DIPLOMARBEIT

Requirements for an Interactive and Educational Construction Generation and Evaluation Tool

ausgeführt zum Zwecke der Erlangung des akademischen Grades
einer Diplom-Ingenieurin
unter der Leitung von

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Wien, November 2017

KURZFASSUNG

In den letzten Jahren eröffneten sich durch die ubiquitäre Verfügbarkeit von verschiedensten Werkzeugen zur Gebäudeevaluierung und -simulation zahlreiche neue Möglichkeiten die Qualität einer Gebäudeplanung bereits im Vorhinein schnell und kostengünstig zu bewerten. Darüber hinaus gibt es mit Building Information Modelling (BIM) einen Ansatz, wie Daten unterschiedlichster Werkzeuge zu einheitlichen Modellierungen vereinigt werden können. Der zugrunde liegende Gedanke ist eine Vereinheitlichung und Vereinfachung des Bau- und Planungsprozesses. Leider zeigen viele Studien, dass die Realität eine andere ist - es gibt vielfach Kompatibilitäts- und Datenintegritätsprobleme, dazu setzt sich der Ansatz aus verschiedenen Gründen nur langsam durch.

Eine mögliche Anwendung des beschriebenen Building Information Modellings - nämlich dieses für Zwecke der Ausbildung in Form eines holistischen pädagogischen Ansatzes heranzuziehen - ist bis dato kaum näher betrachtet worden. Die angestrebte flexible und modulare Architektur von BIM-Systemen, die die Verknüpfung unterschiedlicher Datenstrukturen und verschiedenster semantischer Daten adressiert, zeigt viele Parallelen zu dem, was Planende aber auch Ausführende heute oft mühsam manuell an Informationen zusammentragen müssen.

Diese Masterthese befasst sich mit einzelnen Aspekten dieser Idee:

- Zunächst werden aktuelle technologische Entwicklungen und einige weitverbreitete Software-Werkzeuge und deren Interfaces (auch aus Nicht-Bau-Domänen) betrachtet und miteinander verglichen, um eine Inspiration für das beschriebene Werkzeug zu erhalten. Dabei werden Konzepte wie immersive Virtual Reality (VR), Augmented Reality (AR) und Gaming - Ansätze untersucht.

- Aufbauend auf diesen Untersuchungen wird ein spezifischer Anwendungsfall, basierend auf zwei sehr unterschiedlichen, existierenden Werkzeugen untersucht. Eine weitverbreitete Spiel-Umgebung (Minecraft), dessen Benutzeroberfläche für viele Anwender als sehr intuitiv betrachtet wird, wird als potentielle Datenquelle für eine hochspezialisierte Gebäudesimulationssoftware (die numerische Wärmebrückensimulations-Software AnTherm) herangezogen. Beide Werkzeuge haben

Gemeinsamkeiten (wie das Arbeiten mit "Bauelementen" bzw. "Blöcken"), zeigen aber hinsichtlich Benutzeroberfläche, Datenhandling und den Möglichkeiten der Geometriemanipulation doch große Unterschiede. In der Arbeit wird die Kopplung dieser beiden Werkzeuge für eine vereinfachte und schnellere Bearbeitung von Wärmebrückenproblemen diskutiert. Dabei werden Möglichkeiten aufgezeigt sowie potentielle Probleme adressiert. Mögliche Workflows zur Datenübernahme werden skizziert und hinsichtlich ihres Nutzens untersucht.

Die vorliegende Masterarbeit befasst sich somit mit einem kleinen, aber sehr wichtigen Baustein des beschriebenen Environments, nämlich den Aspekten der vereinfachten und intuitiven Dateneingabe für komplexe Werkzeuge. Es ist davon auszugehen, dass ob der vielen Erfahrungen die jungen Menschen heute im Bereich Gaming und Computer-Nutzung sammeln, solche Ansätze durchaus vielversprechend sein können.

Stichwörter: Bauinformatik, Baukonstruktionen, numerische Wärmebrücken-Simulation, Virtual Reality, Augmented Reality, Minecraft, AnTherm, Workflow-Design.

ABSTRACT

In recent years, the ubiquitous availability of various tools for building evaluation and simulation has opened up numerous new possibilities for quick and cost-effective assessment of building design and planning. In addition, Building Information Modeling (BIM) provides an approach to combine data from a wide range of tools into a comprehensive data space that represents all important aspects of a building. The underlying idea is to unify and simplify the construction and planning process. However, studies have shown that often compatibility and data integrity problems can be observed. Moreover, the general approach is accepted by practitioners and stakeholders slower than expected for a variety of reasons.

A possible application of Building Information Modeling - namely to be used as an educational medium to support a holistic pedagogical approach - has hardly been considered until now. The flexible and modular architecture of BIM systems, which addresses the linking of different data structures and various means of semantic data, shows many parallels to the workflow of researchers and building professionals. The manual acquisition, organization, and structuring of information that is the current practice can be considered outdated, and could benefit from the BIM-ideas, if properly deployed for educational purposes.

This master thesis focuses on important aspects within this idea:

- First, current technological developments and some widely distributed software tools and their interfaces (also from non-construction domains) are reviewed and compared with each another. This is done to obtain inspiration for the described environment. Concepts such as immersive virtual reality (VR), augmented reality (AR), gaming approaches and their educational potential are thoroughly examined.

- Based on these research efforts, a specific application and subsequently the coupling of two existing software tools, which were originally designed for different purposes, is examined. Specifically, a wide-spread gaming environment (Minecraft), often described as intuitive, is considered as a potential input data source for a highly specialized building simulation software (the numerical thermal bridge simulation software AnTherm). These tools share some similarities but show great differences regarding user interface, data handling and the possibilities of geometry manipulation. The coupling of these two tools is discussed and aims at a simplified, more efficient workflow for assessing thermal bridges. Potential problems and opportunities are illustrated. Possible workflows for the data transfer are outlined, examined and discussed regarding their advantages and disadvantages.

The present master thesis engages in a small but very important domain of the described environment, namely the aspect of simplified and intuitive data input for complex tools. Given the wide-spread use of gaming engines such as Minecraft amongst young people, the approach can be considered as a promising idea.

Keywords: construction informatics, building construction, numerical thermal bridge simulation, virtual reality, augmented reality, Minecraft, AnTherm, workflow design.

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ABBREVIATIONS

AEC	Architecture, engineering and construction
API	Application programming interface
BEM	Building Energy Modeling
BIM	Building Information Modeling
BPS	Building performance simulation
CAD	Computer-aided design
CAM	Computer-aided manufacturing
CGI	Computer generated imagery
DWG	Drawing file format
DXF	Drawing exchange format
GUI	Graphical user interface
HMI	Human-machine interaction
IFC	Industry Foundation Classes
ML	Machine learning
NURBS	Non-Uniform Rational B-Spline
OBJ	Object file
OOP	Object oriented programming or modelling
STL	Stereolithography file format
TUI	Tangible user interface
VPL	Visual programming language
VRML	Virtual Reality Modeling Language (before 1995 – Virtual Reality Markup Language)

NOMENCLATURE

U	Thermal transmittance value (U-value), $[Wm^{-2}K^{-1}]$
R	Thermal resistance, $[m^2KW^{-1}]$
R_{si}	Internal surface resistance, $[m^2KW^{-1}]$
R_{se}	External surface resistance, $[m^2KW^{-1}]$
Q	Heat flow rate, [W]
ρ	Density, $[kgm^{-3}]$
c	Specific heat capacity, $[Jkg^{-1}K^{-1}]$
λ	Thermal conductivity, $[Wm^{-1}K^{-1}]$
L^{2D}	Thermal coupling coefficient (length related transmittance for 2D models), $[Wm^{-1}K^{-1}]$
L^{3D}	Thermal coupling coefficient (intrinsically for 3D models), $[WK^{-1}]$
f_{Rsi}	Temperature factor, [-]
$\theta_{si, min}$	Minimum interior surface temperature, [°C]
θ_i, θ_e	Temperatures of inside and outside space, [°C]
μ	µ-factor, [-]
Ψ	Linear thermal transmittance value *Psi*, $[Wm^{-1}K^{-1}]$

1 INTRODUCTION

1.1 Overview

In recent years, building layouts and construction drawings have been almost entirely delivered in 2D. Currently, 3D visualizations (even of complex construction details, mounting and build-up) are becoming a more familiar routine in the workflow of architects and engineers. This might be partly due to the limited efficiency of conventional 2D computer aided design (CAD) and the shortcomings of the 2D representation of design ideas (Ibrahim and Rahimian 2010). However, this change and the implementation of technological innovation are happening very slowly within the building industry. This is surprising given the large impact buildings have on economic, ecological and health aspects of human societies. Other industries, such as the automotive industry, have proven to implement new developments much faster. This rather slow progress in the Architecture-Engineering-and-Construction (AEC) domain can also be observed regarding knowledge transfer processes and general knowledge representation. A noticeable discrepancy in comparison to other branches and domains can be observed in both academia and work life. Architectural education and practice have outgrown their classical definitions. Generally, universities are promoting research projects and are also introducing new courses into their programs with the purpose of addressing the latest innovations and software solutions. However, little has been changed in the way building construction and architecture students are being taught. This is true even in those schools that have implemented modern and effective online courses into their curricular structures.

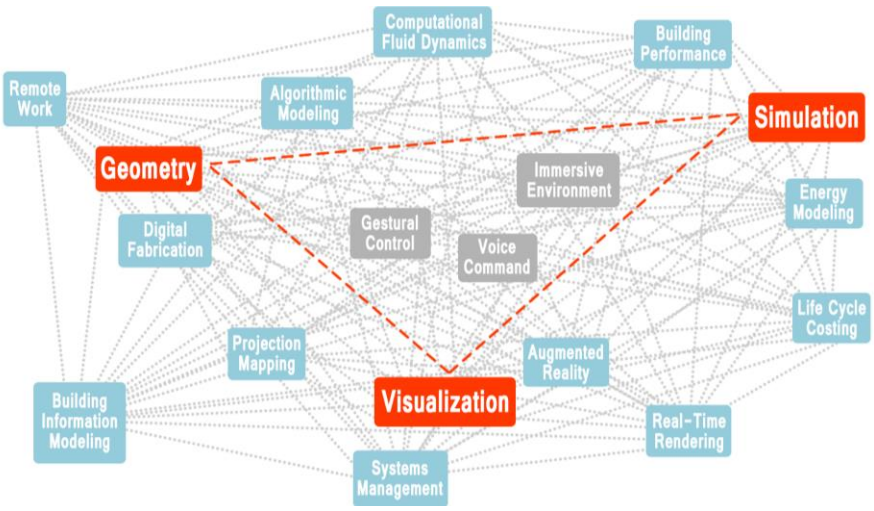


Figure 1: The expanding toolbox of AEC professionals

In contrast, most of the leading architectural practices (and companies from related fields) are experimenting and expanding their toolboxes (Fig. 1). They implement creative solutions from other fields and in some cases create new software solutions for specific design problems. The relationship between innovation lead and university teaching is of crucial importance for future professionals. The resulting diverse palette of tools and workflow possibilities can, however, be overwhelming and confusing for students.

Therefore, the main focus of this master thesis is to conceptualize a new kind of educational software environment, which encompasses the simple generation and evaluation of construction details in an easy-to-grasp and immersive 3D virtual or mixed reality (VR or MR) environment, and investigate possible development approaches.

1.2 Motivation

In comparison to earlier times, it seems that there is not a typical workflow for the architectural practice anymore. The ever expanding tools for planners and architects provide a vast number of workflow solutions that aid building design and solve individual problems in an efficient way. The increasing use of automation techniques (e.g. macros, which represent instructions for the computer to perform particular tasks; add-ins) and data connecting platforms are often relieving professionals from the tedious work of repeating manual tasks like rotating, numbering and plotting a large amount of layouts (Autodesk knowledge network: customization). Nevertheless, AEC professionals are still constantly switching between different design mediums, predominantly between 2D sketches and 3D parametric or building information modeling (BIM) software. Even if a project is accomplished completely within a 3D design environment, this is regularly done on a 2D monitor. One could argue that we are living in a three-dimensional reality and already have the tools to draft, construct and develop models directly in 3D, for instance with the help of interactive VR environments. The rapid development of VR, MR and augmented reality (AR) in recent years and the gamification of learning are bridging the gap between design, gaming, architecture and challenging conventional education traditions (Kapp 2012, Yan et al. 2010).

However, few of the currently available software environments in typical architectural or engineering domains, have been developed for educational purposes in first place or do implement interactive, creativity-promoting features.

Moreover, almost all of the building physics software tools are specifically oriented towards professionals and scientists, which results in a steep learning curve for novice users and inexperienced students.

The creation of a new user-friendly program, reminiscent of a computer game, a program which generates and evaluates construction details and has educational potential could facilitate sustainable architectural practices. The immersive 3D visualization capabilities of such a tool and its dynamic environment should help develop the creative ability of the user and support learning patterns and encourage experimentation (e.g. with new materials). A game-like software tool for building detail construction and evaluation would appeal to novice users and students, and help them focus more on learning about building physics in an entertaining manner, rather than learning to use a complex computer simulation program.

An important question is, however, if it is really necessary to use a 3D visual environment to evaluate a construction detail from a building physics perspective. It is possible to convey the needed input information to a reader on the computer and assign a task to be executed in order to produce the desired output (like in Energy Plus). Although this is true, such performance assessment tools require specialized knowledge and are developed for AEC professionals and scientists, who can manage the sensitive data input and check it during the simulation stages. These tools aim for high precision, but are not suitable for novice users, students and building enthusiasts. Furthermore, novice designers have limited expertise in using an external representation tool to convey their design ideas, but need clear communication means during design studio tutoring (Ibrahim and Rahimian 2010). Therefore, an intuitive VR-or MR-based 3D sketching tool, which allows the users to *draw* directly in space, e.g. in a natural manner just by waving a hand, and supports design team interactivity could overcome conceptual visualization problems. If the tool uses a gaming engine to allow creative exploration in a game world, while educating at the same time, it could make the whole learning experience more immersive and rewarding.

The impact of gaming on many aspects of modern life is undeniable. The phenomenal increase in computer power over the last century, along with its falling price is another catalyst for the development of the gaming industry (Nordhaus 2002, Avent 2014).

Many of the most successful computer games exploit the fundamental concepts of exploration, creation and expansion – basic concepts every human being is drawn to (Boyle 2011, Yee 2006). The urge to create and build is an especially imperative part of human nature, and one of the most intuitive (and beloved) games based on this concept is LEGO. LEGO are physical toys, consisting mostly of interlocking plastic bricks. The idea of playing with uniform, scalable blocks could be translated and used in a VR or MR 3D environment as well, where the simplicity of the "building material" would be an advantage.

1.3 Background

In the following chapters, some important research findings and previous research projects that influenced this study are presented. The current changes and trends in design education, architectural software and the role of gaming in university and work life are shortly outlaid and analysed.

After the following chapters comes the main chapter dedicated to the tool conceptualization.

1.3.1 Overview

There are many software programs which support architectural planning, building performance simulation and energy evaluation in use today. In spite of this, it is often hard to find an integrated approach. The user is usually forced to combine multiple programs or switch between them.

Currently, the design workflow exceeds in complexity and performance assessment via computer simulations with various software tools have become an essential part of the building design process. This has led to the broader use of building performance simulation (BPS) tools between diverse design teams involved in a building project. However, most BPS tools require time to learn, are difficult to use and are developed for trained professionals in the field. Moreover, users prefer the simulation results to be presented in a visual form, rather than in numerical tabulation (Bucevac 2016, Attia 2010).

The interpretation of simulation outputs can not only be a setback for novice users and students, but architects as well. The explanatory power of good visuals improves understanding. After all, visual perception consists of the ability to detect light and interpret it, in order to see. Visual signals from the eye do not only travel to the visual cortex, but convey additional, contextual information, which in turn shapes our visual perception (Roth et al. 2015).

With the introduction complex BPS tools or BIM, program compatibility has not become any less of an issue. To provide an example, all of the materials' specification information has to be gathered and analysed by building professionals. Even then, a thorough building physics assessment (3D thermal bridges, vapour bridges, coupling coefficients, condensate risk and such) can rarely be done directly in the BIM central file. Because of this, import and export actions, and sometimes file conversion of various file formats back and forth are necessary.

To provide an example, one of the very few programs that support the file exchange between a BIM and building energy modeling (BEM) environment is Eco Designer Star by GRAPHISOFT. This program is currently not available in Austria and some other European countries. However, this program, which is working as an ArchiCAD extension, can be compared to an EnergyPlus model working with inputs from SketchUp or another design tool. It is clear that Eco Designer Star supports environmentally friendly and low-energy designs, but during the design process building materials still need to be chosen and adjusted by the professional. The program offers evaluation outputs in the form of diagrams (e.g. heat flow and temperature lines). The benefits of this tool are that the user is able to work with the BIM model and highlight potential thermal weak points, introduce changes and perform an energy simulation. Still, the input for the calculation is tabular and the detail representations are reminiscent of the interface of a 2D vector drafting tool. The program is not interactive, it is highly complex, and has no educational purpose since it presumes that the user is a professional with extensive knowledge and experience in building sciences.

1.3.2 Architectural education and software

Computer aided design and manufacturing (CAD/CAM) software continues to evolve, while AEC professionals are welcoming innovative products form other fields as well. 3D user interfaces (UIs) are suitable for engineers, architects and designers, but sometimes it is a matter of preference. Some engineers still prefer to start the design process with a 2D vector program and then switch to Autodesk's Inventor, because they have more precise control.

With the emergence of many new tools that reimagine the building's frame and push toward a variable and modular component design and with the progress of digital pre-fabrication architects and designers do not have to compromise creativity for structural benefit anymore. Due to the latest innovations in 3D printing, 3D scanning, form generation and digital fabrication the design focus shifts from questions such as *What else is possible?* to *What is sustainable and sensible? Which is the optimal design solution, in terms of energy and material usage? What is the best design considering the comfort of the occupants, the building purpose?*

According to Prabhjot Singh from GE Global Research *„If you are a designer who has always designed for conventional manufacturing, you need to unlearn some of what you know*" (Wujec 2017, p.192).

Even though we might be experiencing the 4th industrial revolution, one of the main issues with current developments is that designers and AEC professionals are drawing, conceptualizing and constructing mostly in a 3D environment, but on a 2D computer flat screen with the help of generic tools, such as a mouse or a pen (Schwab 2017). American computer scientist, regarded as the "father of computer graphics", Ivan Sutherland is convinced that: *„If the task of the display is to serve as a looking-glass into the mathematical wonderland constructed in computer memory, it should serve as many senses as possible.*" (Quote by Ivan Sutherland, Choi 2016, p.14).

Another issue is the seemingly loosening connection between architectural education and architectural practice. Some aspects of the classical architectural curriculum are not as relevant anymore and many students do not know what to expect from real life practice after leaving academia. Usually, architectural education starts introducing and demanding the use of architectural software for design projects on average not earlier than in the third semester of studies. The degree of technological skills that is taught throughout architectural education varies in different institutions, but generally the educational system seems slower in integrating the rapidly evolving technologies of the field. When it fails to provide adequate theoretical and practical courses on new technologies, it leaves the responsibility to the student, who needs in-depth knowledge of relevant software to be competitive in the job market (Rosenfield 2011). Furthermore, although schools are attempting to integrate disciplines and promote collaboration, it is often left at an intentional level. The ongoing compartmentalization of disciplines is one of the biggest issues in architectural education. Collaboration fosters innovation and creativity and teaches about work ethics and other building professionals' operation of work.

An interesting concept, which does not only apply to architectural education, but is highly relevant, is that the common predictive modeling that ruled our educational system is not working anymore. Many praise the "learning sideways" approach, which consists in analyzing and using ideas from other analogous fields and being aware of the pace of change from related industries (Gordon 2017).

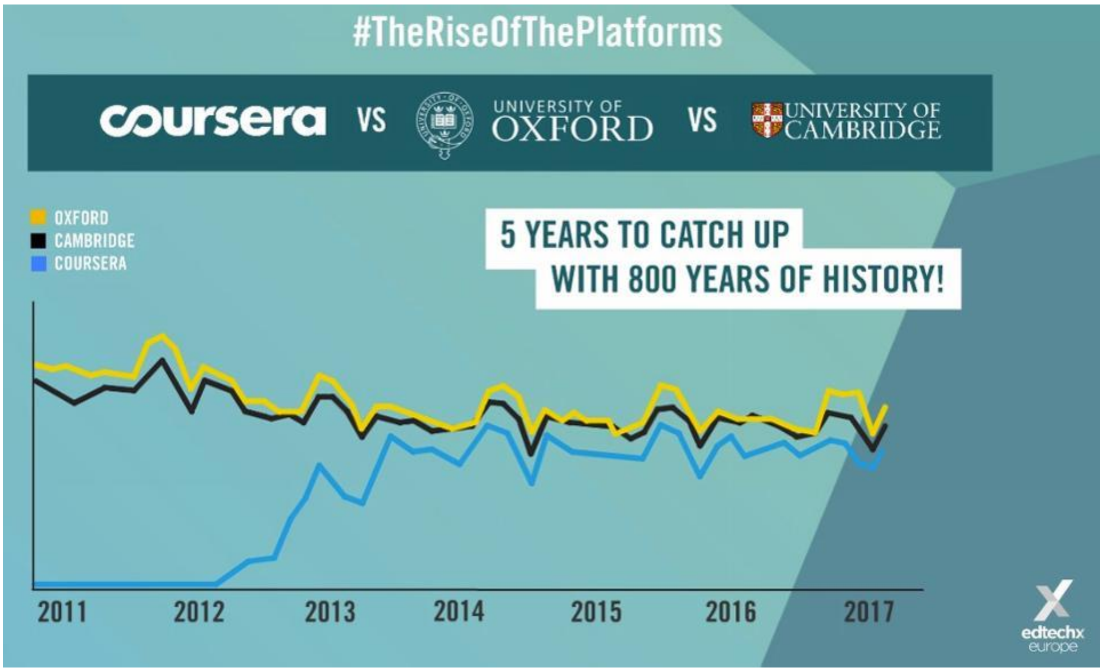


Figure 2: Internet searches, Coursera vs. Oxford and Cambridge Universities (EdTechXEurope)

A public scene integrating different disciplines and innovative research, with students of all ages from all over the world, are massive open online courses (MOOC). They are gaining more and more popularity and an interesting change in the usage of these online learning platforms was observed.

Long-established universities like Oxford and Cambridge are being surpassed in internet searches (Fig. 2) by MOOCs Coursera and EdX (Gordon 2017). Most of these courses are free, self-paced and offer the optional pursuit of a paid university validated certificate for those who want to obtain one after successfully finishing the course. Some architecture students prioritize self-learning and design studios over lectures. These students are more effective when they can control their online course advancement and are not obliged to sit in a classroom at a fixed schedule. Moreover, many architecture students would apply for internships before they have graduated from university, and the option of using a high-quality online platform relieves the stress of pushing off theoretical education for practical experience.

1.3.3 The BIM-Revolution and visual programming languages

The latest BIM tools allow us to create a detailed representation of the building and its construction process in one 3D computer model, which is arguably one of the greatest innovations in architectural practice for the last millennium.

BIM has been around since the 1980s and has greatly influenced the AEC industry, which is still trying to improve the interoperability of BIM platforms. BIM allows different specialized teams to work together on an integrated design project where multidisciplinary information is superimposed on the building model. The strategy of maintaining a database of all of a structure's components and capabilities, including costs, schedules, estimating data and the ability of creating accurate complex models is exciting and useful. With clash detection, the complex 3D designs can also be checked thus avoiding small drawbacks during design process. A shared knowledge resource from conception to demolition, BIM makes it easier to make replacements, updates and tweaks. BIM is implemented during the whole life cycle of an asset and stands for integrated design, collaborative working, better coordination, efficient simulation and analysis, improved working on site.

5D BIM is a term widely used in the CAD industry today and it refers to the intelligent linking of individual 3D CAD components or assemblies of components with time and cost (or schedule and budget) related information (Guillemet 2016).

BIM is not only about working and collaborating faster and cheaper – it is used to improve and measure quality - especially for massive, complex projects. BIM's comprehensive database, including semantic data and its use in the building life cycle, actually enables various game plays like walk-throughs and complex building operation testing (Yan et al 2010). Object oriented programming or modeling (OOP) (including objects and their properties) facilitates the access of comprehensive data and makes the integration of BIM with games feasible.

Software development leader Autodesk recognized this potential and created an online service called Autodesk LIVE that allows the user to create an immersive, interactive 3D visualization from a Revit model. The tool does not require any visualization expertise and quickly generates a fully-navigable 3D model from a BIM model (Ravenscroft 2016). Amar Hanspal, senior vice president at Autodesk, reflects upon the interconnectivity of the gaming and AEC industry: *„LIVE is a perfect example of how film and game development is influencing client expectations in the AEC world"* (Ravenscroft 2016).

The next generation of BIM is computational BIM which helps professionals to easily optimize the design for any number of goals and quickly compare different options. It is sometimes called parametric BIM, or the next step toward generative design turning the database into a design collaborator. Under normal circumstances, designers iterate a process until they arrive at an optimal solution. Computation allows for decisions to be programmed based on known constraints, design requirements and rules, with the aim of achieving the best and most efficient solutions. Computational BIM brings order to projects involving massive and overly complex architectural endeavors. Currently, with the power of cloud computing design exploration and optioneering offer a much wider range of possibilities than before (Wujec et al. 2017, pp.93-101).

Early computational design began with equations and programming scripts. Now graphical / visual programming and algorithmic modeling are leading the way. In computing, a visual programming language (VPL) is any programming language that replaces text with pictures or symbols of physical things and manipulates program elements graphically rather than by specifying them textually. With the increasing complexity of 3D models and the desire for interactivity, visual programming tools have made computational design more accessible and gave designers the option to explore multiple solutions in real time. Visual programming tools include names such as Grasshopper and Dynamo (Wujec et al. 2017, pp.93-101).

Dynamo works with Revit and similar software and is an open source tool. Grasshopper is a graphical algorithm editor that runs within Rhino3D (Rhinoceros 3D modeling software). It is for designers who want to build their own form generators and are exploring new shapes using generative algorithms.

1.3.4 Architecture and generative design

Recent advancements in artificial intelligence, machine learning and the simulation of complex phenomena have enabled software to participate in the invention of form and become generative. Generative design is a new design workflow essentially consisting of a “capture, compute, create” chain of making. Generative design is a design process where objectives, rules and restrictions are the needed input information and the solutions, which are not restricted by form, are the output. Solutions as produced by the computer may be data, a design or a model. A trade-off is possible as well, the final overview and decision is made by the designer. Algorithms help explore the endless possible solutions for the most fitting to the issue at hand. Generative design not only helps designers to create, but sometimes also “discover” designs. (Wujec et al. 2017)

Computers are becoming creative partners in the design process. The improved processing power of computers and availability of cloud computing – using a network of remote internet servers to store, manage and process data – are accelerating the uptake. It seems that the era of digital crash testing and building simulation is flowing to the era of machine learning. Computers are shifting from being passive representation and documentation tools to being creative partners. *„The more computable something is, the more it will be improved and optimized as algorithms seek value. As algorithms advance they abstract complexity out of many steps of design and making into simpler actions.”* (Wujec et al. 2017, pp.87-91)

There are some public generative design platforms and popular open source creative tools as well, for example NodeBox, Element or Noodl. Autodesk is incorporating generative design in its new tool Autodesk Netfabb 2018, which is the successor of the successful project Dreamcatcher. Project Dreamcatcher was an experimental design platform which focused research probes into generative design systems (Fallon 2017).

Generative design is now flowing into a wide range of CAD programs and therefore becoming more accessible to designers. It seems that machine learning (ML) and human-machine interaction (HMI) is going to play a major role in the future of building science and architecture.

1.3.5 Architecture in the augmented era

Flat 2D screens cannot comprehensively display complex 3D structures. Designers are usually compensating that by working on multiple viewports and on different sections and slices of the 3D model. Different transparency settings for selected parts or layers of the model are another way to avoid this inconvenience and inspect the 3D design.

However, in recent years the digital and physical worlds are growing more and more linked, the border between matter and data is disappearing. Today it is just as simple to print a 3D digital model as it is to scan a 3D real model. As a result, augmented offices and radical customization are becoming the norm instead of the exception (customized sports equipment, clothes, jewelry, office supplies, building parts, etcetera) (Wujec et al. 2017).

Digital sensors are bridging the gap between the physical and the digital world, broadening our ability to perceive our surroundings and suggesting new ways of designing. They are enhancing perception depending on resolution and improving fabrication techniques. All of the properties of the physical world can now conveniently make the jump into the digital - temperature, physical stress, motion, atmospheric pressure, infrared radiation and many other measurable markers.

Furthermore, the cost of common sensors is continuously dropping (Wujec et al. 2017, pp.30 -42).

„Welcome to the Augmented Age. In this new era, your natural human capabilities are going to be augmented by computational systems that help you think, robotic systems that help you make, and a digital nervous system that connects you to the world far beyond your natural senses." (Conti 2016)

Another rapid development of the last years, very closely interlinked to the progress made with digital sensors, is VR. VR is an immersive 3D computer generated simulation that can be experienced by the user when wearing a VR helmet or viewer. As a practical technology, VR is already widely successful. There are applications in medicine, e.g. in surgical training, in augmenting surgery, neurological rehabilitation, in scientific visualization apps for chemistry, neuroscience and other fields.

Now VR is transforming itself from a visualization tool to a design tool, and the rapidly developing AR and MR are undergoing the same process. AR is similar to VR, but it does not exclude the real world, it loads digital information and data on top of it. MR is the most flexible of the three as it lets the user see the real world while simultaneously seeing virtual objects, which behave as "real objects" embedded in the real world, at least from the perspective of the user. These interactive objects are believable and not just an overlay.

Efforts to build VR, AR and MR into the workflow of architectural design are being made and new high-end technological releases like Oculus Rift and Microsoft HoloLens are supporting the process. According to Microsoft, Microsoft HoloLens is the first self-contained, holographic computer that enables the user to interact with holograms and with digital content in their surroundings. Microsoft HoloLens can create semi accurate wire meshes of the observed objects that exist in real life and allows the user to pull objects from the PC-screen to MR via hand gestures and voice command. (Microsoft 2017)

Another interesting development by Microsoft is HoloStudio. It is a design application intended for use with HoloLens and with it the user can model 3D objects with natural gestures and movement and use holographic tools modeled from real-life tools to create their designs as real holograms. (Microsoft 2017)

The theory behind VR technology is that virtual environments are more intuitive to people, and allow for more interaction with the designs, as are traditional layouts.

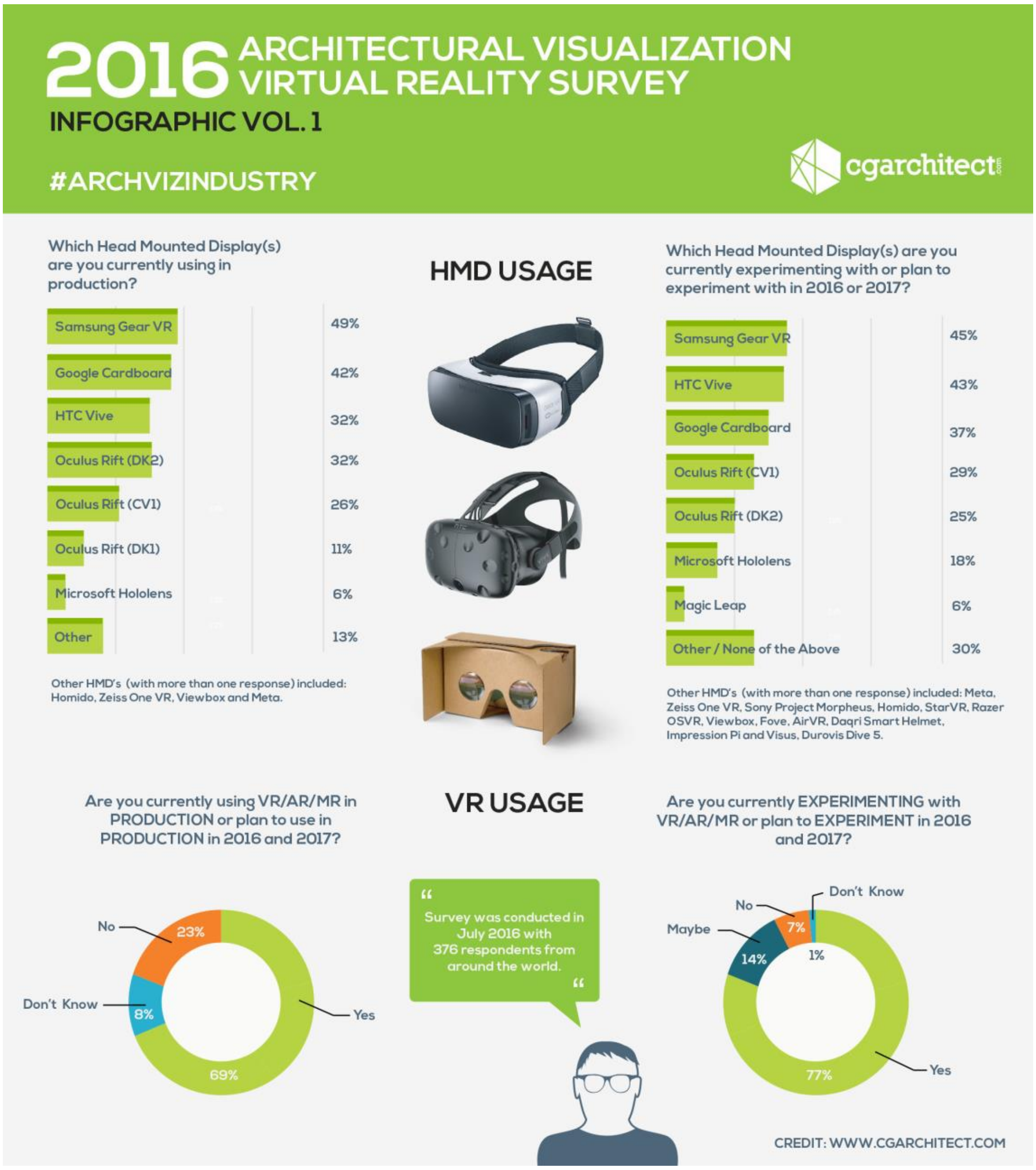


Figure 3: Mottle's survey reveals the increasing usage of VR among architects and the brands they are opting for (http://www.cgarchitect.com/2016/07/survey-results-vr-usage-in-arch-viz)

The realistic virtual objects hold the potential to upgrade or unlock designers' cognitive abilities. Studies show that in comparison to using drawings the interaction with a VR or other immersive environment (like AR or MR) delivers much better results when it comes to finding problems that could be defined with the model, or the design (Nikolic 2017, Johnson 2016).

Studies have already been done on digital sketching systems using the benefits of a VR or MR toolset which could develop models on a computer by drawing directly in 3D space, in a natural and quick manner, or creating surfaces by just waving your hand. One example of that concept is an experiment called "*Augmented Reality and the Fabrication of Gestural Form"* performed in Princeton in 2011 by the innovative Greyshed-team. The project consists of the implementation of an android application, a VR panoramic viewer, and a computer. Users' head and hand positions are tracked in 3D space and the coordinates are sent in real time, wirelessly over the internet to the headset. The headset positions the virtual camera based on these coordinates and the smartphone's geomagnetic sensors. Thus the user can generate gestural form by initializing functions via voice command.

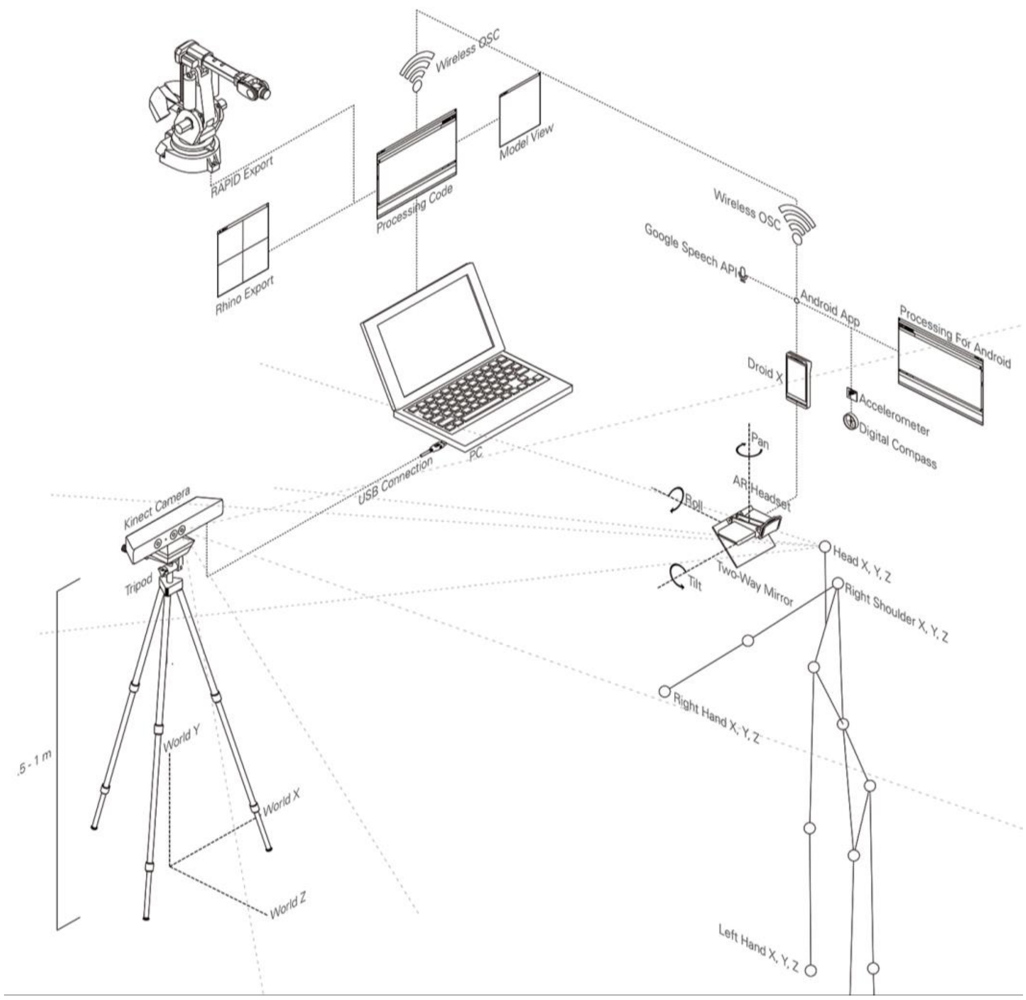


Figure 4: Augmented Reality and the Fabrication of Gestural Form: Setup (Johns 2011)

Multiple functions can be run simultaneously. The person can explore the scene in first person augmented reality before speaking the command *Rhino* to open the exported geometry on a nearby computer and finish the design or send it to the 3d printer (Johns 2013).

Another interesting project that uses a similar logic and exploits augmented reality is Tactum – a "fabrication-aware" design system. *„Tactum is an augmented modeling tool that lets you design 3D printed wearables directly on your body. It uses depth sensing and projection mapping to detect and display touch gestures on the skin"* (Gannon 2015). This means that the user can poke, rub, or pinch the geometry that is being projected onto their arm in order to design their own ready-to-print, ready to-wear jewelry.

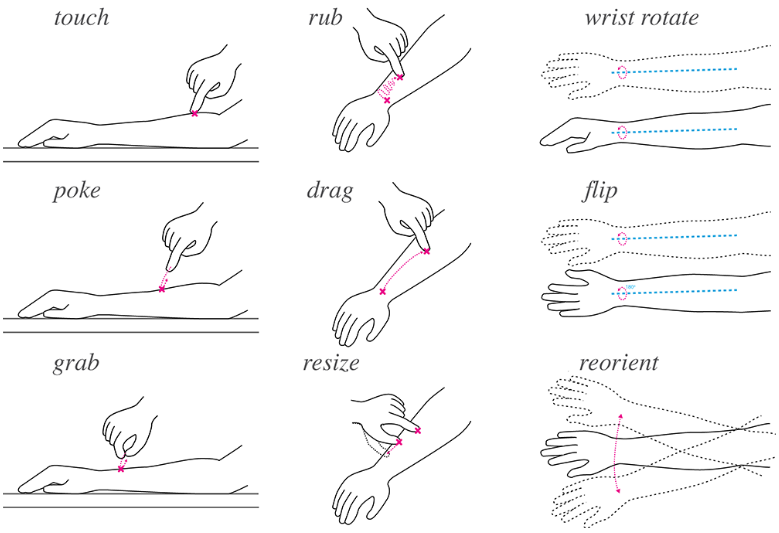


Figure 5: Tactum, skin-centered design, manipulation of design forms (Gannon 2015)

Figure 6: Tactum, generating the interactive digital geometry that is projected onto the skin (Gannon 2015)

It is obvious how with the help of information technology, designers have gone beyond the limits of working on a desktop computer or a drawing tablet. Now tangible user interfaces (TUIs) are gaining increasing attention. TUIs are a reminder of the missing sense quality of touch in digital sketching. A study done by Ibrahim and Rahimian in 2010 observes and documents *„ [...] an obvious gap between the designer and the design artefact when they were not able to grasp and touch their designed virtual models."* (Ibrahim 2010)

Researchers are trying to overcome this obstacle in human-computer experience and enhance the interactivity with the virtual objects. One recent study titled *„Touch hologram in mid-air"* combined a pair of MR smart glasses and a haptic device, namely high-profile MR device HoloLens from Microsoft and the touch development kit from Ultrahaptics. By mixing a holographic display and an array of ultrasonic transducers, a tangible feedback system was supported. This gives a spatial reference in order to drastically enhance the presence of the object. Furthermore, many successful commercial products have been developed for user body tracking in recent years, such as Kinect and Wii remote. The related technological techniques and methods are applied to other MR virtual endeavors, like Microsoft HoloLens and Magic Leap (Fig. 7). (Chen 2016, Kervegant 2017)

Nevertheless, the realization of a 3D image holographic display supporting real-time interaction that allows the observation of real-time interactive 3D holographic objects without goggles is a challenge mainly because of three limitations: speed of data transmission, hologram generation, and holographic image projection. Because if these drawbacks, currently there is no prototype system that meets the requirements for mainstream consumer use.

