Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Architecture and Design
Department of Architecture and Technology

Anshuman Abhisek Mishra

Possibilities and challenges of workflow for multidomain performance assessment and optimization of solar façades

Master's thesis in Sustainable Architecture
Supervisor: Francesco Goia
Co-supervisor: Dr. András Reith
June 2022

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Kunnskap for en bedre verden

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Colophon

GENERAL

Title	Possibilities and challenges of workflow for multidomain performance assessment and optimization of solar façades
Sub-title	Developing and documenting the possibilities and challenges of a BIM-BEM based multi-domain performance assessment tool using industry standard software to perform multidomain performance assessment and optimization of solar façades through the different stages of façade design using a live-link between the BIM and the BEM model
Defense Date	7-8th June, 2022

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GUIDANCE

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Co-supervisor	Dr. András Reith
Credentials	CEO, ABUD

Preface

This master's thesis is the graduation project, as the final assignment of my 2yr MSc Sustainable Architecture Program at NTNU, Trondheim. This project was developed as part of my Exchange at ABUD, Budapest from Jan-June 2022. It's interesting how fast time flies, and this has been a challenging, but motivating and fulfilling 2 years of study life at NTNU!

My interest in this particular thesis topic emerged from the understanding of a developing gap between the mismatch of a sudden bloom of technological solutions in the AEC that gives the options for more data and evidence driven design, but also makes it complicated & confusing due to the challenges of interoperability. However, with newly developed tools, there is a possibility to streamline this workflow, especially for BIM-BEM linkage, that can lead to faster performance evaluations and can, thus, promote a transition towards more performance-driven design approaches in Architecture.

Looking back at these 4.5 months journey of my master's thesis, I would like to express my gratitude to everyone who has helped and supported me. I would like to thank my co-supervisor Dr. András Reith for his invaluable inputs to my project, to Evangelos Kyrou, consultant at ABUD, for helping me with the technical aspects of the Solar façade project, and ABUD for accommodating me for this period in their office in Budapest. I would also like to thank Alina Galimshina, PhD, student at ETH Zurich, who helped in sharing resources for the Bombyx plugin. I would also like to thank contributors on the McNeel forum, including Scott Davidson of McNeel and Associates, for addressing my queries regarding using Rhino.inside.Revit. Finally, I would like to extend my special thanks to my supervisor Francesco Goia, for his guidance, advice and insights throughout this process and for always finding time to discuss the key issues in my thesis.

Furthermore, a note of thanks to my colleagues, friends and fellow students as well as my parents who supported and motivated me throughout the process of this thesis. I hope this thesis proves as useful to others, as it has helped me in developing a better understanding about this subject!

Anshuman Abhisek Mishra .
May 2022

Abstract

Buildings today are recognized as a major source of global emissions and the AEC (Architectural Engineering and Construction) Industry is undergoing a massive shift in its approach to designing, constructing and operating buildings. There is, thus, an emphasis on the integration of Solar Photovoltaics across different components of the envelope-roof, façade etc of the building, leading to an increase in the adoption of BIPVs (Building integrated Photo-voltaic) for maximizing solar conversion. However, working with façades is challenging as it serves multiple functions, both functional as well as aesthetic, and undergoes many design updates through the design cycles of a project. With the current workflows between Building Information Modelling (BIM), which is a system/tool to develop & manage architectural models and the Building Energy Modelling (BEM), which is used to perform energy analysis, the process is inconsistent, time-consuming and prone to errors, due to changes of file formats and data loss. This thesis aims to study the possibilities and challenges of the new developments in BIM-BEM linkage that can enable multidomain performance assessment of various solar façades. For this, a generic geometry with material information is generated in a BIM environment, linked through intermediate tools to a BEM platform where several type of performance assessments are possible. This link is a 'live-link' between the two platforms, eliminating the process of working on copies of the original BIM model. This workflow is then used to do a demonstration performance assessment of Transparent PV integrated façade element, as a case study and the steps for developing this linkage are documented. Autodesk Revit is considered for the BIM environment, Rhino-Grasshopper and a number of Grasshopper Plugins for the BEM and a new Rhino tool, called Rhino.Inside®.Revit is used to establish this live link. This thesis is not an end in itself but an initiation to the number of possibilities that opens up when working with live-links between BIM and BEM. The final outcome is to contribute to the broadening of knowledge of new ways to integrate the design and building performance assessment, and this would further lead to increased accessibility, improvement and innovation in the performance-driven design of current and future high-performance buildings.

