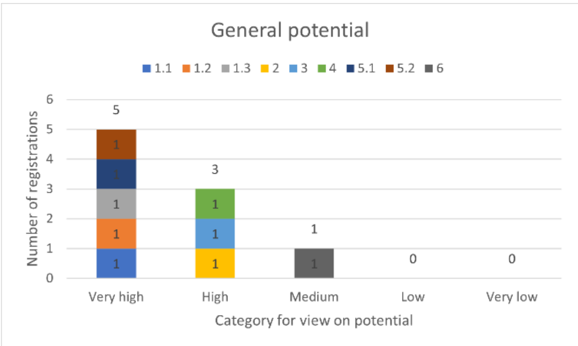

Figure 4.26: Results of general potential.

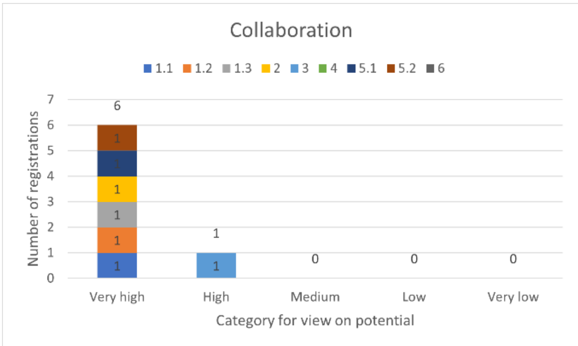

Figure 4.27: Results of collaboration.

4.3.1.2 **Collaboration**

- View on potential for positive impact on collaboration on complex tasks.

One might question what collaboration has got to do with an educational tool mainly meant to be used individually by students. The reason why potential effects on collaboration are highly relevant is that the knowledge acquired from the tool will be used when working in design teams together with students, clients, and colleagues from a wide span of disciplines, on projects involving large complexity. The following quote from the interviews is an example of a view on the tool's potential benefits in regards of teamwork on complex tasks "In the event of disagreements, it can help resolve conflicts" (Interview 1, Appendix 2). Based on the context this statement is interpreted to be a result of the tool providing everyone the same overview and understanding of the topic. As the thematic analysis show, most of the participants regarded the model's potential in this area to be high.

4.3.1.3 **Emergence**

- View on potential for demonstrating new aspects emerging from connected elements.

In the thematic analysis, emergence is used about the model's ability to demonstrate how there is often a need for a balance between different endeavoured goals, which emerge from separate aspects aspiring to reach goals on the opposite side of the scale for shared properties. An example of what can be considered an emergence in the simulation model is the need for a balance between having an amount of glass area that provide the room with adequate daylight, while at the same time does not let it suffer from overheating in the summer or too much heat loss during winter. The following quote is an example of an answer interpreted as the model having potential for demonstrating emergence, when talking about the considerations that must be made to design spaces with good daylighting, comfort, and energy performance all at once "This shows that there are more things to think about when you consider all factors together instead of one at the time" (Interview 6, Appendix 2). Looking at the results, we see that there are five registrations of emergence in the transcribed interviews, all in the category of "very high" potential for ability to break down complexity.

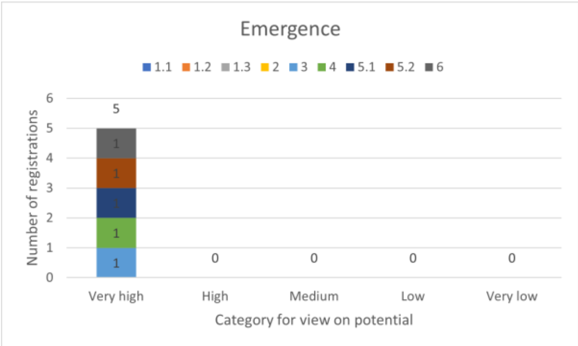

Figure 4.28: Results of emergence.

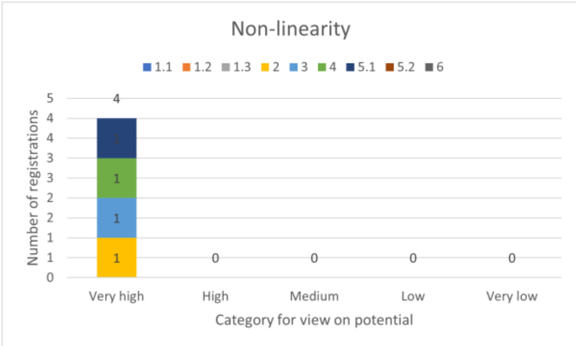

Figure 4.29: Results of non-linearity.

4.3.1.4 **Non-linearity**

- View on potential for demonstrating variable relations between input and output.

A good example from the prototype is the non-linear relationship between insulation thickness and U-value in the exterior walls. In this project, non-linearity has also been used about the models' ability to demonstrate how among design changes that might appear to be of equally substantial extent, some have a great impact on certain performances, while others are barely noticeable. When conducting the thematic analysis, this code has been registered to phrases regarding the potential to demonstrate how some design decisions impact different results in different ways. An example is showed with the following quote "(…) How much does changing the window size help compared to turning the building or adding more insulation?" (Interview 5, Appendix 2).

4.3.1.5 **Feedback loops**

- View on potential for providing feedback on effect of design changes.

In the thematic analysis, this concept is used for the model's ability to give feedback to the user about how their design changes impact building physics parameters like energy demand and daylighting. An example is also the model's ability to separate positive and negative feedback, by showing blue colours on the 3D geometry when the users' proposed design is performing well, and red if not. By this definition, it almost explains the whole point of the tool and parametric simulation modelling in general. Naturally, the interviews therefore show many registrations of clear opinions about the tool’s high potential to provide feedback loops the way they are defined in this thesis. As many as 12 registrations is the highest score for a single category in the whole analysis. With this category being “very high” potential for demonstrating feedback loops, this suggests that parametric simulation can in fact be well suited for this purpose.

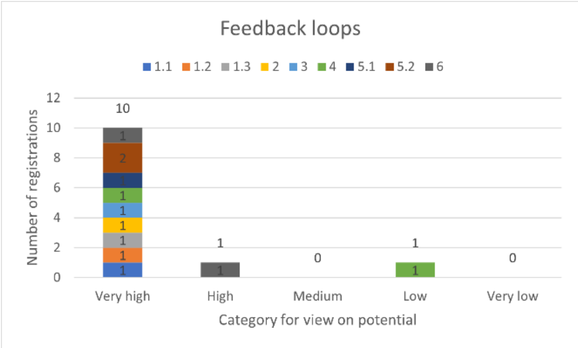

Figure 4.30: Results of feedback loops.