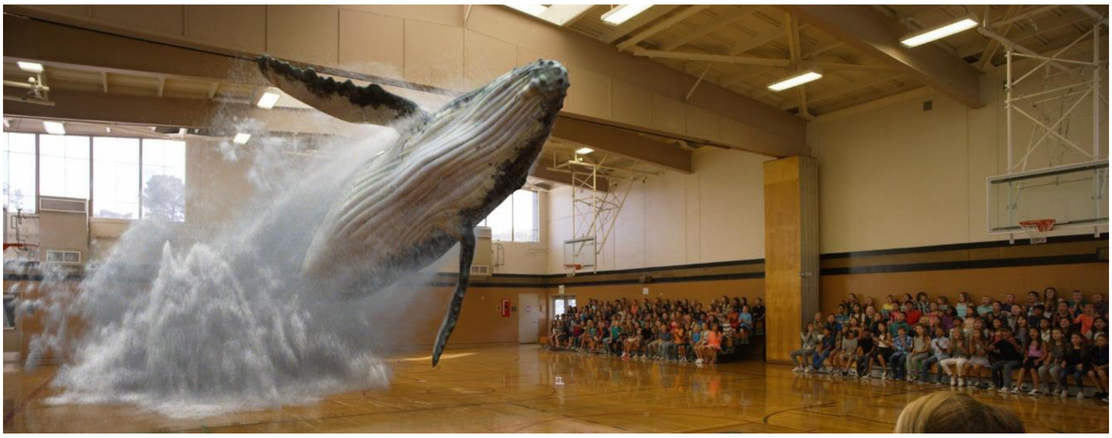


Figure 7: Concept art from Magic Leap show the sorts of experiences the company wants to make possible (https://www.roadtovr.com/magic-leap-ceo-gearing-ship-millions-things/)

There are, however, some volumetric 3D image displays on the market, which do not require goggles. Volumetric displays create 3D imagery visible for the unaided eye, via the emission, scattering, or relaying of illumination from well-defined regions in (x,y,z) space (Fuhrmann 2016, Geng 2012). Just recently, one of the leading company names in the field, Voxon Photonics, has officially announced that the "*most advanced 3D volumetric display*", the Voxon VX1, is available to purchase. The device is capable of projecting over half a billion points of light every second into physical volumetric space and two such devices have already been delivered to some educational facilities. (Lynton 2017)

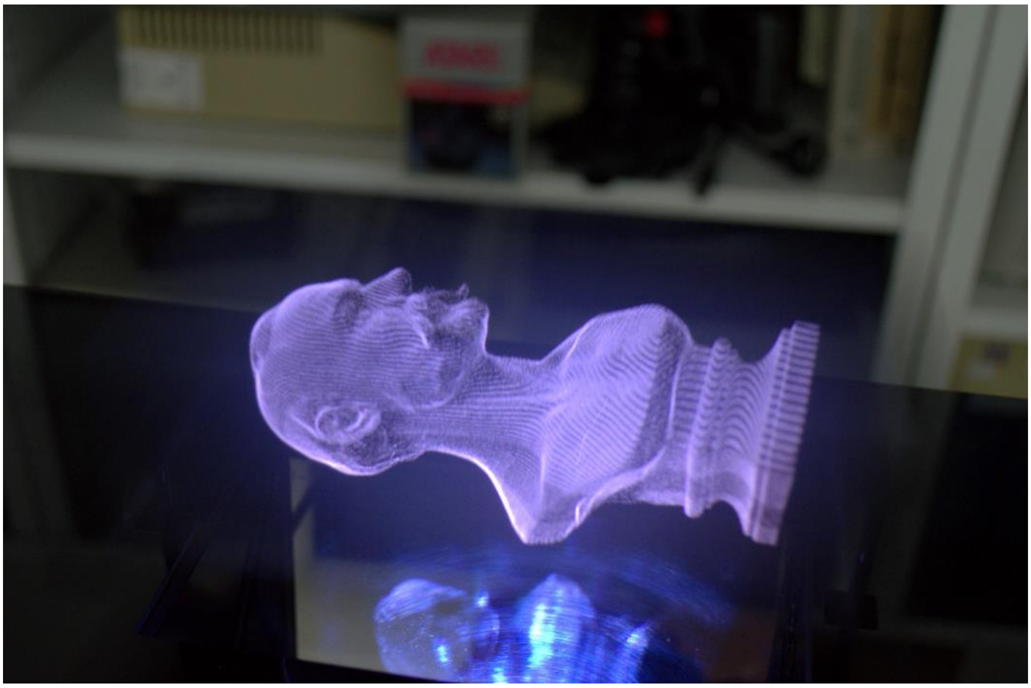


Figure 8: Voxon in FHM magazine, Sculpture (http://voxon.co/voxiebox-in-fhm/)

A company called Holoxica is examining a different approach. Holoxica is currently working on, what they call, their third generation holographic display, which should create a volumetric space in mid-air with independently addressable voxels in (x,y,z). All holographic technology is based on the physical principles of diffraction. A single pixel, or voxel, in 3D space, that can be switched on or off and thus would approximate a display. (Khan 2013, Holoxica Limited 2017)

1.3.6 Architecture and gaming

Architecture, one of the classical arts, and gaming – commonly perceived as a time-waster activity, seem to progressively support each other's work. Many game designers cooperate with architects to develop their worlds, whereas architects and building science professionals experiment with new technological solutions that incorporate well with the gaming world, e.g. integrating BIM, VR and gaming engines for real time architectural visualizations (Yan et al. 2010). Game engines such as Unity and Unreal are already being used in the AEC community to create highly polished virtual reality environments and experiences. They are frequently used to visualize spaces and render architectural models in immersive environments. Translating CAD or BIM models into VR used to take considerable time and programming knowledge. The Unity gaming engine made the process of bringing Revit and other 3D models into a virtual reality space much easier. This flexible tool ensures rapid iteration and fluid workflow, and thus allows AEC professionals to create realistic interactive walkthroughs for their clients (AEC Magazine 2017).

Because of the latest innovations and the increase in computer power, architecture is contributing more and more to a realistic gaming experience. The next generation immersive gaming experience allows players to escape the real world, transfer all their senses into a different space where they can explore every corner of the architecture, which sometimes is a complete replica of existing cities and other times an imaginary world (Carrapa 2014, Smit 2014). With the fast technological development in recent years and the emergence of new software solutions, the connection between architecture and gaming seems to tighten. It gains momentum and transfers into other fields as well, such as real estate and property development.

Another reason why 3D gaming environments are unique, and will continue to have an influence on the field of architecture, is the user mobility. User mobility in games is greater than the general 3D animation or the typical 3D design interface, and the drive to create something of your own, explore it and improve it, is very strong. Furthermore, with the technological boom games have become about full immersion, which is a presentation opportunity most architects and designers would like to be able to deliver for a client. According to Andy Radley *„Gaming engines will continue to creep into construction"* (Kenny 2010).

A good example of the influence that modern gaming has on architecture is the video game Minecraft. With the help of Minecraft, millions of children, young people and adults around the world use their imagination and creativity to create new amazing worlds, cities and buildings. Similarly, with other digital tools, work today's architects and urban planners. An exciting project shows and consolidates the similarities of these processes - Blockholm.

Blockholm is a project that finished recently and explores the connection between gaming and architecture in practice. Ulf Månsson and the team at Sweco Position AB had been experimenting with spatial data, the FME software, and Minecraft, and after collaboration with The Swedish Centre for Architecture and Design the project launched. Blockholm is a Minecraft replica of Sweden's capital Stockholm, which is accurately represented, but there are no buildings. It was a blank canvas for enthusiastic builders from anywhere in the world to create a new city (Majury 2013). In November 2013 the public gained access to interactive world of Blockholm on a Minecraft server. After the end of the project a selection of Blockholm's built-up plots was actually built in scale 1: 5 and shown in the exhibition at the Architecture and Design Center in Stockholm (Karlsson and Bohm 2014).

The Blockholm project shows how the digital gaming world's creativity can be used for increased influence and citizenship dialogue in urban development projects nationally as well as internationally. A similar project was started in the German city of Heidelberg for the development of a large city quarter on the grounds of Patrick Henry Village and the results of the creative citizen engagement were shown in a public exhibition in March 2017. A new platform was used for the collective co-creation called 20.000 Blocks. It was developed at the Digital Design Unit (DDU) of the Technical University of Darmstadt in collaboration with the international building exhibition (Internationale Bauausstellung) IBA Heidelberg. The platform is based on Minecraft and can be adapted for various architectural, urban and design tasks. The initiator of 20.000 Blocks, architect Anton Savov, is also the founder of studio AWARE, which focuses on empowering inhabitants imagination and helping people to create and personalise their own surroundings through games, computational design, 3D printing and digital fabrication. (DDU 2017, CEBIT 2017)

Video gaming's strengths are similar to those of architecture in their ability to draw together other art forms and present something new and compelling to discover. According to some researchers' prognosis, within the next 10 years game engines are going to change the way AEC professionals work. (Witsil 2017)

2 TOOL CONCEPTUALIZATION

This study was done in the larger context of the COGENT (construction generation and evaluation tool) concept, suggested by Pont and Mahdavi (COGENT research proposal for the Excite initiative, TU Wien 2016). The initial idea suggested the conceptualization of a new kind of interactive software tool that allows an intuitive and comprehensive approach to building construction details by exploiting the creative potential that virtual environments have to offer as a medium, compared to a traditional graphical user interface (GUI) operated on a flat computer screen.

The concept for the new tool was then narrowed down and further specified. The purpose is the conceptualization of a new educational software design tool based on multi-sensory, interactive learning and learning through gaming. The tool's primary goal is the exploration of building construction design and evaluation. It is intended to promote creativity, exploration and learning and should provide quick access to learning resources. The target audience for the new educational tool comprises of students and building enthusiasts, not professionals. The tool should therefore be able to support multi player mode or live discussions with peers and teachers.

The main idea is to integrate a gaming engine with a building physics assessment tool for use in an augmented environment. The user would create their own 3D design in the gaming VR or MR environment in an intuitive way by using hand gestures and voice commands. When the object or building construction component is ready to be evaluated from a building physics standpoint (weak points in the thermal barrier, thermal bridges) the performance assessment calculation engine would be called upon during gameplay. After a quick check of properties and boundary conditions the user can initiate a simulation run. The outputs would take a visual form, directly mapping the 3D model with, to give an example, heat flow lines. Through the immersive visuals, graphical output and the gestural control over the holographic objects, the users would be prompted to use more than one sense simultaneously while working on their project. This is a multi-sensory learning technique used to facilitate long term memory and support learning.

The nature of this concept is allowing of great creative exploration and expression, but the main focus of this master's thesis is to first provide a theoretical background and second experimentally investigate how such a concept could work. This could be done in many different ways and with different approaches, e.g. programming the new tool from scratch or re-programming an existing tool as a plug in. However, for the purposes of this project a framework for testing the possibility for interoperability and information transfer between already existing commonly used software, primarily a gaming environment and a numeric thermal bridge simulation tool, was created. These chosen two main pieces of software for this goal are the immensely popular game Minecraft and the renowned numeric thermal bridge simulation tool AnTherm.

Having the scope of this project in mind, and also considering the current state of technological advancement (explored in detail in the previous chapters), the simple, same-sized, scalable Minecraft building blocks have a considerable advantage for usage in an interactive MR design environment. Another upside of this choice is that the multinational technology company Microsoft, producer of one of the high-end MR devices – Microsoft HoloLens, purchased the game franchise Minecraft and its development studio Mojang in 2014 (Mojang 2014). And lastly, the form of the simple building block is intuitive for learners, it is reminiscent of LEGO blocks, and is suitable for more elaborated gestural control.

The choice of software tools already being made shifts the main focus to the interoperability between Minecraft and AnTherm. The question is if a crossover module (a translator of representation and materials) is needed between the game world Minecraft and the assessment engine AnTherm, to facilitate the data access, transfer and usability between Minecraft and the calculation engine.

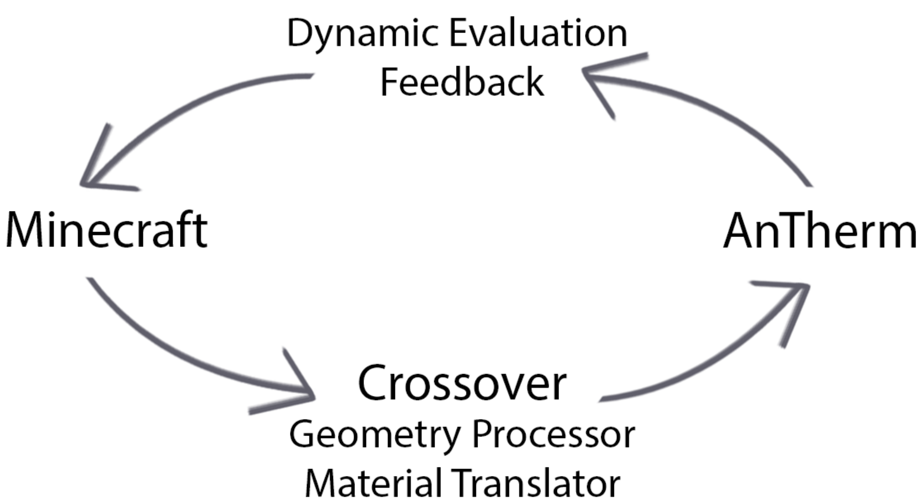


Figure 9: A representation of possible data access facilitation between Minecraft and AnTherm

2.1 Requirements and functionalities

The largest part of the requirements specifications for a new tool deals with the functional requirements, which include system input, processing and output. It deals with questions such as, how will the tool operate and support the geometry, the semantic properties of different construction components and how will databases be integrated. In this study, the input, the processing and the output generation are all part of the real-time 3D “sketching” and real-time interaction with a 3D holographic image in MR. This process requires a very fast data stream and precise focus control.

The functional requirements, however, do not guarantee the usability of the system and usability is a crucial system requirement. Usability is commonly defined as ease-of-use. The usability requirement specifies how easy the system must be for new users, how the overall functionality is perceived by the user and how efficiently the system carries out user tasks. Usability is nested in user satisfaction, tool performance, level of simplicity in operations, error susceptibility. Usability is therefore a non-functional requirement, because it does not specify parts of system functionality. It is possible to have adequate functionality and inadequate usability. (Lauesen 2008, Sawyerr 2014)

Therefore, it is common practice to conduct many usability tests while the software is still under development. The Usability assessment is used to *measure* the quality of the human-computer interface. „*Aside from providing specific cues as to how to improve the tool's usability, the results deliver some general insights regarding the skill-dependent user expectations from the interface designs of building performance assessment tools. If User interfaces of software or hardware components do not provide an acceptable level of usability, users start to avoid using these appliances*.” (Wujec et al. 2017)

Traditionally, the definition of usability consists of five basic factors: ease of learning, task efficiency, ease of remembering, understandability, subjective satisfaction (Lauesen 2008). Given that the target audience for this study is students, pupils, building enthusiasts and game lovers, the tool should meet their user requirements. It has to be easily accessible, understandable and flexible. It should support learning and creative exploration.

The tool should provide a 3D design environment with a thermal performance calculation engine that provides integrated databases (e.g. material libraries, building standards and norms). The latter facilitate the geometric and semantic data properties respectively. The integrated semantic databases or repositories could be coupled through HTML links (web linked data ontologies, as successfully done in the SEMERGY project) (Ghiassi 2013). The user should be able to design a building construction detail directly in 3D space, or on a physical plane in their immediate surroundings, through hand gestures and voice commands. The assessment engine for the thermal bridge simulation and building envelope evaluation represents the reasoning interface and should support steady state thermal calculations (in accordance with the norms, most importantly EN ISO 10211). The focus of the simulation engine is the evaluation and elimination of thermal bridges in steady-state conditions and optimization of the building envelope. Thermal bridges encompass all types of thermal bridges - geometrical, material-related and hybrid thermal bridges. The mechanical systems and devices which could be used to condition a building are not taken into consideration. Building component activation is not considered as well.

During the design phase the user should have visual access to semantic properties, norms and other learning support. The interactive 3D holographic object should offer visual feedback and highlight gaps or voids inside the building construction component, as they represent potential errors. The automatic identification of alternative materials, common usage of the material and examples of similar construction details from existing buildings could be another useful option in real-time interaction. The properties that the semantic interface needs in order to support this automatic identification could be extracted from the web-based sources and restructured in the web linked data ontology (as in the SEMERGY project, Ghiassi 2013).

The tool should remain flexible and open to the possibility of gradually integrating new and upcoming requirements and developments, new innovative materials in its repositories. After all „*In 1980, designers could choose from about 60,000 different materials to work with. Today the number is well over 300,000 and will likely double within a decade.*" (Wujec et al. 2017)

The output of the evaluation results should be graphical and in 3D. It could be mapped directly on the 3D hologram and dynamically change its representation parameter or style according to the wish of the user. The explanatory power of visual 3D graphics, which are supposed to be scalable and observable from all sides and angles, is no doubt superior to the traditional tabular output.

It would also be interesting to have the ability to feel the temperature on the surface of the 3D holographic image and learn through haptics. As mentioned in the background chapters, experiments with *tangible* holograms have been made with the introduction of airborne ultrasound pressure or force feedback, but it seems that this aspect of current technology still needs to improve.

In order to answer the initial question about system functionality and system operation in the constraints of this study case, only the chosen software for the experimental work and possible extensions will be reviewed: The material databases are embedded in the chosen building physics software. The existing libraries and template catalogues with building construction examples are a sufficient basis for the experimental framework of this project.

3 THEORETICAL FRAMEWORK

3.1 Building physics

3.1.1 Thermal bridges

Thermal bridges are weak spots within a building's structure, a disruption in the building envelope where heat is transferred at a substantially higher rate than through the surrounding envelope area. They usually occur at junctions or where the material structure of a building component changes. Thermal bridges can be the cause of higher energy consumption due to thermal outflow, they can lead to condensation and mold formation and uncomfortable surface temperatures in a living space.

In order to avoid thermal bridges it is suggested that the shape of the building should be compact, because sharp building corners and complex building envelope geometries are more likely to create geometrical thermal bridges. It is also recommended to avoid any kind of penetration of the insulation layer and vapour barriers, always when possible, and to keep the building structure coherent, without gaps. After construction thermal bridges can be detected on thermograph photographs.

There is a common classification that divides thermal bridges into three types: geometrical, structural or hybrid thermal bridges. Further detailed information on the classification and the numeric calculation of thermal bridges is provided in the master's thesis „*Generation and Application of a BIM-based repository of highly insulated building construction details*" by Bucevac (2016).

Regarding the current implementation of thermal bridge numeric simulation tools by professionals, the status quo in the AEC industry shows that all of the commonly used software programs have one similarity: all require a high degree of specialization and are not for laymen. Most have very similar functionalities, graphics as well, and all support tabular input and output data, which is potentially error prone, due to the repetitive manual input. A few of them approximate rounded forms to rectangular blocks, thus becoming more error prone, because the areas of contact surfaces are magnified by transition to rectangular blocks. There are some Multiphysics programs, which are used for thermal bridge simulation as well, but their application is even more complex and they are typically used by scientists and engineers to mathematically model and numerically solve problems that involve multiple simultaneous physical phenomena. These tools allow more precision, the workflow can be customized and the equations can be modified, but they require a very high degree of knowledge.

3.1.2 Architectural and energy models

Building energy modeling (BEM) is a rapidly evolving area of expertise, especially in recent decades. Practices that optimise architectural designs and have proven useful for AEC professionals include high performance and energy reduction as essential aspects of the design process. There are, however, differences between an energy model and an architectural model.

The visual character of the architectural building model and the referenced construction documents is very important, as it conveys the architectural idea, the design to the client. The technical experts on energy modeling require only a set of input information which is relevant for the energy performance evaluation, and, generally, fewer variables lead to a shorter simulation time. To give a more broad definition, an energy model is a calculation engine which accepts inputs such as building geometry, system characteristics, and operations schedules to produce outputs such as energy balance and performance comparisons.

Energy and resource modeling has developed its own terminology. Some concepts could be confusing because of the ever evolving field and the expansion of widespread and high performance building codes. The definitions that follow the most common types of energy performance modeling are Design Performance Modeling (DPM), Building Energy Modeling (BEM). DPM is prepared during the early stages of design and gives informed predictions about a building's performance before engineering systems are incorporated. BEM is physics-based and is used to simulate and predict a building's anticipated energy use and estimate energy savings, as compared to a standard baseline. These models are important for the sustainable development of a project and address the interrelationships among resources and how they are handled. (Hemsath 2017, Li 2014)

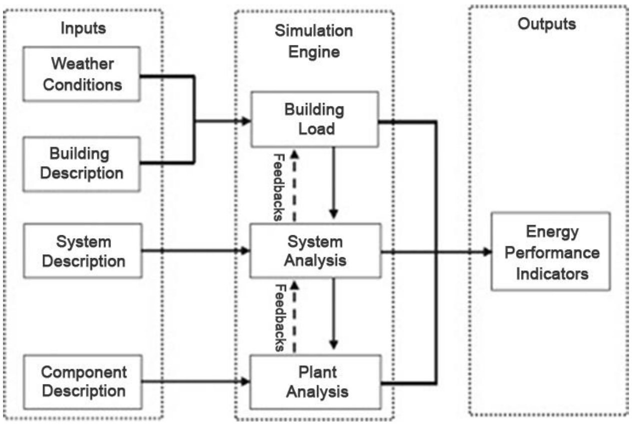


Figure 10: General data flow and main procedure of detailed simulation fromReview of building energy modeling for control and operation (Li, 2014)

Even though architects have already become deeply engaged in energy modeling and building performance assessment, there are still complications. The interpretation of simulation results that lack visual quality and their integration back into the design process is one of the setbacks for architects. A study shows that a small percentage of the available energy performance tools are intended for architects, and an even smaller percentage are being implemented by architects in initial design stages (Bucevac 2016, Hemsath 2017).

Gradually, as sustainability gained importance, the definition of building performance shifted to include sustainability and ecological impact of design decisions. Structural engineers, building physicists and other technical experts got more involved in evaluating the energy efficiency of buildings. This lead to the increased collaboration with architects and design teams. Specified building simulation programs require familiarity with building physics, energy modeling and green building codes. However, architects do not have to become technical experts on energy modeling, but need a working understanding of the process, in order to support the integrative work with other team members.

Designing with energy in mind requires the technical understanding of tools and technology. The specific physical properties and characteristics of materials and enclosures define the need for building system, to additionally condition the building, be that mechanical or passive heating, cooling, air circulation, lighting, etc. Energy has typically been addressed at the building systems level, mostly during the last century but generally since the profession of the great building master (german: baumeister) seized to exist. Up until the 19th century the master builders were responsible for a building from design to realization and owned a design studio as well as a construction company. At the end of the 18th, beginning of the 19th century, heavily influenced by the break of the Industrial Revolution, architecture and engineering started separating into separate professions. An architect at that time would have designed mostly private houses or religious buildings. The architect of today has a much more varied work portfolio and is bound to collaborate with other disciplines, such as material science and energy modeling. (Wilkinson 2001)

"*To exploit the full capability of these modeling tools, we must transform our design approach from a sequential process to a collaborative process, where all of the disciplines involved in the building design and construction work as a team from the beginning*." (Lynn G. Bellenger, P.E., Fellow ASHRAE President 2010-2011, "Modeling a Sustainable World")

3.2 Design education

3.2.1 Design tools and methods

The design studio environment at universities has not changed much throughout the past century. The Studio Culture Task Force of the *American Institute of Architecture Students* (AIAS) (Koch et al. 2006) observed that the status quo and the current changes in architectural education are not in alignment with today's fast changing world and ever-expanding design tool box, especially in the context of technological innovations. (Bashier 2014)

Currently, it seems that students intuitively value project appearance more than the actual design process. The design process is usually limited to form finding and form making, and the meaning of a sensible systematic approach to design before investing in form optimization techniques is misunderstood. The efforts to teach design methods and to restore a balanced relationship between creativity and rationality in the design process are not always reaching the pupils because of the outdated educating tools. The reason for this is related to the difficulties associated with conventional design methods and the inability of educational institutions to rapidly implement new technological innovation in the curriculum.

3.2.2 The human learning experience

What does acquiring new knowledge and modifying old knowledge mean in the era of computing and "big data"? Humans experience learning and value their own information generated through these experiences and in a way which is not always comparable to the ways in which computers analyse and quantify information.

Moreover, knowledge does not exist forever once generated, it goes away over time. The human brain forgets and even within short time periods of 14 days large parts of the acquired knowledge is already lost. Many psychological experiments support this finding, but in the study cases where meaningful content was used for the experiment, the results showed slightly longer time periods. Adding to this is the fact that the content of already completed tasks is being forgotten very quickly. In psychology this phenomenon has been known since the 1920s as the Ziegarnik effect or “cliff-hanger”. This effect is currently being continuously reinforced by modern information technologies, which convenience people into believing that any kind of knowledge is electronically documented somewhere, regardless of the quality or type of documentation. It is because of this notion that people forget particularly effectively. (Rupp 2014, p.20)

Figure 11: The digital dementia (Rupp 2014, p.20, Abb.1.5: Die digitale Demenz)

There is another theory that supports the notion of multi-sensory learning. The main concept is that when multiple learning channels work independently more synapses fire up and a more vivid memory is saved in the long term memory. For humans learning happens mostly through physical, cognitive, and emotional interactions with the external environment. (Zhou 2015)

Multi-sensory learning is sometimes being investigated by using tangible user interfaces (TUIs) to evaluate the influence of interactivity and haptic perception. According to some cognitive scientists, multi-sensory learning is superior, but others suggest that although sensory perception and movement are very important, high interactivity could be overwhelming and actually have a distracting influence, thus leading to a lower learning performance (Pouw 2016, Skulmowski 2015). Every child, every human has the innate ability to learn, but people are all different as individuals. Individual people have different learning "pathways" that are specific to them. Therefore, different methods would have different impact and vary in magnitude.

It is often said that 2/3 or 60% of the brain is "involved" in vision. However, probably less than 20% of the brain is involved in "visual-only" functioning. The remaining capacity is involved in either vision-and touch-related functioning, or vision-and motor-related, or vision-and spatial navigation, etcetera. There is generally a smooth gradation from areas fully-specialized to one concentration point to areas involved in many things. A recent study found that neurons in "V1", the primary visual area, are modulated by motor behaviour, proving that there is not any part of the brain that is entirely dedicated to visual perception only. (Bohnhoeffer 2012)

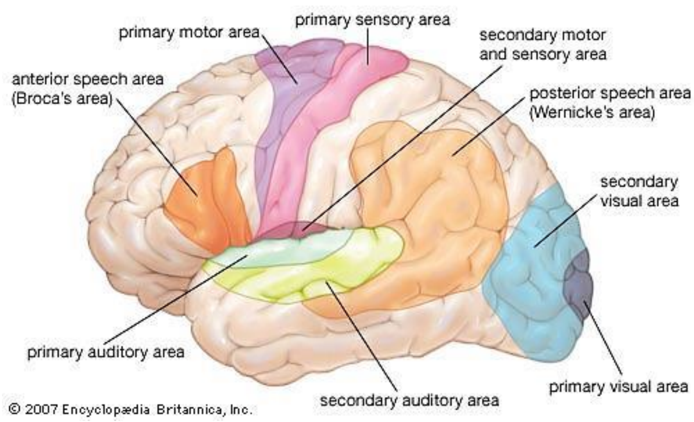


Figure 12: Functional areas of the human brain. Encyclopaedia Britannica Inc., Biology, Neuroplasticity

All these experiences emphasize that immersive VR and MR experiences engaging the sensorimotor system should have a positive impact on the educational environments (Choi 2016, p. 2).

Most people would describe the immersion in VR as feeling that this virtual world or construct is real. Björk and Holopanien (Björk 2006) divide immersion into four categories: sensory-motoric immersion, cognitive immersion, emotional immersion, spatial immersion. Spatial immersion means that the user is perceptually convinced by the simulated world. Human senses interact for information to be perceived. The better an individual is at combining visual and auditory information, the better they can remember the lecture or seminar, or what they have just learned. This conclusion demonstrates the effectiveness of teaching methods which simultaneously make use of multiple senses, like the teaching method developed by Italian educator Maria Montessori.

3.2.3 The gamification of education

Most AEC professionals are using heterogeneous design media to solve different problems in different design stages, or during performance assessment, and this can be overwhelming, especially the time consuming and demanding additional adjustments import and export actions. There is disintegration in the design parts. Also, the majority of existing modeling and performance assessment software entail a high degree of specialization from the users. This can be hard for novice designers and students, investing a lot of time to learn the programs, rather than learn about architecture and building science.

Following the results of recent research, scientists argue that essential intellectual competencies are falling because of the disadvantages of conventional testing (Mueller 2009, Wiggins 2011). One of the arguments is that the educational system fails to provide authentic assessment for students, not making them demonstrate meaningful application of the acquired knowledge and skills, engage in essential problems and perform effectively and creatively. While some researchers support the notion that the digital revolution has caused schools to fall through the cracks of the new digital divide (Collins and Halverson 2010), transforming our lives in a way that soon enough will make university degrees unnecessary, others claim that design education can benefit from new technology and from the educational potential of games. „*The engagement achieved through games means that gamification is a concept that needs to be part of every learning professional's toolbox*." (Kapp 2012, p.1)

Carlos Martinez, adjunct professor of design at the School of the Art Institute of Chicago, reflects on the same educational problem, and insists that academia should motivate architecture students to „(…) *step outside their own worlds* (…)" and teach them to expand their creative boundaries by looking at a project not just from the perspective of a designer.

Changing gameplay and operating different characters with different missions is a very basic concept in gaming environments. Players are able to express themselves via their in-game character and evaluate a different perspective. Games have an undeniable appeal, not limited only to a younger audience, such as students. The promise of achievement, the social element, and the complete immersion in a different world of creativity, imagination and possibilities are some of the most important motivation subcomponents in gaming. Others include the drive to better oneself, the sense of competition, conflict or cooperation. Research in psychology can help in explaining the appeal of games and the mechanics of motivation.

In psychology, motivation is a theoretical construct to explain human behavior and is a collective concept of a person's actions, desires and needs. It explains the direction of a behavior and the desire to want to repeat a behavior (Maslow 1943, Deci and Ryan 2012). Deci and Ryan divide the term *motivation* in intrinsic and extrinsic motivation, i.e. internal and external motivation (Deci and Ryan 2012). Extrinsic motivation occurs when the performed behaviour or activity's goal is to gain a reward or avoid punishment. Intrinsic motivation involves engaging in a behaviour or activity that brings joy and is personally rewarding, but not because of an external reward.

The meaning of the word *game* represents something well known and well embedded in the collective human understanding. However, there are many definitions of the term *game*. According to Raph Koster and his seminal work *A theory of Fun* the definition of a game is*: „A game is a system in which players engage in an abstract challenge, defined by rules, interactivity and feedback, that results in a quantifiable outcome often eliciting an emotional reaction."* (Koster 2013)

Therfore, *gaming* is the act of playing games, whereas the term *gamification*, derived from the word *game,* stands for *„(…) using game-based mechanics, aesthetics and game thinking to engage people, motivate action, promote learning, and solve problems."* (Kapp 2012, p.10)

„*On its surface, gamification is simply the use of game mechanics to make learning and instruction more fun. It seems "fake" artificial or like a shortcut. It's not. Underneath the surface is the idea of engagement, story, autonomy, and meaning. "* (Kapp 2012, p.21)

The popularity of online multiplayer games is increasing and gains acceptance as a tool in more and more educational fields. Some educational institutions are even using games such as World of Warcraft to teach economics and foreign languages (Choi 2016, p.121). Putting the focus on gamification techniques increases engagement and relevance, and assists students with associating knowledge with real situations (Kapp 2012, p.22). The provided support materials in the form of games as part of the curriculum do not need to have "fun" listed as a goal, because the four major aspects that improve learning recall and application are interactivity, context, challenge, and story. Stories, avatars, game feedback are game elements with effective application to learning. Simulations and games build more confidence of learned knowledge for the job application than traditional classroom instruction. (Kapp 2012)

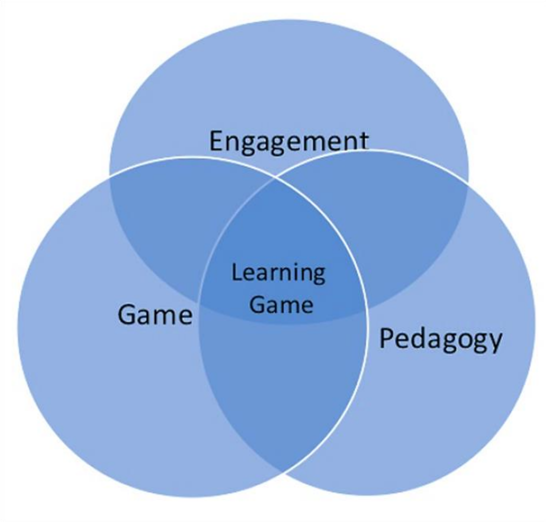


Figure 13: Learning by Doing (Kapp 2012, as adapted from Aldrich, C.. Pfeiffer, p.80)

According to one study case, a computer math facts game encouraged learners to complete a greater number of problems at a voluntarily increased level of difficulty (Lee 2004). There are many other unique gaming environments created with the purpose of not only entertaining, but educating. These “serious games” cover many various topics such as human rights, biology, sustainability, mathematics, quantum physics, programming, and many others (Majury 2013, MinecraftEdu 2017). Games for impact offer a mass learning experience that is currently being implemented in the educational system of some countries. Many universities have already accepted the challenge to create and validate games for educational purposes, thus establishing programs in research, design and development.

The computer game Block`Hood with its unique gaming and educational purpose is just one example of a “serious game”. It is educational and explores the connection between games and architecture, contemporary urbanism and ecology. Block’hood is a neighborhood-building simulator and players have access to more than 200 building blocks to build with and to create unique neighborhoods and discover the implications of their designs. The game incorporates concepts of ecology and sustainability as additional resources are needed to create more prosperous neighborhoods. Players must be careful to avoid the decay of their city blocks. The units should not run out of resources and become a strain on other complimentary units around them.

Another interesting example is Minecraft. The open source game is usually being described as a survival or creative sandbox game and is one of the most popular games with a large fan base (Fig. 14).

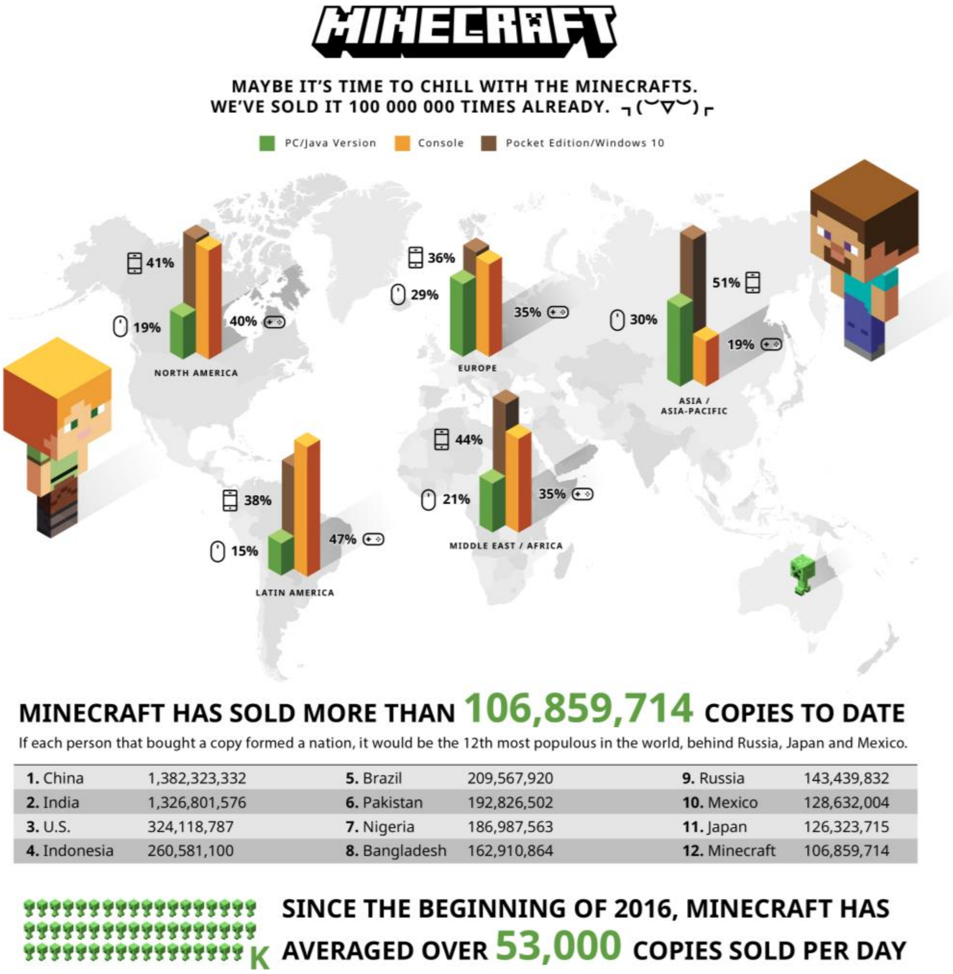


Figure 14: "We've sold Minecraft many, many times! LOOK!" (Hill 2016)

It promotes creativity, collaboration and problem solving. There are multiple gameplay modes and different worlds with a different set of rules available. The educational version of the game, which is being implemented in some schools, teaches about teamwork, coding, physics and math. Minecraft's Education Edition has some additional features and is suitable for the classroom as it provides log in options for the whole class and teachers, and allows them to work together and discuss projects at any time. The pupils learn to set goals for themselves and to finish their projects. The class becomes a supportive social community and everyone can choose their own avatar. Minecraft conveys a special feel, gives the players the freedom to construct anything with the available same-sized building blocks and to modify the game if they wish to, by coding new mods (modifications), using mods shared by the community or downloading official add-ins published by Mojang. The mods add content or alter gameplay. They create new gameplay mechanics, items, and assets for the game. Mods can be created on all computer operating systems and usually this is how players get inspired to learn new programming languages. (Minecraft 2017)

The aforementioned modifications and the creation of server plug-ins allow players to change the game itself. Many gamers are technophiles and science enthusiast, which is why many of the mods published by the community can be used for educational purposes. Minecraft has been named one of the best games of the 21st century because it is so simple and yet offers an amazing palette of creative possibilities and is still expanding and currently working on better graphics (Fingas 2017, McDougall 2010).

The Viktor Rydberg secondary school in Stockholm, Sweden even introduced Minecraft as a mandatory part of its curriculum. Teachers believe the game is worthwhile for students, because: "*They learn about city planning, environmental issues, getting things done, and even how to plan for the future.*" (Arbeiter 2015)

Figure 15: Kings landing from Game of Thrones in Minecraft (https://www.cnet.com/pictures/kings-landing-from-game-of-thrones-minecraft-style-pictures/)

4 DEVELOPMENTAL FRAMEWORK

4.1 Method

The research method for this work is based on a framework that tests the file compatibility and general interoperability of Minecraft and AnTherm. The framework consists of three test workflows, which include different software solutions, aiding the transfer and translation of data between Minecraft and AnTherm. The software that is used as a middleware is chosen according to Minecraft's and AnTherm's software logic and the number of translations that are needed. For the initial test trials and the first study case a simple detail is used, and a complex corner detail is implemented for the second study case. The three workflows and the software tools used for the purpose of this master's thesis are presented in the following table:

Table 1: General description of the used workflows with listed software

1. Minecraft → Mineways → 3ds Max → AutoCAD → AnTherm
2. Minecraft → Mineways → Rhino → AnTherm
3. Minecraft → FME → AnTherm

After introducing the used software, software logic and file formats in the next chapters, the workflows are explained in more detail. Minecraft and AnTherm share some similarities in visual representation, because everything is approximated by cuboids in 3D space, but have a different logic when it comes to data structure and software functionality. These characteristics and the kind of data that is required for the data transfer are presented in the following chapters.

4.2 Research objective

The main research objective is to answer the question whether a qualitative data transfer between the game world Minecraft and a building assessment engine, in this case AnTherm, is possible. The results of this research should indicate if achieving interoperability is possible, if integrating Minecraft with a building simulation engine is possible. Another research objective is to examine if material definitions and properties are transferred between the two platforms during the tests done on the case studies, and if not, how this could potentially be developed. An interesting aspect of this issue is whether it would be possible to connect the game world to the simulation engine only by the use of a crossover module (a translator of representation and materials) to facilitate the process. In this way the user would not have to manually enter material properties or readjust them.

4.3 Software and file formats used in this work

4.3.1 AnTherm

AnTherm offers a heat flow calculation for building construction elements, assessment of thermal heat bridges and vapour bridges. It is a highly esteemed, reliable thermal bridge simulation software used among building professionals. It offers 3D and 2D stationary (steady state) and transient (harmonic, periodic) heat flow simulation. The simulation results are validated according to the minimum and maximum values, as given by latest standards, and conform to EN ISO 10211 and EN ISO 10077 for stationary conditions and to EN ISO 13786 for transient. (AnTherm Help 2017)

The import and export of CAAD files (Drawing Interchange Format - DXF) is supported and the program offers an adjustable catalogue with example details. The most recent version of AnTherm also supports the import of 3D DXF and IFC (Industry Foundation Class) files. The objects in an IFC file are imported together with the assigned materials, if present. The output of the simulation can be printed as a report or visually represented as isolines, streamlines, hedgehog vectors, isotherms, etc., mapped on the the building element and saved as an image. Moreover, the user is able to switch between visual styles. (AnTherm Help 2017)

However, designing building construction details inside the program's user interface is not easy. For the 2D construction the user operates with specific Cartesian coordinates to create rectangular shapes. Any desired curvature has to me approximated to a group of rectangular shapes. From the 2D construction the user can develop a 3D detail, e.g. through revolving the 2D representation or converting the construct to a layered 3D object. These processes obviously have their limitations when it comes to design complexity, flexibility and visual conveyance of design intent or progress.

Furthermore, AnTherm expects that the user has extended knowledge of building physics and is able to make assumptions when it comes to the input of materials, material properties and boundary conditions. For the not-so-qualified user, a program of such complexity is not suitable.

Another setback that affects mostly students and young building enthusiasts is that the software is relatively hard to discover, unless the educational institution demands its usage. The last available tutorials are from a few years ago and there is no online social community for design support and ideas exchange. The software page is also hard to find in a google search on a PC and impossible to find on a smartphone, because the website does not support the representation on certain mobile devices (HubSpot's Website Grader 2017).

AnTherm 8.133.1 has been used for this master's thesis, the educational license for which was kindly provided by AnTherm for the time span of this study.

4.3.2 Minecraft

Minecraft is a multi-platform independent computer game with basic computer graphics and no storyline to it designed in 2009 by Swedish programmer Markus "Notch" Persson. It was later developed and published by Mojang and had the official release on the 18th of November 2011. In September 2014 Minecraft, a registered trademark of Mojang Synergies, was purchased by Microsoft. Microsoft acquired Mojang together with the Minecraft intellectual property and currently markets the Minecraft Windows 10 Edition and Minecraft on Microsoft HoloLens. The game has gained such popularity, that with sales across all platforms, Minecraft is officially the second best-selling video game of all time (Mojang 2016).

The Minecraft map uses XYZ coordinates and enables players to explore, build (and destroy) anything they are capable of imagining out of textured cubes in a 3D procedurally generated world. The X, Y and Z values indicate the player's position in the map. The X-axis determines your position East/West while the Y-axis stands for vertical distance (sea level is at 64 on the Y-axis), and the Z-axis represents horizontal displacement in the North-South direction. The terrain is generated in chunks of 16*16*128 blocks. Basically, "(…) *a Minecraft world is composed of an arbitrary number of Region files, and a "level" file. The level file defines the metadata for the world, while the region files define the blocks that shape the terrain.*" (FME Desktop 2017).

Apart from having creative freedom, multiple gameplay modes allow the player to also explore and craft items or gathering resources in order to combat for survival. In creative gameplay mode, the player has unlimited resources and free access to all types of building cubes, and the ability to fly. Moreover, players can play the maps created by other players in adventure mode. In this context the goal of the game is not to be fun, but methodical yet creative. The player has to be disciplined and do many repetitive things in order to gather enough resources or skills, to survive, and most importantly, if they desire to create an interesting world, build a unique house. According to the game's creator, Markus Persson, "*Minecraft is to a large degree about having unique experiences that nobody else has had. The levels are randomly generated, and you can build anything you want to build yourself*." (Statt, 2013)

Minecraft 1.12.1 for Windows 10 has been used for this thesis.