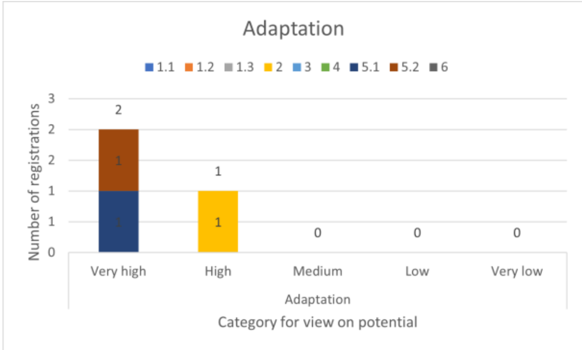

Figure 4.31: Results of Adaptation.

4.3.1.6 **Adaptation**

- View on potential for correcting previous misconceptions.

The interpretation and use of this code might not match completely with the aspects of adaptation and resilience as described in the theory. In the thematic analysis it is used for the model’s ability to help the users adjust their perception of how a phenomenon works when they learn more about how things are connected. As the result show, this code was also difficult to find connections to in the answers, with only three registrations in total. Whether this is because the term is irrelevant and wrong interpreted or because it is difficult to apply to the model is hard to tell. However, in the definition used for it in this analysis, it is believed to have a potential, partly due to the holistic view of the model. This can also be supported by the three registrations from the interviews.

4.3.2 Threshold Concepts

Threshold concepts is used as a theme for the analysis of data and representation of results in this thesis because it is closely related to complexity (16). Seeing how the participants perceive the potential of the simulation model to perform within aspects of threshold concepts can therefore be helpful when investigating its ability to help students handle complexity.

4.3.2.1 **Transformation**

- View on potential for changing the students’ perception of a subject or phenomena.

As explained in the theory, this is the main feature of threshold concepts (17). Only four registrations of this ability have been found in the answers from beta testing, but these are all in the “high” and “very high” categories for potential. Whether these can be considered proper threshold concepts or not is arguable, but since we are always considering interpretations of view on the potential and not the actual effect of the model, it can be reasonable to assume that they are representable. An example from an interview defined in the analysis as demonstrating potential for transformation is the following quote: “In a way, I think it could have a lot of potential. For example, it is nice to be able to see the difference from TEK17 and other rules for comparison. This is a new aspect of the architecture that we don’t see when we are only thinking of design or doing some building science exercises" (Interview 4, Appendix 2). Even though a model using parametric simulation is not pivotal for comparing results against standards, this is just an example of the model's ability to open new perspectives on topics known from before.

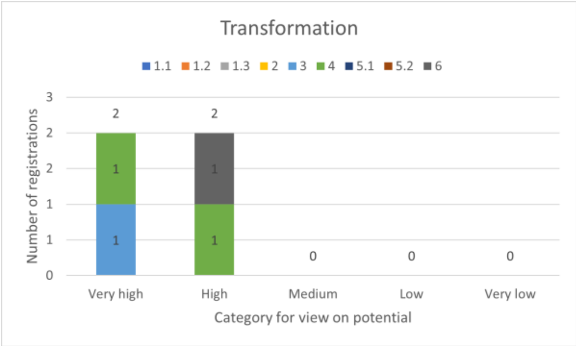

Figure 4.32: Results of transformation.

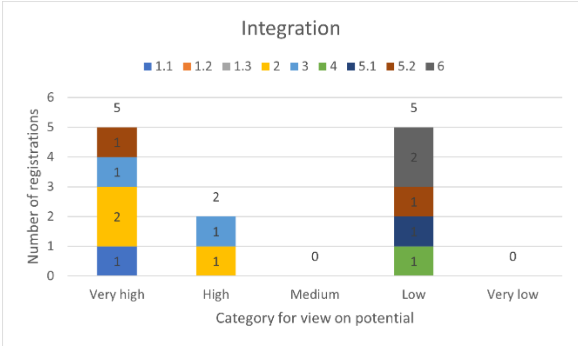

Figure 4.33: Results of integration.

4.3.2.2 **Integration**

- View on potential for revealing new interconnections.

As the results show, this code has registrations from the same participants in the categories for "low" and "very high" potential. This is because the registrations for some codes are assigned a category based on whether the prototype uses its potential to visualize aspects in a clear or confusing way. This might be a confusing way of registering the different views, since both can have high potential, regardless of effective or not in the prototype. However, it is important to show that the simulation model have both benefits and limitations within the same aspects of threshold concepts, like the two following interview quotes show "I like that it is using the actual house. Normally, it can be difficult to connect design and graphs" (Interview 1, Appendix 2). This illustrates the benefit of connecting results with design through 3D geometry in the model. The next quote, on the other hand, demonstrate a challenge of too many interconnections and results displayed in the same model. "There is a lot of information in one place, and you don't quite know where the changes are when you adjust a parameter" (Interview 5, Appendix 2).

4.3.2.3 **Irreversibility**

- View on potential for giving understandings that cannot be reverted from.

Irreversible understandings are powerful aspects of threshold concepts, and the interview responds highlighted and registered in this code might not qualify properly to hold the characteristic. An example registered as reversible in the transcripts is the following quote, when talking about changing climate location "Nice to be able to compare this, as there are actually quite large differences from north to south, which make a big difference in performance, even though there is no change in the design" (Interview 2, Appendix 2). Even though the understanding of impact of climate is hard to unlearn, this does not necessarily make it a threshold concept, as it might be missing other characteristics, such as the fact that it is not difficult to learn or understand in the first place. However, the results suggests that the potential for demonstrating irreversible characteristics can still be present in the model.

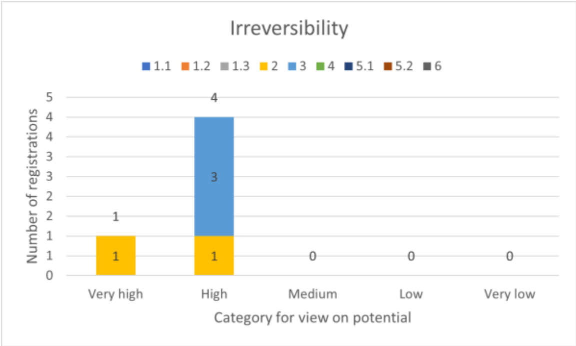

Figure 4.34: Results of irreversibility.

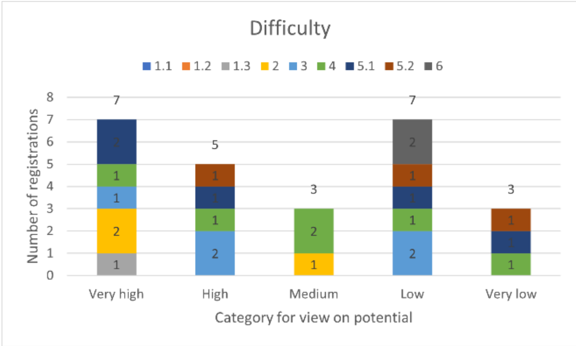

Figure 4.35: Results of difficulty.

4.3.2.4 **Difficulty**

- View on potential for avoiding overwhelming or troublesome experience in the start.

In the prototype, this can reflect the overwhelming of seeing too many results, connections, and impacts in the beginning. An example of a feature of the model that can have led participants to answer in ways coded as low potential for avoiding overwhelming complexity is the psychrometric chart, as it appeared difficult to understand. Here, the use of the categorization might be counterintuitive, as a lot of answers regarding such an overwhelming or confusing experience is registered in the category for "low" potential of illustrating the concept. As discussed in 4.3.2.2, this might be a confusing way of categorizing the registrations, but it is done to separate the answers interpreted as having positive and negative views on the model's potential to deal with the difficulty, not only being troublesome. This method for categorization resulted in the highest number of total registrations in the whole thematic analysis and shows some nuanced views on the model's potential for visualizing initially troublesome content. A total of ten registrations finds the content of the model to be too overwhelming, three on "medium", while twelve registrations found the model to have good potential for dealing with troublesome characteristics of the topic.

4.3.2.5 **Holistic view**

- View on potential for demonstrating a holistic view and the boundaries of the field.

An example of a holistic view demonstrated by the prototype is the table of benchmark values for energy intensity. As mentioned there, this uses a focus on energy optimization as a holistic view on impact of multiple design decisions. The following quote demonstrate the benefit of such a holistic approach. "A lot is connected, and it can therefore be nice to have it together, so that you can see the whole picture" (Interview 2, Appendix 2). There are plenty of similar statements in the transcripts, and the results of this code show as much as ten registrations for this code, all in the categories of "high" and "very high" potential for breaking down complexity. However, it is worth mentioning some the feedback in other codes imply that too much information displayed at once also can be overwhelming. If using the same categorization logic as in the codes integration and difficulty, registrations about too high level of complexity and too many results in the codes for results and level of complexity, under user experience, could have been registered as "low" potential for the holistic view to deal with complexity effectively in the prototype. An opponent approach to the holistic view would be the more traditional way of going into detail on one aspect of a topic at the time. Some would argue that learning the details of individual elements before applying them in relation with other is an important educational principle (2, 5). However, what this thesis demonstrates is that there can be advantages of also providing a holistic view when dealing with complex subjects in education. Ideally, a combination of both approaches would probably be preferrable.

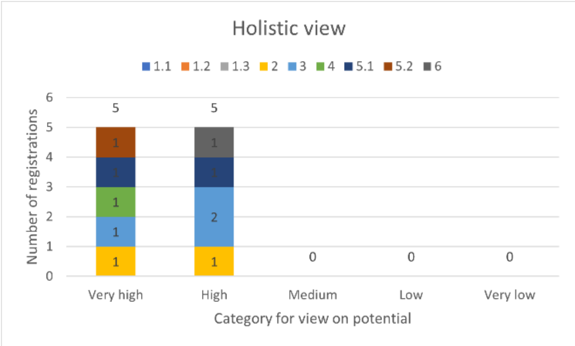

Figure 4.36: Results of holistic view.

4.3.3 User Experience

Feedback from users in the target audience of the tool is valuable data in software development. The closed beta testing of the prototype provided useful findings about methods and solutions chosen regarding user interface and experience of the tool. Some of the findings within this theme came from direct questions, while others were coded and interpreted and like in the rest of the thematic analysis.

4.3.3.1 **Flexibility**

- Opinion on freedom of choice to change properties of elements in the model.

As discussed in chapter 4.2.1, the number of changeable input parameters should be considered closer in future development and might benefit from being divided into modules like in the original plan. The results of the thematic analysis of answers from beta testing and interviews show split opinions on the optimal level of freedom, but the majority suggest that the prototype might have too many changeable parameters in one place.

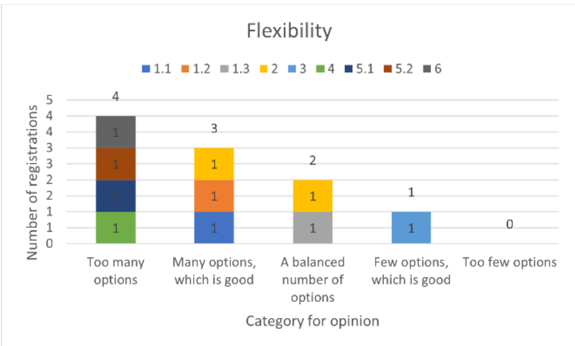

Figure 4.37: Results of flexibility.

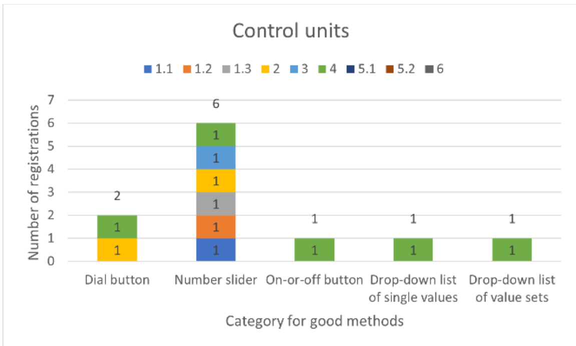

Figure 4.38: Results of control units.

4.3.3.2 **Control units**

- Opinion on method for adjusting input parameters found to be most intuitive.