4.3.3 Mineways

Mineways is a free and open-source program developed by software engineer, author and expert in computer graphics Eric Haines (currently Senior Principal Engineer at Autodesk) (Akenine 2008, Autodesk 2017). The application functions as a quick Minecraft exporter for 3D printing or rendering with well acknowledged software programs like Blender, 3ds Max, Maya, Cinema 4D. With Mineways the user is able to select various blocks from within the game, trim them up to the wished model boundaries and export them into other file types. Any Minecraft creation can be exported and used for making images, movies or 3D prints. The 3D models can be printed on a personal printer or through a third party service provider. Viewing on the web, e.g. through Sketchfab, is possible as well. Mineways has many other features, but the one that is important for this study is the "export individual blocks" and "export separate types (by material)" options. Currently, this is not offered by other exporters. (Mineways 2017)

Mineways is up to date with the latest Minecraft releases and compatible with all versions. The application is capable of exporting the model into the OBJ, STL, VRML 2.0 file formats. The OBJ file format was the one used for this study. The OBJ file format is a text-based common 3D image file format used to store and exchange 3D data among 3D image editing programs. It was created with the intention to provide a very simple solution for exporting and importing geometry from a wide range of different 3D applications. It is a representation of a geometric object that is composed of vertices, curves, polygons, and surfaces. However, the most commonly used OBJ files contain only polygonal faces. (Murdock 2017)

Mineways version 5.10 has been used for this master's thesis.

4.3.4 3ds Max

Autodesk's 3ds Max is a 3D modeling, animation, and rendering software package developed by Autodesk. It supports a wide range of different aspects, from modeling and animation to lighting and post-production and the program is widely used by various professionals like architects, game developers, designers and artists. 3ds Max offers a wide range of modeling and texturing tools and a well-known classical user interface, which remained loyal to the structured interface of the original release. The program support many different file formats and OBJ, DWG, DXF, STL are among them. (Murdock 2017, Autodesk Support & Learning 2017)

Autodesk 3ds Max is one of the oldest programs of its degree and its workflow tools have made design visualization easier. The 3D modeling and rendering software also allows specialists to create detailed worlds for computer games and engaging VR experiences. As other programs from this category, 3ds Max works with polygonal mesh geometry.

Meshes are faceted representations of 2D and 3D surfaces. They are represented as a series of connected lines in the program's viewport in wireframe mode, and as connected facets in shaded mode. The points at the corners of the facets are called vertices. The lines that connect these vertices are the edges of the faces of the mesh, which in a standard mesh representation are simple triangular or quadrangular polygonal faces. A polygon is considered a closed sequence of three or more edges connected by a surface. Although mesh faces are often considered planar, this is an incorrect assumption. Only triangle meshes are guaranteed to have all planar faces.

Such polygonal mesh 3D modeling is used primarily for the CGI (computer generated imagery) in movies and games, because of the advantages of the modeling process and the easily adjustable complexity, which depends on the number of polygons. These polygons can potentially be endlessly subdivided into smaller polygons, for a finer, more realistic image quality. Polygonal mesh modeling is not popular among AEC professionals, because, regardless of how complex some polygonal mesh models might seem to be, their numerical representation is not precise enough. AEC professionals work with programs that rely on mathematical principles and construct and design geometry based on them in order to be completely accurate. Some of the mathematical principles were first discovered and applied by the car industry, because the precise algorithms were needed to describe very complex curvatures. The discoveries of engineers, mathematicians and physicians like Paul de Casteljau, Pierre Bézier, Carl de Boor are greatly responsible for the birth of modern 3D computer modeling, curve representation, transformative and freeform design and modern fabricationa and manufacturing. Their formulas and algorithms found wide application in CAD/CAM systems especially. (Murdock 2017, McNeel 2017, Bézier 1993)

The student version of 3ds Max 2018 has been used for this master's thesis.

4.3.5 Rhino3D

Rhinoceros (Rhino3D or simply Rhino) is the *„world's most versatile 3-D modeler"* and offers a set of free-form 3-D modeling tools that foster unlimited creative modeling potential. The program can create, edit, analyze, document, render, animate, and translate NURBS (Non-Uniform Rational B-Splines) curves, surfaces, and solids, point clouds, and polygon meshes. Basically, Rhino is a CAD modeler which uses NURBS for precision modeling. The program is used primarily by designers, engineers and architects and is strongly oriented toward parametric modeling. Grasshopper is Rhino's most famous graphical parametric modeling plug in application. (Rhinoceros 2017)

NURBS, are mathematical representations of 2D or 3D geometry. They can precisely describe any shape, be it a 2D line or curve to the most complex 3D geometries, like organic free-form surfaces or solids. NURBS models are very accurate and because of that flexible and can be used in any design process like illustration, construction, animation and even manufacturing. A NURBS surface is always infinitely smooth, because it is based upon the mathematical principles that were used to create it. Therefore, a change in density of the isocurves is in this case optional and does not affect the model's accuracy. (Rhinoceros 2017, McNeel 2017, Schultze 2013)

There are many useful plug-ins and extensions for Rhino, because of its NURBS geometry. The precise and well-known definition of NURBS lets computer scientists and programmers easily create custom software applications for those who need custom solutions. Furthermore, the amount of information required for a NURBS representation of an object's geometry is smaller than the amount of information required by other common representation methods, and its quality can be quickly evaluated. NURBS geometry's qualities make it an optimal tool in computer-aided modeling. Many industry-standard methods are used to exchange NURBS geometry and it is possible to move geometric models between various modeling, rendering, animation, and engineering programs. Rhino supports many file formats such as 3dm, OBJ, DWG, DXF, etcetera. (Rhinoceros 2017, McNeel 2017)

The trial version of Rhino 5.0 has been used for this master's thesis.

4.3.6 AutoCAD

Autodesk's AutoCAD is a computer aided design (CAD) software for 2D/3D drafting and construction. AutoCAD is used across a wide range of industries, by architects, designers, project managers, engineers, and other AEC professionals. AutoCAD Architecture (ACA) is a vertical version of AutoCAD which is specifically suited to improve architectural work.

AutoCAD's main file format is DWG. The interchange file format DXF, is standard for CAD data interoperability, more so for 2D drawing exchange. AutoCAD is one of the oldest and most used construction and modeling software in the AEC field. Its geometry representations are mathematically generated and various settings options allow the user to adjust modeling precision. The program works with 2D polylines, 3D polylines, 3D solids, surfaces and mesh objects modeling. Many Customized add-on apps and APIs (application programming interface) are also available. The latest AutoCAD release allows team collaboration across desktop, cloud and mobile technologies. (Autodesk 2017)

The student version of AutoCAD 2018 has been used for this master's thesis.

4.3.7 Revit

CAD formats, like the ones discussed in the previous chapter, lack building information. They are purely geometrical data transfer formats. BIM integrates geometric and non-geometric information, which is needed , for example in a building physics (or any other type of building assessment) software, or in a computer game. Autodesk's BIM software Revit support various file formats and RVT is the program's main file type. However, Autodesk's Revit provides fully certified IFC (Industry Foundation Classes) import and export as well. The IFC file format is maintained by buildingSMART® IFC international data exchange standards. The file format is an interoperability solution between different software programs for the import and export of building objects and their properties. (Autodesk 2017)

The student version of Revit 2018 has been used for this master's thesis.

4.3.8 FME

FME by Safe Software is a data integration software that offers modeling spacial support as well. Initially the company's goal was helping forestry companies exchange maps with the responsible government body. This technically possible but cumbersome and highly error-prone task is what inspired Don Murray and Dale Lutz to co-found Safe Software in 1993 and continue developing it today. The company has grown tremendously and partners with other major software companies, some of whom embed a portion of Safe Software's technology in their products.

FME offers the possibility to work with all kinds of data that might be needed, regardless of its format, in one central spot, and not lose anything in translation. The tool can convert, transform, merge, validate, reproject, inspect, style and filter more than 375 file formats. The FME Workbench is where this happens and where the user can build their workspace, which is repeatable and thus any process can be automated. FME's drag-and-drop GUI relies on graphical programming with modules, but no coding is required.

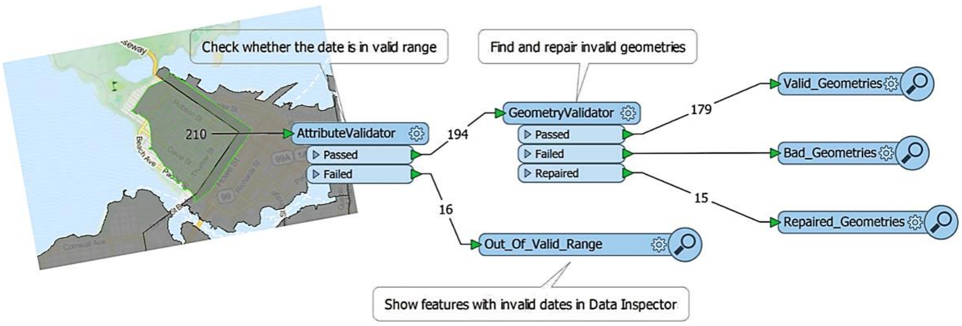


Figure 16: FME data validation example (https://www.safe.com/fme/fme-desktop/)

The software offers hundreds of data reader, writer and transformer tools to choose from. The readers read the input data, while the writers generate the output data. The transformers are the connecting building blocks used in FME Workbench and each has a specific function. They can be combined to solve more complicated transformations. The transformations could affect the content, structure or geometry of a dataset.

FME Desktop 2017.1 has been used for this master's thesis, the educational license for which was kindly provided by Safe Software, as well as valuable community support and helpful open discussions with Safe Software's senior members.

4.4 Interoperability and compatibility

In computer science terminology "interoperability" denotes the ability of computer systems or software to cooperate, to exchange and make use of the exchanged information without special effort on part of the user, in order to achieve a common objective. Different levels of software interoperability can be abstractly compartmentalized and defined. "Semantic interoperability" is the ability to automatically interpret the exchanged information meaningfully. (Charalabidis 2014)

"Compatibility" on the other hand usually means just that computer software or hardware produced by different companies can be used together, without having to be altered to do so. *„Compatibility specifically related to software is called logical compatibility. (…) Software compatibility is the ability of software to work on a given configuration of hardware and operating system.*" (Koreneff 2005, p.85)

The software and file formats used in this work are outlaid in the previous chapter and it is evident that AnTherm somehow stands apart from all the construction and design tools.

The AnTherm software works in a different way, when compared to the 3D modeling programs used in this study. The software tool works with precise geometrical definitions based on coordinates and currently cannot differentiate between a solid and a wireframe model.

AnTherm uses primarily Cartesian coordinates in 2D or 3D space (Fig. 17) in order to model and identify solids. It can work only with rectangular shapes that are parallel to the main axes. Any curvature has to be approximated by rectangles and depending on its complexity can substantially prolong the simulation time.

The Minecraft world is composed of a three-dimensional grid of blocks, which extends indefinitely along the two horizontal axes (X and Z-Axis). In Minecraft's coordinate system (Fig. 18) the Y-Axis is the one that represents height. The values can be relative or absolute, positive or negative, and denote how far away the player is from the model's center. On the Y axis the highest point is 256 and is the top of the map.

The game Minecraft can be considered partly voxel-based or voxel-like because it initially used voxels to store terrain data, but does not use voxel rendering techniques. A voxel (volumetric pixel) is the three-dimensional equivalent of a pixel and the smallest building block of a 3D object. It is a volume element in a grid. While the Minecraft World has a voxel representation, it is rendered by using polygons, like most video games.

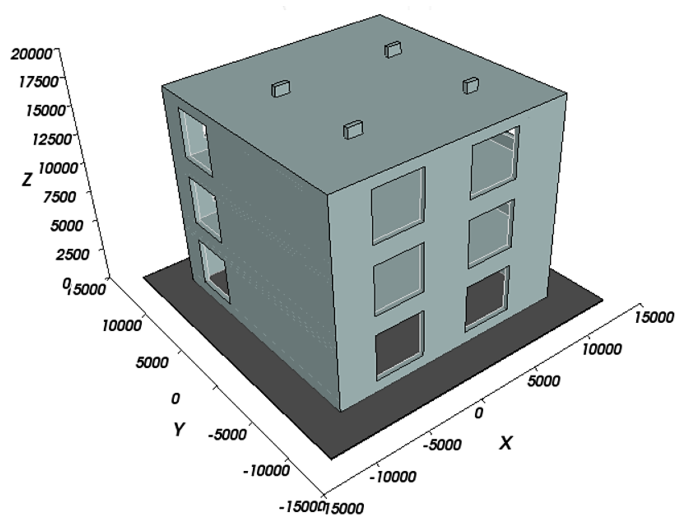


Figure 17: AnTherm's coordinate system (http://help.antherm.kornicki.com/hj_start.htm)

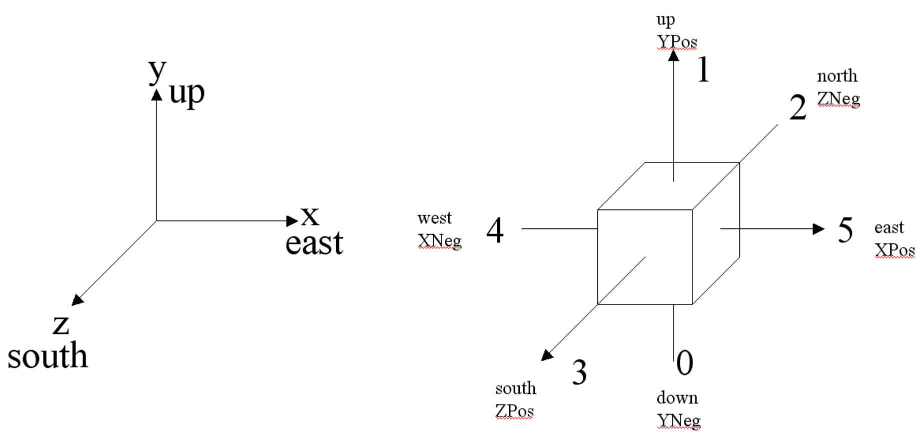
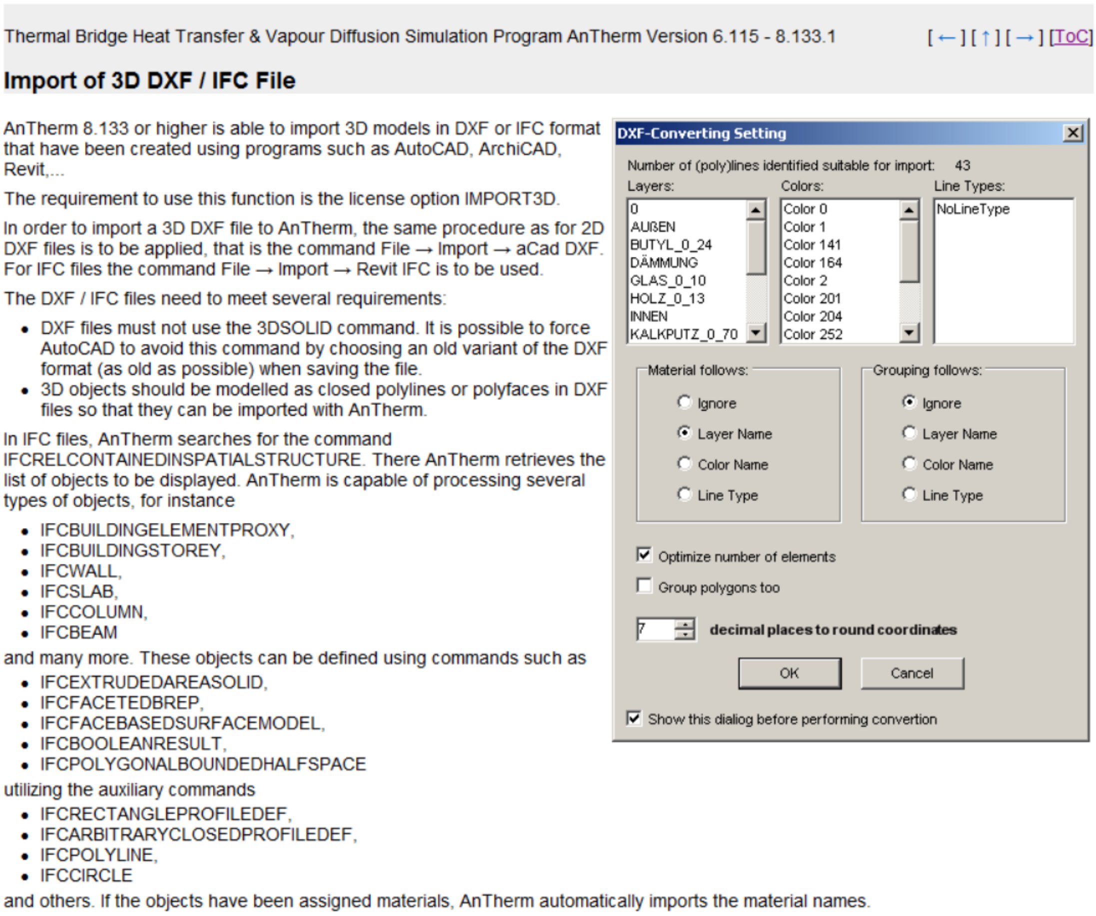


Figure 18: Minecraft's coordinate system (http://greyminecraftcoder.blogspot.co.at/2014/12/blocks-18.html)

Generally, another criterion to be fulfilled in order to satisfy the requirements for a successful building detail simulation of thermal bridges is the proper subdivision of the building model. This should be done according to the EN ISO 10211 standard in a way that no differences in the calculation outcome between the building model itself and a singular building detail should appear. However, this is outside the scope of this master's thesis, which uses only separate building construction components for its purposes, and more detailed information regarding whole building junctions assessment can be found in Mirjana Bucevac's master's thesis *Generation and Application of a BIM-based repository of highly insulated building construction details.*

AnTherm has a set of requirements for importing 2D or 3D geometry into the program. The geometry of the objects in the import files has to be defined and organized in a specific way before being suitable for import (Fig. 19).



Thermal Bridge Heat Transfer & Vapour Diffusion Simulation Program AnTherm Version 6.115 - 8.133.1 [←] [↑] [→] [ToC]

Import of 3D DXF / IFC File

AnTherm 8.133 or higher is able to import 3D models in DXF or IFC format that have been created using programs such as AutoCAD, ArchiCAD, Revit,...

The requirement to use this function is the license option IMPORT3D.

In order to import a 3D DXF file to AnTherm, the same procedure as for 2D DXF files is to be applied, that is the command File → Import → aCad DXF. For IFC files the command File → Import → Revit IFC is to be used.

The DXF / IFC files need to meet several requirements:

- DXF files must not use the 3DSOLID command. It is possible to force AutoCAD to avoid this command by choosing an old variant of the DXF format (as old as possible) when saving the file.
- 3D objects should be modelled as closed polylines or polyfaces in DXF files so that they can be imported with AnTherm.

In IFC files, AnTherm searches for the command IFCRELCONTAINEDINSPATIALSTRUCTURE. There AnTherm retrieves the list of objects to be displayed. AnTherm is capable of processing several types of objects, for instance

- IFCBUILDINGELEMENTPROXY,
- IFCBUILDINGSTOREY,
- IFCWALL,
- IFCSLAB,
- IFCCOLUMN,
- IFCBEAM

and many more. These objects can be defined using commands such as

- IFCEXTRUDEDAREASOLID,
- IFCFACETEDBREP,
- IFCFACEBASEDSURFACEMODEL,
- IFCBOOLEANRESULT,
- IFCPOLYGONALBOUNDEDHALFSPACE

utilizing the auxiliary commands

- IFCRECTANGLEPROFILEDEF,
- IFCARBITRARYCLOSEDPROFILEDEF,
- IFCPOLYLINE,
- IFCCIRCLE

and others. If the objects have been assigned materials, AnTherm automatically imports the material names.

Figure 19: AnTherm import requirements (AnTherm Help)

For the 3D DFX file import, it is possible to import closed 3D polylines or polyfaces. A polyface mesh geometry (consisting of unified singular faces) in AutoCAD is represented as a kind of a polyline entity, which it seems is why AnTherm is able to recognize it. For the IFC file format the basic object types are supported.

After the import of a DXF file into AnTherm, AnTherm essentially reads only the vertices and polylines. The polylines are then interpreted as faces. The program assumes that each face borders a solid object. AnTherm cannot interpret polylines just as a set of lines.

Aside from the import requirements specification (Fig. 19) available from the program's "Help" menu on the main toolbar, currently there are no other instructions, examples or cookbooks on the matter. After the initial test trials of 3D DXF and IFC file import into AnTherm it was determined that very simple 3D geometry created in AutoCAD can be easily imported into AnTherm as a 3D DXF file (Fig. 20), whereas the import of basic geometry created in Revit into AnTherm as an IFC file can be problematic (Fig. 21). After many more test attempts it was ascertained that either AnTherm's latest version's functionality is not yet complete or vital information regarding import requirements or file preparation is missing. The AnTherm team confirmed that the software version which supports 3D DXF and IFC import is currently still under development and was very helpful in providing further information and version updates.

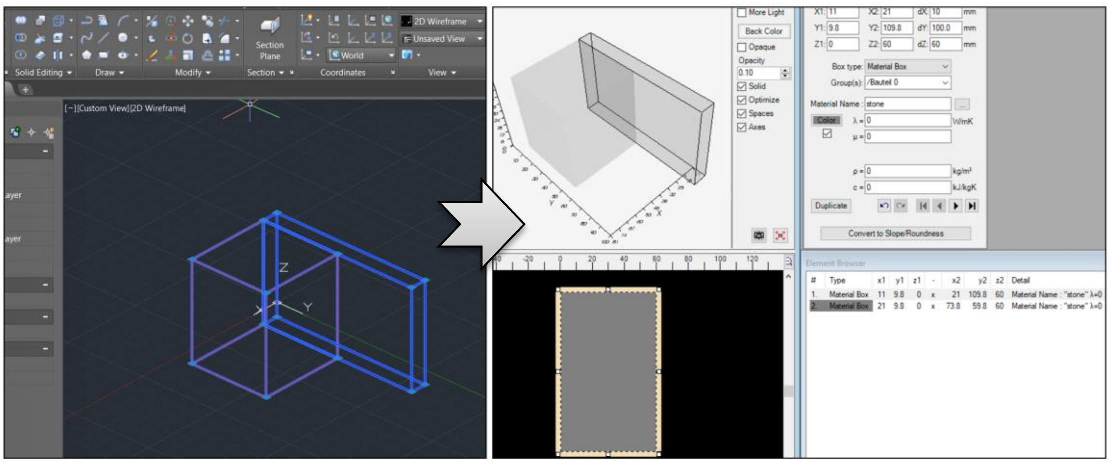


Figure 20: Basic geometry modelled in AutoCAD and imported into AnTherm

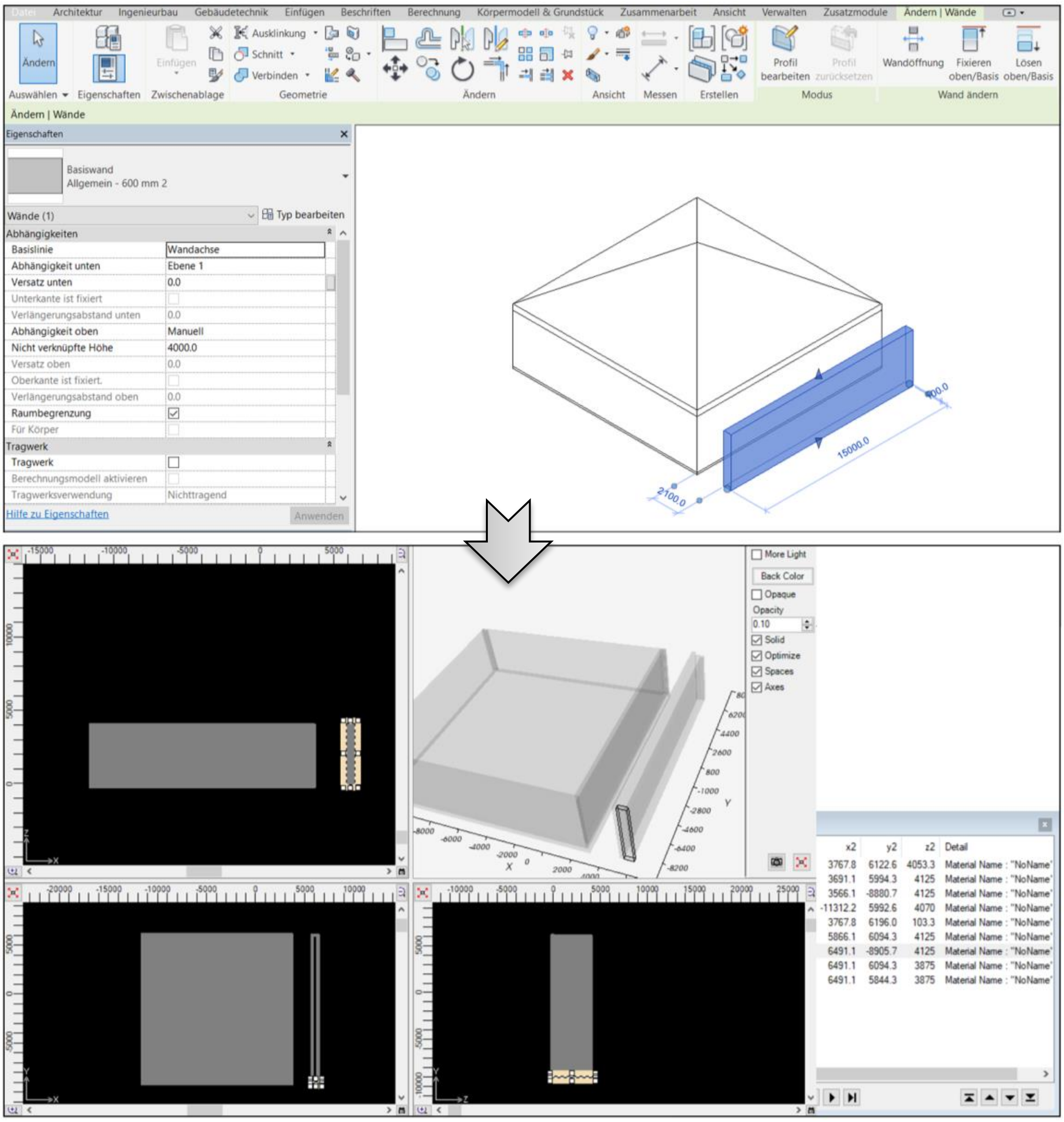


Figure 21: Basic building elements modelled in Revit and imported into AnTherm (IFC 4, IFC 2x3)

4.5 Design workflows and case studies

4.5.1 Case studies

Figure 22: Minecraft play mode, study case 1, Void World (Superflat World Type)

For the first case study a simplified corner detail of a stone wall with a wooden slab and a wooden corner niche is built in Minecraft as a Minecraft World (Fig. 22). Three different building blocks are used in the process – stone, wood and birch wood planks. In order to have only the building detail in the Minecraft World and no other landscaping, a Void World is created. Therefore, it looks as if the building component is floating in the air. All of the present "air blocks" and the "builder" are ignored and not exported with the Mineways exporter.

For the second case study a more complex corner detail is chosen from UNIPOR's online thermal bridge catalogue for passive houses (UNIPOR's "Wärmebrückenkatalog für Passivhäuser"). It is an exterior wall – base slab corner detail with the concrete slab going above a heated basement (Fig. 23, 24 and 25).

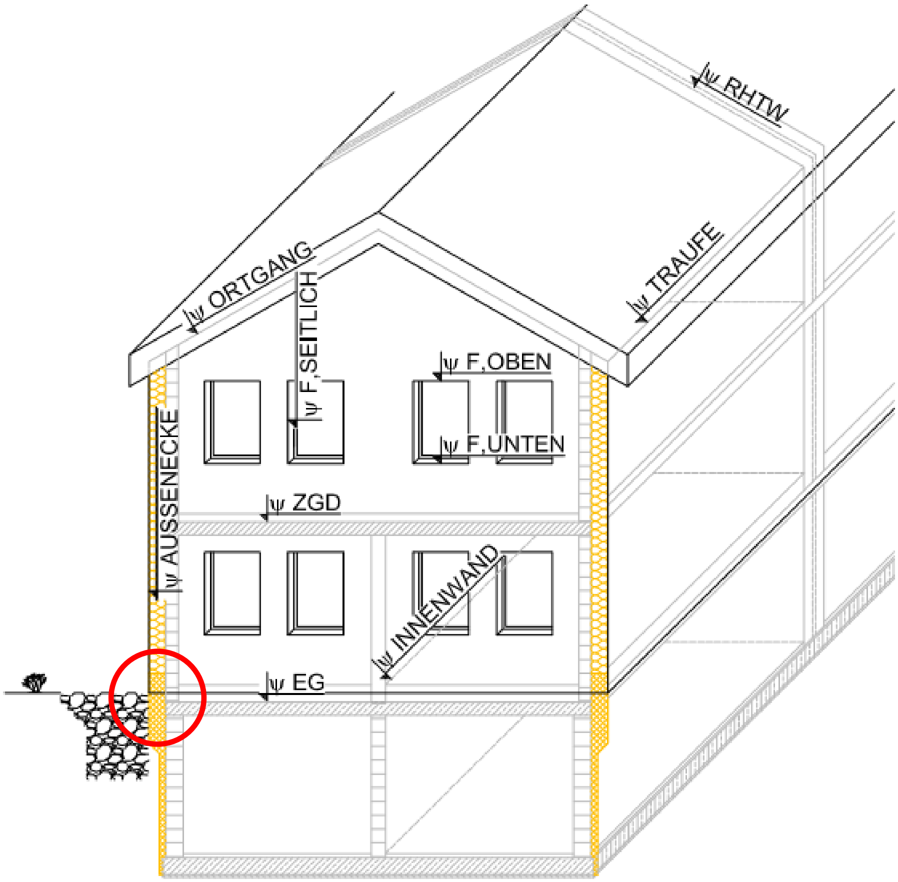
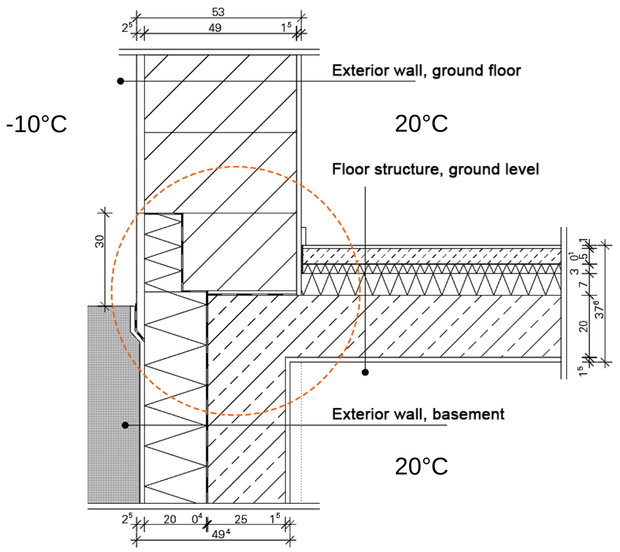


Figure 23: An illustration of important junctions and the building detail's position, also showing the linear thermal transmittance coefficient Ψ (Wienerberger 2004, p.4)



Floor structure, ground level:

flooring	10mm	
cement screed	50mm	λ = 1,40 W/mK
polyethylene film		
footfall insulation	30mm	λ = 0,040 W/mK
insulation	70mm	λ = 0,035 W/mK
reinforced concrete slab	200mm	λ = 2,30 W/mK
cement plaster	15mm	λ = 0,70 W/mK

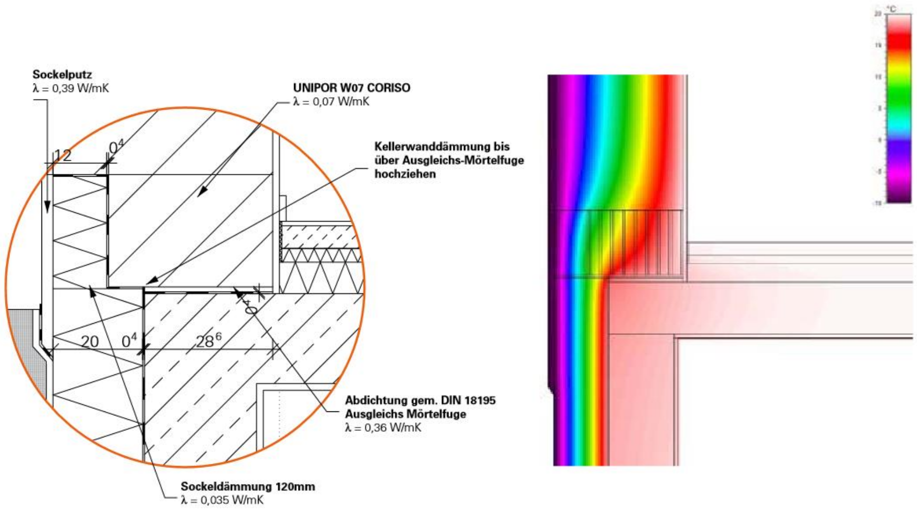
Exterior wall, basement (exterior to interior):

protective foil (dimpled sheeting)		
perimeter insulation	200mm	λ = 0,035 W/mK
sealing		
reinforced concrete wall	250mm	λ = 2,30 W/mK
cement plaster	15 mm	λ = 0,70 W/mK

Exterior wall, ground floor (exterior to interior):

lightweight fibre plaster	25mm	λ = 0,30 W/mK
bricks with integrated insulation filling	490mm	λ = 0,07 W/mK
gypsum plaster	15mm	λ = 0,70 W/mK

Figure 24: Baseline corner detail, exterior wall and concrete slab over heated basement (UNIPOR 2017, p.20)



Wärmedurchgangskoeffizient	
U-Wert der Außenwand: U_{AW}	0,137 W/(m²K)
U -Wert der Kellerwand: U_{KW}	0,167 W/(m²K)

Wärmetechnische Beurteilung:
Der Anschluss hat einen positiven Wärmedurchgangskoeffizient. Der Anschluss ist jedoch für Passivhäuser geeignet. Der ermittelte lineare Wärmedurchgangskoeffizient ist bei Berechnung mit dem PHPP anzusetzen.

Berechnungsergebnisse	
Ψ_a	0,023 W/(mK)
f_{Rsi}	0,95
$\Theta_{si,min}$	18,6 °C

Figure 25: Baseline corner detail, thermal assessment results (UNIPOR 2017, p.20)

Again, a void world is used for the creation of the second study case detail in Minecraft (Fig. 26 and 27). This time the dimensions are to be considered more carefully before building and exporting the detail, so that they would represent a realistic size and be suitable for the thermal simulation. The thermal simulation results would ultimately be compared to UNIPOR's detail thermal evaluation results in their building components catalogue (Fig 24 and 25).

In this context, deciding the building blocks' size for the export of the second case study with Mineways is a challenge. The block dimensions in the game itself cannot be changed, all of the building blocks are same-sized and every block has a default size of 1x1 meters. When exporting the Minecraft Wolrd into an OBJ file with Mineways, however, one can set the desired block dimension. In order to achieve a certain degree of "fine detailing", without making the model too "heavy" for the following import and export actions, a size of 50x50mm is chosen. In this way, even the smallest layers, which would have the thickness of one block, remain easily modifiable after the import in a design program. The water vapour barrier and bituminous sealing are the only left out layers due to their small thickness and because they are not taken into consideration in the thermal assessment during the simulation with AnTherm.

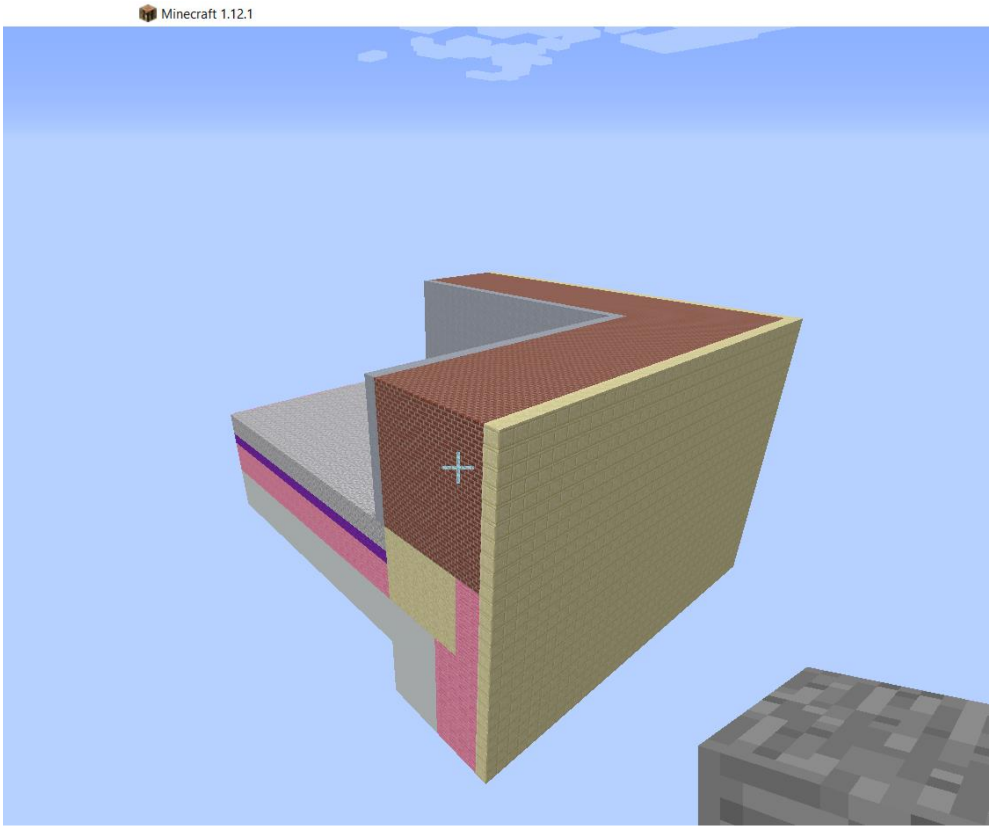


Figure 26: Minecraft study case 2, play mode, Void World (Superflat World Type)

Figure 27: Minecraft study case 2, play mode at night, Void World (Superflat World Type)

4.5.2 Workflows

For the first two workflows (Fig. 32 and 33) the saved Minecraft World is exported with Mineways (Fig. 28 -31) and saved as an OBJ file. As previously discussed, Minewyas offers the option of exporting individual blocks or separate types according to material. After several trials it is concluded that the first option (Fig. 31) is more feasible for the import in Rhino while the second one (Fig. 29) is more useful for the import in 3ds Max.

The grouped geometries are easier to use for the adjustments in 3ds Max that the import in AnTherm requires. In 3ds Max it is convenient to select all edges and extract the polylines, in order to export them in a DXF file. This process is faster if the blocks are not separated individually, but in group elements by material. In Rhino, on the other hand, the individual blocks are grouped by layer name during the import and the user can choose if they wish to ungroup them. The resulting polygonal mesh can also be easily exploded into singular polygons. During all conversion stages the used unit is millimetres.