The clear winner of the method for adjusting input parameters is the number slider. This is valuable feedback for future development of the user interface. However, this also might be the method most impacted by lag due to simulation time, which is a challenge to work on. One participant was registered in all five categories, as they were all found to be the best fit for their different purposes. "Nice with a combination, such as the one in the model. Depends which parameters we are talking about, but all the ones used here are the most intuitive for their purpose. The proportion of glass in the wall, for example, is very suitable for adjusting with sliders. Here it would be strange if you had to enter a number for the share yourself" (Interview 4, Appendix 2). This confirms the idea behind the modelling, that the right control unit depends on the operation.

4.3.3.3 **Results**

- Opinion on suitable number of results displayed at the time.

Following the trend of the evaluation of flexibility and level of complexity, the opinions on number of visible results show an even more clear indication that there is a bit too much being displayed in the model at the time. However, this could partly be due to the fact that in the testing, the participants could move around in the viewports of results in Rhino, deviating from the set-up illustrated in figure 4.3. This is what they had to do to change between which result to focus on and might have led them to be overwhelmed by all the results visible, even though they were not supposed to focus on all of them at once. As discussed in chapter 4.2.1, this is something that should be improved in future development, by organizing the results in a more structured way.

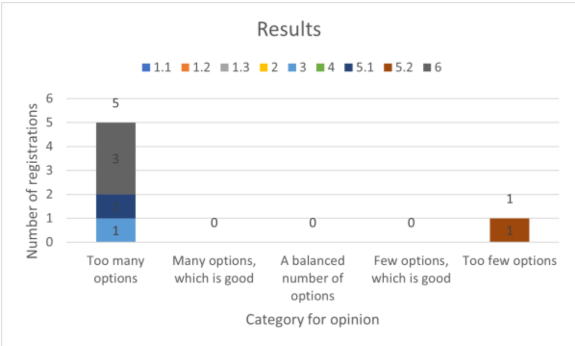

Figure 4.39: Results of results.

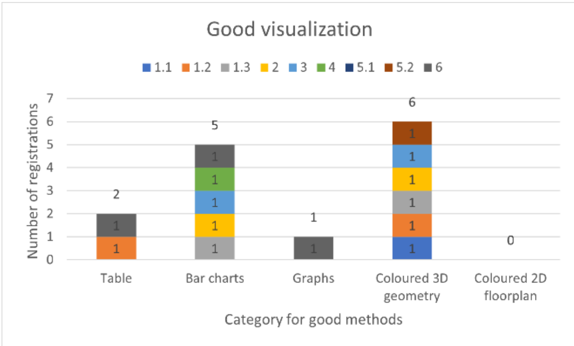

Figure 4.40: Results of good visualization.

4.3.3.4 **Good visualization**

- Opinion on method for visualizing results found to be most effective.

In a tool which purpose is to visualize connections between design decisions and effect on building physics' results, finding out which visualization method is regarded as most effective among the users is quite important. According to the analysis, the winner here is the 3D geometry of the design coloured based on results from simulation of total energy intensity. As elaborated on in chapter 4.2.10, this is a good demonstration of potential benefits of parametric simulation software used in this way.

4.3.3.5 **Bad visualization**

- Opinion on method for visualizing results found to be least effective.

A type of feedback just as important as the good, is feedback on what is considered to be the least effective visualization method used in the prototype. Here, the graphs stand out, with four registrations. Even though it might not be a favourite in general, it might also have a lot to do with missing information about the graphs in the prototype, as discussed in chapter 4.2.12 and 4.2.13.

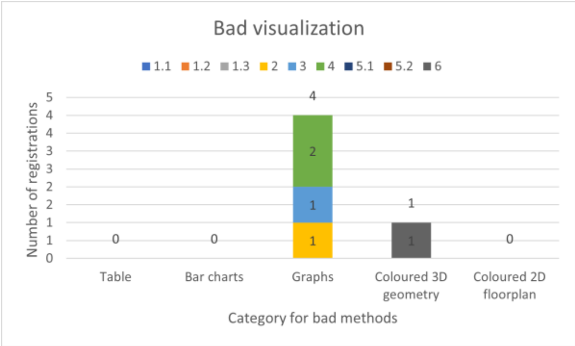

Figure 4.41: Results of bad visualization.

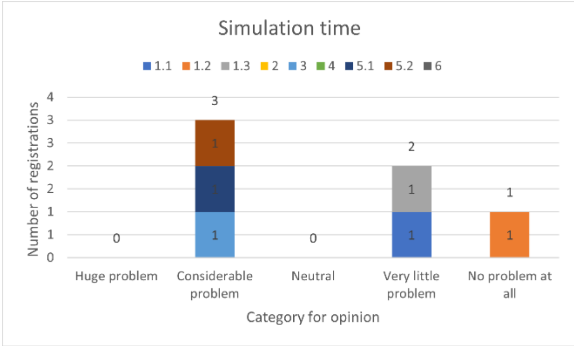

Figure 4.42: Results of simulation time.

4.3.3.6 **Simulation time**

- Opinion on problem of simulation time resulting in lag when changing parameters.

A topic that was brought up a few times during testing of the prototype was the lag of some features due to the few seconds of simulation time when adjusting some parameters. As the coded transcripts show, the views on this are a bit different. Some say that it is no problem at all, while for others it was a more important drawback of the tool. It must also be noted that some responses in regards of the lag take into account that it is a prototype in an early stage of development, meaning that they might see it as a bigger problem in a further developed and more finished version. The following is an example "Off course, it reacts a little bit slow, but that must be expected in the start phase" (Interview 1, Appendix 2). As discussed in chapter 4.2.4, there are different considerations that must be made to find a good solution for the challenge of the simulation time.

4.3.3.7 **Level of complexity**

- Opinion on level of complexity of the content.

Some important findings of the closed beta testing were that the tool might be a bit too complex for the students in the undergraduate course that it is designed for. The following quotes says this about the prototype. "Perhaps a bit too advanced for students at our stage" (Interview 5, Appendix 2). Even though the model is planned to fit the content of their specific course, the challenges met in development of the prototype might have led to a less effective tool then what the planned tool potentially could have been, and what is possible to achieve with parametric simulation in a future development with more time and resources available.

Earlier user involvement would also have benefitted the prototype, as discussed in chapter 4.1. At the same time, it is not always possible to develop a tool that is as effective for everyone in its target audience. "Don't quite see how the model will be appropriate for students at our level, 1st grade. Many people just want to pass and stay afloat, then you don't have to look at all these connections. Can be difficult to understand" (Interview 6, Appendix 2). This quote implies that even though the content of the prototype is based on the syllabus of their building science course, it doesn't necessarily mean that all students have everything under control. A version of the tool with different options for levels of complexity could have helped with this problem, as suggested by some students.

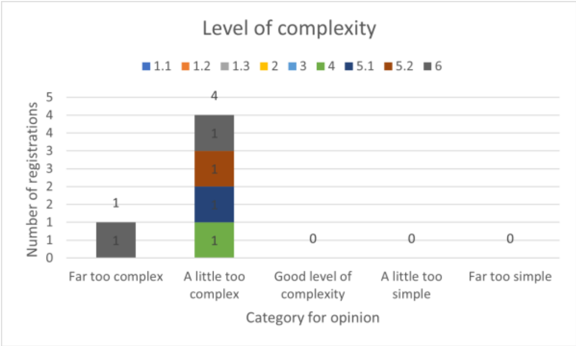

Figure 4.43: Results of level of complexity.

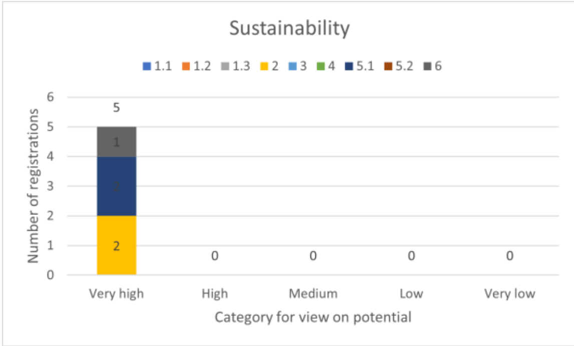

Figure 4.44: Results of sustainability.

4.3.3.8 Sustainability

- Potential for helping students make design choices that are good for sustainable buildings.

For all five registrations of this topic, the students brought it up unprompted, without sustainability being mentioned in any questions. Even though sustainability is a naturally related topic of energy simulations and architecture in general, these results can support the assertion made in chapter 4.2.11, about students typically being interested in climate and sustainability. As suggested there, this is an angle that can be utilized to get students engaged in features of the software.

4.3.3.9 Overall user experience

- Impression of each participant's opinion of overall user experience based on their expressions in testing and interviews.

Like the code for general potential, this code is also registering one vote per participant, to have a clear overview of the overall user experience of the prototype. This code is also based on the participant's expressions during beta testing. The results range from "bad" to "very good", which indicates that the prototype could be on the right track to a proper tool. However, the participants registered in the category "very good", have probably taken into consideration that they were testing a prototype and not a finished product when expressing themselves of the user experience.

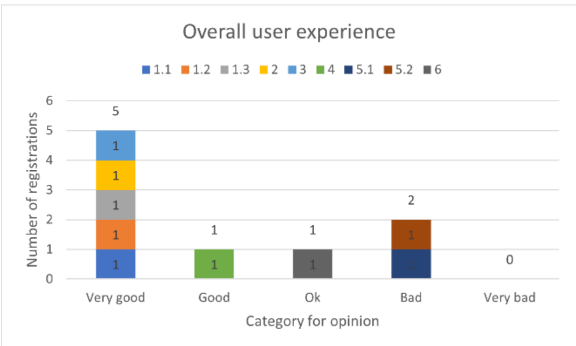

Figure 4.45: Results of overall user experience.

5 Conclusion

In this study we have investigated how parametric simulation can be used as a tool for deep learning experience in Building science. We have demonstrated important steps in the development of a prototype, through planning, modelling, and closed beta testing. All three phases have provided useful experience, that can benefit both future development of the tool and similar software, the use of parametric simulation in education, and in turn help bridge the gap between architecture and building science. The results have also been beneficial for answering the research question of this thesis, which was "How can parametric simulation software be used to develop an educational tool for helping students in building science handle complexity?"

The process of developing a prototype of the tool has underlined the importance of a good plan, clear goals and objectives, early user involvement, an outline of the planned content, and beta testing with feedback of user experience. Modelling the prototype with very little prior experience in parametric simulation has proven to be a steep learning curve. When time and resources are limited, the ability to narrow down the scope, while still achieving the desired results, are crucial to be able to complete. Modelling the prototype has also shown that following the plan made early in the beginning is not always as practicable to construct technically, especially when dealing with topics of high complexity and many interconnections. Allowing for changes to be made along the way is therefore helpful when working on an exploratory project with a short time frame.

The prototype constructed for this thesis is not to be considered a finished tool to be used in education. Rather, it is developed and used in this thesis as an example of how parametric simulation can be exploited for the purpose of breaking down complexity in education. The solutions used for the prototype have been chosen to solve the specified tasks in an efficient way, while at the same time enabling comparison of different methods, for the purpose of exploration and feedback generation. Values and results are not controlled or quality checked and should not be relied upon as a realistic. However, the concepts they illustrate have provided useful insights on possible ways of handling complexity in building science using a holistic approach.

The closed beta testing and interviews with building science students in the target audience for the prototype have provided valuable feedback for this study. Even though it is challenging to measure the tool's effect on students' understanding and ability to handle complexity, the data resulting from the thematic analysis of their answers have given some interesting indications of the tool's potential to help with some key principles of complexity. These indications have been used to discuss benefits and limitations of the prototype and reflect on how parametric simulation can be used as a tool for deep learning experience in building science.

To summarise the findings of the analysis, it can be ascertained that parametric simulation has potential for helping students handle complexity in education. There are large benefits from of the possibilities by demonstrating emergent aspects and interconnections, breaking down initial difficulty, and in general presenting a holistic view of the complex topics. Examples of other positive aspects discovered through the interviews are students' views on the tool's potential benefits for climate and sustainability, and for providing a common understanding in teamwork on complex tasks. The findings also point out potentials for improvement of the prototype, which are important for the user experience. The nature of this ranges from descriptions and visualizations of results to division of content, overwhelming levels of complexity and challenges of reducing simulation time for a smoother operation. This is all valuable feedback, which should be taken into consideration in further development of the tool.