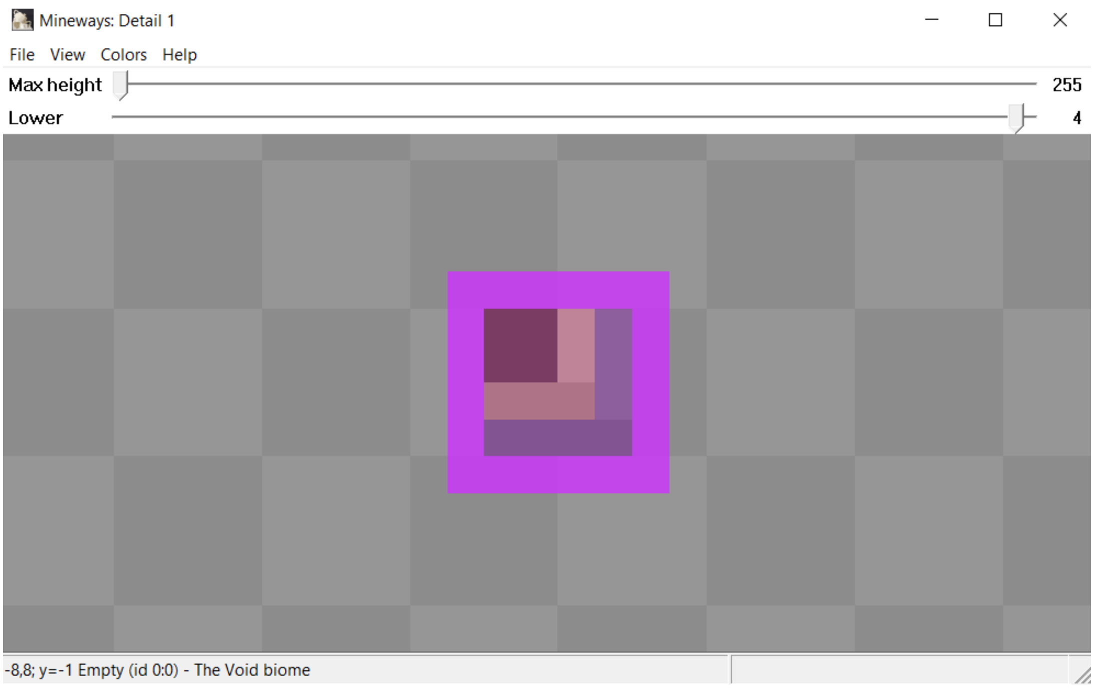


Figure 28: Trimming the Minecraft World for the first study case and exporting it with Mineways

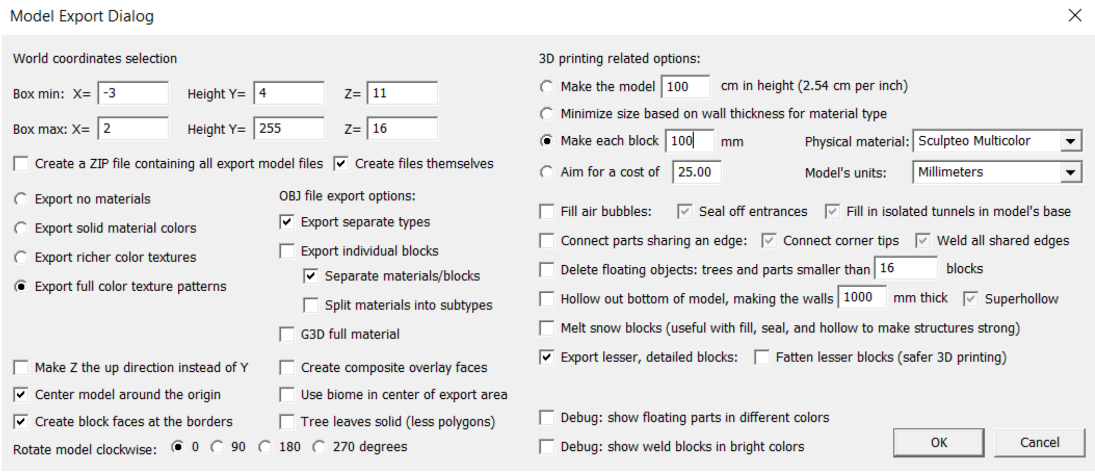


Figure 29: Exporting the Minecraft World for the first study case with Mineways, settings dialog

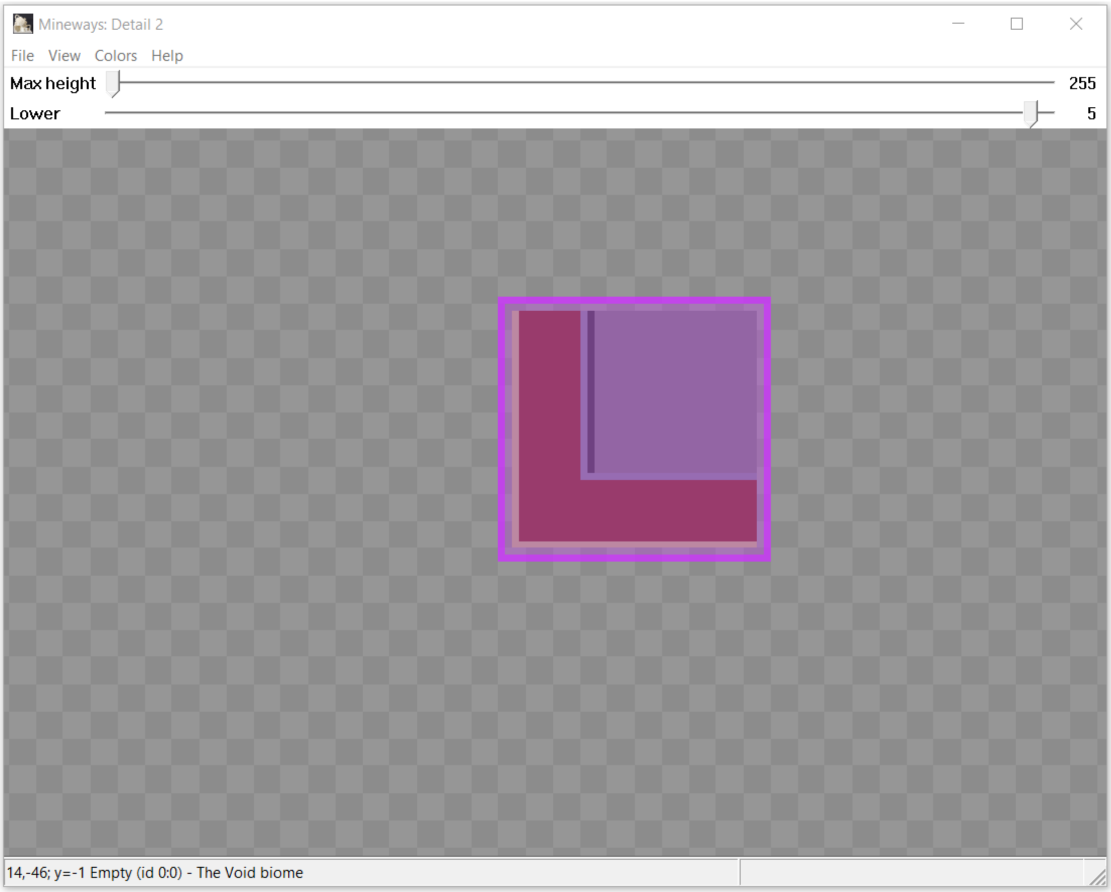


Figure 30: Trimming the Minecraft World for the second study case and exporting it with Mineways

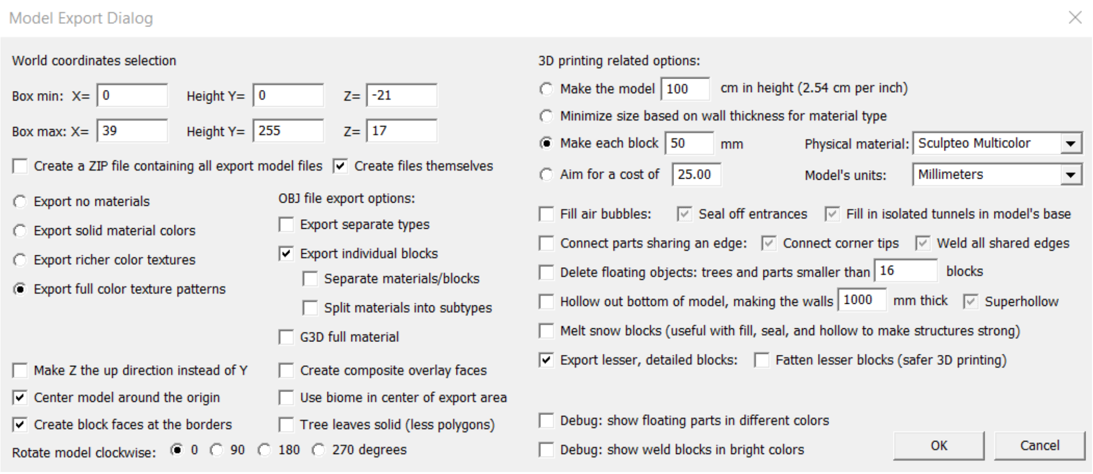


Figure 31: Exporting the Minecraft World for the second study case with Mineways, settings dialog

After the Minecraft World is exported with Mineways the resulting OBJ file is imported into 3ds Max or Rhino. This is where the process actually splits into two separate workflows, illustrated in Figure 32 and 33.

The third workflow (Fig. 34) does not need the Mineways exporter, it uses only Safe Software's FME in order to transform the Minecraft World into a usable IFC file which at best can be directly imported into AnTherm.

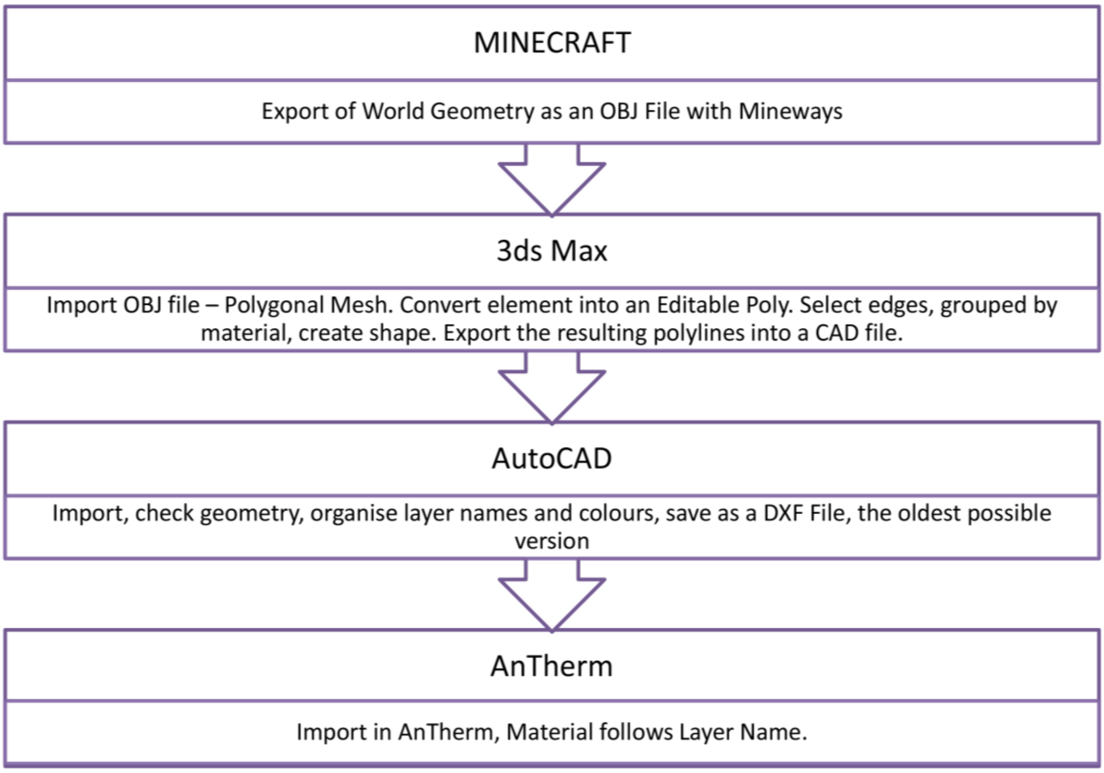


Figure 32: Workflow 1

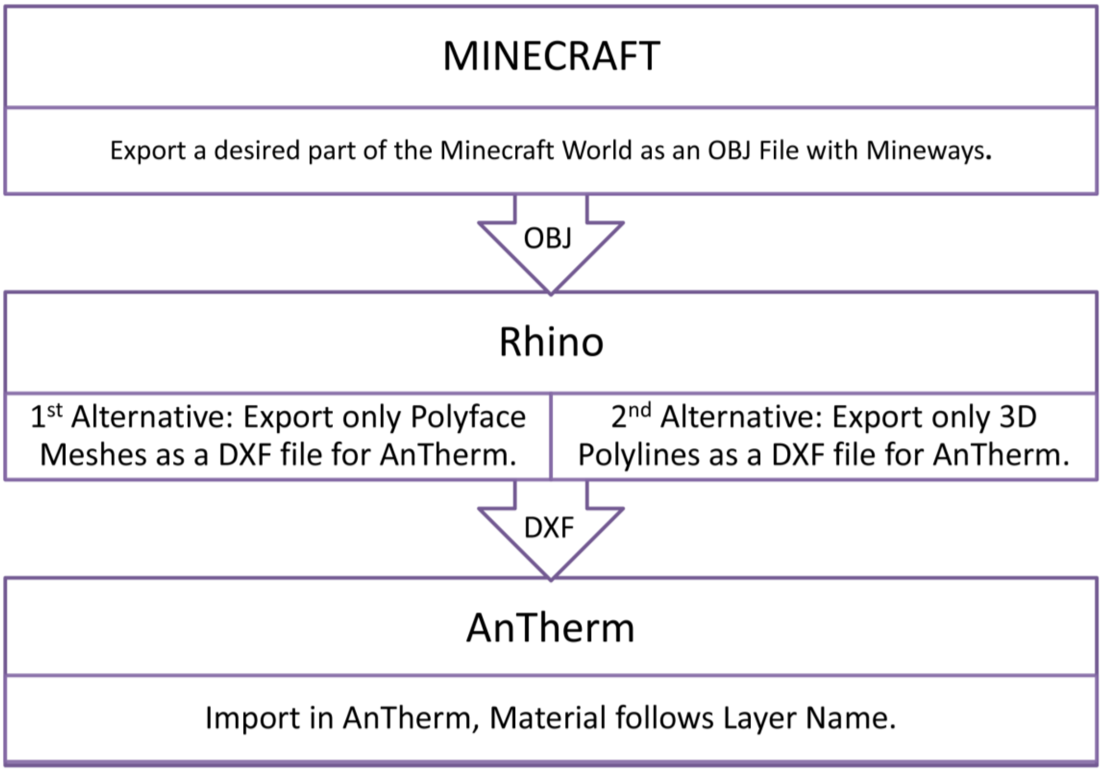


Figure 33: Workflow 2

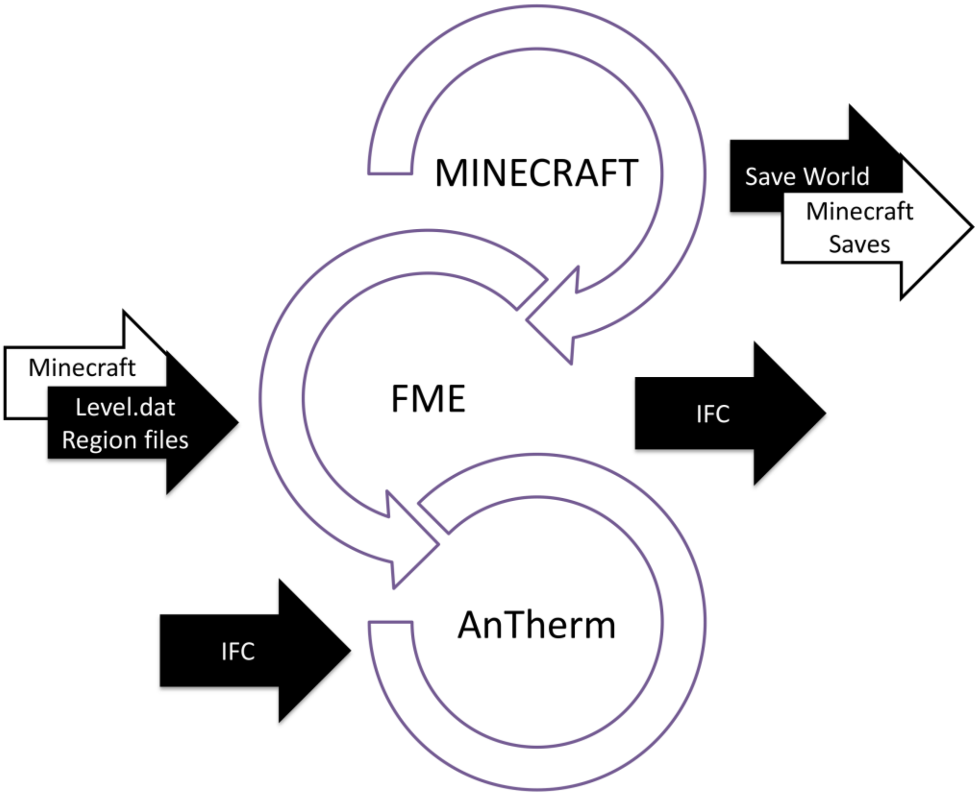


Figure 34: Workflow 3

In the first workflow, the OBJ file is imported into 3ds Max and the polygonal mesh of each group of blocks, depending on material and layer name, becomes visible. The imported geometry is then converted to an editable poly, if not specifically chosen at import. Also the objects ZY-axes need to be flipped, because in Minecraft, the X- and Z-axes represent length and width, and the Y-axis represents height (Fig. 35, 36). After selecting all the desired polygonal edges, the command “create shape” is executed in order to extract the polylines for each element (Fig. 37, 38) and export only these selected polylines with the corresponding layer structure as a DFX file. The resulting DXF file is then opened in AutoCAD for a quick check of the layers and 3D polylines, as they should all be closed and planar (Fig. 39). AutoCAD is needed in order to save the exported geometry as the oldest possible DXF file format. AnTherm works best with the older AutoCAD DXF file formats and the import alone becomes very slow when the object has not been simplified to the least count of closed rectangular 3D polylines (Fig. 39). AutoCAD cannot read an OBJ file directly, which is why 3ds Max steps in for this scenario.

Directly exporting the model’s mesh geometry from 3ds Max as a DXF file is also possible, but this geometry definition is not supported by AnTherm for a number of reasons. The 3D mesh objects created with AutoCAD-based products, released 2010 and later, are not recognized by AnTherm. Different capabilities apply to legacy polyface and polygon meshes (Autodesk 2017). The polyface mesh geometry is represented as a variant of a polyline entity in DXF, which is why AnTherm is able to read it.

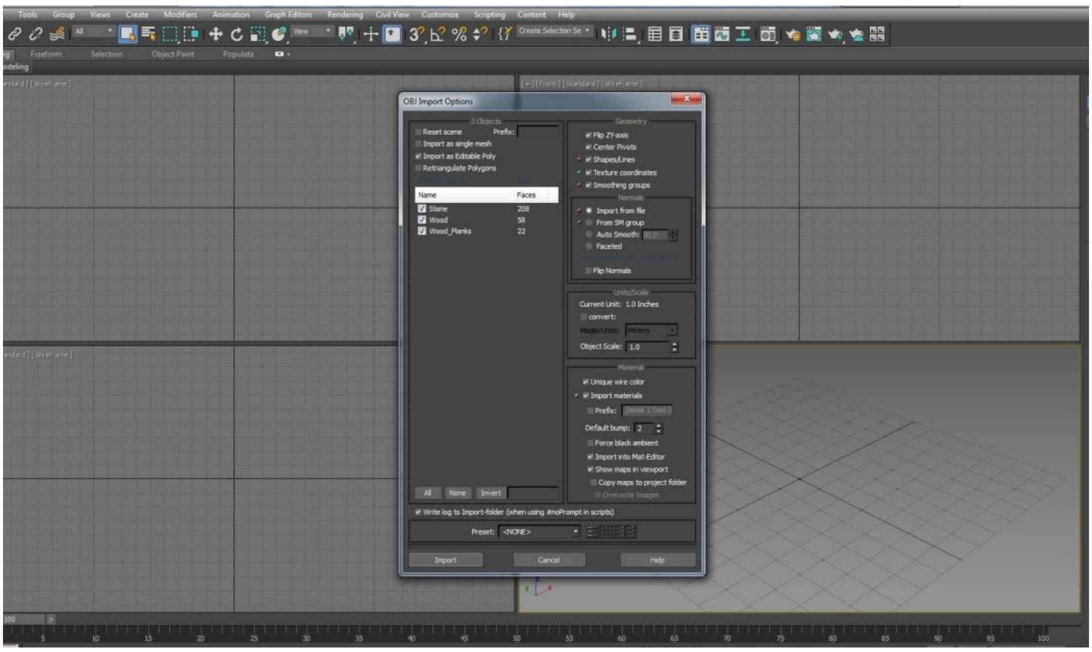


Figure 35: Workflow 1: Importing the first study case OBJ file into 3ds Max, settings dialog

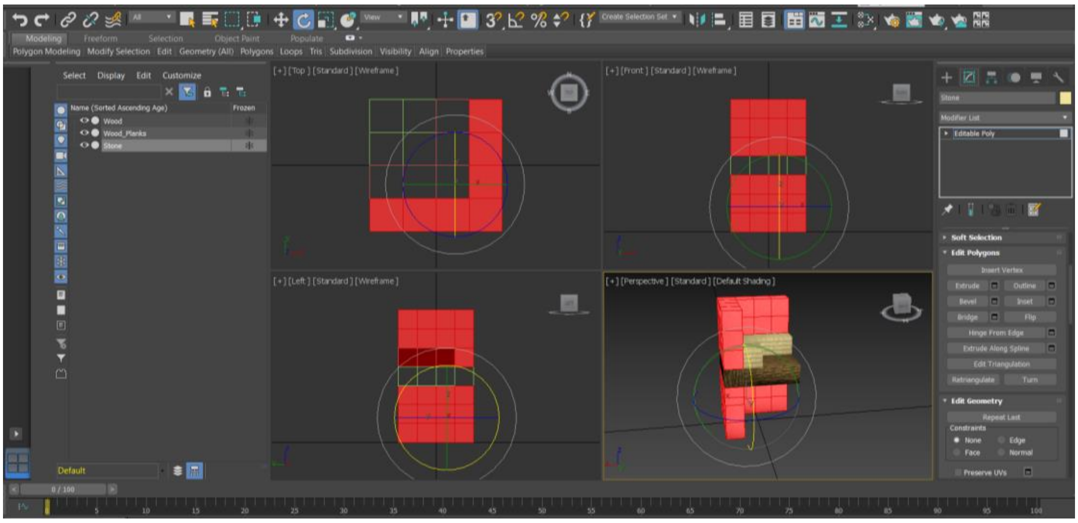


Figure 36: Workflow 1: The first study case OBJ file in 3ds Max, "stone wall" editable poly is selected

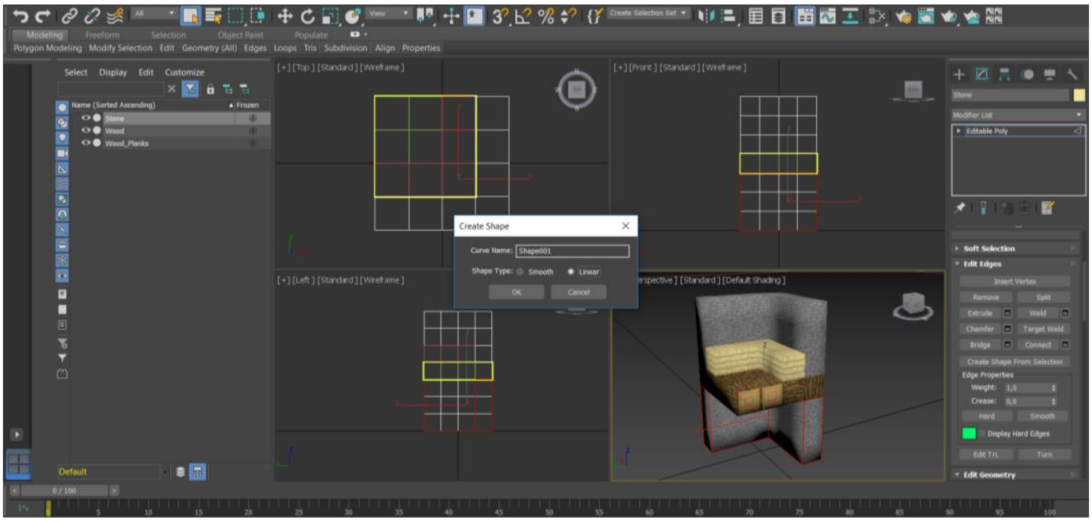


Figure 37: Workflow 1: Creating linear shapes (extracting polylines) from element edges of the first study case in 3ds Max

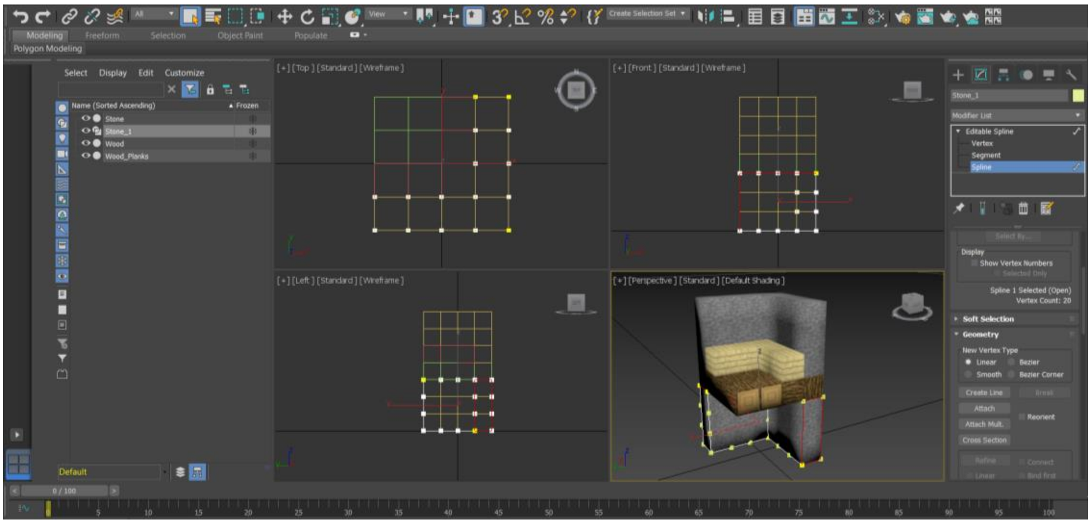


Figure 38: Workflow 1: Adjusting the created polyline in 3ds Max for the first study case

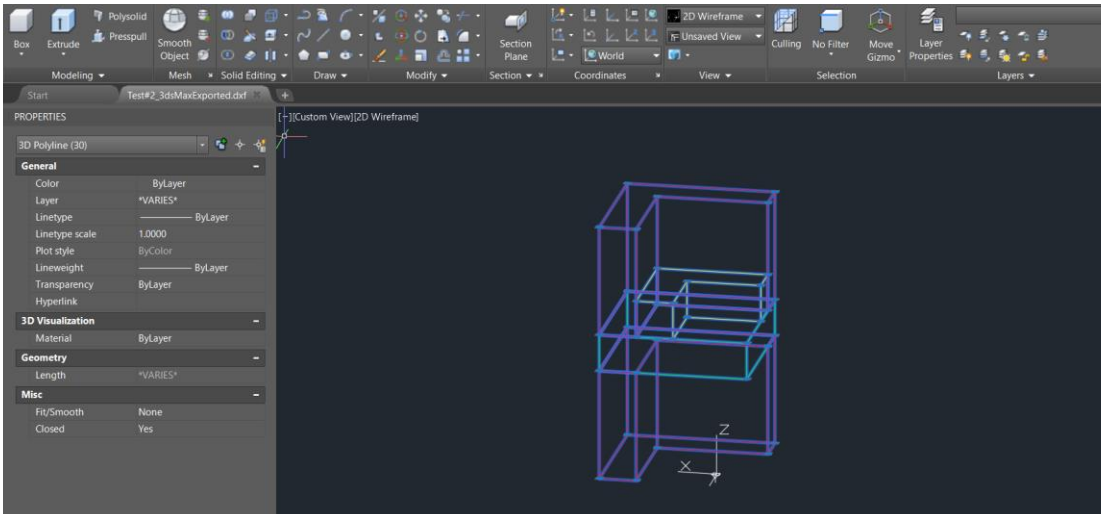


Figure 39: Workflow 1: The extracted polylines for the first study case imported in AutoCAD

Nevertheless, 3ds Max offers support for NURBS geometry as well. With 3ds Max's surface modelling tools it is possible to simplify and convert the elements to a form of editable surfaces: an editable poly, editable mesh, editable patch, or NURBS object. It should therefore be possible to create a polygonal mesh out of the converted NURBS object, which would have to be reduced in complexity and exported for further adjustment in AutoCAD.

This process is, however, slow and inefficient, and is considered redundant in the context of this study. 3ds Max has very powerful surface shaping tools, but Rhino is more intuitive and stable when it comes to complex yet precise geometrical representation. Rhino offers more detailed geometry diagnostics, which is important for a comprehensive geometrical conversion and preparation for transfer.

The second workflow is more straightforward, because Rhino supports a wider range of geometries which it can modify and translate. The imported objects are grouped by layer during the import in Rhino (Fig. 40). At import, the object's Y-axis is again mapped to the Z-axis (Fig. 40), because in Minecraft, the X- and Z-axes represent length and width, and the Y-axis represents height.

The imported geometry is a closed double precision polygon mesh, which is then converted to a NURBS polysurface by using the "mesh to NURB" command. Thus the the object becomes a (faceted) NURBS structure (Fig. 41).

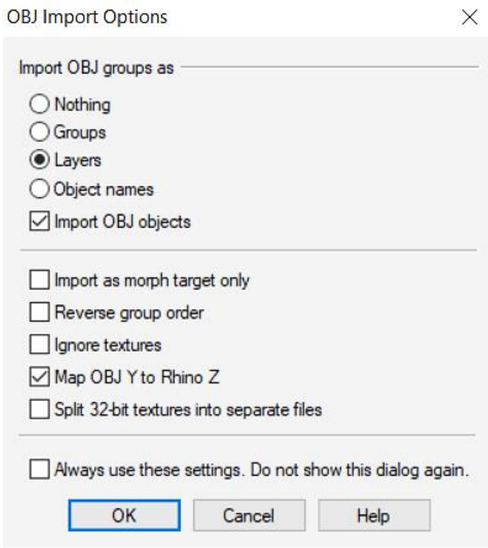


Figure 40: Workflow 2: First study case, Rhino import options

A single NURBS facet is created for every original mesh face (in this instance - the polygons of the minecraft cubes) joined into a polysurface. For the first alternative of the second workflow, each group of polysurfaces divided by layer is modified with the “merge all faces” command. Thus the polysurfaces are simplified and separated into single basic surfaces in the following steps. Then all of the ready surfaces in each layer are selected, converted to open polygon meshes and joined together in a polyface mesh (Fig. 41-43). This geometry is then exported as a DXF file of the oldest possible version.

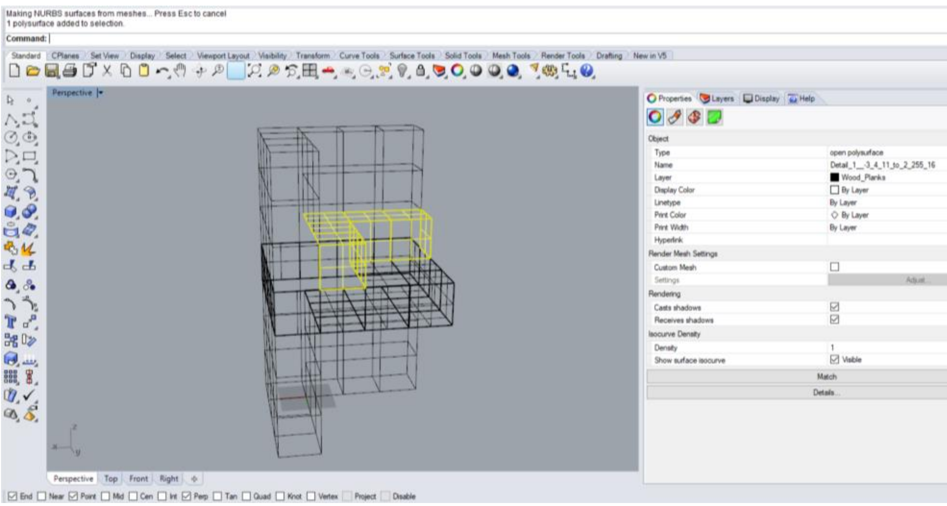


Figure 41: Workflow 2: The first study case in Rhino, MeshtoNURBS, polysurfaces

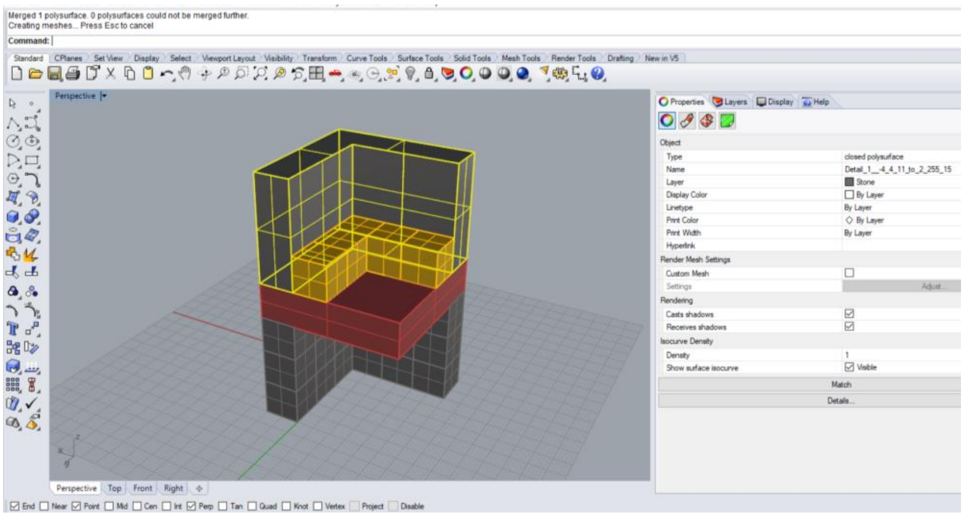


Figure 42: Workflow 2: Merging all faces for each polysurface of the first study case in Rhino and creating open polygon meshes for DXF export as polyface geometry

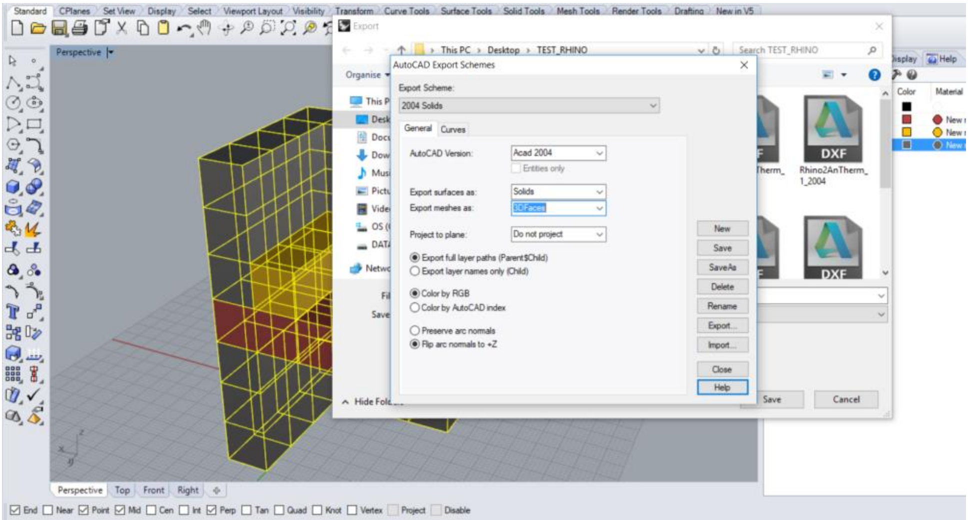


Figure 43: Workflow 2: Exporting the first study case in Rhino; it is possible to export surface or mesh geometry as mesh or 3D face geometry

For the second alternative approach of the second workflow the edges of each polysurface are extracted or created with the “duplicate border”, “duplicate edge” or “extract wireframe”, command (Fig. 44). After turning the isocurve display off the “extract wireframe” command can be used to duplicate all borders and just the borders at once. The generated polylines are then diagnosed; the layer structure and names are checked. Afterwards the selected geometry is exported as 3D polylines in a DXF file (Fig. 45). In the second workflow the use of AutoCAD is unnecessary due to Rhino’s broad functionality, but could be useful in case there is a double check of the geometry is needed (Fig. 46, 47).

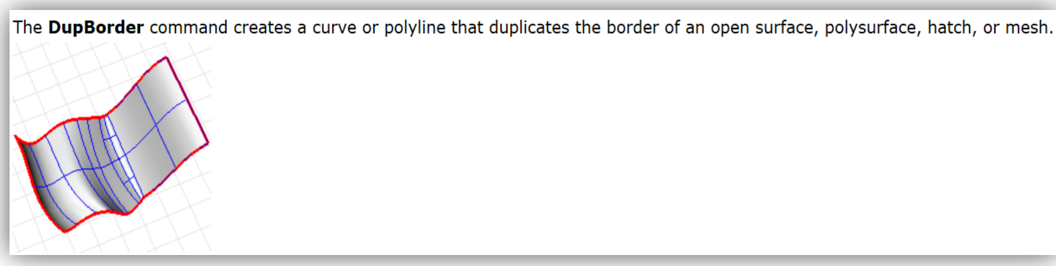


Figure 44: Rhino3D, DupBorder command (McNeel 2017)

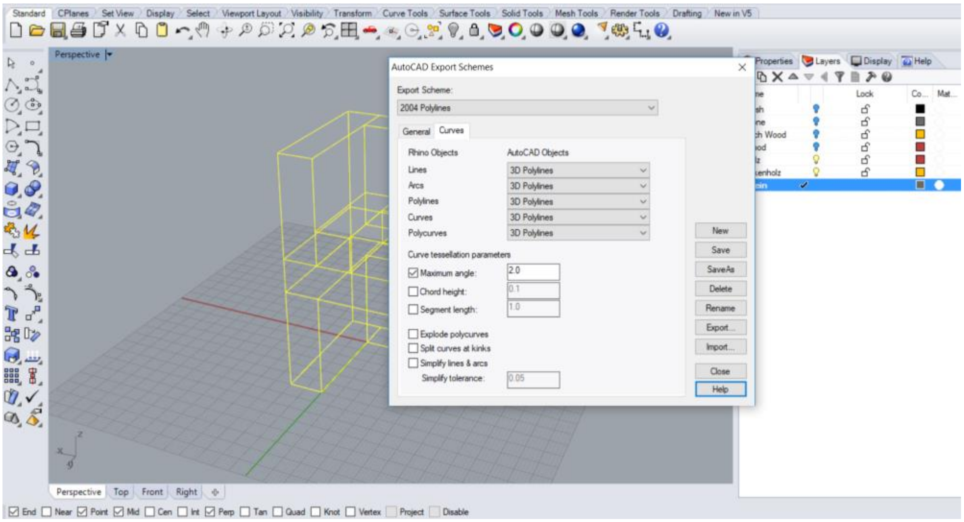


Figure 45: Workflow 2: The first study case in Rhino, extracting polylines from polysurfaces and exporting selected as 3D polylines

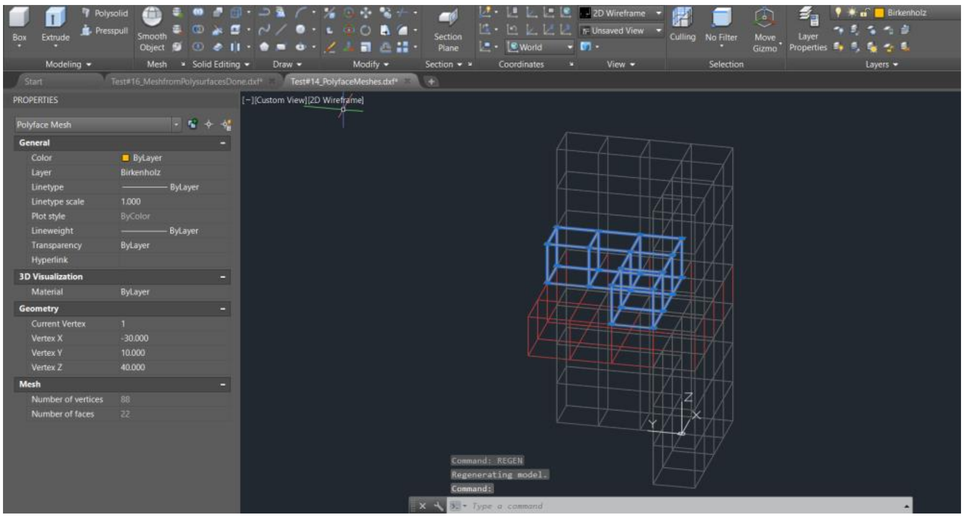


Figure 46: Workflow 2: The polyface mesh geometry of the first study case separated by material and imported in AutoCAD

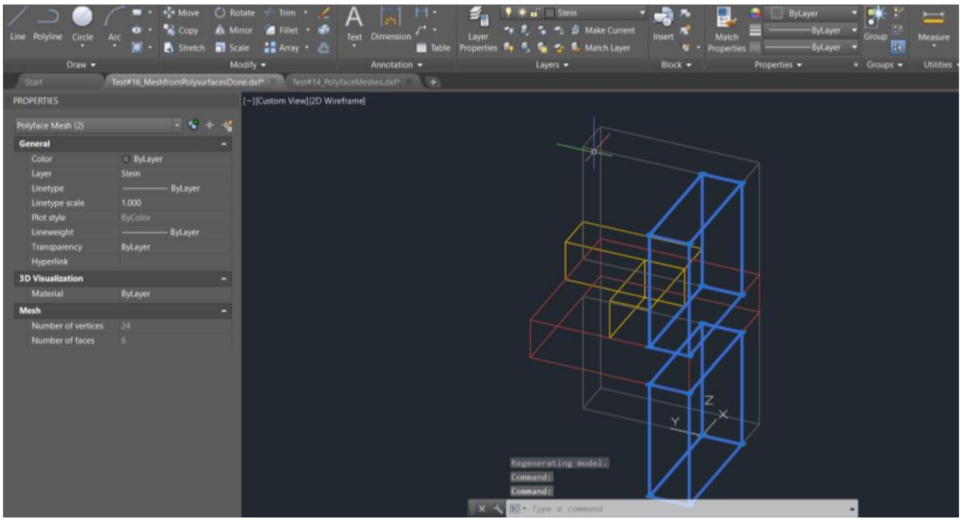


Figure 47: Workflow 2: The reduced polygonal mesh geometry of the first study case separated by material and imported in AutoCAD

The third workflow, as seen in Figure 34, loads directly the Minecraft World's saved level and region files in FME's Workbench with the help of a Minecraft Reader.

The Minecraft format is structured as a point cloud and can only be read as such by FME. Afterwards, it can be converted into other formats by using as many transformers as needed. The Minecraft Reader reads the components, however, when it comes to blockData and blockID the Workspace is not instantly aware of their presence and the user has to type them in as non-standard components in the "Point Components to Preserve" parameter of the "PointCloudCoercer" transformer. BlockID and blockData are two components Minecraft blocks are identified by.

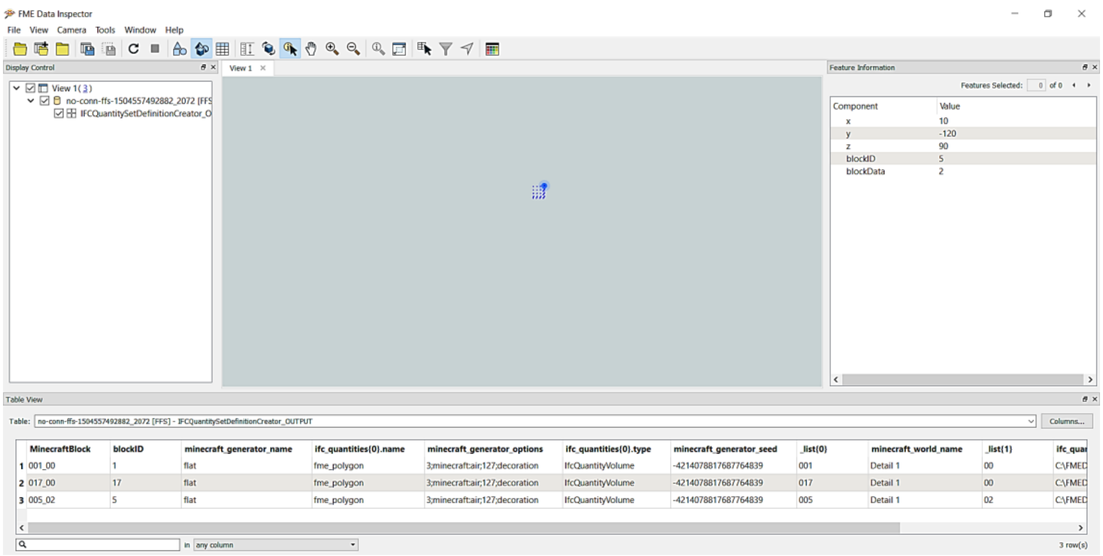


Figure 48: Workflow 3: FME Inspector view after translating the Minecraft World of the first study case into a point cloud

After this step, the point cloud is transformed into individual points by selection of this setting. The specific coordinates and the preserved non-standard components are then available as attributes on each point. The x-component in the input point cloud is mapped to the X-axis, the y-component is mapped to the game's Z-axis, but in order to maintain correct spatial relationships, the y-component's values are also scaled by -1. The z-component in the input point cloud is mapped to the Y-axis and is limited to the size of 0 – 255 because of the game engine restrictions.

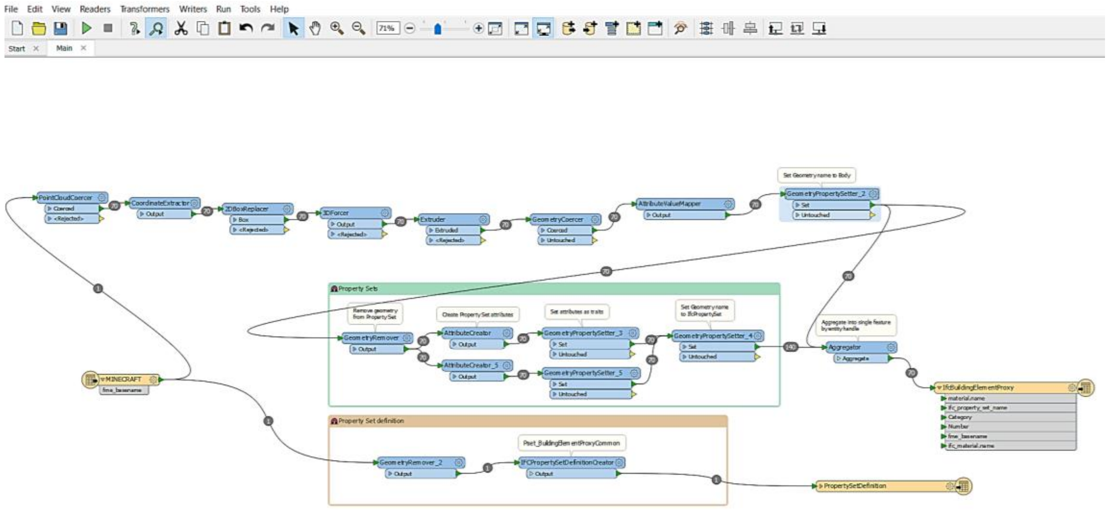


Figure 49: Workflow 3: The first study case in FME's Workbench view

The process proceeds in transforming the points into cubes, which are to be written to the IFC file format. This is achieved by building squares by using a point's *x* and *y* as minimal coordinates, and *x+1*, *y+1* as maximal coordinates. The squares are then extruded to create cubes, which are assigned a new attribute – a material name, which is previously translated from the blockID attribute. The official and full list of Minecraft block types with blockID and blockData can be found on Minecraft Wiki's webpage (Minecraft Wiki 2017). The numbers above the blocks represent the blockID. To give an example, a block of "Stone" has a blockID of 5. The smaller indices beside blockID define blockData components. After a successful translation run (Fig. 49) the generated geometry as well as every other step of the process chain can be inspected with FME's Inspector (Fig. 48, 50). The cubes can be written to the IFC file format, for an example, as an "IfcSlab", "IfcWall", "IfcBuildingElementProxy". After the successful translation the new geometry is saved in the IFC file format.