This study contributes to the fields of education both in general and in building science and architecture, and to the work with parametric simulation and software development. Experiences from the development process are useful for future work with the project, as well as in other software developments. The same goes for the findings of the modelling phase, which also have resulted in the prototype acting as an example of how parametric simulation can be used as a tool for deep learning experience in building science. The files for the prototype are available for download via the link in appendix 1, as of 26th May 2023. Finally, the results of the thematic analysis provide indications of how students view the effect of such a tool, which can be useful for reviewing and improving education and adapting teaching methods to new available technology. In turn, this can lead to more engagement and higher quality in education, closer collaboration, and increased understanding between the fields of architecture and building science, and buildings of higher quality and performance in an even broader perspective.

5.1 Future work

The prototype developed and tested in this thesis is planned as a part of a larger project of developing a complete and functional tool for building science education. As illustrated in table 2, only some parts of the planned content are included in the prototype. This leaves a large potential for future work. In addition to this, the development and beta testing have also revealed potential for improvements and future work. Some things can be improved relatively quick and easy, by structuring and describing results better. Other potential improvements require larger amount of time and resources. Plugins can for example be used to connect control units and visualized results to panels outside grasshopper, providing a better user interface.

A restructuring of input and output parameters into modules, like initially planned, could also have been beneficial. For example, could the design and total energy demand always be visible, while input parameters and detailed results vary according to the specific parameters being explored at the time. This would have reduced a lot of the overwhelming complexity of too many options and results that some students experienced during testing, while still providing the holistic view that the results have suggested to have potential of being very effective.

Finding a way of reducing the lag caused by the simulation time could also be a large improvement for the user experience. This could for example be done by pre-simulating design options and storing them in a package file that could be downloaded by the user together with the simulation file and reloaded for use in the tool. However, depending on the freedom of choice in the tool, this would take a lot of time to perform, and the exact solution for reloading results is left for future work.

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Appendices

Appendix 1: Link to download page for files of developed prototype.

Appendix 2: Transcribed interview answers.

Appendix 3: Table of coding for thematic analysis.

Appendix 1: Link to download page for files of developed prototype.

The files for the prototype of the simulation model developed for this thesis is as of May 26, 2023, available for download on the following web address: https://doi.org/10.5281/zenodo.7972499

Appendix 2: Transcribed interview answers.

Do you think this tool has potential for improving students' general ability to handle complexity, regarding the interconnection of building science and architecture?

Interview 1

All: Yes, think it seems like it has great potential

1: Enables faster and easier testing of different designs. Can quickly see if what you thought would have an impact really does or not.

2: No need to do calculations for each design option. You see the effect right away.

Interview 2

I am seeing how the program can be good in early stages of design, because it gives an overview of what is usually a bit overwhelming in the start.

Could work well in education too.

Very nice to see a connection between several things you learn in the course. You often have to calculate heat and electricity consumption etc, but it is hard to know how much impact design decisions have compared to each other. It is good that this can be compared here. A lot is connected, and it can therefore be nice to have it together, so that you can see the whole picture.

Interview 3

I think the model can certainly help. I have come across something that was a bit similar in high school science, where we set up and adjusted various components and saw the results in a graph, just like here. This was very instructive and gave a good understanding of the topic.

In any case, I think the model can be helpful as long as you understand how to use the software and what the results that come out mean.

Interview 4

In a way, I think it could have a lot of potential. For example, it is nice to be able to see the difference from TEK17 and other rules for comparison. This is a new aspect of the architecture that we don't see when we are only thinking of design or doing some building science exercises.

If you calculate it manually, you only get a number that you often don't know what to do with. You don't know if the results are good or bad, or how much impact different design decisions have compared to others. So, a good thing about this model is that you see what it means in the big picture.

Interview 5

1: I think it could be good with a model that collects all relevant parameters. So far in the study, we have mostly looked at certain topics separately. Among other things, we have used a physical solar path study a little before. But it is difficult to understand the influence between several parameters. How much does changing the window size help compared to turning the building or adding more insulation. It is difficult to understand what is actually environmentally friendly. Sometimes you think it is, but then it might not be after all. A model like this could help with all this.

1: It would be very good if we could use this model to test what we do in the projects we work on.

1: If this had been a website with a slightly better user interface and a slightly faster response, I would have used it all the time to check things out for my projects.

2: Interesting to see how the various design choices affect both energy use and daylight, so that there needs to be a balance in the amount of windows. I certainly believe that such a model can be useful if it is developed a little further.

Interview 6

Nice to see how parameters play out and affect each other.

When I need to deal with complex tasks, I like to use the following approach:

1. Get an overview of how to solve the task. What are your main problems?
2. Assess which tasks require different solutions

3. Look at the whole picture and get an overview. Might need to go back and forth between previous steps.

This program might have the potential to work like that.
It could be useful to set up threshold values, to have something that detects and shows warning triangles if the result of the design approaches the limit value.

How does this model affect your ability to see a holistic view of the course and understand how the various parts affect each other?

Interview 3
Many graphs collected in one place make it clear that there are many factors that determine what something really turns out to be. Can be useful for getting people to understand the whole, while also seeing how certain parts affect each other in different ways.
Interview 4
I think such a model will work best in the initial phase to make an estimation.
When you want to make more detailed assessments later in the process, you are often unsure whether you can trust the results that such a model provides.
Interview 5
1: I think it could be brilliant to go into detail to see the results of everything we learn to calculate manually.
2: Thinks that it can be very cool to see how the building you design performs in reality.
Interview 6
Gain another understanding of how windows affect where it is nice to sit, where there are problems with glazing and cold draft, where there is good daylight, and at the same time how this impacts the energy use. This shows that there are more things to think about when you consider all factors together instead of one at the time.
However, I think it might be too complicated for students at our level.

How do you think using this model can contribute to collaboration with others on complex tasks?

Interview 1
3: In the event of disagreements, it can help resolve conflicts.
2: Everyone has the opportunity to influence decisions and have an overview of the decision-making basis.
Interview 2
If the focus is on sustainability, the model can be used as a tool, as it helps to highlight what works to reduce energy use, etc.
Can also lead to less debates about what works and what doesn't. Everyone gets the same overview.
Interview 3
If there is a lot of details, it may be good to work with it alone to avoid collision with others working with the same model.
It might be good to use the model as a tool to work with things or understand the principles properly on your own first. Afterwards, you can show others what you have been thinking.
Interview 4
In general, I think that it is a bit early for us to use such a model, which is so advanced. We do not relate so much to what is possible to build, rules and realities. As we progress and have to familiarize yourself with these rules, such a model can certainly be relevant. It gives you a new perspective on it.
Interview 5
1: Could be useful in discussions about the environment and impact on energy use, for example.
1: Nobody quite knows what is actually best or most appropriate in the given situations.
2: It can be very good to use the model as a central point of view, if everyone can understand it well.
The nice thing is that everyone can relate to it, but then you have to know how it works and what all

the results mean. It helps little if there is only one person who has the expertise to understand how the model works and what the results mean.
1: In projects, it would have been useful to have the model as an overview of the facts about technical aspects and performance in different aspects.