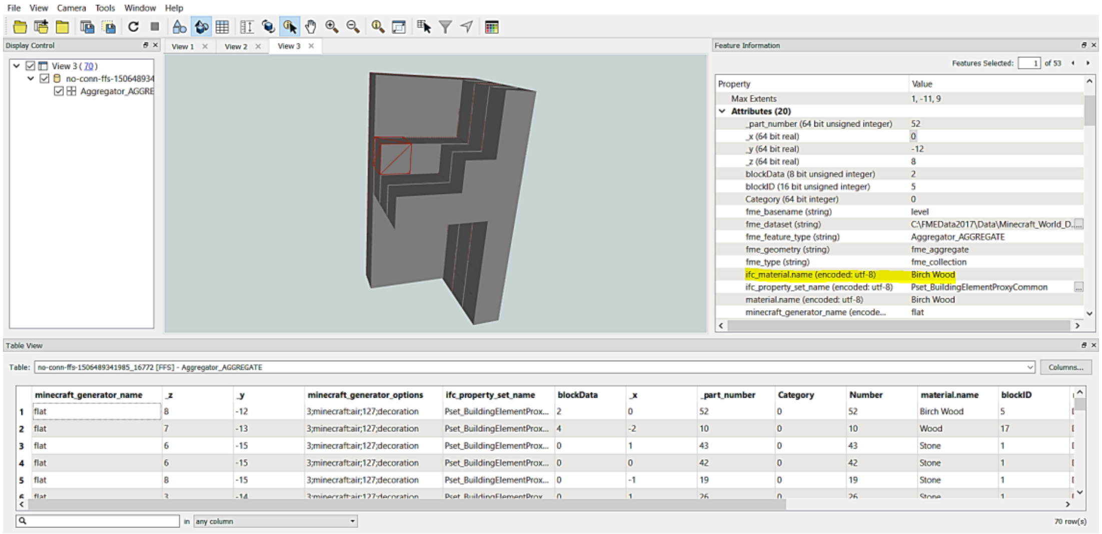


Figure 50: Workflow 3: The first study case in FME's Inspector view after successful translation

The second case study follows the same steps, but is focused only on the second and third workflows due to Rhino's broader functionality and FME's flexibility.

In the second workflow, after the successful export of the Minecraft World for the second study case, the OBJ file is imported into Rhino and the mesh geometries are grouped by layer (Fig. 51 - 53). The polygonal meshes are then converted into polysurfaces and the polylines are generated as already described for the first study case. Some layers, such as the interior and exterior plaster layer, are easily modified to have a thickness of 15 and 25mm accordingly, since after the export from Minecraft the thinnest layer has a thickness of 50mm. After ordering the layers, setting the correct names and colours and checking the properties of the polylines (Fig. 54 - 56) the new geometry is ready to be exported as a DXF file (Fig. 57).

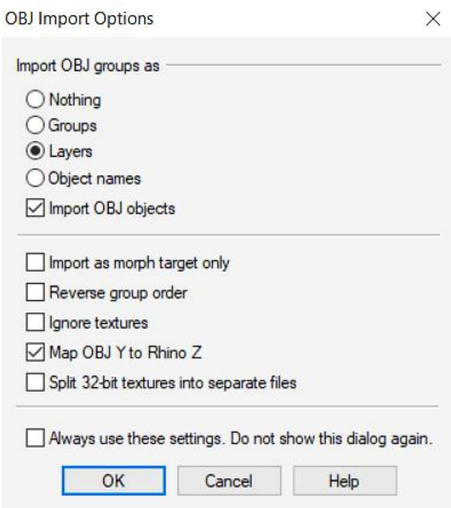


Figure 51: Workflow 2: The second study case, Rhino import options

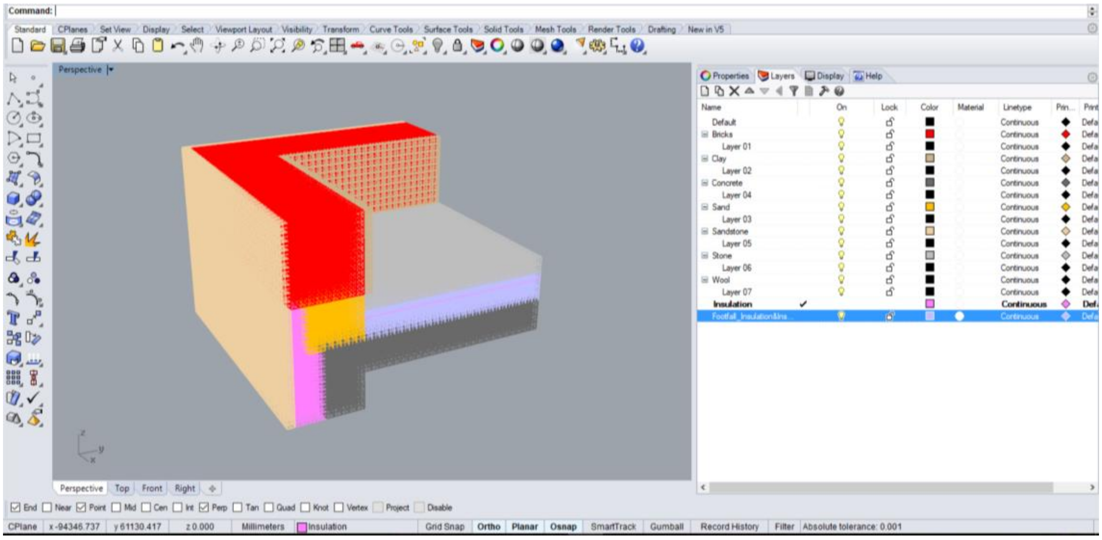


Figure 52: Workflow 2: The second study case imported in Rhino as a mesh geometry

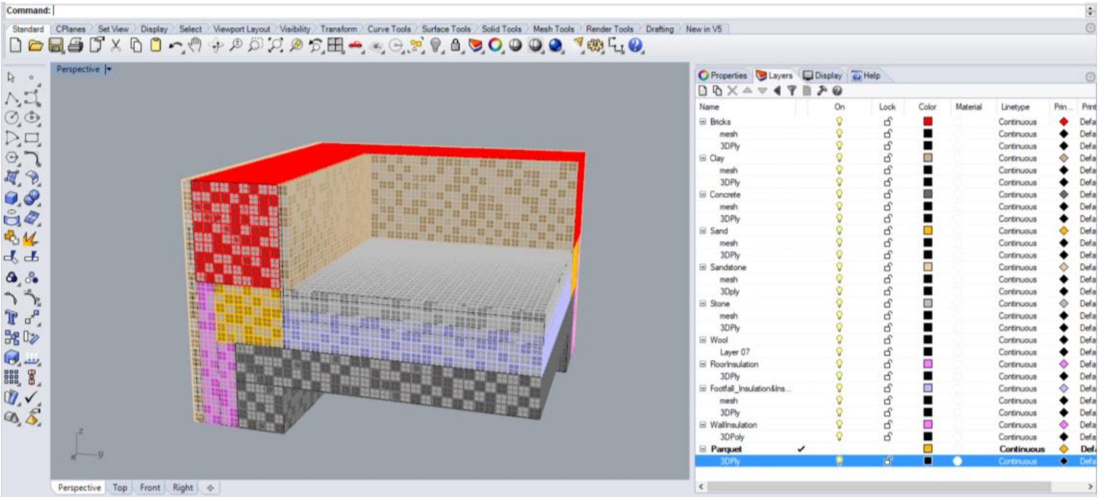


Figure 53: Workflow 2: MeshtoNURBS command, adjusting the layer order of the second study case and extracting polylines

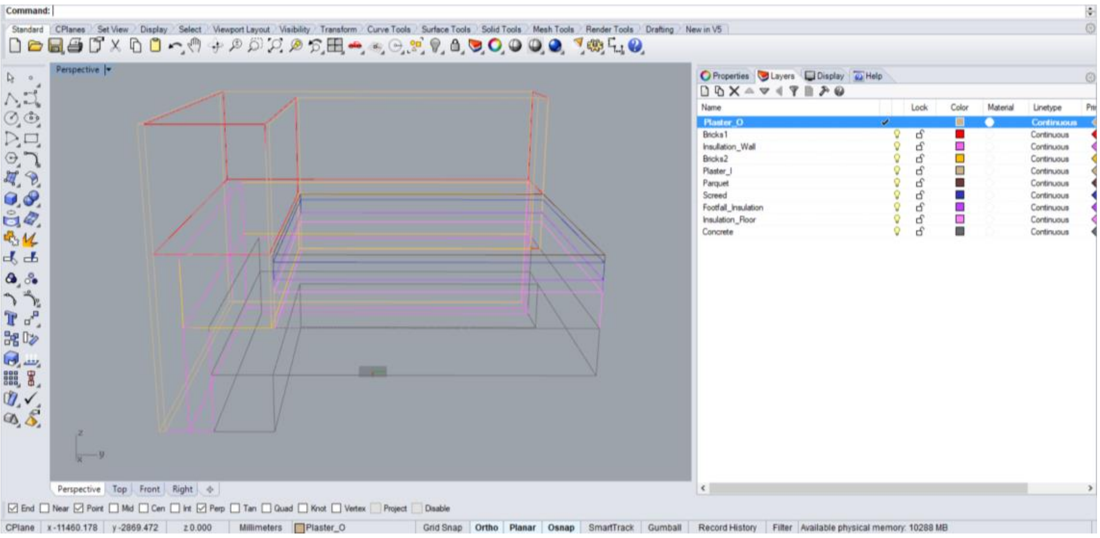


Figure 54: Workflow 2: The polylines of the second study case ordered by layer

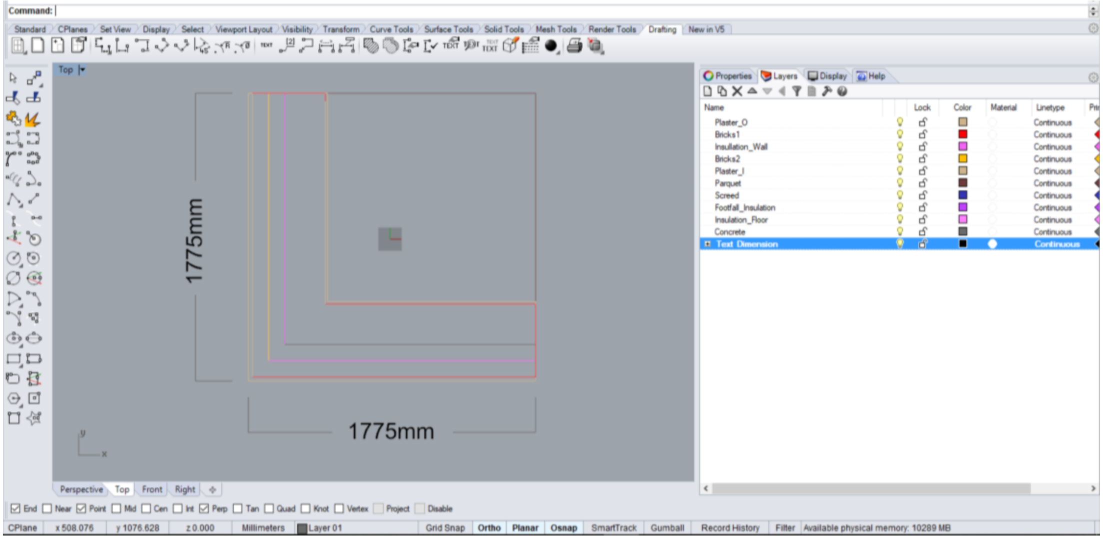


Figure 55: Workflow 2: The extracted polylines of the second study case in top view with dimensions

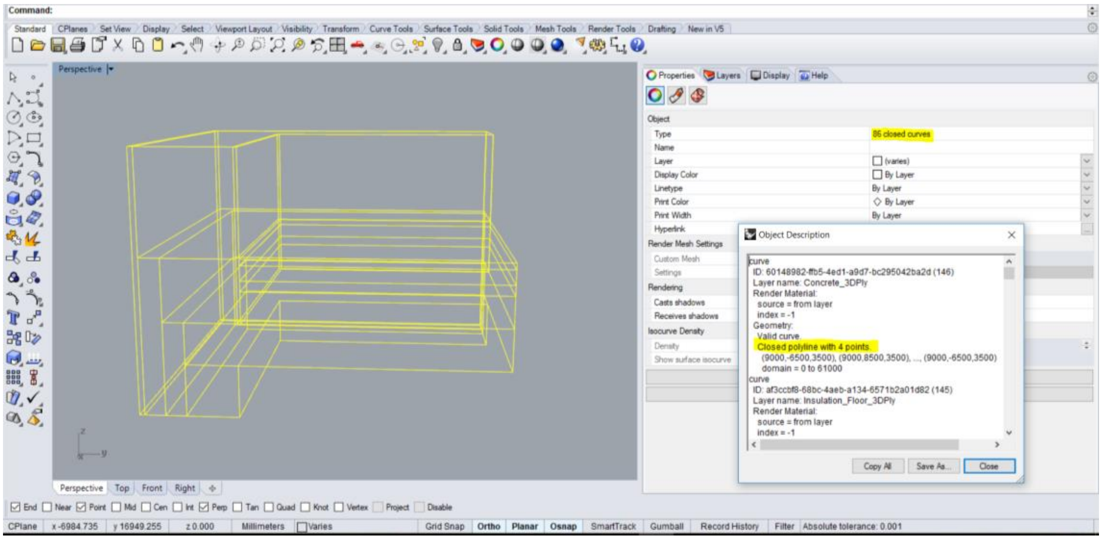


Figure 56: Workflow 2: Checking the polylines' properties of the second study case

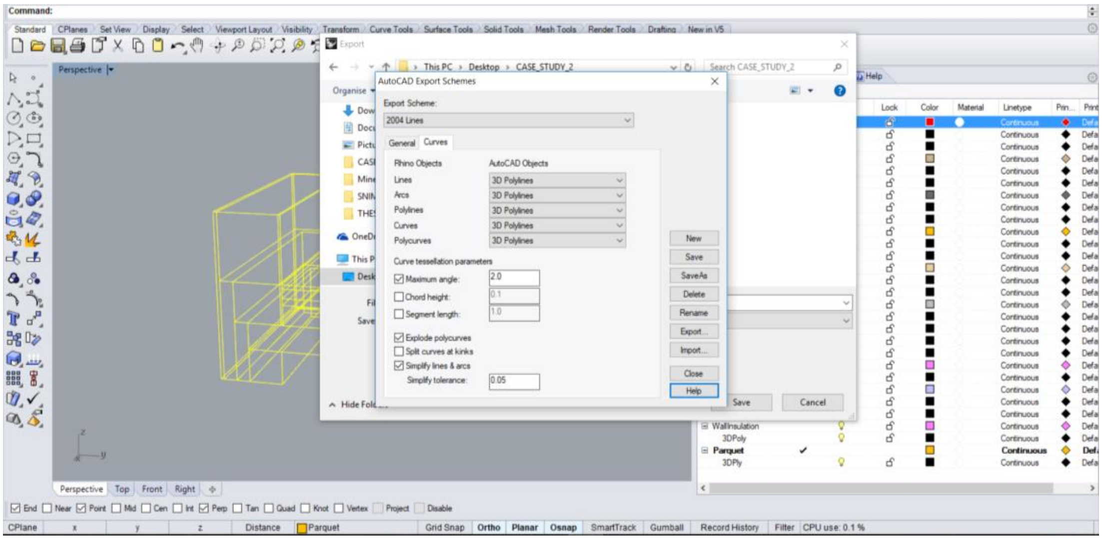


Figure 57: Workflow 2: Exporting the second study case to the DXF file format, settings

The FME Workbench model for the second study case looks identical as the model for the first study case, since the transformation process is the same. The only thing that changes is the reader input and assigned IFC material names.

The further steps and the results after the DXF and IFC import in AnTherm for both study cases are presented in the following chapter.

5 RESULTS

5.1 Overall performance and important parameters

The AnTherm software version used for this study, as already stated in chapter *4.4 Interoperability and compatibility* is currently under development. The AnTherm Team continuously provided new version fixes during the span of this study. The software's not yet full functionality when it comes to importing and working with 3D DXF and IFC files partly explains the results in the following chapters.

The most important criterion considered in these case studies (when a thermal simulation is possible) is the temperature factor. The temperature factor f_{Rsi} has to be below 0,71 for the mold growth assessment criterion to be fulfilled, and below 0,69 for the condensation assessment criterion to be fulfilled.

Table 2: Reference surface thermal resistances according to the ISO 6946 standard

	R_{si} [m^2KW^{-1}] Internal surface resistance	R_{se} [m^2KW^{-1}] External surface resistance
Heat flow direction		
Horizontally	0,13	0,04
Upwardly	0,10	0,04
Downwardly	0,17	0,04
Surface Temperatures		
Heated rooms	0,25	0,04
Unheated rooms	0,17	0,04
Glazing	0,13	0,04

Table 3: Introduction of important nomenclature

	Symbol	Unit
Thermal transmittance value (U-value)	U	$[Wm^{-2}K^{-1}]$
Thermal resistance	R	$[m^2KW^{-1}]$
Heat flow rate	Q	$[W]$
Density	ρ	$[kgm^{-3}]$
Specific heat capacity	c	$[Jkg^{-1}K^{-1}]$
Thermal conductivity	λ	$[Wm^{-1}K^{-1}]$
Thermal coupling coefficient (length related transmittance for 2D models)	L^{2D}	$[Wm^{-1}K^{-1}]$
Thermal coupling coefficient (intrinsically for 3D models)	L^{3D}	$[WK^{-1}]$
Temperature factor	f_{Rsi}	[-]
Minimum interior surface temperature	$\theta_{si, min}$	[°C]
Temperatures of inside and outside space	θ_i, θ_e	[°C]
µ-factor	µ	[-]

Table 4: Boundary temperatures

	Temperature
Interior	
Heated room	+20°C
Heated basement	+20°C
Unheated basement	+5°C

Table 4: Boundary temperatures

Exterior	
Exterior space	-10°C

5.2 Case study 1

The results for the first case study from the first and second workflow are identical, because both DXF imports of the closed 3D polyline geometry are successful when it comes to correct geometrical representation. The import of the polyface mesh from the second workflow into AnTherm is however unsuccessful, the model's geometry is hollow (Fig. 58).

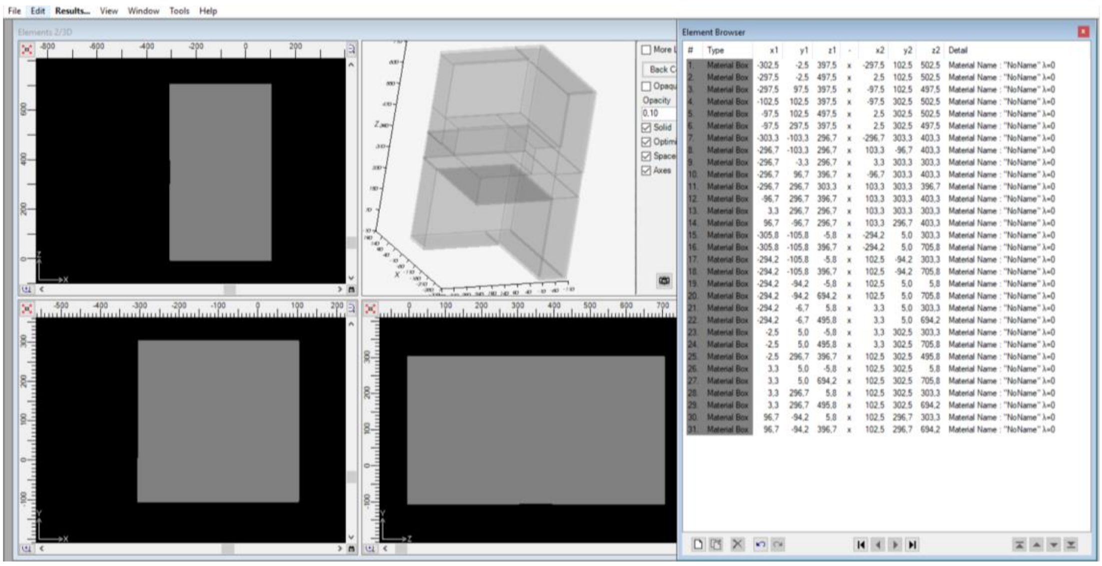


Figure 58: Case study 1, the DXF file with the polyface mesh geometry from the second workflow imported in AnTherm

After this result, the first alternative of the second workflow has to be repeated, but the object geometry is simplified and exported as singular 3D faces from Rhino by choosing this export option. The DXF file is then imported into AnTherm and the import is successful. It could be argued that the used terminology in AnTherm's instruction sheet (Fig. 19) regarding data transfer from other programs should be clarified, especially the import of DXF files that should supposedly contain polyfaces.

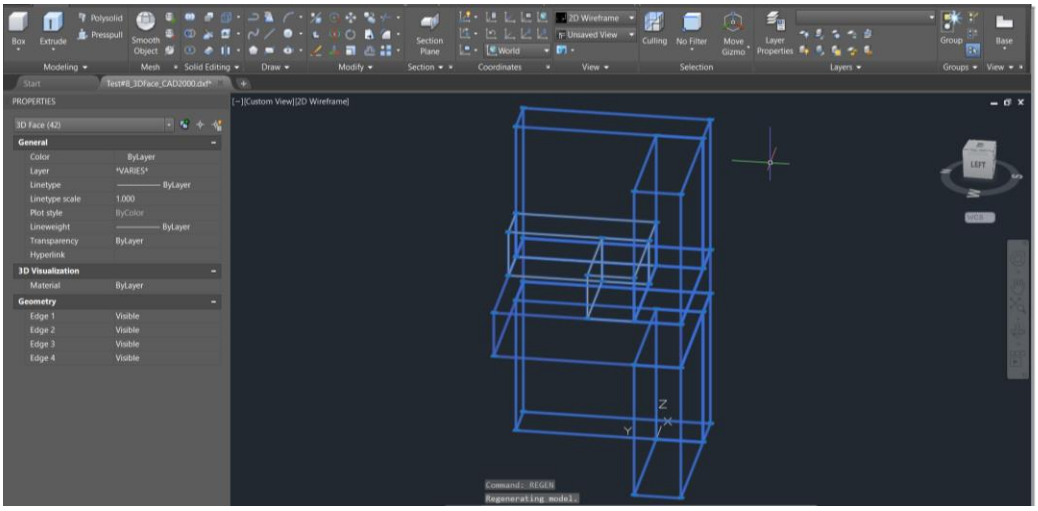


Figure 59: Case study 1, geometry exported as 3D faces from Rhino, imported in AutoCAD

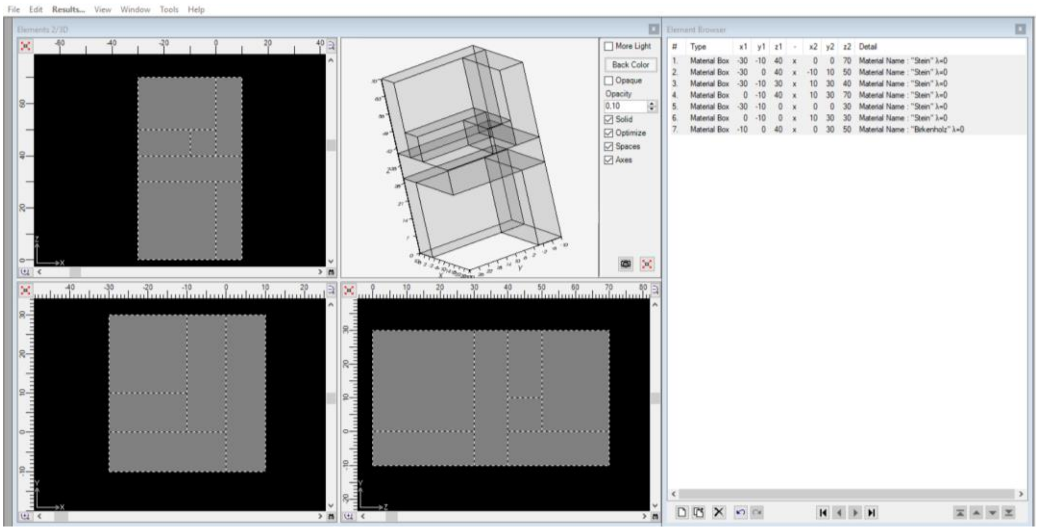


Figure 60: Case study 1, the DXF model composed of 3D faces imported in AnTherm

When the 3D DXF file is imported into AnTherm, in spite of the geometrical definition being correctly read and regardless if the DXF file contains 3D polylines or 3D faces, one of the layer names is dropped (Fig. 60, 62). The material names of the correctly imported layers are present, but grouping by layer colour does not function. After adjusting the layers and adding space boxes for the interior and exterior spaces the model is ready for the calculation with AnTherm (Fig. 63). The numerical outputs for this case study are presented in Table 6. The graphical result is visible in Figure 64.

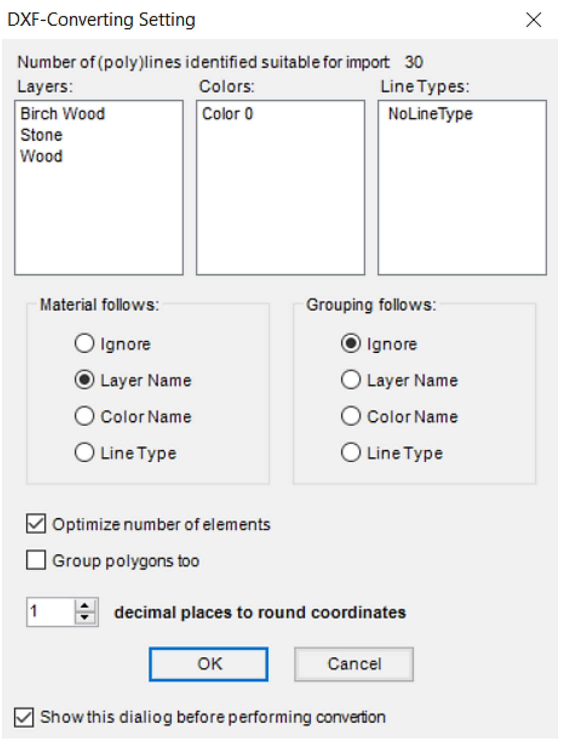


Figure 61: Case study 1, DXF import settings in AnTherm

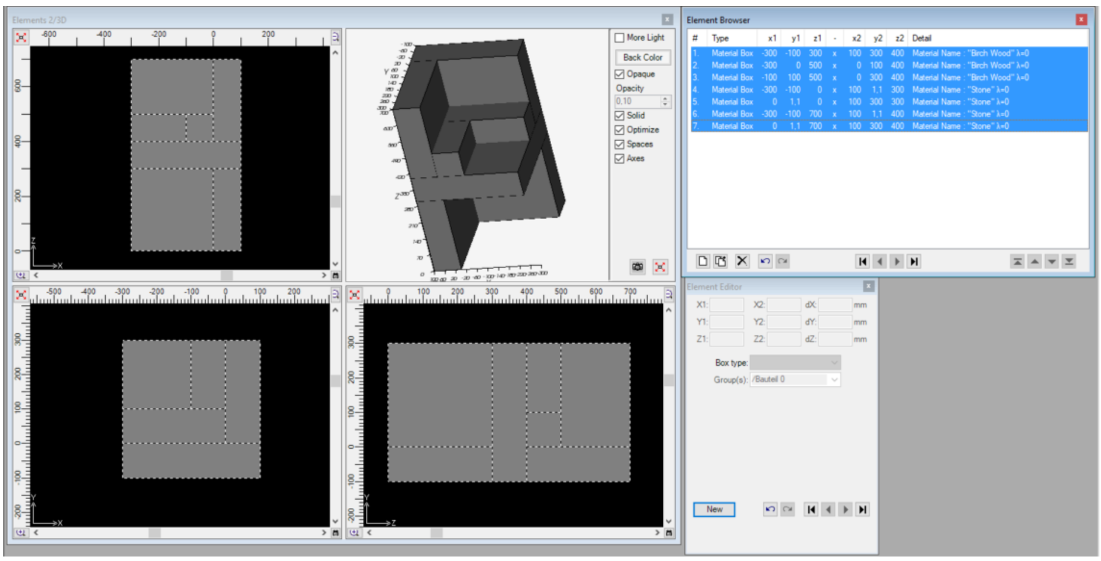


Figure 62: Case study 1, the DXF file containing 3D polylines imported in AnTherm

Table 5: Case study 1, materials and used heat transfer coefficients

Materials

c	Name	λ [$Wm^{-1}K^{-1}$]	μ [-]	ρ [kgm^{-3}]	c [$Jkg^{-1}K^{-1}$]
	Oak-Hardwood	0,2	40	800	1250
	Solid stone	0,32	10	500	840
	Plywood	0,15	400	800	2000

Used heat transfer coefficients

c	Room	Rs(H)	Rs(T)	Description
	Exterior	Rs=0,04 m²K/W	Rs=0,04 m²K/W	Outside space
	Interior	Rs=0,13 m²K/W	Rs=0,25 m²K/W	Heated room

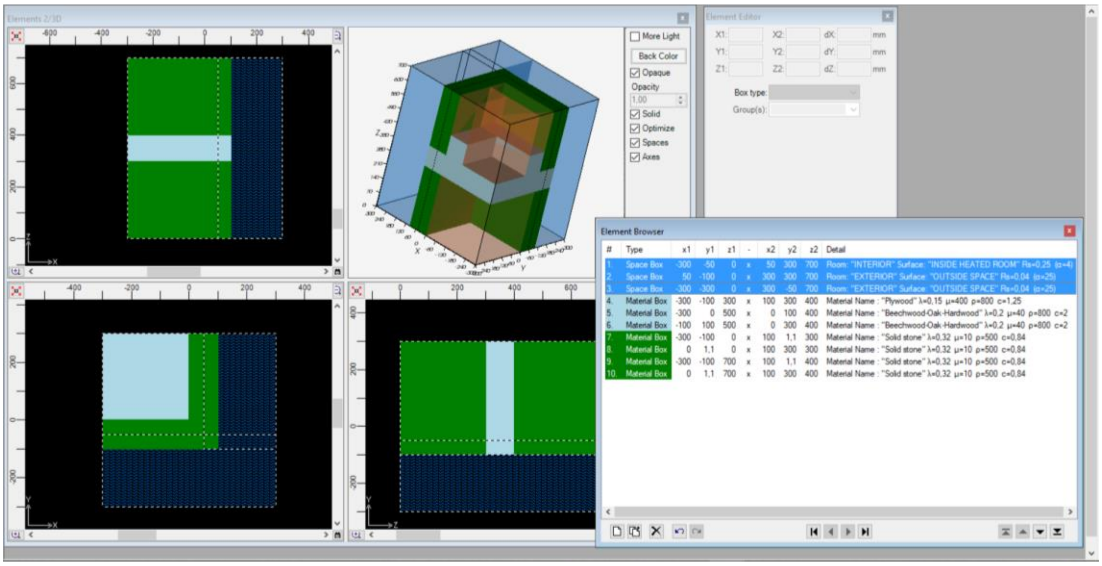


Figure 63: Case study 1, the finished model in AnTherm

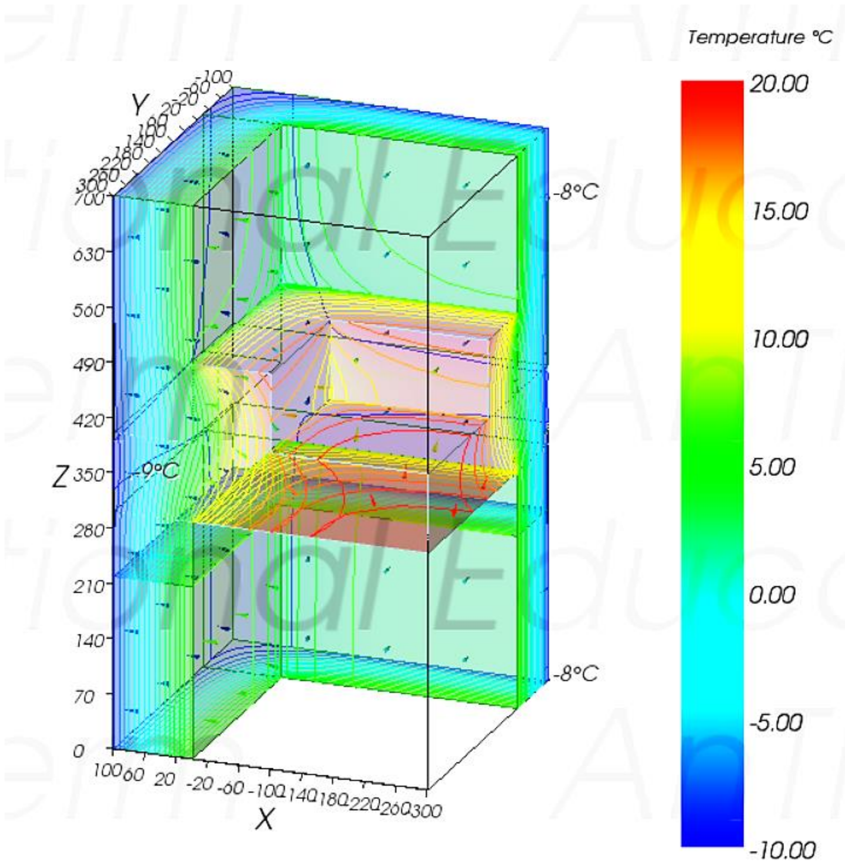


Figure 64: Case study 1, graphical output results, 3D perspective

Table 6: Case study 1, output results

L^{3D} [WK^{-1}]	$\theta_{si,\ min}$ [°C]	f_{Rsi} [-]
0,797705	0,93	0,36

The results for the first case study from the third workflow cannot be produced, because of several reasons. The import of the IFC file into AnTherm is not accurate and the translated and assigned material names are not imported at all. Much more effort is required to modify the layers and fill void spaces than to construct it anew in AnTherm (Fig. 65 and 66). In AnTherm the imported geometry is split into many flat solids with spaces between them, even when the FME translated geometry is an ifcBrepSolid (Fig. 67), an extrusion. After multiple AnTherm updates and numerous attempts to translate the Minecraft file to different IFC entities it is determined not to apply this workflow for the second study case.

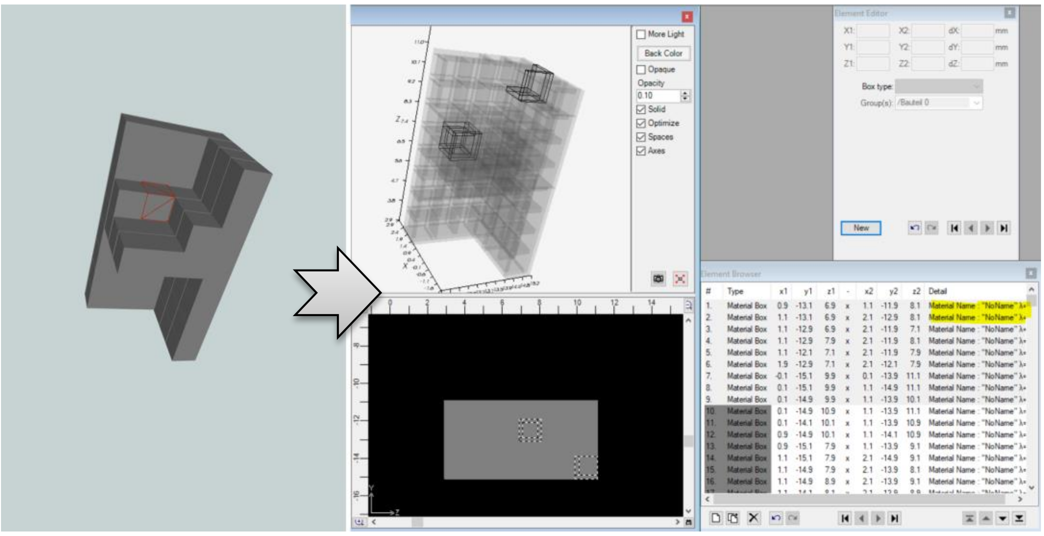


Figure 65: Case study 1, the IFC file imported in AnTherm

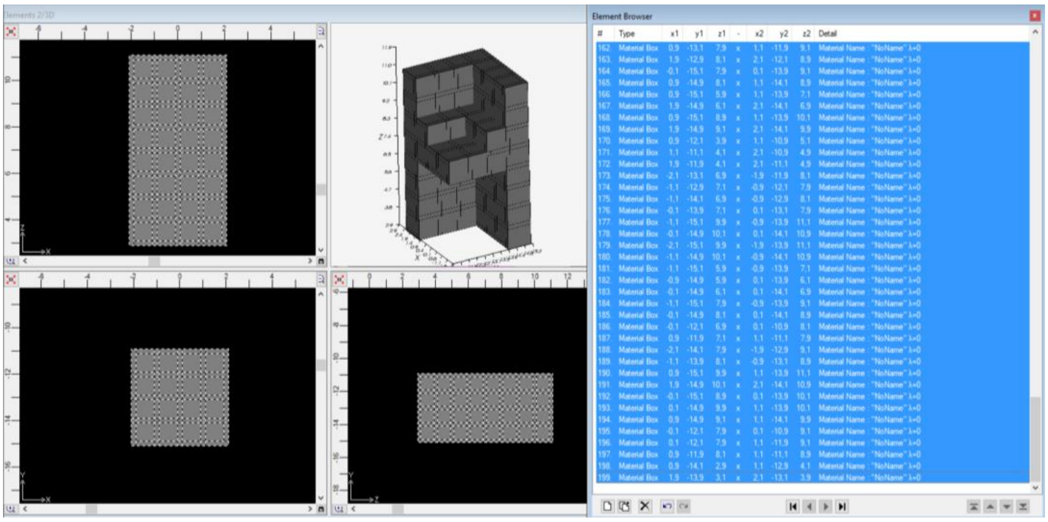


Figure 66: Case study 1, the IFC file imported in AnTherm, geometry translated to “ifcBrepSolid”

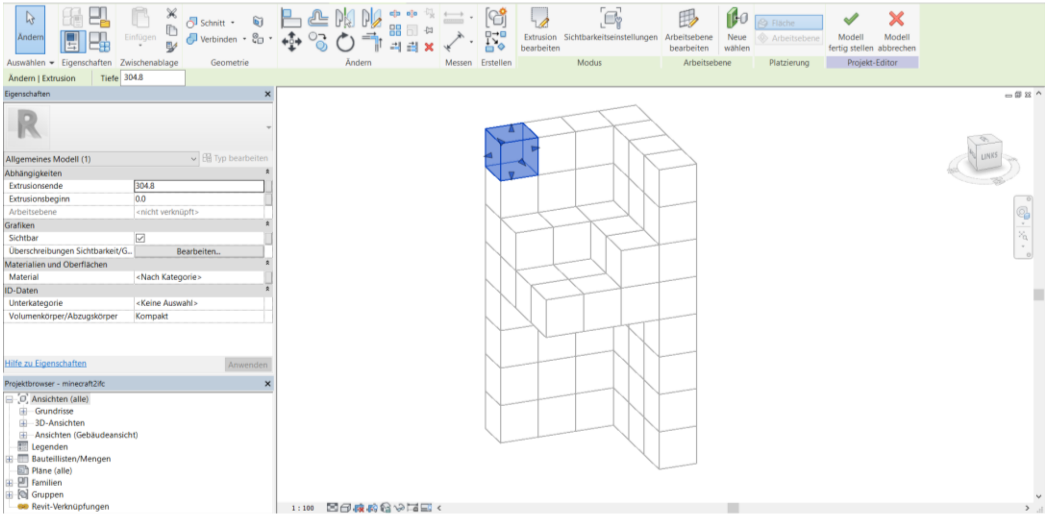


Figure 67: Case study 1, the imported IFC file in Revit after translation, cubes as extrusions

5.3 Case study 2

When the DXF file of the second case study from the second workflow is imported into AnTherm it is visible that the horizontal floor layers are merged into one single layer (Fig. 69, 70). The material names of the correctly imported layers are present, but grouping by layer colour does not function.

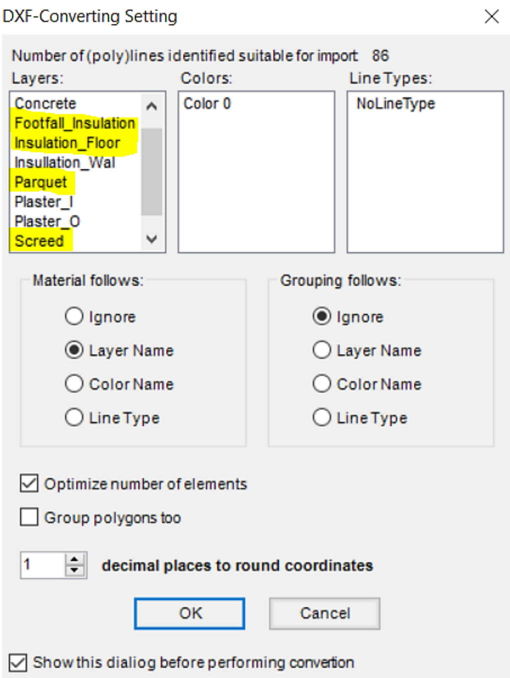


Figure 68: Case study 2, DXF import settings AnTherm

In order to understand why the horizontal layers are merged together when importing them, a separate file containing only these layers is imported into AnTherm as a test DXF file. The result, however, is the same.

As a next step, a different approach is tested: the affected layers are shifted on the horizontal plane, so that each layer does not have an even border with the neighbouring layer. When importing this DXF file into AnTherm the program recognizes and differentiates that these are separate layer boxes, but again does not import the layer names correctly (Fig. 69 - 71). These issues had to be manually rectified (Fig. 71 - 74).

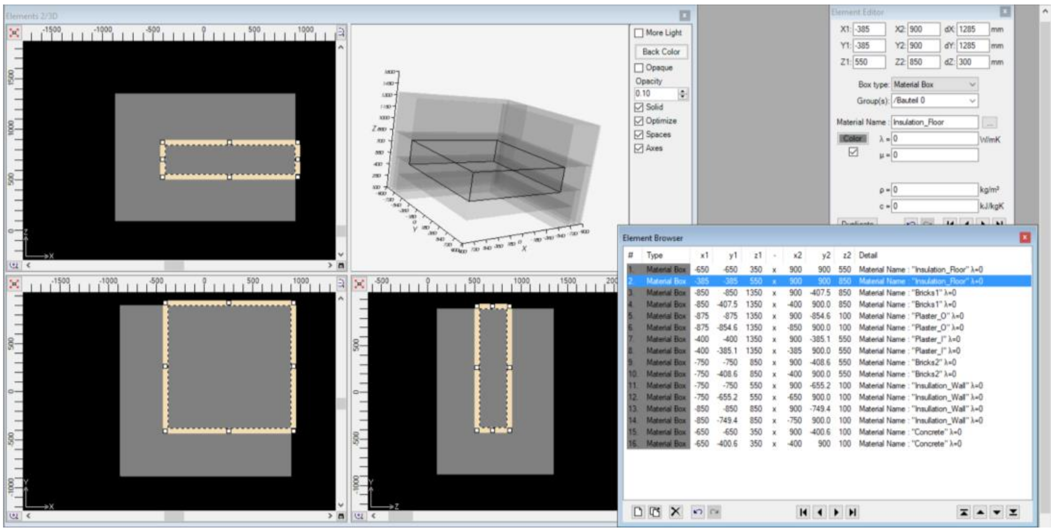


Figure 69: Case study 2, DXF imported into AnTherm, 4 floor layers are merged into one layer

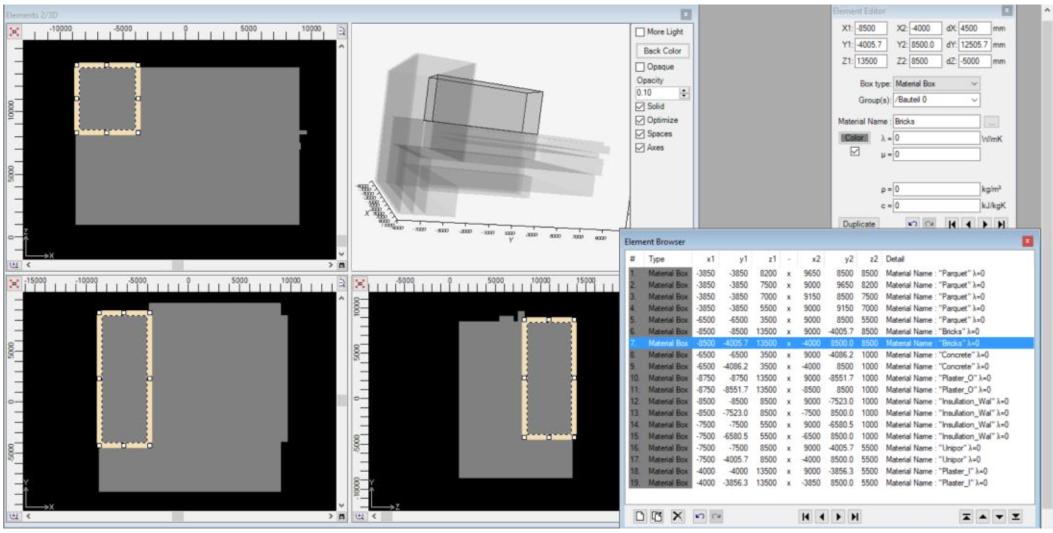


Figure 70: Case study 2, a copy of the DXF file with shifted floor layers imported into AnTherm

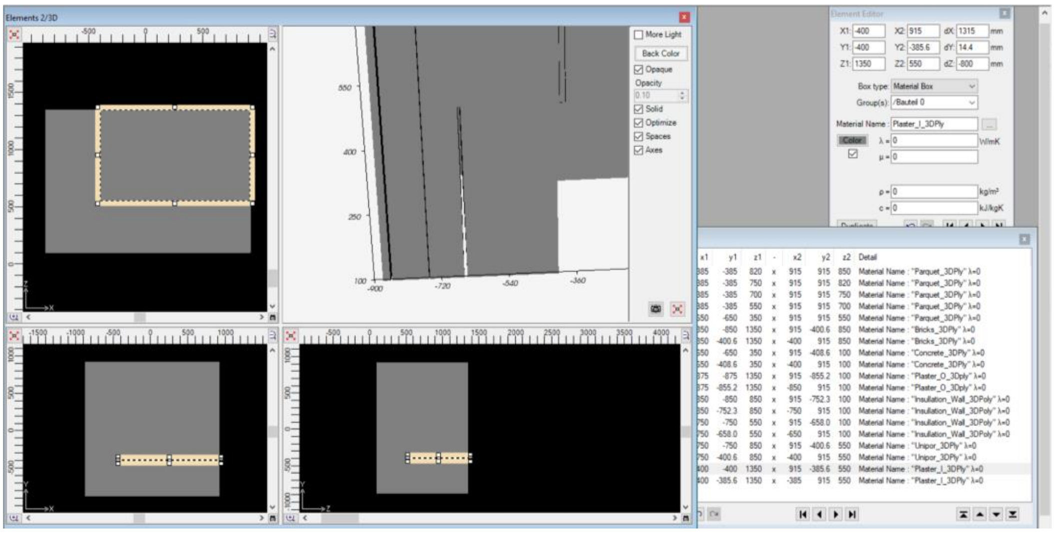


Figure 71: Case study 2, additional geometrical errors after import into AnTherm

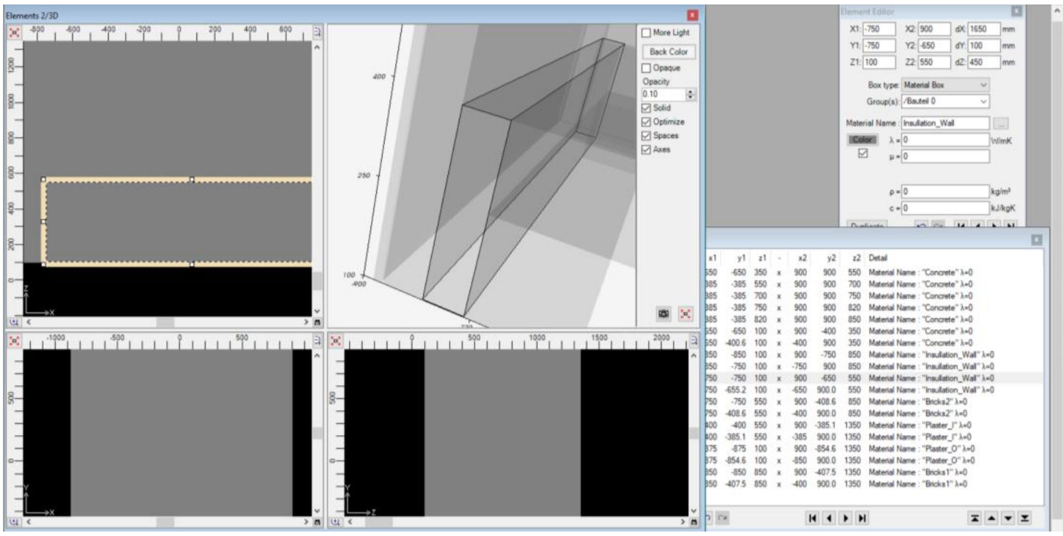


Figure 72: Case study 2, adjusting layer geometry in AnTherm

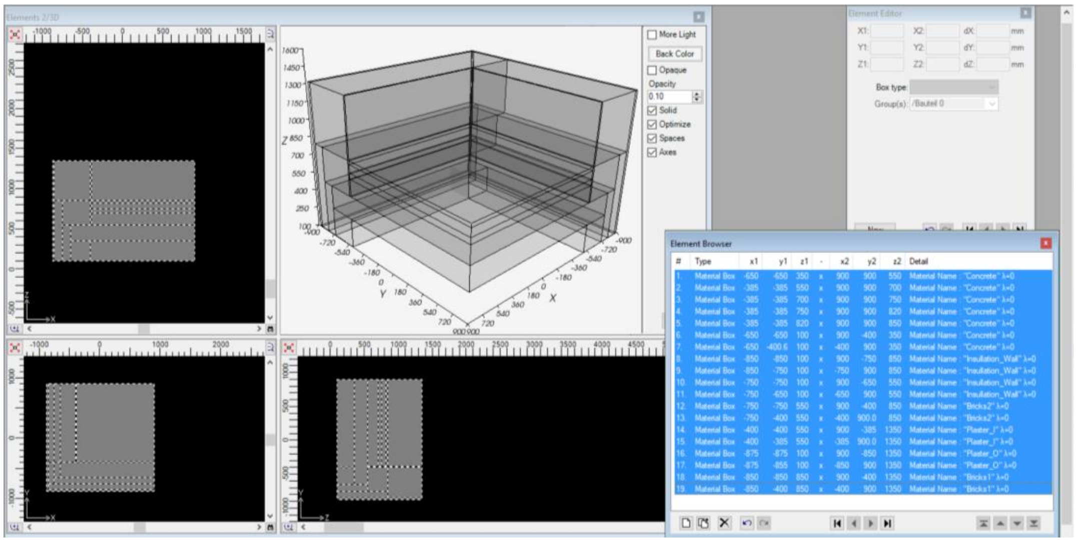


Figure 73: Case study 2, adjusted layer geometry in AnTherm

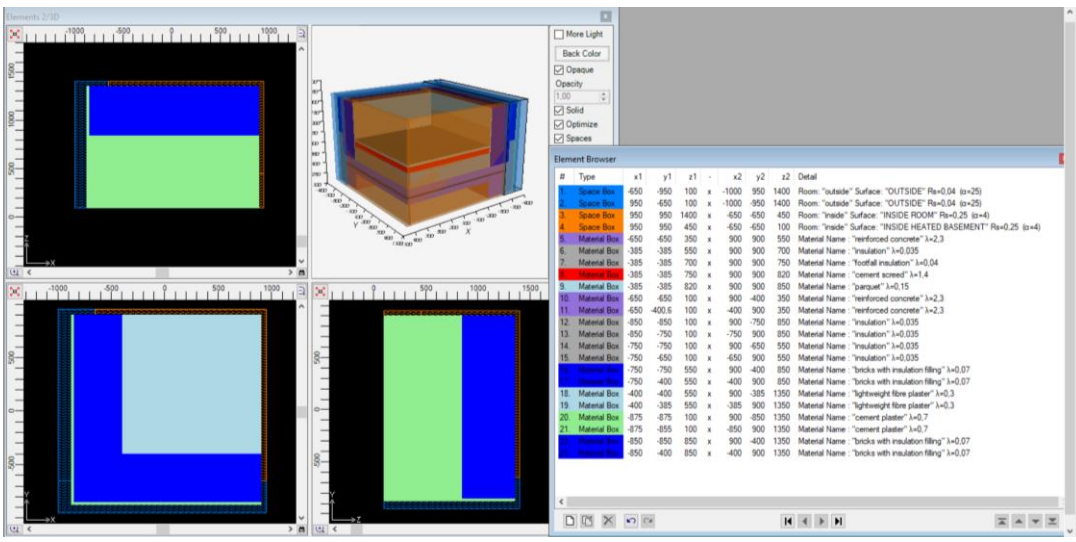


Figure 74: Case study 2, layer properties modifications in AnTherm

Table 7: Case study 2, materials and used heat transfer coefficients

Materials

c	Name	λ [Wm⁻¹K⁻¹]	μ [-]	ρ [kgm⁻³]	c [Jkg⁻¹K⁻¹]
	Cement screed	1,4		1800	1,08
	Footfall insulation	0,04	2	90	1,5
	Gypsum plaster	0,7		1600	1,1
	Insulation	0,035	150	150	
	Lightweight fibre plaster	0,21	15	700	1,24
	Reinforced concrete	2,3		2400	
	Soil	2		2000	1
	Strip parquet flooring	0,15	50	600	2,34
	Bricks with integrated insulation filling	0,07	10	700	

Used heat transfer coefficients

c	Room	Rs(H)	Rs(T)	Description
	Interior	Rs=0,1 m²K/W	Rs=0,25 m²K/W	Heated basement
	Interior	Rs=0,13 m²K/W	Rs=0,25 m²K/W	Heated room
	Exterior	Rs=0,04 m²K/W	Rs=0,04 m²K/W	Outside space

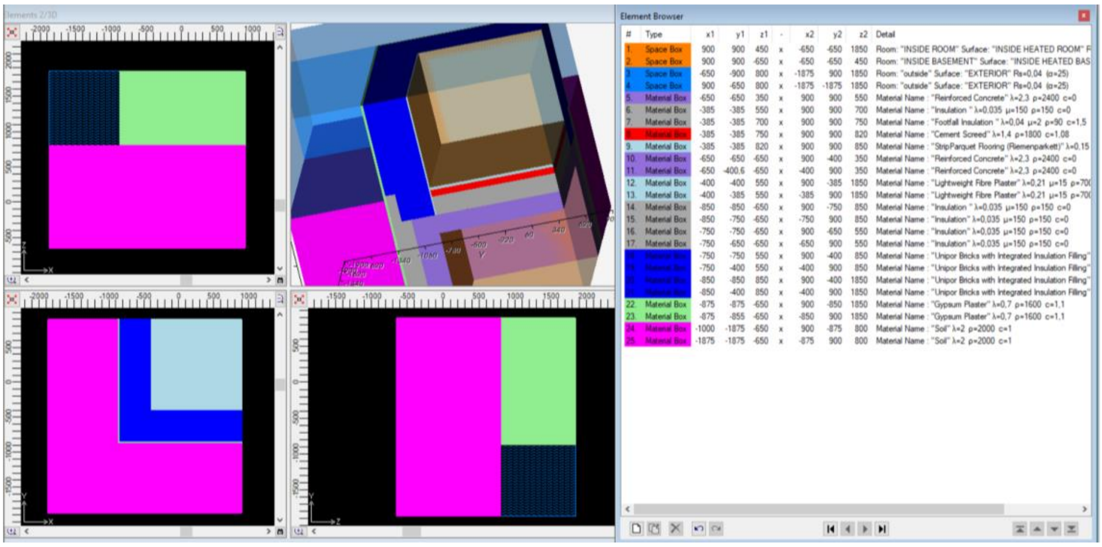


Figure 75: Case study 2, last modifications, addition of materials and space boxes in AnTherm

After adjusting the faulty layers the model's dimensions are slightly modified. The walls are extended so that the 3D model remains symmetrical (Fig. 75). After this the correct materials are assigned to each layer and space boxes for the interior and exterior spaces are added. The thermal simulation results for the second case study correspond almost precisely to the results in UNIPOR's Thermal Bridge Catalogue for Passive Houses (Fig. 76, Table 8 and 9, and Fig. 24, 25).

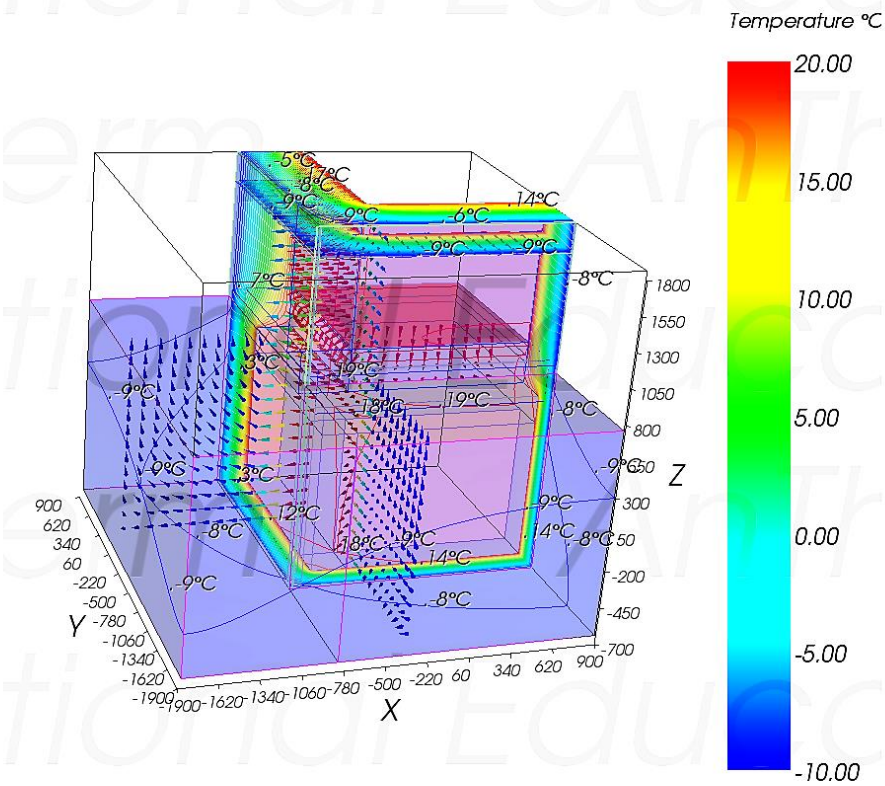


Figure 76: Case study 2, graphical output results, 3D perspective

Table 8: Case study 2, output results for room on ground floor

Room on ground floor above basement		
L^{3D} [WK^{-1}]	**$\theta_{si,\,min}$ [°C]**	**f_{Rsi} [-]**
0,848514	16,90	0,90

Table 9: Case study 2, output results for heated basement

Heated Basement		
L^{3D} [WK^{-1}]	**$\theta_{si,\,min}$ [°C]**	**f_{Rsi} [-]**
1,095881	17,42	0,91

6 DISCUSSION

The developmental part of this thesis shows that it is possible to design in Minecraft and evaluate the building designs with AnTherm. Although the user can choose from various software solutions to act as connecting links and execute the sensible conversions, any conversion and any import or export of data hides potential risks.

The three workflows function smoothly up to the export of the DXF and IFC files. The most challenging step of the process is the import in AnTherm. This is partly because geometric and semantic data had to be transferred and translated between many applications and partly due to the fact that the first release of AnTherm which supports this kind of file import is still under development.

The 3D DXF import into AnTherm works very well with rectangular simple geometries, but other shapes are more error prone and the user has to have experience with the program. It can occur that not all are imported layers correctly, as AnTherm would sometimes merge a few, or drop material names. For instance, if a few elements that have the same shape and size (and not necessarily the same thickness) are stacked upon each other, the program will probably merge them together. Furthermore, when the user models e.g. an L-shape, or similar irregular geometry, it should be modeled only for one face (ground or side) of the object geometry. Otherwise, AnTherm might not recognize the geometry. Complex shapes are more problematic for import into AnTherm, they can slow down the process and often need to be simplified. The “group by color” command option, which opens when importing files into AnTherm, does not work and the process of checking the object geometry and layer names after import is overall slow.

The first and second workflow work very well and the object’s geometry is successfully exported as 3D polylines and imported in AnTherm. Some of the aforementioned issues like missing layer names occur and need to be manually corrected. Therefore, a step of adjusting, fixing and checking the geometry is in any case needed. This process is much faster and more comprehensive in terms of geometry preparation and analysis in the second workflow. Rhino’s inherent functionality combines intelligent surface modeling and parametric modeling. Its powerful geometry diagnostics and the possibility to save DXF files in many DXF versions and edit geometry export schemes increase workflow efficiency and save time.

An interesting issue is the unsuccessful geometry import of the polyface mesh from the alternative second workflow. The following successful import of 3D faces into AnTherm questions the used terminology in AnTherm's instruction sheet (Fig. 19) regarding 3D DXF data import requirements. The instructions state that only closed polylines and polyfaces are supported. As already mentioned, there are three different definitions for mesh geometry in AutoCAD and some depend on the program's release date. When it comes to 3D faces, they cannot be unified in a mesh object in AutoCAD without converting them into joined surfaces and then into a mesh. Overall, the information in the help sheet needs clarification, and the introduction of some examples or tutorials would be useful.

When it comes to the third workflow and the IFC import into AnTherm, the guidelines for the preparation of the IFC files are not very detailed as well. The import of the Minecraft model as a transformed IFC file into AnTherm does not produce a clean geometry that is a suitable basis for further work. The import results in a lot of elements and looks very different from the import in the first or second workflow, even though the source file is the same. The only observable parallel between the third and second workflow is that the IFC file import as well as the 3D DXF file import of the polyface mesh into AnTherm produce hollow elements. This issue was present in the initial tests with IFC files, where only simple IFC building elements are constructed in Revit and imported into AnTherm

AnTherm recognizes both IFC 2x3 and IFC 4.0 file formats, but does not support all of the common commands from the standard for IFC interfaces. The cube geometry in the IFC file is built form a point cloud format (generated from the Minecraft World) and the cubes are either generated as extrusions or composite surfaces (faces). They are then defined as an IfcBuildingElement, which could be an IfcWall. Walls and extrusions, however, are challenging for AnTherm, the best results are produced with a basic one layer wall with a thickness of 200mm.

Nevertheless, the FME translation was successful and the transformed geometry definitions were examined in FME's Inspector and successfully exported. This could mean that either a discrepancy between supported entity definitions is the reason why the imported geometry in AnTherm is not entirely correct or that some definitions are missing and not yet supported in one of the programs.

However, AnTherm is precise as a calculation engine and the results from the thermal simulations are accurate when compared to baseline building construction models.

The AnTherm software team is currently working introducing more support for the IFC file format and expanding AnTherms functionality. Thanks to AnTherm's development department, some of the import issues that have occurred in this study are now fixed, for example the import of simple roof geometries and some material names. The development team behind Safe Software's FME is currently broadening their transformer gallery and their support for IFC files as well.

Considering the aforementioned conditions, a result that is described by a successful import in AnTherm with mostly correct geometry, layers, scale and grouping, from either of the discussed formats is deemed positive. All of these criteria are fulfilled in the first study case, but the results in the second study case can actually be compared to the results of the used baseline model (Fig. 77).

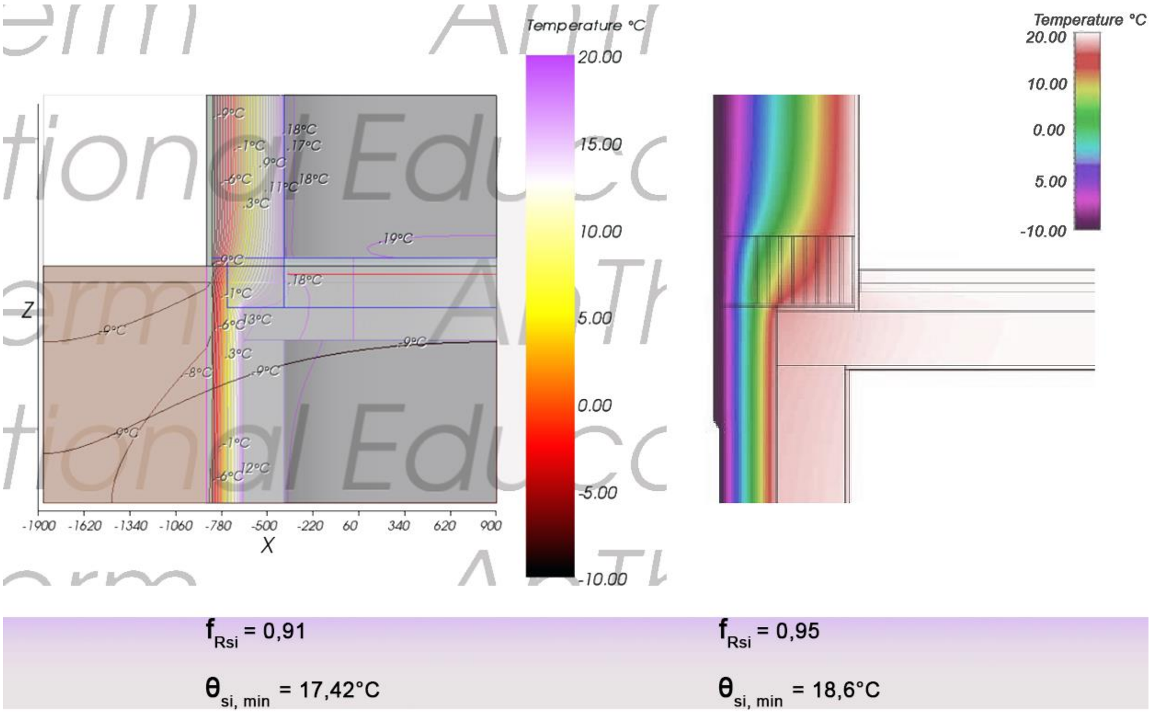


Figure 77: A comparison between the thermal simulation output of the second study case (left) and the results of the baseline model (right) from UNIPOR's Thermal Bridge Catalogue (UNIPOR 2017)

The results of this work represent a conceptual study based on theoretical background and experimental trials with Minecraft and AnTherm, and many other applications acting as middleware. According to the results, it is possible to integrate the software, to connect Minecraft to a building physics simulation engine, such as AnTherm. The challenging aspects could be the adaptation to either a BIM (IFC) translation path or a combined geometrical and material translation path. The translation and automatic recognition of material definitions is one of the most important issues that need to be investigated further. However, with the steady development of the functionalities of AnTherm's latest release and the deepening connection between the gaming world and building information modeling, the realization of such a concept would be not only feasible, but also logical.

7 CONCLUSION AND RECOMMENDATIONS

The objective of this work was to first identify potential technologies for an improved knowledge transfer in the AEC domain and then specifically examine potential data interchange between two software environments, namely the gaming engine Minecraft and the numeric thermal bridge simulation tool AnThern. Data interoperability is a crucial requirement for a (close to) seamless building information modeling approach, and thus it seemed to be worth of examination if and how these two environments could be used to facilitate thermal bridge assessment.

Regarding the first part of this thesis it can be said that many technology advances have been made in recent years that sooner or later will also get relevant for the building domain. However, further developments for most of the presented technology are required to enable these technologies to be used for the broad market in the AEC domain.

Regarding the developmental part it can be said that based on the experiences in this work, a principle coupling of the two tools is possible. The workflow to design a construction detail in Minecraft and then assess its thermal performance in AnTherm seems to be a viable way. However, it has to be said that the concept “Minecraft and AnTherm” can be used simultaneously in a back and forth design-and-evaluate process is currently not a very user-friendly one. The data transfer process is slow, it requires the implementation of different tools, and the data conversion or transformation can be considered error prone.

To summarize, the utilization of Rhino3D and Safe Software’s FME certainly provide the best options as intermediate tools between Minecraft and AnTherm. Moreover, FME is currently expanding the scope of their IFC support.

The transformation process that was chosen for the translation with FME (for the third workflow) is capable of working fast only with small Minecraft worlds, whose point clouds contain a few hundred to a few thousand points. If a bigger Minecraft world that has hundreds of thousands or millions of points is considered for export, a different approach would be more suitable. For instance, it is possible to generate rasters from point clouds and with the help of this basis - create polygons. Afterwards this geometry can be extruded, defined as an “IfcBuildingElement” and saved as an IFC file. Alternatively, there are other possibilities for generating and defining the geometry, which could make use of AnTherm's DXF file import functionality.

Future research should address the improvement of the data transfer process. For instance, a clear data transformation scheme could be generated that helps to avoid the current bottlenecks, such as the random dropping of a layer name, and bigger issues, such as inaccurate geometry representation. Minecraft's creator, Markus Persson, has an unconventional approach to such problems, summarized in the phrase "hellre än bra" - translated from Swedish it means someone who prefers spontaneity over perfection. Persson documented Minecraft's development openly and in continuous dialogue with players. (Goldberg 2015)

Future development should focus on programming a new GUI that connects Minecraft with the building performance assessment engine, or a new modification to Minecraft's game, that allows the integration of a building physics plugin.

Another future research and development effort could focus on the generation of an improved GUI that enables the connection of Minecraft to building performance assessment engines, or a modification in the Minecraft kernel that allows the integration of a building physics plugins. Another possibility could be to outsource a functionality in the new application. A software developer could create an application programming interface (API) for the online multiplayer game to connect to online assessment services, thus outsourcing a requirement of the design application for building physics assessment.

An ideal solution would be, however, the creation of a new software that integrates a building physics simulation engine into Minecraft's creative gaming world, so that the calculation engine could be called from within the game itself. Such a built-in functionality would preserve Minecraft's immersive, intuitive environment full of uninhibited creative potential. AnTherm, on the other hand, is one of the best numeric thermal simulation engines for steady state and transient building simulation, but has a very rigid GUI and is not suitable for novice users. If the user has previously worked with other software tools that use different coordinate systems and have a different viewport layout, the transition would take some time. Moreover, it is not easy to find information about AnTherm online or on a mobile device, which is crucial for today's young generation. The children of today are digitally literate even before entering school and students research and study mostly on mobile devices, which are slowly changing the way public media works. Furthermore, according to psychological research, people have an instinctual tendency to overweight easily available and easily accessible products. This tendency is called availability misweighing tendency.

Through the immersive visuals of latest holographic technology the user would experience the design and learning process, and express their design intent in a new way. The user would be prompted to use more than one sense simultaneously and thus facilitate long term memory. Mapping the graphical output directly on the 3D holographic object in MR after the calculation has finished would provide the opportunity for fast visual feedback and collective discussions.

For further research and development, the possibility to scale any selected individual block, or group of blocks, to any desired size would be crucial, because of the many different layer thicknesses used in building detail components. Aiding the design process with a void detection command could be beneficial as well.

The selection or grouping of blocks in a certain fashion is very important. An intuitive gesture for all these actions could be easily found, for implementation e.g. with HoloLens. Thus, designing with hands and voice command in a multiplayer mode, building holographic designs and discussing them openly with colleagues in real-time, while the assessment engine is continuously mapping the visual thermal evaluation results onto the 3D holographic object could become a real learning and creative experience.

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10 APPENDIX

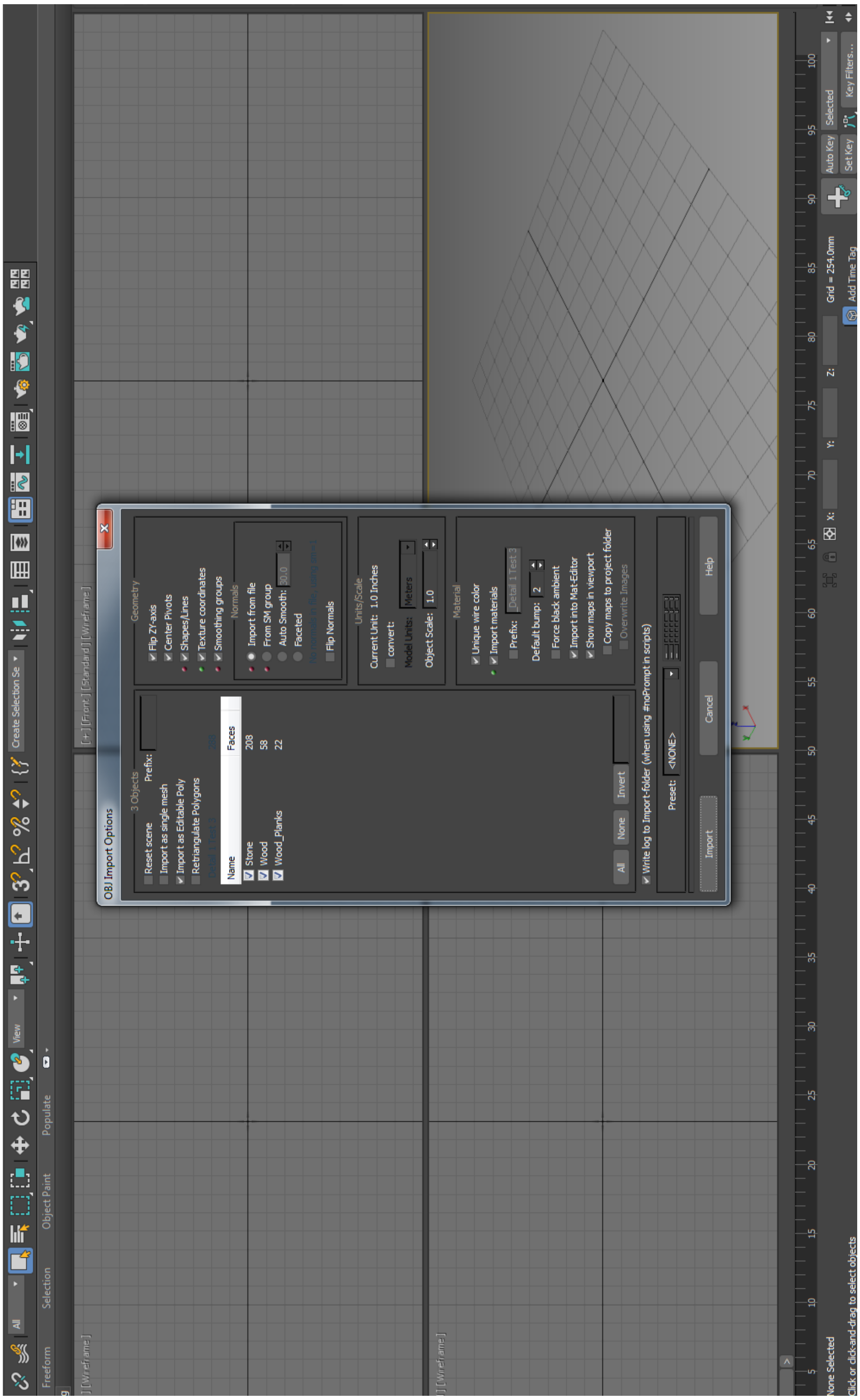

Figure 35: Workflow 1: Importing the first study case OBJ file into 3ds Max, settings dialog

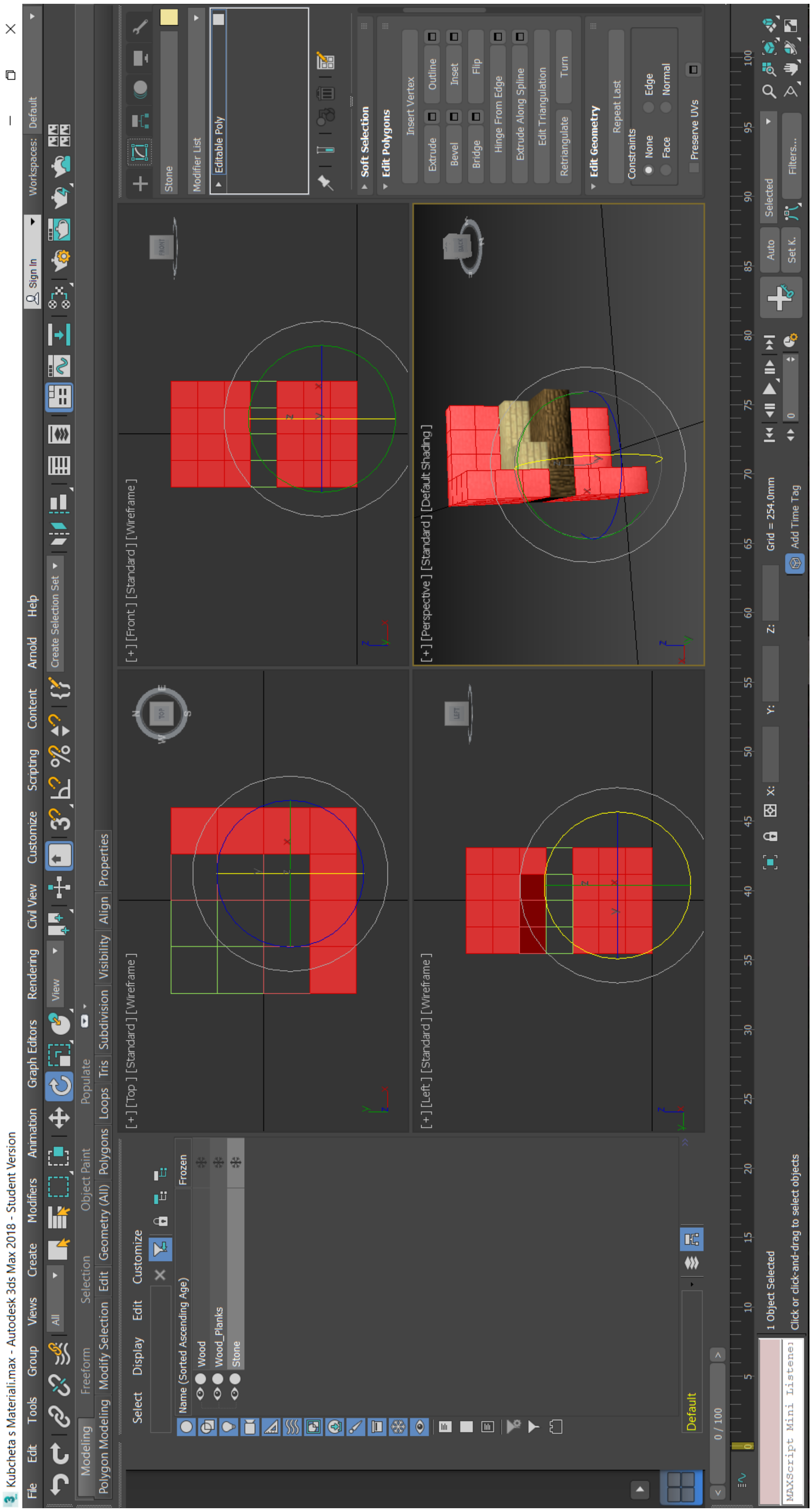

Figure 36: Workflow 1: The first study case OBJ file in 3ds Max, “stone wall” editable poly is selected

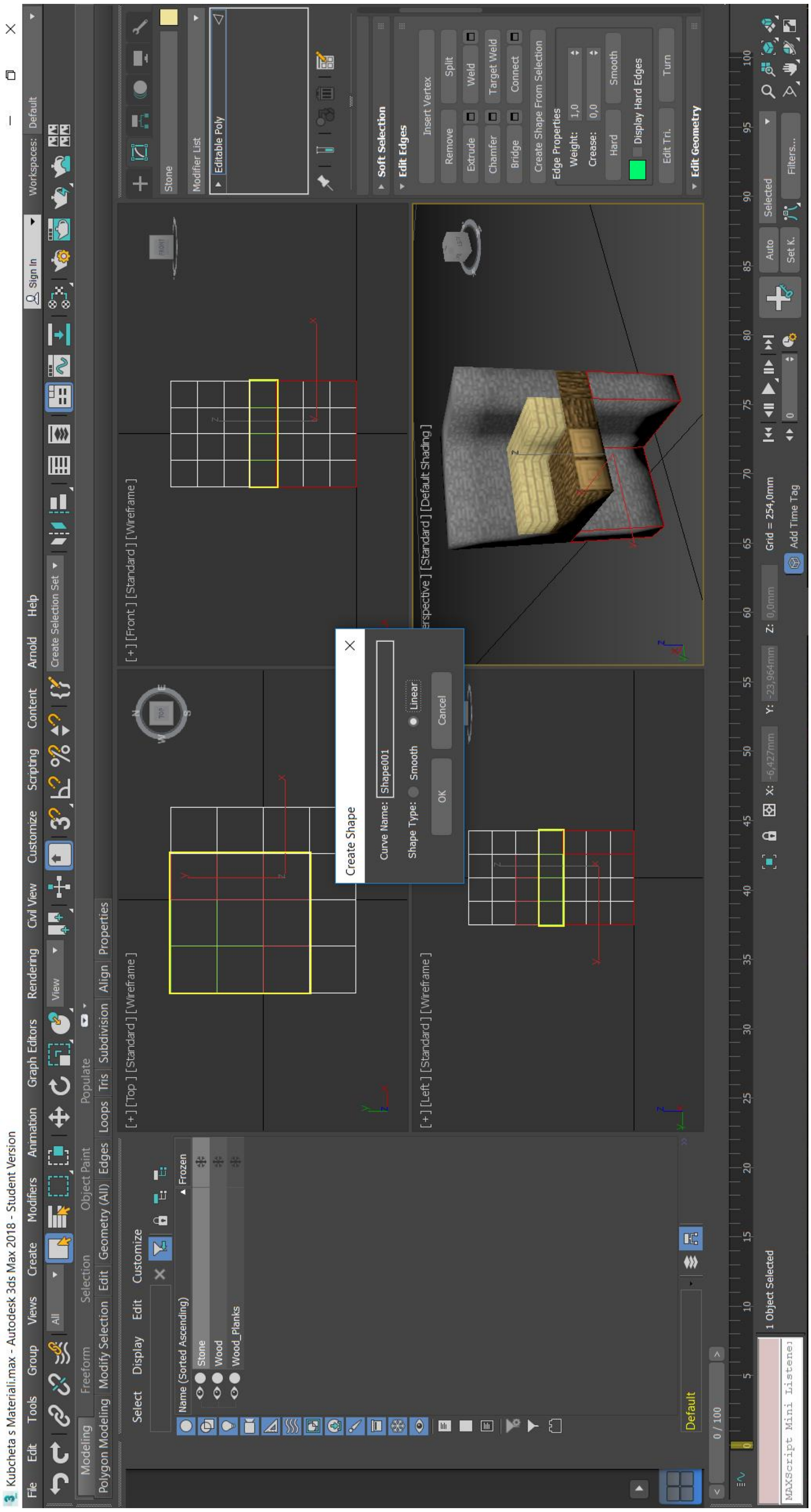

Figure 37: Workflow 1: Creating linear shapes (extracting polylines) from element edges of the first study case in 3ds Max

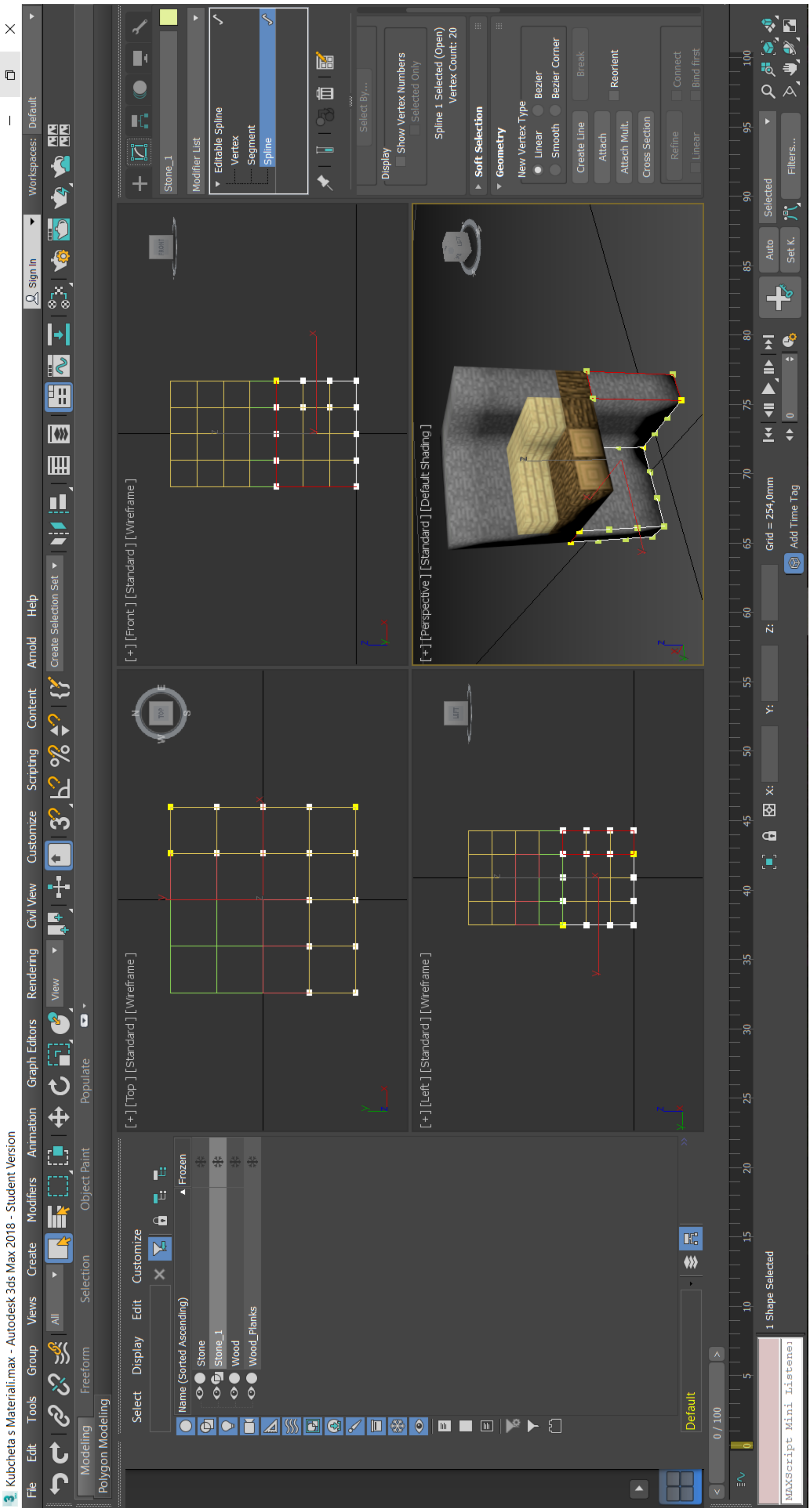

Figure 38: Workflow 1: Adjusting the created polyline in 3ds Max for the first study case