User Experience

Do you think you learn best when you have great or little freedom of choice to change elements in the model?
For example, do you prefer to be able to adjust many parameters for the same element, such as the windows and sun shading, or to concentrate on fewer or only one parameter at a time, such as climate and orientation?

Interview 1
All: Advantage with great freedom of choice, like in this model.
1: People will often quickly switch to other tools if you cannot change everything you want.
3: Must be intuitive though.
3: A narrower approach can be an advantage in some cases. A more complex version than this can be overwhelming at the start when learning something for the first time.
1: The problem is often that programs are not very intuitive.
2: The reason I use Rhino sometimes is that it is intuitive, easy to learn, you can find functions by writing commands etc. Apart from that, I use ArchiCAD.
Interview 2
Up to individuals. Too many options make it difficult to choose. Then there are also the nerds who want to go into detail about everything. I think it's appropriate the way it is here.
Interview 3
It may be okay to have a few choices initially, for those who are not that familiar with the subject. When going more in depth, one can rather add more factors. In this way, you avoid being overwhelmed at the start.
Interview 4
Ok with several opportunities at the start, but preferably an increase over time. Depends a little on which choices suit the situation. I wondered why it was possible to adjust the length and height, but not the width.
What would be optimal was if there had been a choice for the complexity, so that you could open more functions step by step as you progressed in the process.
Interview 5
Both: It would have been very attractive if you could choose the level of complexity and details of available options.
1: If you could initially choose a quick version to use on a sketch etc. Would have been very helpful. Then you can possibly go into more detail when you need it in a project later
2: If I had been asked to try out this model and familiarize myself with it, I would not have known where to start, and would not have understood much of it.
2: Would probably prefer to have less choices to deal with at a time, at our level. Later, however, it could be very good to have a model like this where you can test out more detailed analyses.

For adjusting parameters in the model, you have tried both dial buttons, number sliders, on-or-off buttons, and drop-down lists with either single values or complete value sets.
Which adjustment method did you find most intuitive or appropriate for the operation it was supposed to perform?
Interview 1
1: I liked best the possibility of adjusting window parameters on the facade.

2: Can help us set some limits.
3: Get a clue on how to achieve the desired goals. Otherwise, you have to set everything up yourself, and then risk the engineers saying it is not achievable.
1: Regarding the adjustment method, I like the slider best.
2: Me too.
1: It seemed a bit safer to be able to adjust it than if you have to go to the drop-down menu and check the options of what you can adjust to.
3: I agree.
Interview 2
The favourite was location. Nice to be able to compare this, as there are actually quite large differences from north to south, which make a big difference in performance, even though there is no change in the design.
The wheel for orientation was also nice
Sliders also work well for what they are used for here. There wouldn't have been many other options.
Interview 3
Slider, as long as it is synchronized, so that you can see the changes quickly. Then you can clearly see whether the result increases a lot or just a little.
Interview 4
Nice with a combination, such as the one in the model. Depends which parameters we are talking about, but all the ones used here are the most intuitive for their purpose. The proportion of glass in the wall, for example, is very suitable for adjusting with sliders. Here it would be strange if you had to enter a number for the share yourself.

Among the visualization methods you have seen in the model, there are displays of results both in the form of tables, bar charts, balance charts, graphs, colouring of the 3D model and colour maps on the floor plan of the model. Which visualization method do you think best brought out the results it was supposed to show?
Interview 1
All: Colour on 3D building is best.
1: I like that it is using the actual house. Normally, it can be difficult to connect design and graphs.
3: Also good with column diagrams as long as they are comparable.
2: Good with a table showing the relationship to requirements.
Interview 2
Haven't looked at graphs that much before, so I think they are a bit difficult. The bar charts here were easy to understand straight away.
The box with colour based on energy demand makes you understand the connection straight away. I'm a bit used to this visualization from maths.
Interview 3
House in colour is very clear. Then you know quite intuitively whether you are in a good or bad position in terms of the performance that the design entails.
Otherwise, bar charts are also easy to read. As long as they are simple and clear, bar graphs are very nice.
Interview 4
The diagrams are fine, but it would be better if you could make them become proper diagrams that pop out and are displayed in 2D in a window outside of Rhino.
Interview 6
Energy use is perhaps the most interesting to look at, as this is important for the climate and the environment.
Prefer diagrams over 3D model.
It would have been good to see the 3D model as well if you had had the option to hide it from the rest.
Interview 6

I like the table best. It would have been nice to have 2-3 tables at the top, then possibly graphs and 3D below.

Which visualization method did you find most difficult to understand?

Interview 2

The PV graph is difficult to understand at first. When you first zoom in and read what is written on the axes, you understand it too. It is nice that it is included though, so that you can know the potential environmental benefits.

Interview 3

The solar energy production diagram. Looked quite complex, and I didn't quite understand what it was at first.

Interview 4

Solar energy production was a bit difficult to read at first glance. It was also a bit difficult to see what the result was for. Whether it was energy use or energy production, as well as what the difference between the two diagrams for each of the roof surfaces is. When you know it, it makes sense, but could have been explained.

Psychrometric chart was also difficult to understand when there is no info about what some of the passive measures are or what the dots of data represent.

Interview 5

1: To be completely honest, it's a bit difficult to see what's going on at any given time. There is a lot of information in one place, and you don't quite know where the changes are when you adjust a parameter.

2: The slider lacks a little feedback as it lags a little. I want to look at other diagrams at the same time as looking at the model, which is difficult in the 3D viewport.

Interview 6

Nice to see changes, but not necessary with a 3D model. Can compare two solutions calculated manually as well, as long as they are comparable.

Can be a lot to take in at once.

Don't quite see how the model will be appropriate for students at our level, 1st grade. Many people just want to pass and stay afloat, then you don't have to look at all these connections. Can be difficult to understand.

Is there anything you would like to highlight as good about the model? What did you like best?

Interview 3

That you get the opportunity to visualize the building itself that is involved. You get to see the design together with the results it produces.