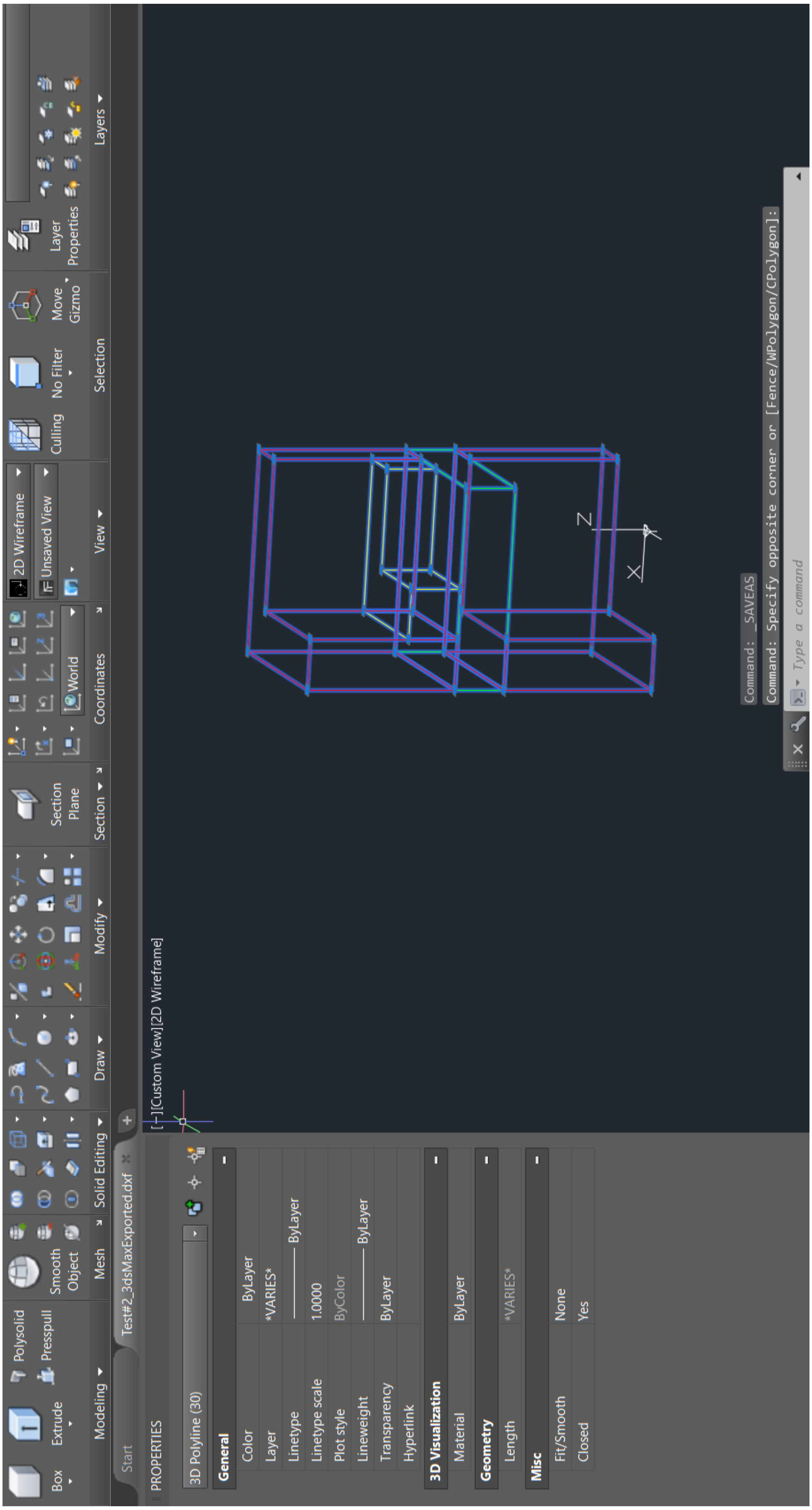

Figure 39: Workflow 1: The extracted polylines for the first study case imported in AutoCAD

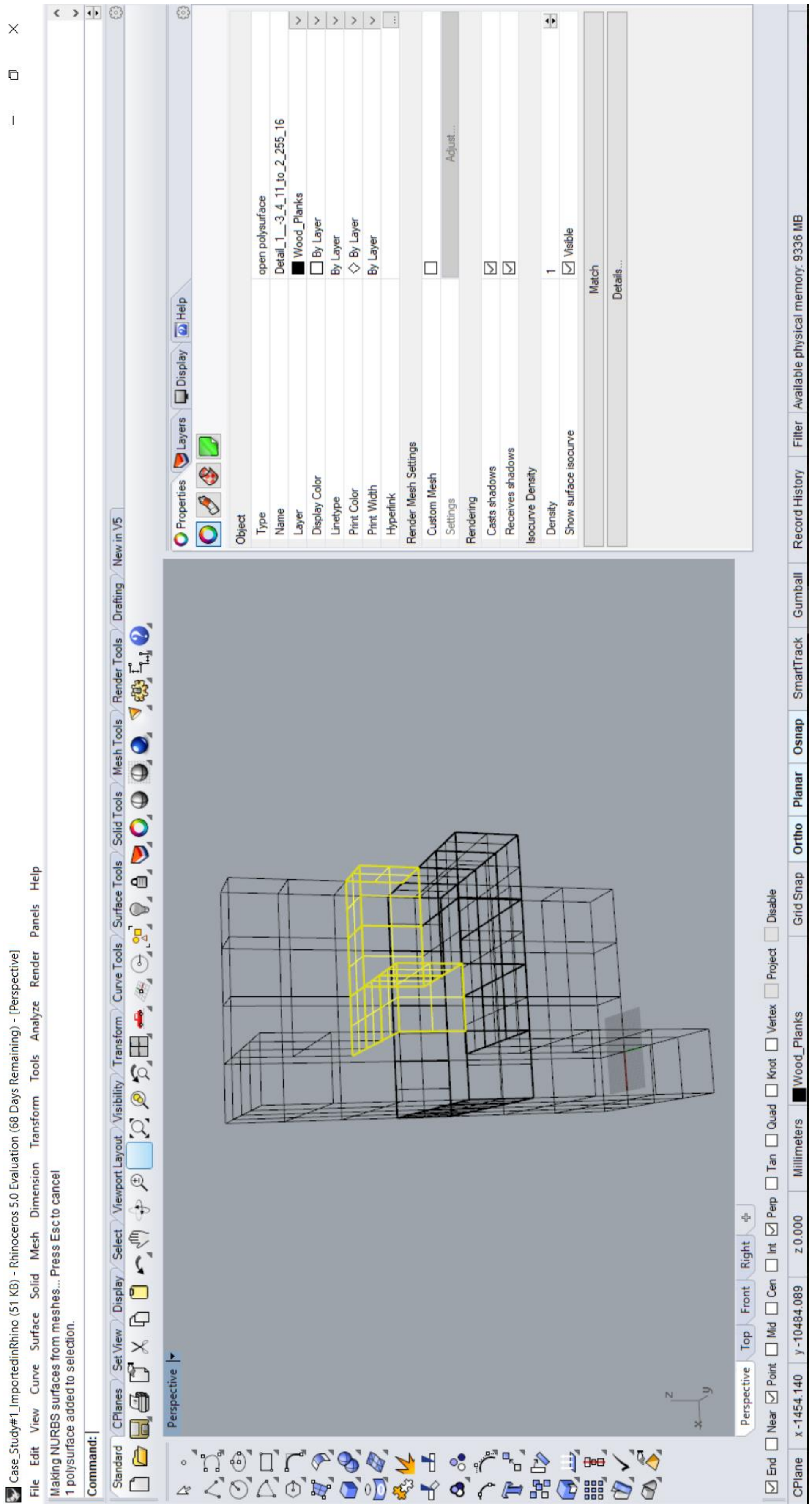

Figure 41: Workflow 2: The first study case in Rhino, MeshtoNURBS, polysurfaces

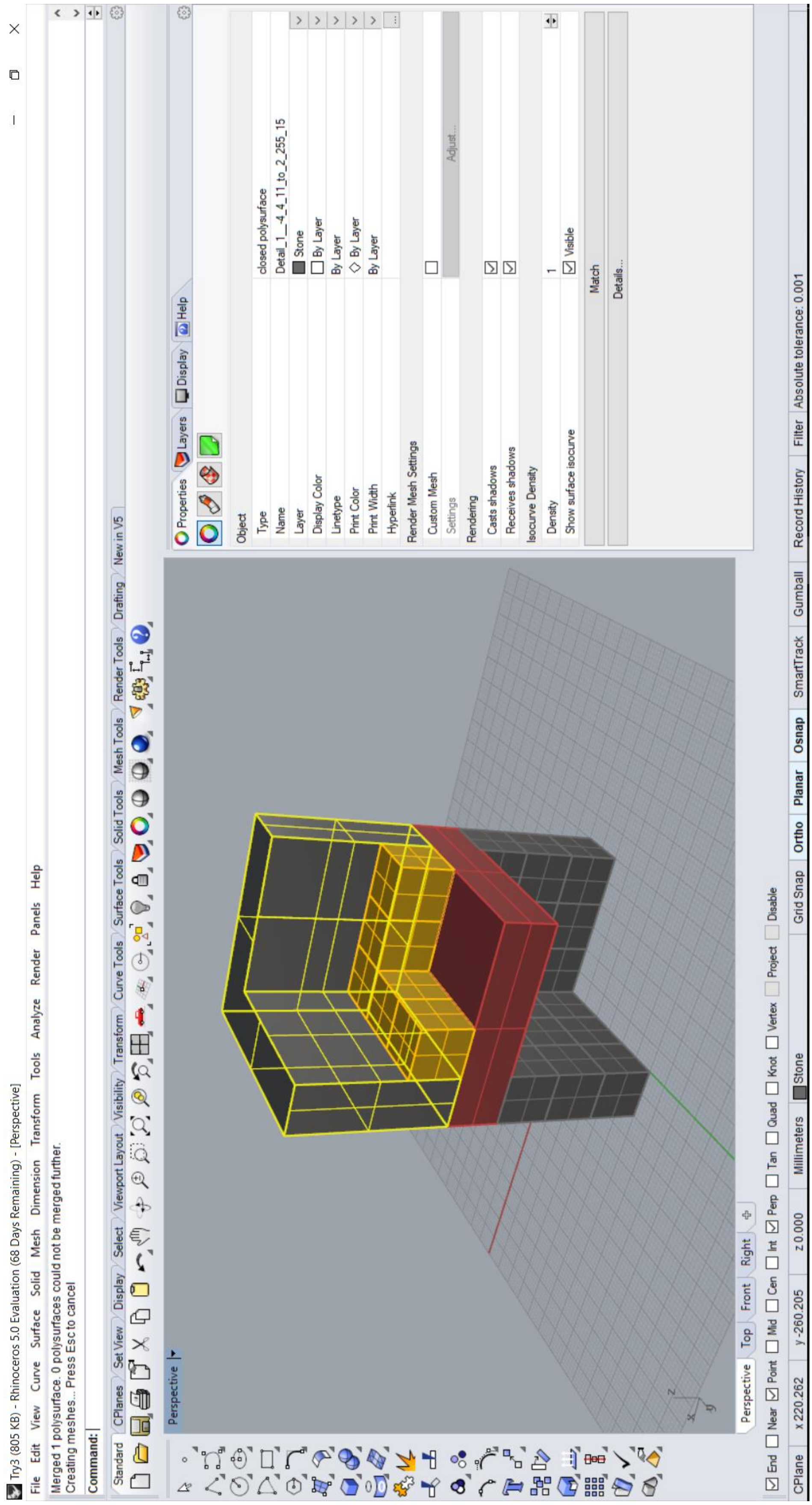

Figure 42: Workflow 2: Merging all faces for each polysurface of the first study case in Rhino and creating open polygon meshes for DXF export as polyface geometry

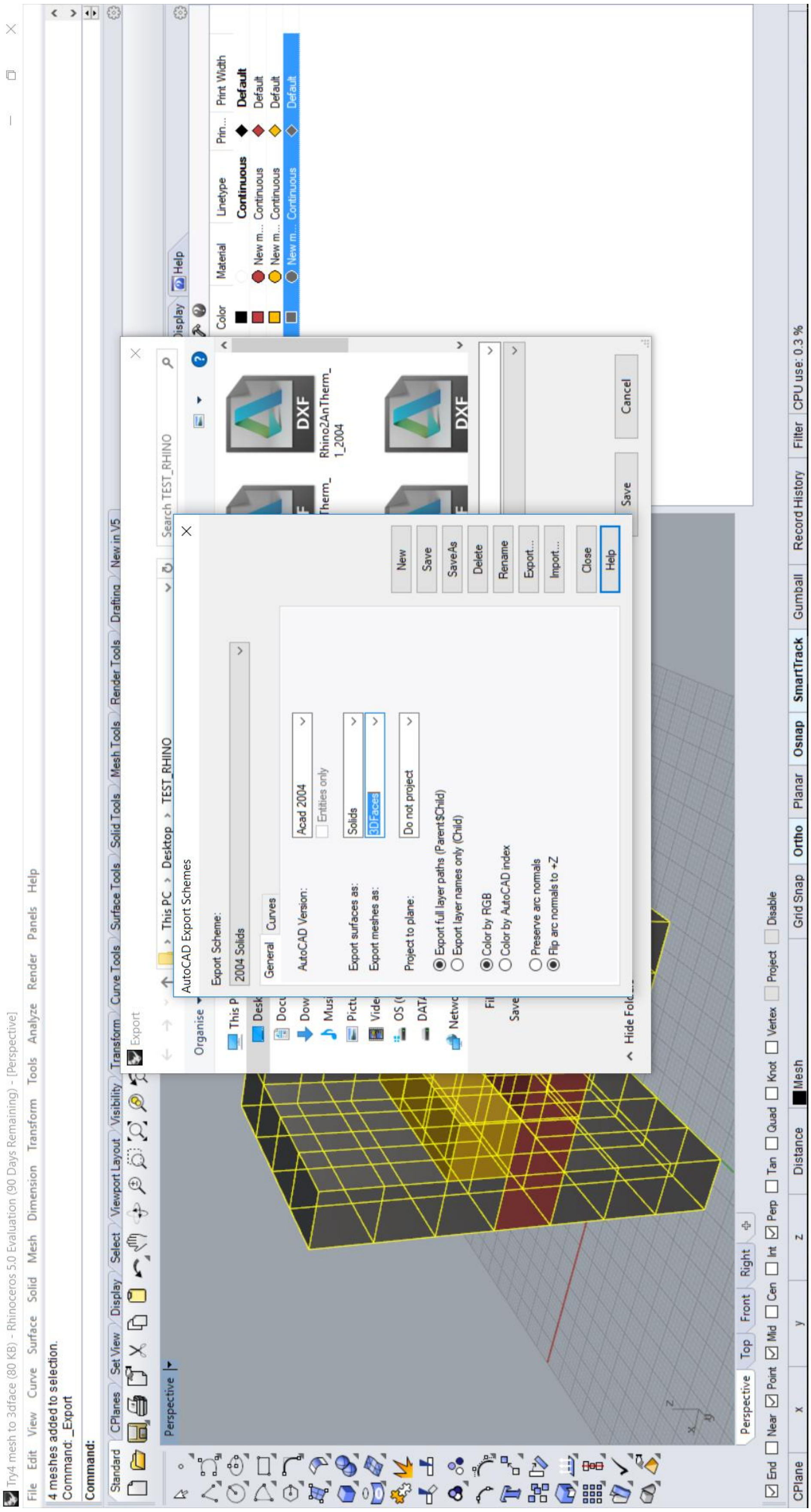

Figure 43: Workflow 2: Exporting the first study case in Rhino; it is possible to export surface or mesh geometry as mesh or 3D face geometry

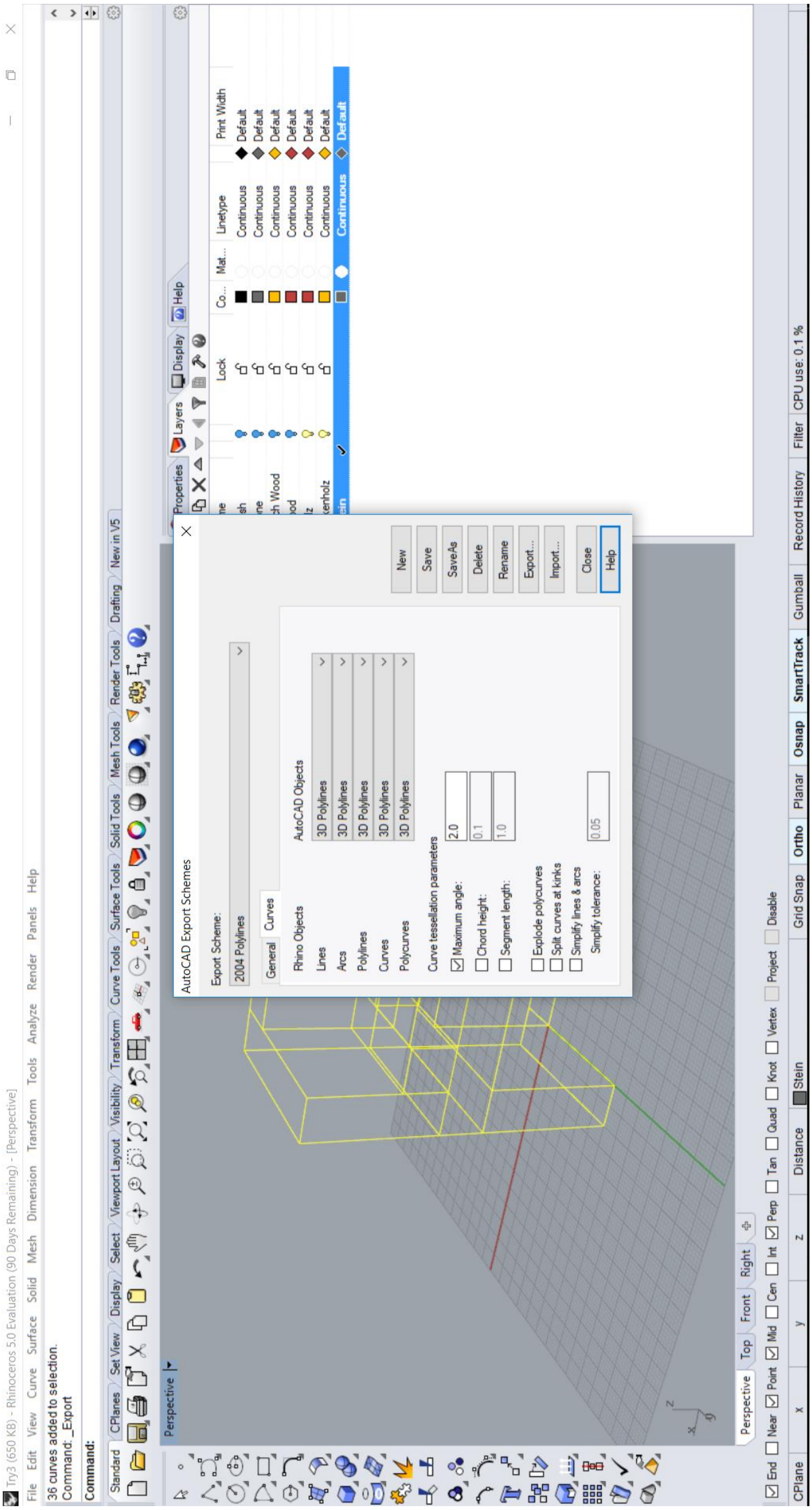

Figure 45: Workflow 2: The first study case in Rhino, extracting polylines from polysurfaces and exporting selected as 3D polylines

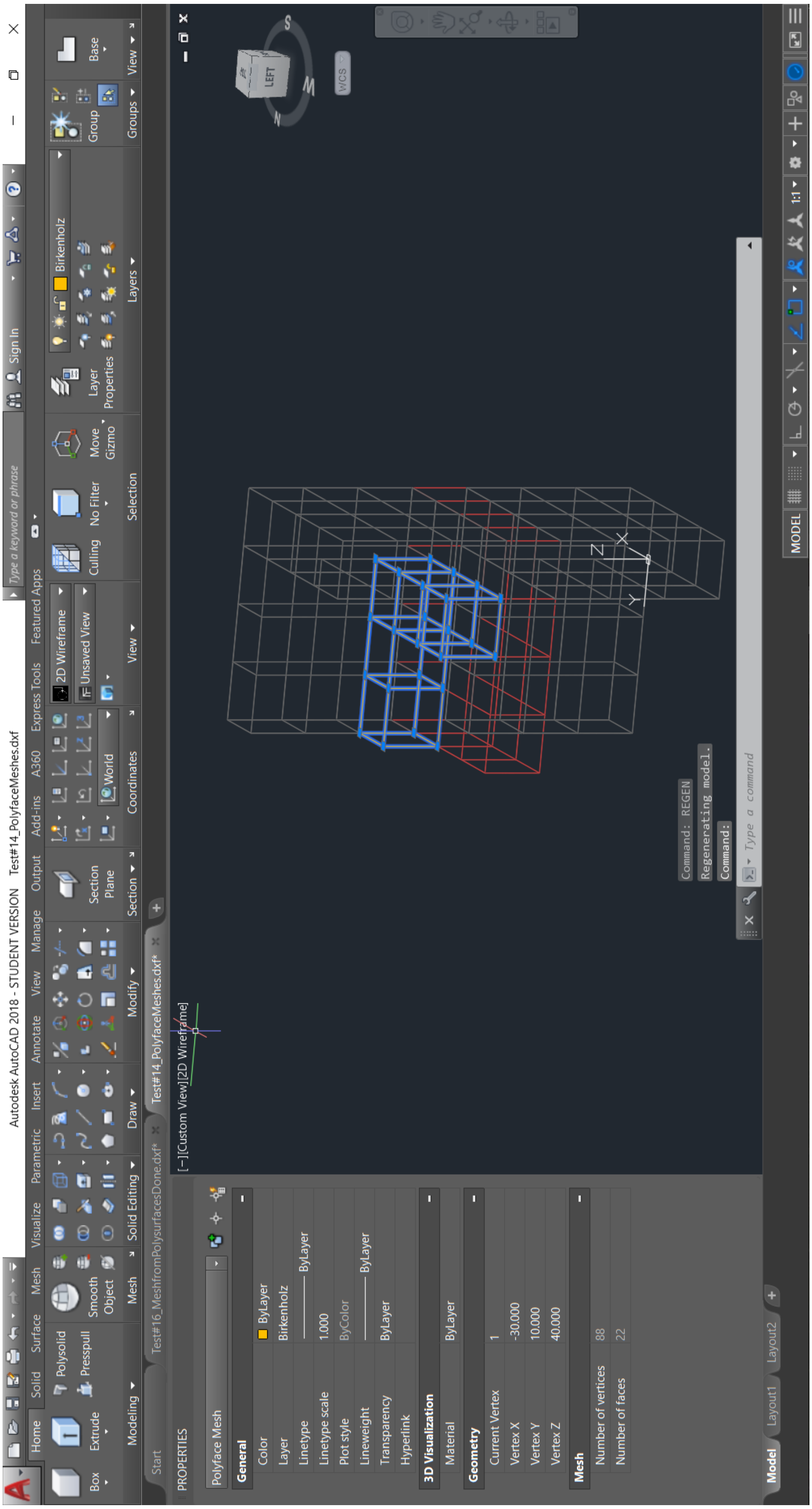

Figure 46: Workflow 2: The polyface mesh geometry of the first study case separated by material and imported in AutoCAD

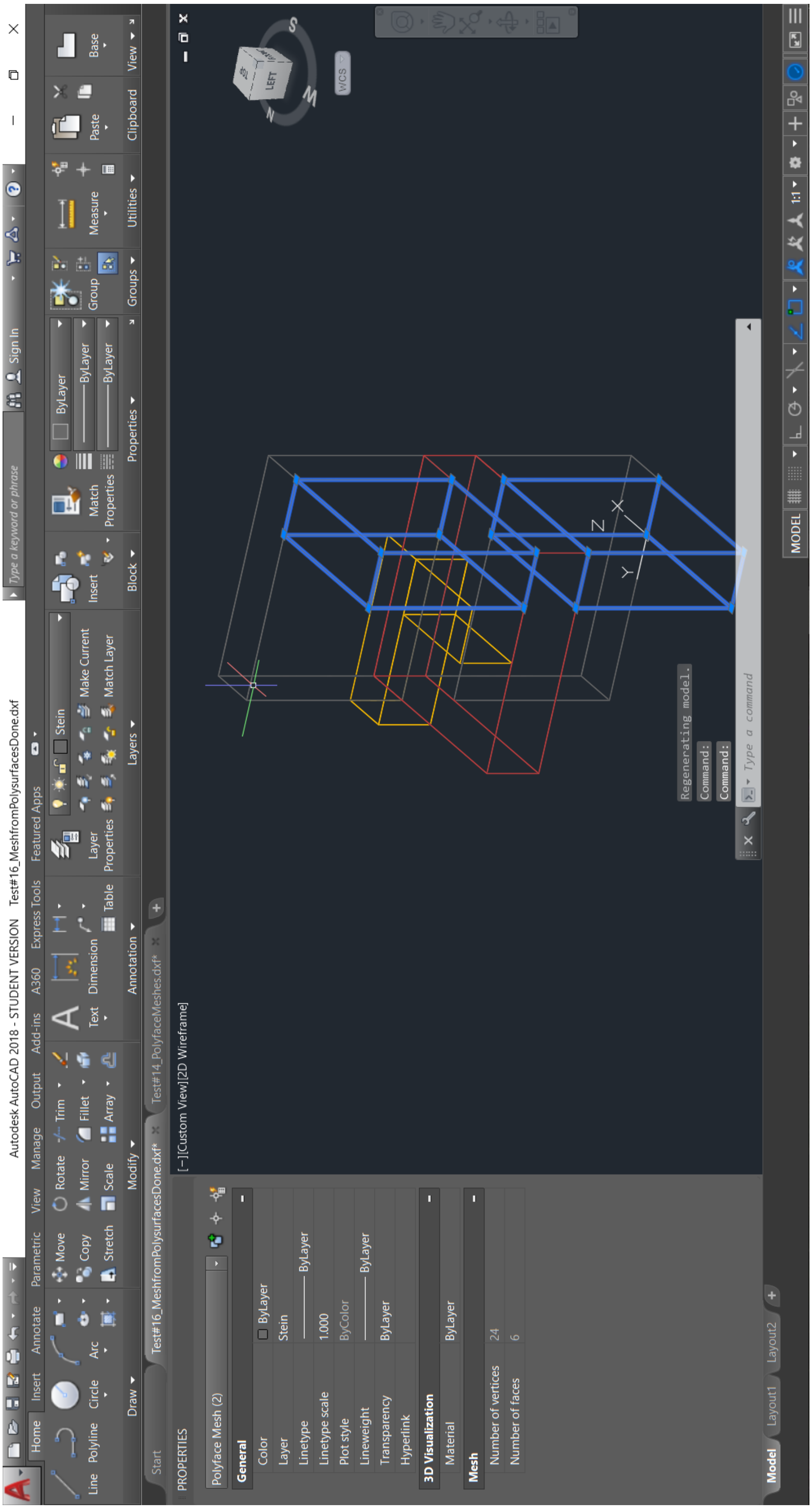

Figure 47: Workflow 2: The reduced polygonal mesh geometry of the first study case separated by material and imported in AutoCAD

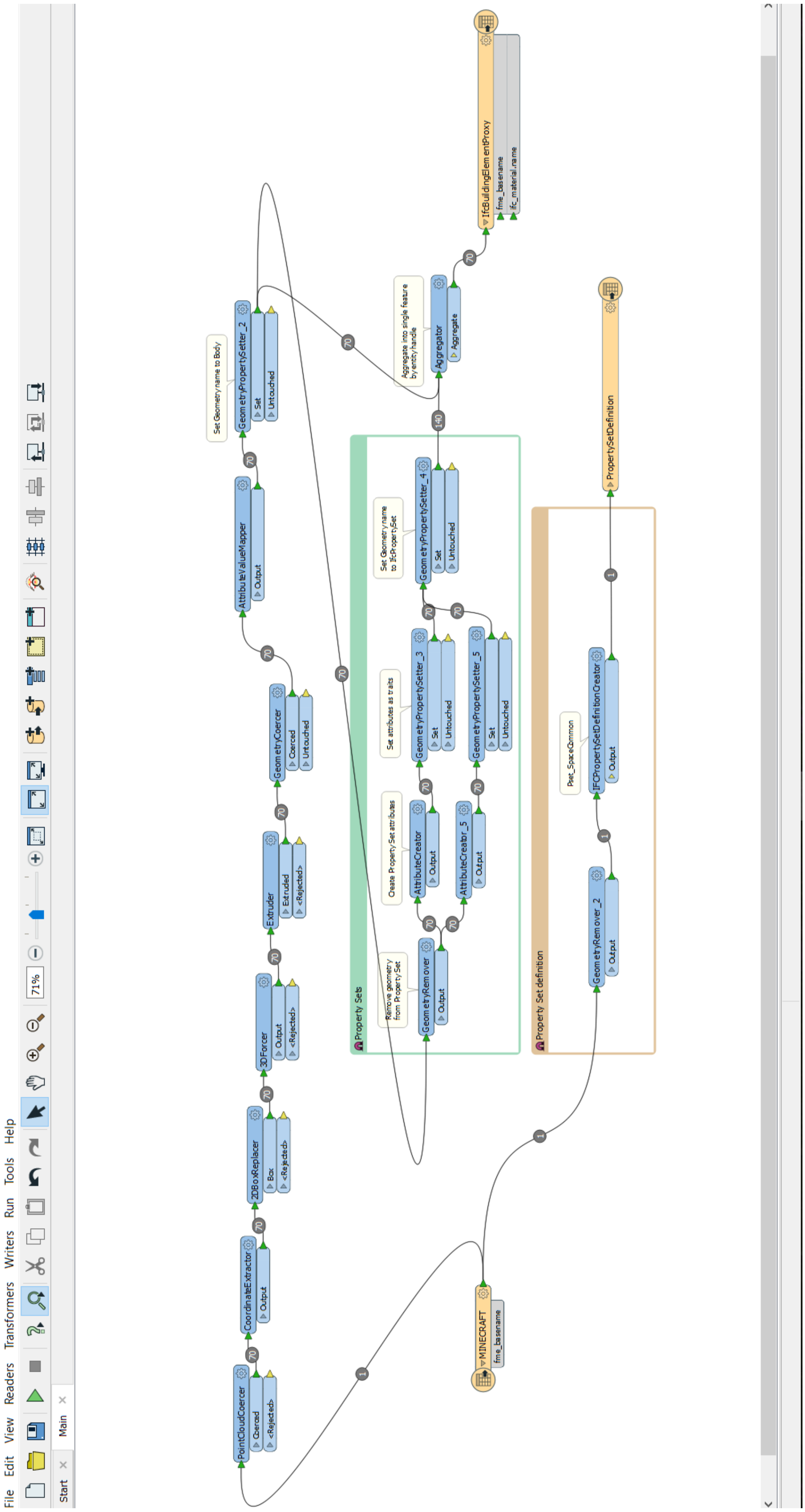

Figure 49: Workflow 3: The first study case in FME's Workbench view

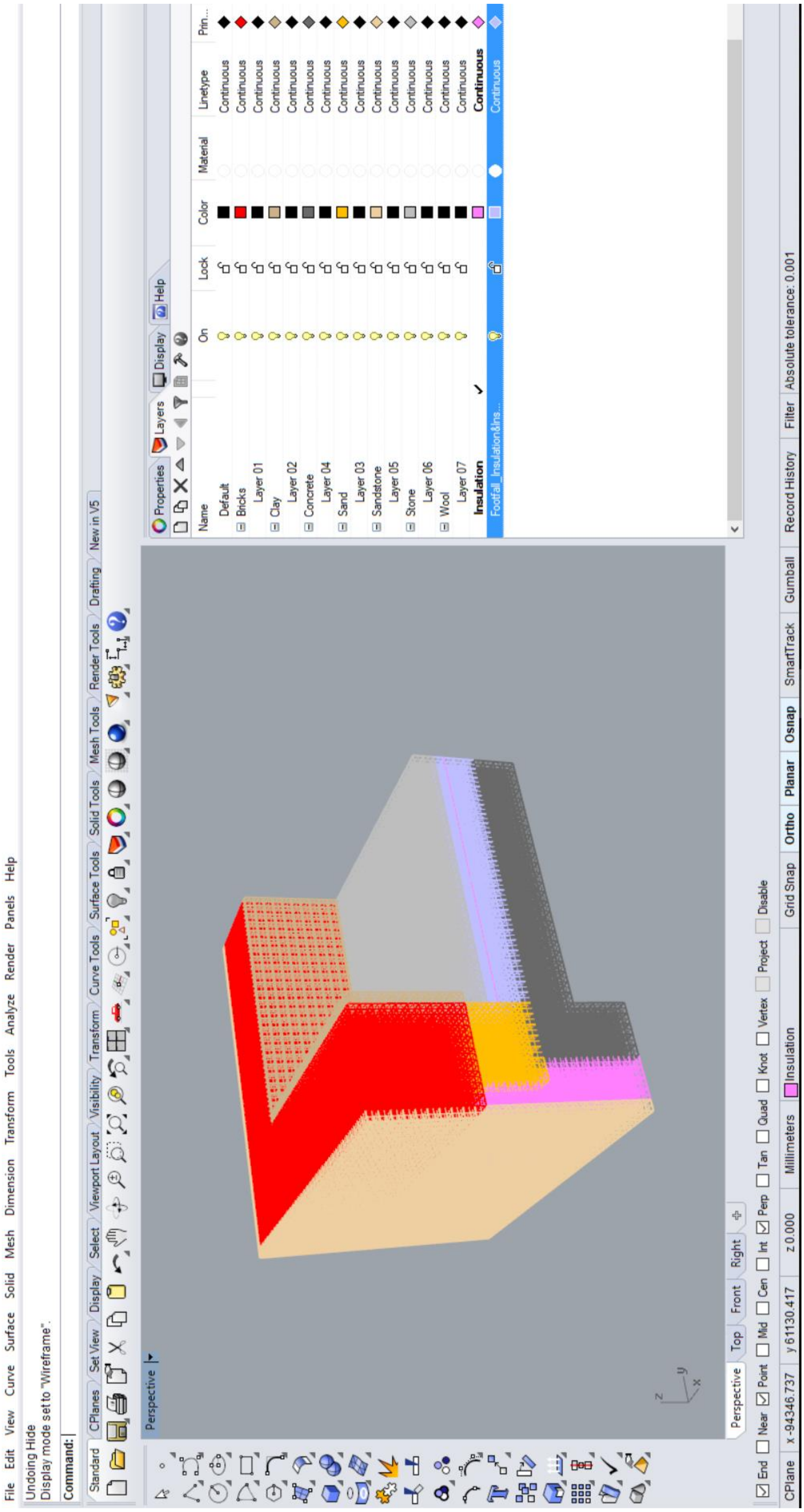

Figure 52: Workflow 2: The second study case imported in Rhino as a mesh geometry

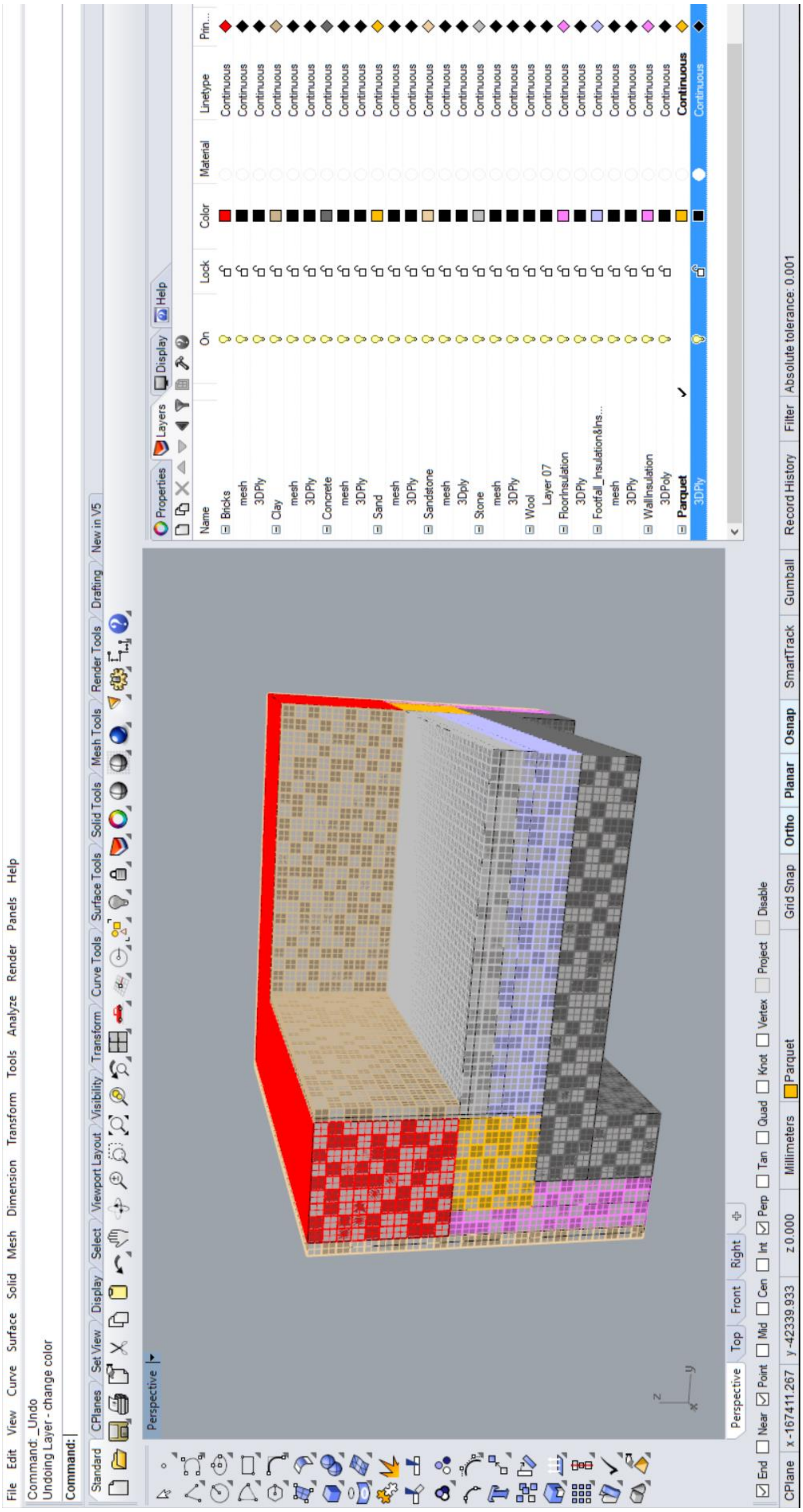

Figure 53: Workflow 2: MeshtoNURBS command, adjusting the layer order of the second study case and extracting polylines

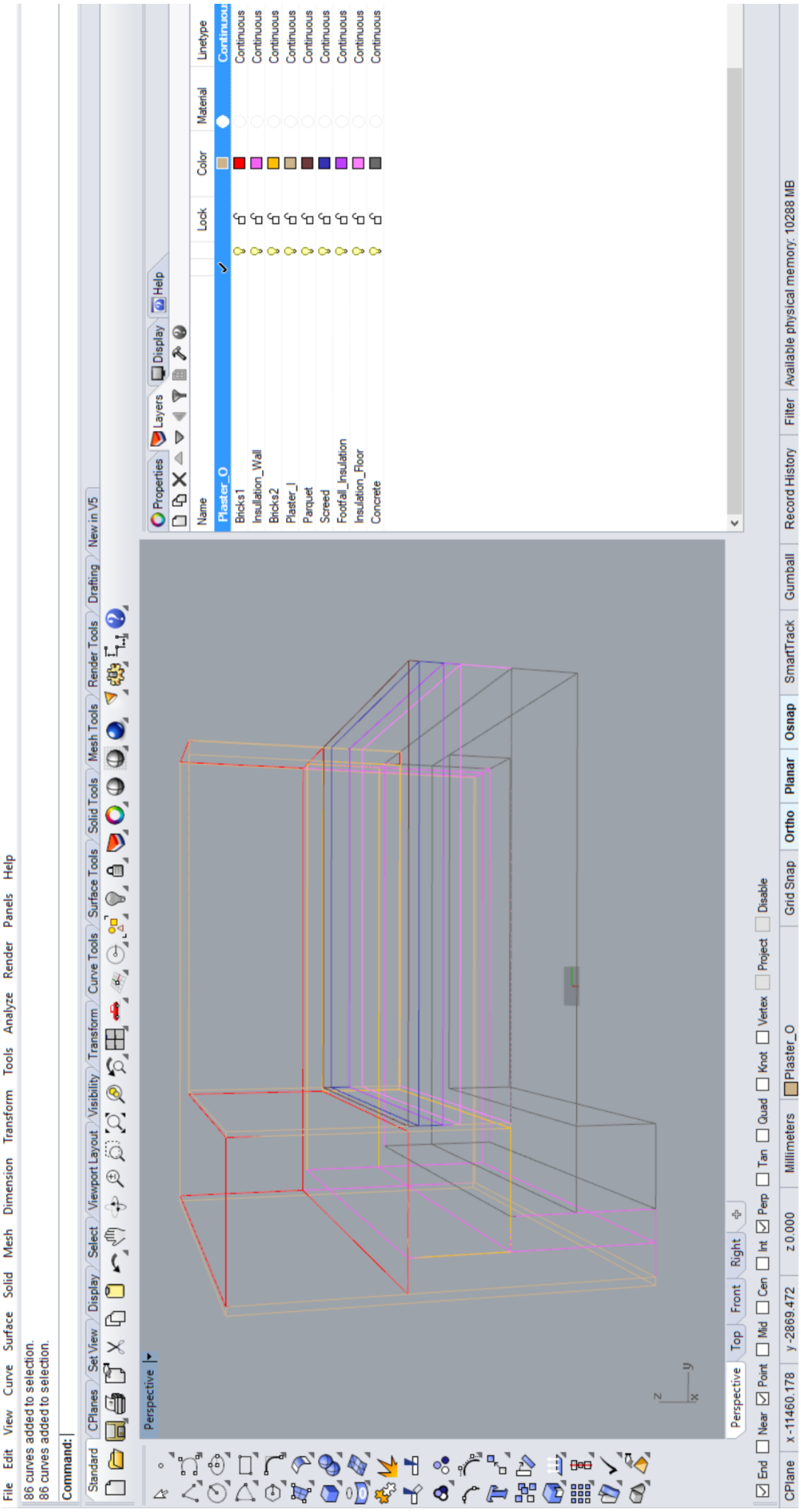

Figure 54: Workflow 2: The polylines of the second study case ordered by layer

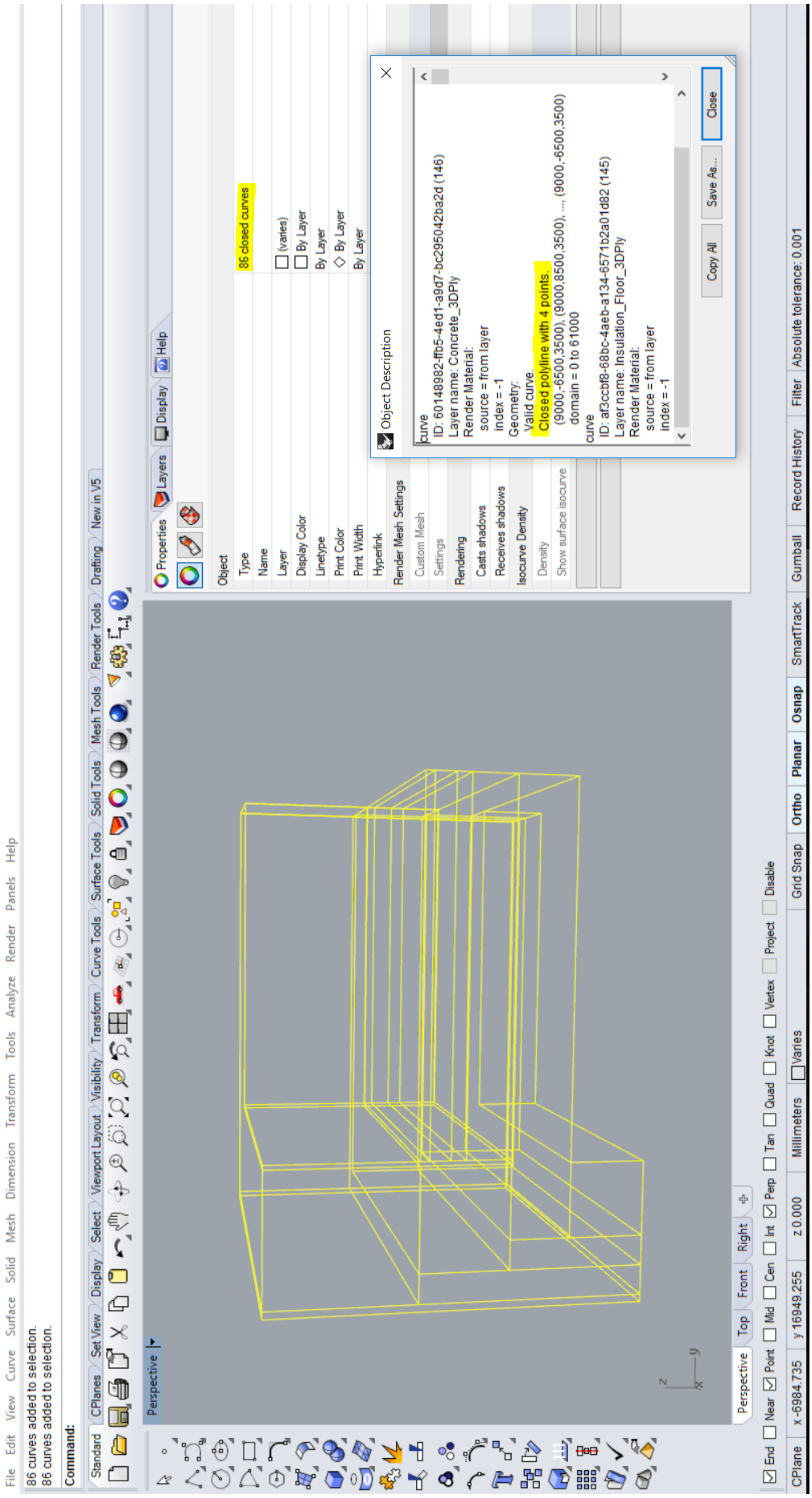

Figure 56: Workflow 2: Checking the polylines' properties of the second study case

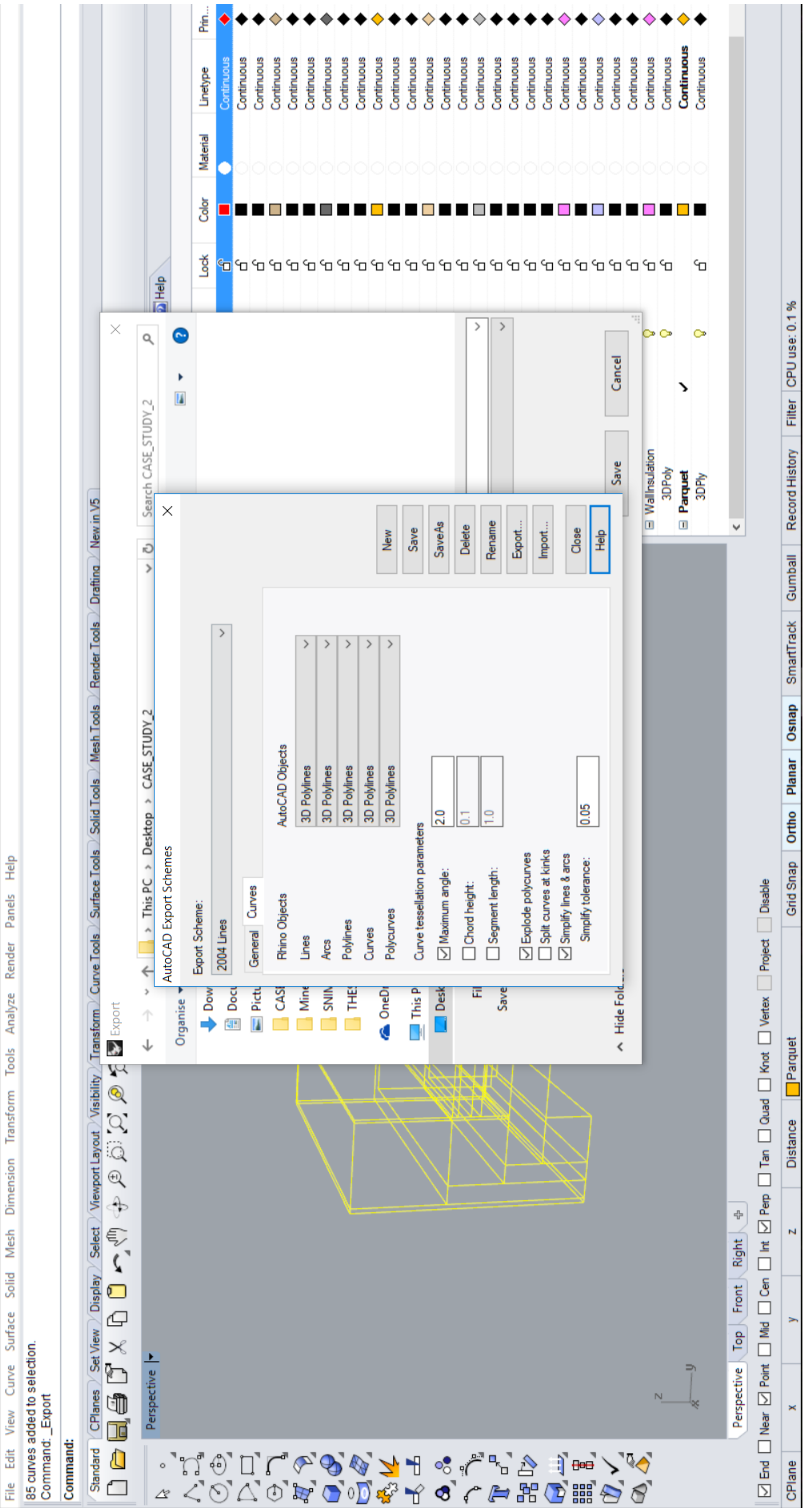

Figure 57: Workflow 2: Exporting the second study case to the DXF file format, settings

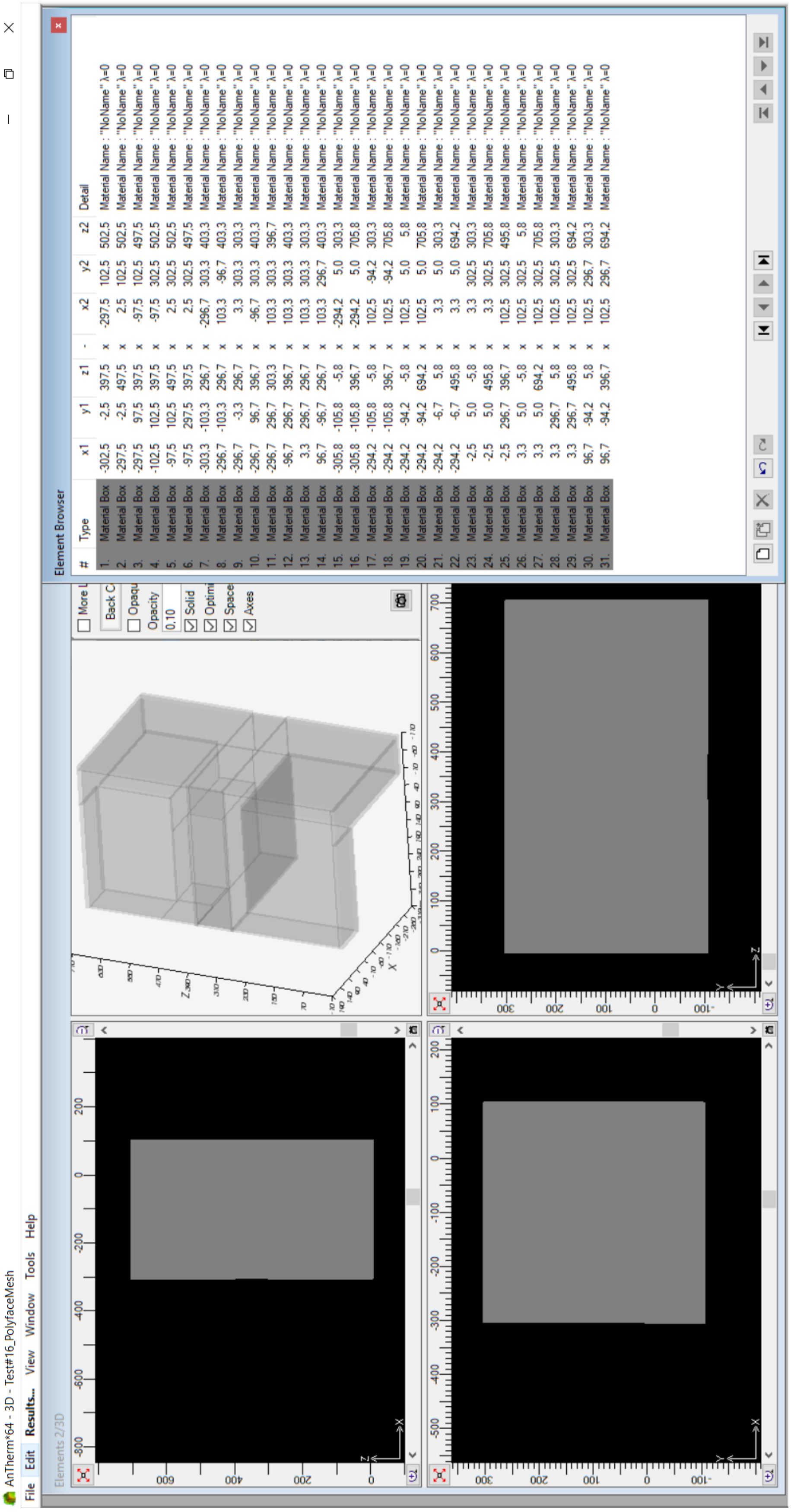

Figure 58: Case study 1, the DXF file with the polyface mesh geometry from the second workflow imported in AnTherm

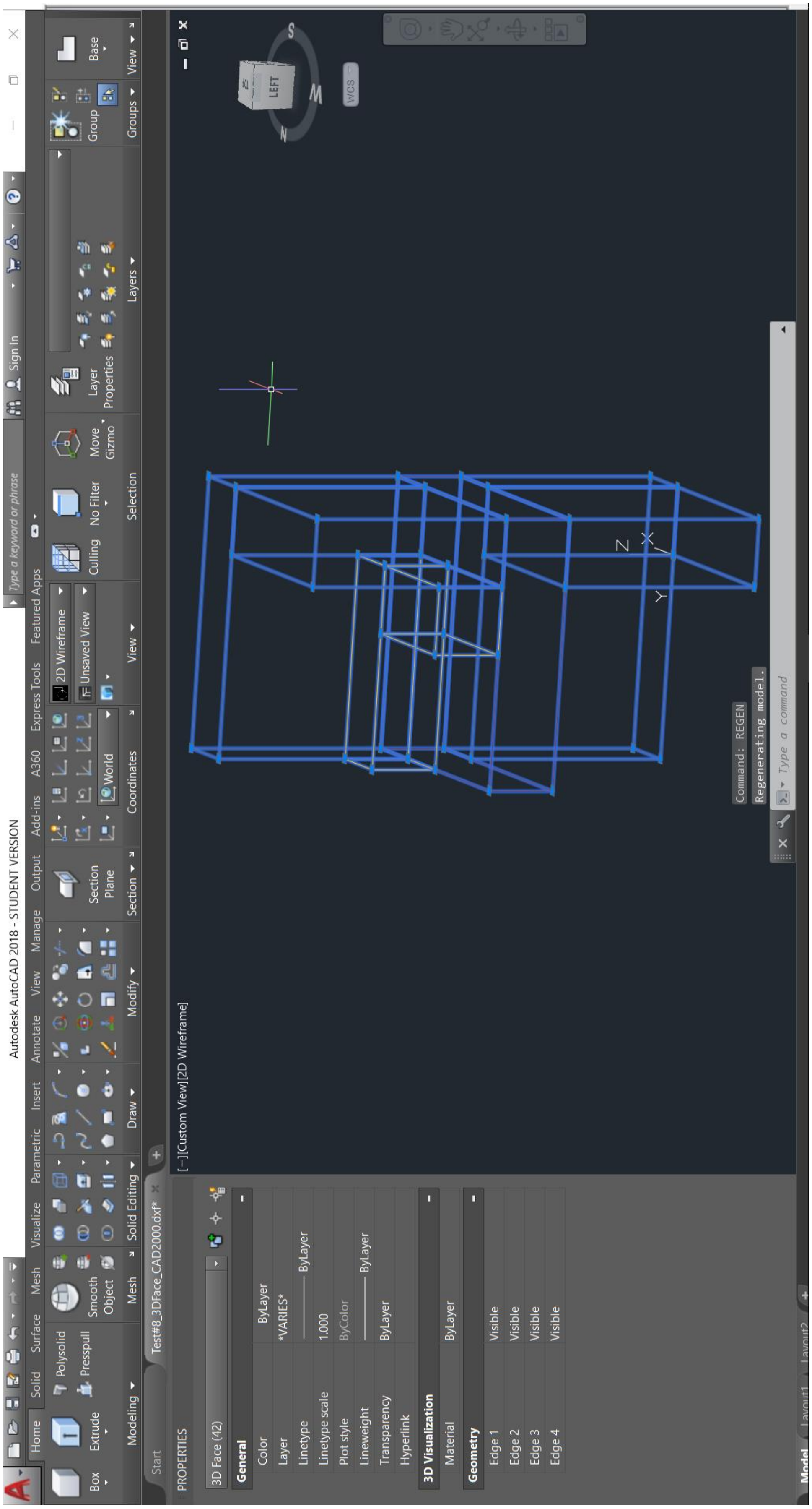

Figure 59: Case study 1, geometry exported as 3D faces from Rhino, imported in AutoCAD

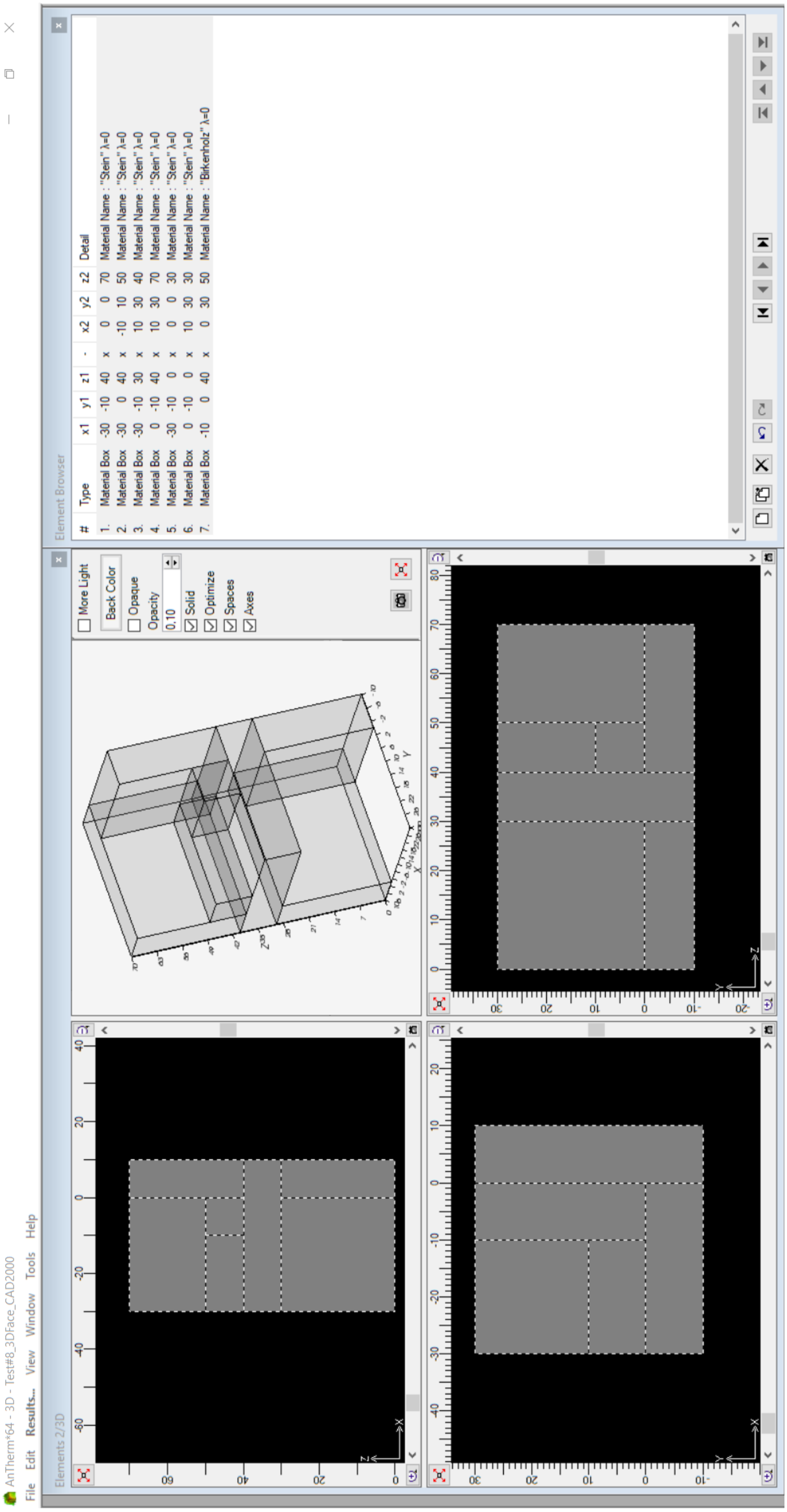

Figure 60: Case study 1, the DXF model composed of 3D faces imported in AnTherm

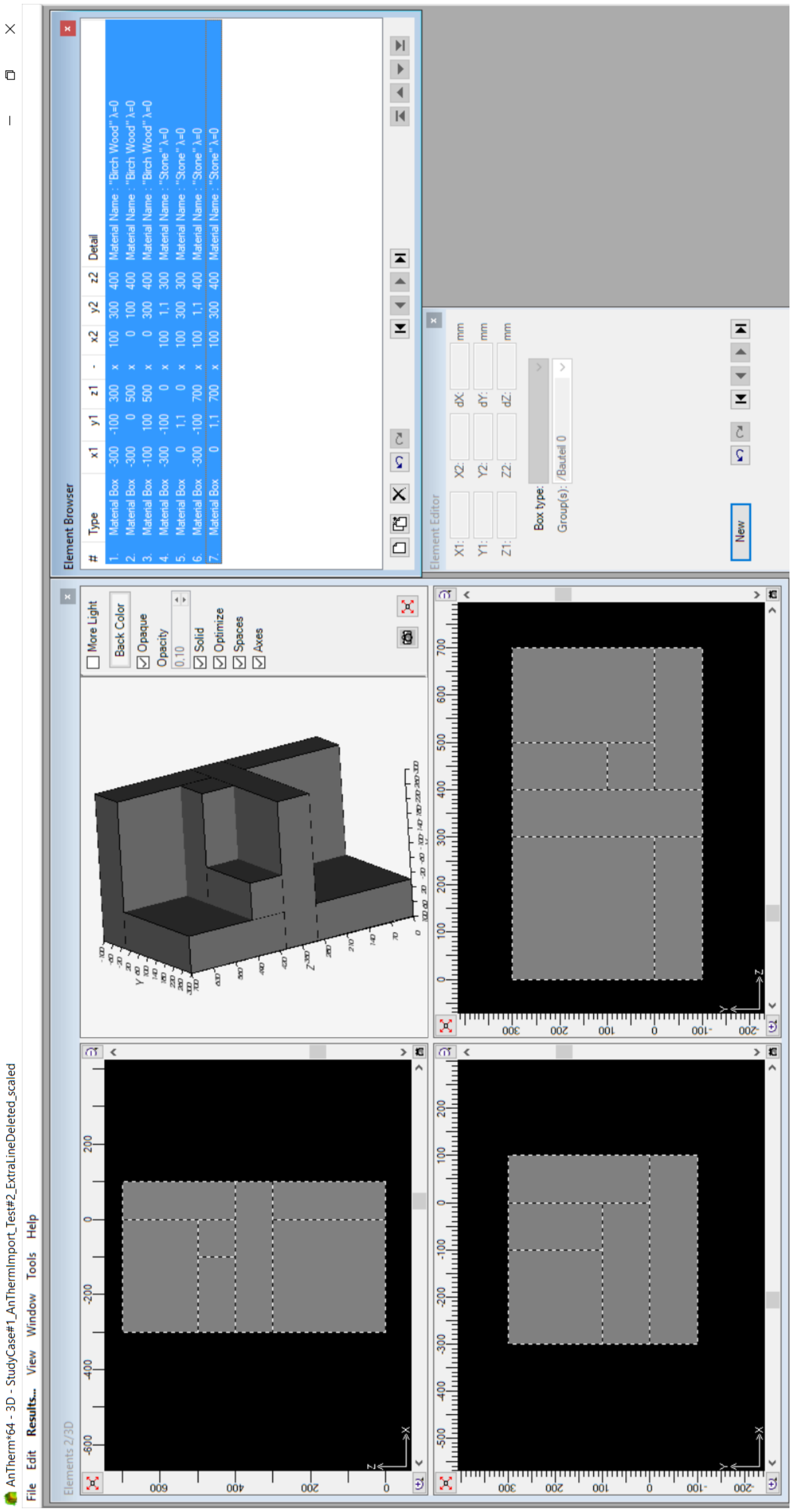

Figure 62: Case study 1, the DXF file containing 3D polylines imported in AnTherm

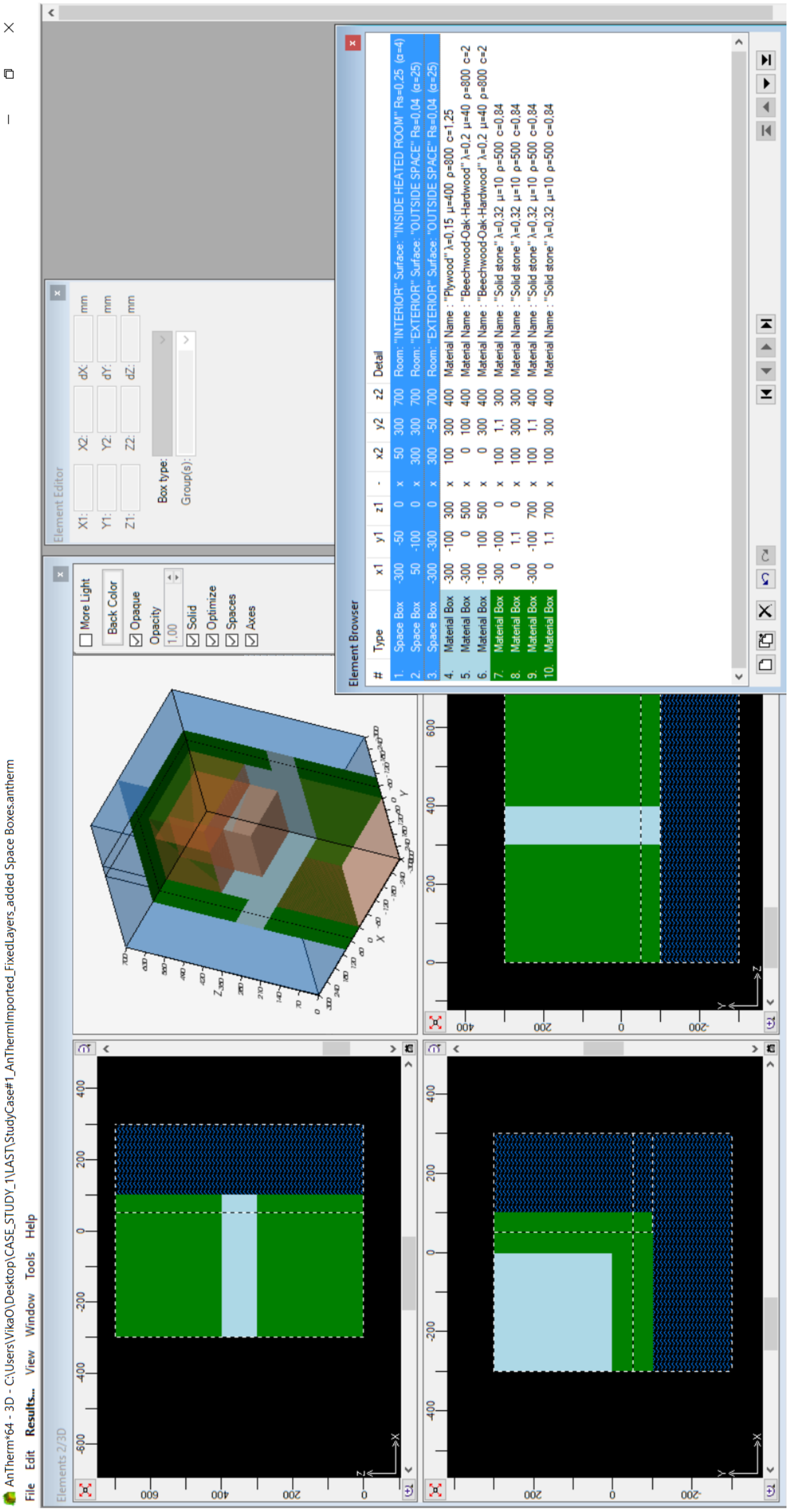

Figure 63: Case study 1, the finished model in AnTherm

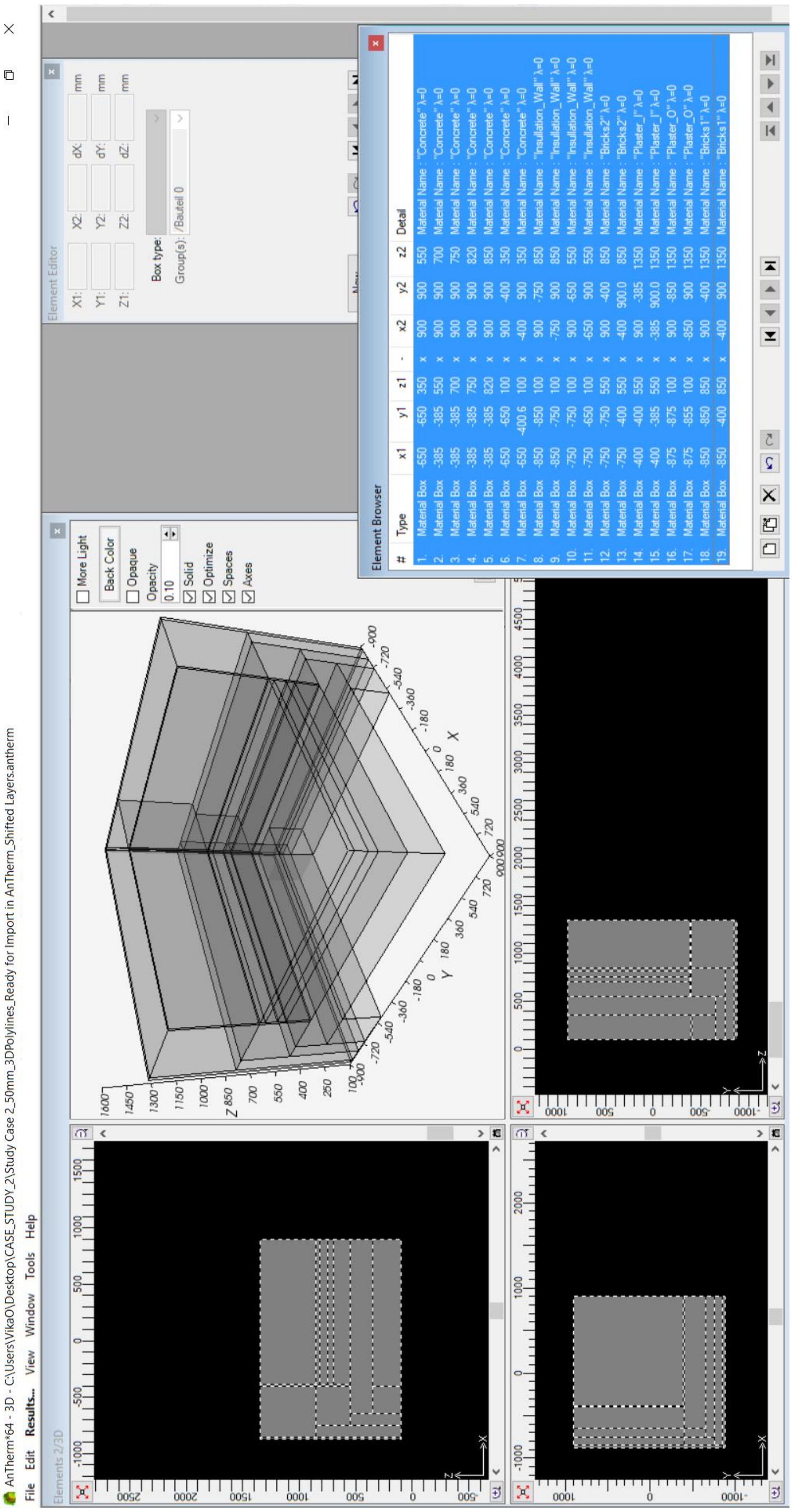

Figure 73: Case study 2, adjusted layer geometry in AnTherm

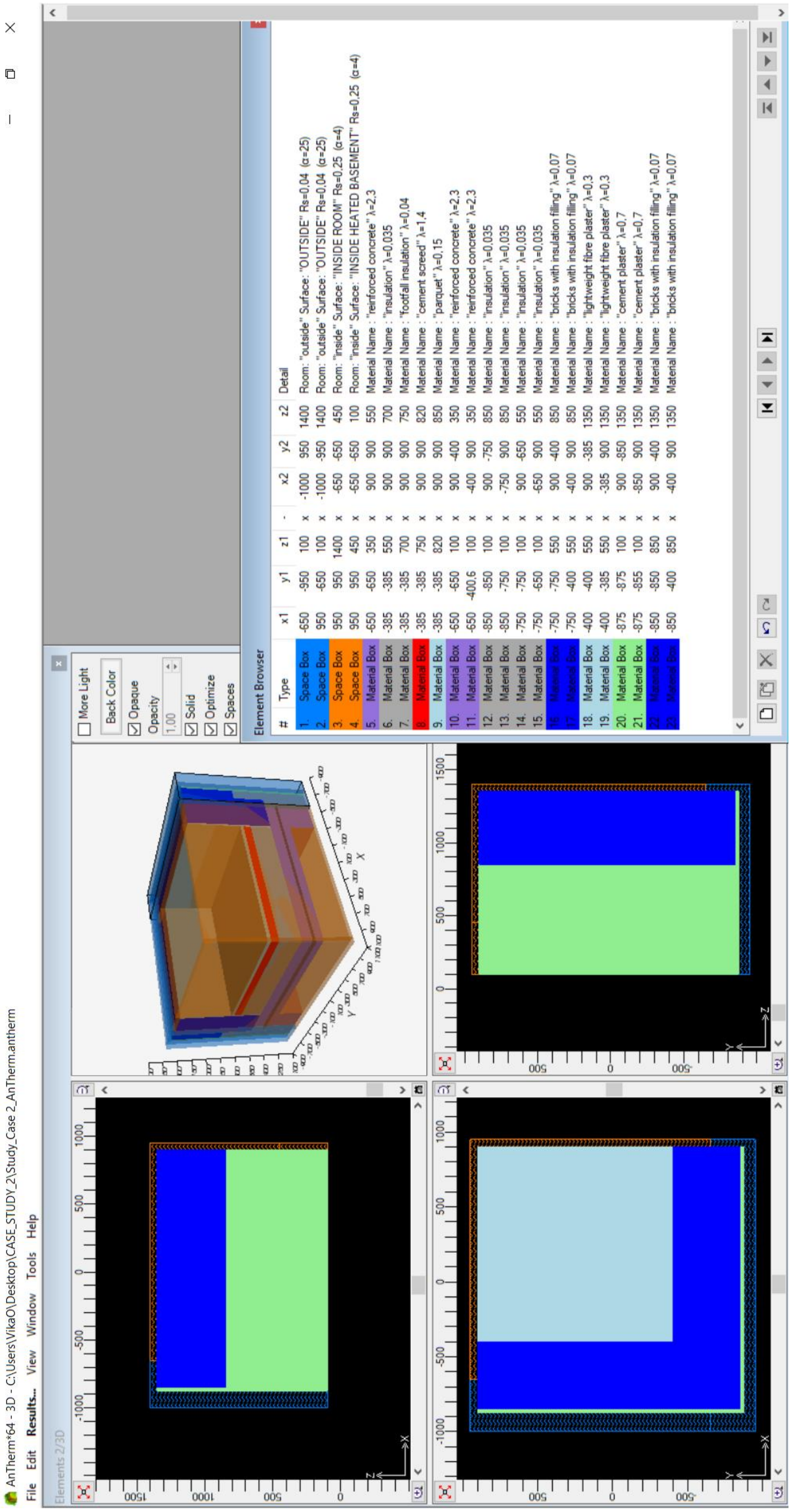

Figure 74: Case study 2, layer properties modifications in AnTherm

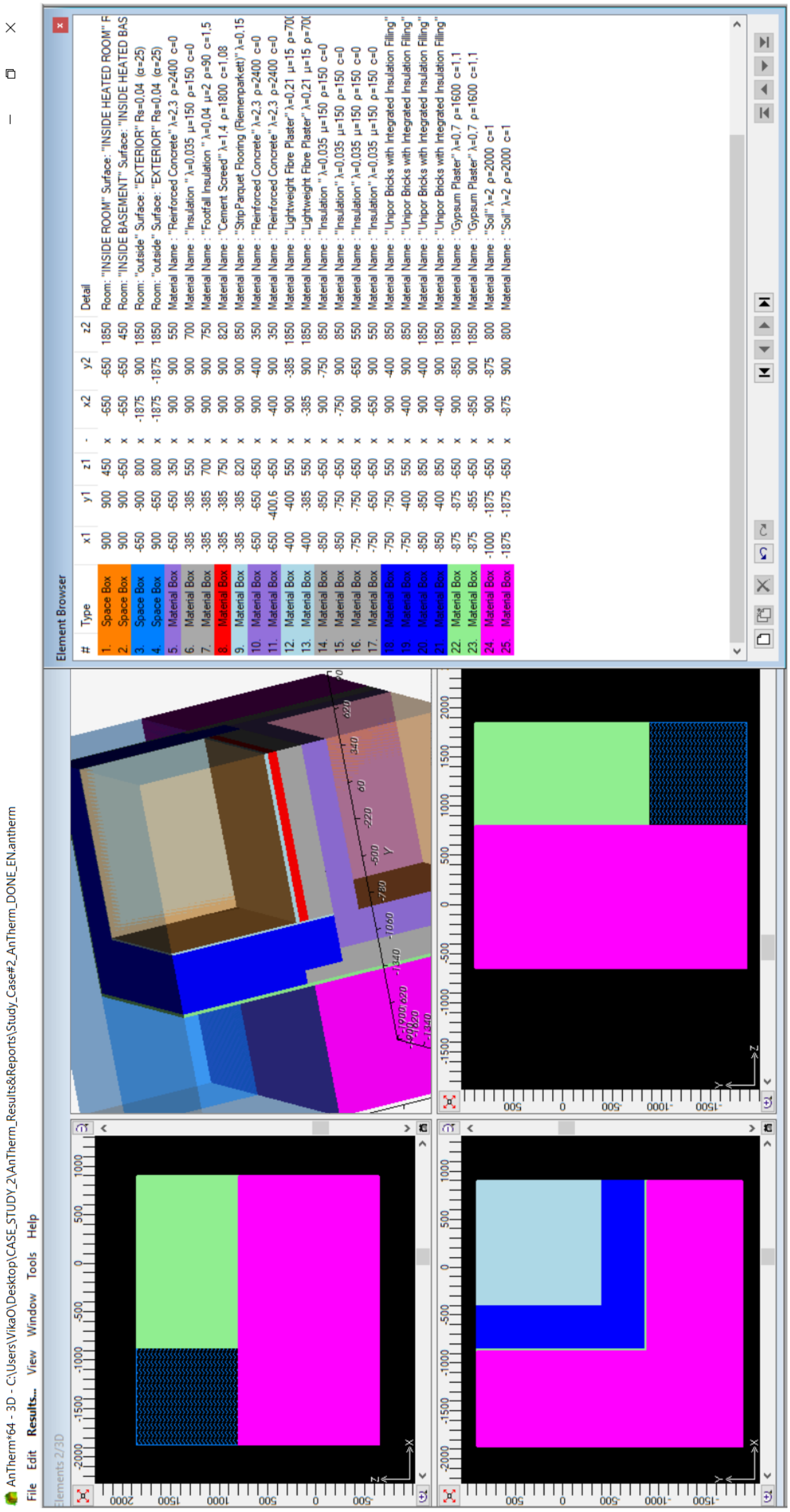

Figure 75: Case study 2, last modifications, addition of materials and space boxes in AnTherm

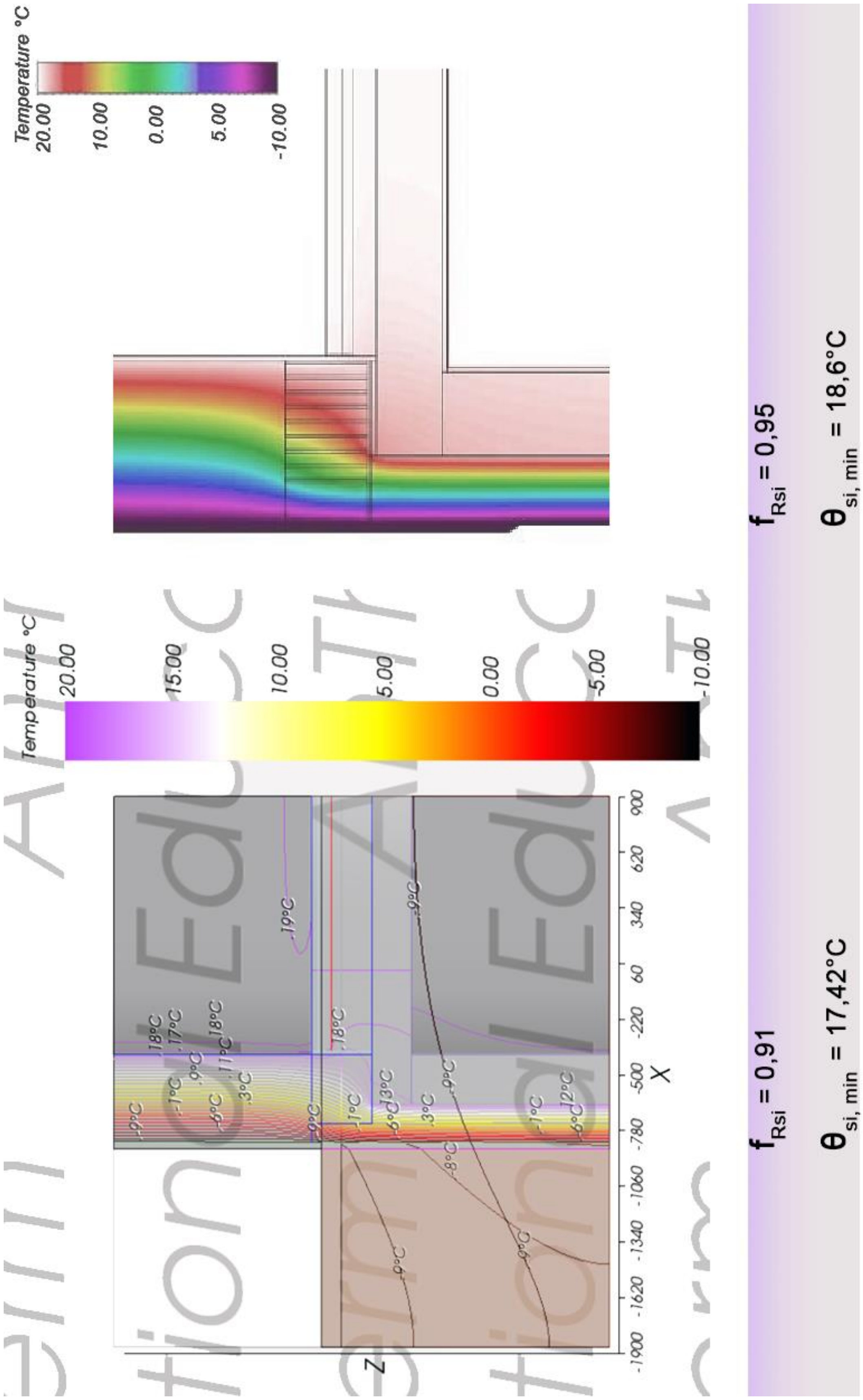

Figure 77: A comparison between the thermal simulation output of the second study case (left) and the results of the baseline model (right) from UNIPOR's Thermal Bridge Catalogue (UNIPOR 2017)