I also liked that you get an overview of so many things at the same time.

Interview 5

2: Really liked the way you can see colours on the 3D model to know how you fit according to the standard etc.

Is there anything you would like to point out as bad/challenging about the model? What did you like the least?

Interview 4

Not ideal if people start tinkering with the components for the calculation behind. Should probably hide them better.

Interview 1

3: Off course, it reacts a little bit slow, but that must be expected in the start phase.

1: Whether it is a big problem depends how slow it would be when finished.

2: The lag in this model does not impact the user experience much.

3: If it takes 6 hours it's boring, but a few seconds is no problem.

1: ArchiCAD also lag sometimes, so people are used to a bit of waiting.

2: It is anyway much better than manual calculation.

3: Much better than the alternative.

Interview 3

Can get a bit messy if there is too much going on in the model at the same time. It would have been an advantage if there was an option to hide some diagrams, so that you can focus on the ones you want at a time.

Interview 4

It would be cool if you could enter your own place, not be limited to choosing those that have been entered as options in advance. I don't know how much data is required for that, but if there is only a little data that can be retrieved from the web, it would be good if you could introduce a function where you choose the place you want from a map or something like that.

Interview 5

1: That there is a lot happening at once, and that it does not update very quickly. Still think it has the potential to be very good if you develop it further. If I could have had the program in a version that was a little easier to use and understand, I would use it all the time.

2: A bit challenging to know what actually belongs to what, but can be a very good tool for those who want to get to know it properly. Perhaps a bit too advanced for students at our stage.

Interview 6

It would have been better if you could see diagrams alone.

Appendix 3: Table of coding for thematic analysis.

Theme	Complexity				
Code	**General potential:** View on potential for improving general ability to handle complexity				
Categories	Very high	High	Medium	Low	Very low
Answers	1.1, 1.2, 1.3, 5.1, 5.2	2, 3, 4	6		
Code	**Collaboration:** View on potential for positive impact on collaboration on complex tasks				
Categories	Very high	High	Medium	Low	Very low
Answers	1.1, 1.2, 1.3, 2, 5.1, 5.2	3			
Code	**Emergence:** View on potential for demonstrating new aspects emerging from connected elements				
Categories	Very high	High	Medium	Low	Very low
Answers	4, 5.1, 5.2, 6, 3				
Code	**Non-linearity:** View on potential for demonstrating variable relations between input and output				
Categories	Very high	High	Medium	Low	Very low
Answers	2, 4, 5.1, 3				
Code	**Feedback loops:** View on potential for providing feedback on effect of design changes				
Categories	Very high	High	Medium	Low	Very low
Answers	1.1, 1.2, 2, 3, 4, 5.1, 5.2, 5.2, 6, 1.3	6		4	
Code	**Adaptation:** View on potential for correcting previous misconceptions				
Categories	Very high	High	Medium	Low	Very low
Answers	5.1, 5.1	2			
Theme	Threshold Concepts				
Code	**Transformation:** View on potential for changing the students' perception of a subject or phenomena				
Categories	Very high	High	Medium	Low	Very low
Answers	3, 4	4, 6			
Code	**Integration:** View on potential for revealing new interconnections				
Categories	Very high	High	Medium	Low	Very low
Answers	2, 2, 5.2, 3, 6, 1.1	3, 2		5.1, 5.2, 6, 4, 6	
Code	**Irreversibility:** View on potential for giving understandings that cannot be reverted from				
Categories	Very high	High	Medium	Low	Very low
Answers	2	3, 2, 3, 3			
Code	**Difficulty:** View on potential for avoiding overwhelming or troublesome experience in the start				
Categories	Very high	High	Medium	Low	Very low
Answers	2, 1.3, 2, 3, 5.1, 5.1, 4	3, 4, 5.1, 3, 5.2	4, 2, 4	6, 3, 6, 3, 5.1, 5.2, 4	5.2, 4, 5.1
Code	**Holistic view:** View on potential for demonstrating a holistic view and the boundaries of the field				
Categories	Very high	High	Medium	Low	Very low

Answers	2, 4, 5.1, 5.1, 3	3, 3, 6, 5.1, 2			
Theme	User Experience				
Code	**Flexibility:** Opinion on freedom of choice to change properties of elements in the model				
Categories	Too many options	Many options, which is good	A balanced number of options	Few option, which is good	Too few options
Answers	4, 5.1, 5.2, 6	2, 1.1, 1.2	1.3, 2	3	
Code	**Control units:** Opinion on method for adjusting input parameters found to be most intuitive				
Categories	Dial button	Number slider	On-or-off button	Drop-down lists of single values	Drop-down lists of value sets
Answers	2, 4	1.1, 1.2, 1.3, 2, 3, 4	4	4	4
Code	**Results:** Opinion on suitable number of results displayed at the time				
Categories	Too many options	Many options, which is good	A balanced number of options	Few option, which is good	Too few options
Answers	6, 5.1, 6, 3, 6				5.2
Code	**Good visualization:** Opinion on method for visualizing results found to be most effective				
Categories	Table	Bar charts	Graphs	Coloured 3D geometry	Coloured 2D floorplan
Answers	1.2, 6	1.3, 2, 3, 4, 6	6	1.1, 1.2, 1.3, 3, 5.2, 2	
Code	**Bad visualization:** Opinion on method for visualizing results found to be least effective				
Categories	Table	Bar charts	Graphs	Coloured 3D geometry	Coloured 2D floorplan
Answers			2, 4, 3, 4	6	
Code	**Simulation time:** Opinion on problem of simulation time resulting in lag when changing parameters				
Categories	Huge problem	Considerable problem	Neutral	Very little problem	No problem at all
Answers		5.1, 5.2, 3		1.1, 1.3	1.2
Code	**Level of complexity:** Opinion on level of complexity of the content				
Categories	Far too complex	A little too complex	Good level of complexity	A little too simple	Far too simple
Answers	6	5.1, 5.2, 6, 4			
Code	**Sustainability:** Potential for helping students make design choices that are good for sustainable buildings				
Categories	Very high	High	Ok	Low	Very low
Answers	5.1, 2, 2, 6, 5.1				
Code	**Overall user experience:** Impression of each participant's opinion of overall user experience based on their expressions in testing and interviews.				
Categories	Very good	Good	Ok	Bad	Very Bad
Answers	1.1, 1.2, 1.3, 2, 3	4	6	5.1, 5.2	

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