Keywords: BIM, BEM, Façade, Performance Assessment, Workflow, Transparent PV

Sammendrag

Bygninger i dag er anerkjent som en viktig kilde til globale utslipp, og AEC (Architectural Engineering and Construction)-industrien gjennomgår et massivt skifte i sin tilnærming til design, konstruksjon og drift av bygninger. Det er derfor lagt vekt på integrering av solcellepaneler på tvers av forskjellige komponenter av konvolutttaket, fasaden etc av bygningen, noe som fører til en økning i bruken av BIPV-er (Bygningsintegrert fotovoltaisk) for å maksimere solenergikonvertering. Arbeid med fasader er imidlertid utfordrende siden det tjener flere funksjoner, både funksjonelle og estetiske, og gjennomgår mange designoppdateringer gjennom designsyklusene til et prosjekt. Med dagens arbeidsflyt mellom Building Information Modeling (BIM), som er et system/verktøy for å utvikle og administrere arkitektoniske modeller og Building Energy Modeling (BEM), som brukes til å utføre energianalyse, er prosessen inkonsekvent, tidkrevende og utsatt for feil på grunn av endringer i filformater og tap av data. Denne oppgaven tar sikte på å studere mulighetene og utfordringene til den nye utviklingen innen BIM-BEM-kobling som kan muliggjøre multidomene ytelsesvurdering av ulike solfasader. For dette genereres en generisk geometri med materialinformasjon i et BIM-miljø, koblet gjennom mellomverktøy til en BEM-plattform hvor flere typer ytelsesvurderinger er mulige. Denne koblingen er en "live-link" mellom de to plattformene, og eliminerer prosessen med å jobbe med kopier av den originale BIM-modellen. Denne arbeidsflyten brukes deretter til å gjøre en demonstrasjonsytelsesvurdering av Transparent PV-integrert fasadeelement, som en casestudie og trinnene for å utvikle denne koblingen er dokumentert. Autodesk Revit vurderes for BIM-miljøet, Rhino-Grasshopper og en rekke Grasshopper-plugins for BEM og et nytt Rhino-verktøy, kalt Rhino.Inside®. Revit brukes til å etablere denne live-lenken. Denne oppgaven er ikke et mål i seg selv, men en initiering til antall muligheter som åpner seg når man arbeider med live-links mellom BIM og BEM. Det endelige resultatet er å bidra til å utvide kunnskapen om nye måter å integrere design- og byggeytelsesvurderingen på, og dette vil videre føre til økt tilgjengelighet, forbedring og innovasjon i ytelsesdrevet utforming av nåværende og fremtidige høyytelsesbygg.

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Abbreviations

BEM	Building Energy Modelling
BEP	Building Environmental Performance
BIM	Building Information Modelling
cDA	Continuous Daylight Autonomy
E_PV	Energy produced by the Photovoltaics
E_tot	Total (net) energy demand
EPW	EnergyPlus Weather (file)
EU	European Union
ghp	Grasshopper
HB	Honeybee
LB	Ladybug
LOD	Level of detail
LOI	Level of Information
PV	Photovoltaic Cells
RIR	Rhino.inside.Revit
SHGC	Solar Heat gain co-efficient
Tvis	Visible Transmittance
U	U-value
WWR	Window-wall ratio
ZEB	Zero Emission Building

1 Introduction

Architecture and building sciences are two inter-related disciplines that support each other but are very distinct in nature. With increasing concerns for sustainability, evaluation of building performance and environmental impacts has become almost an imperative for all new projects. Building environmental performance (BEP) analysis is a complex process that has many aspects: energy performance, daylight analysis, thermal comfort, indoor air quality, acoustics etc, and each of these studies has its own distinct study parameters. BP studies today are increasingly carried out in the digital environment, where there are many tools & platforms that must interact and inter-operate to be able to generate useful results. The goal of building performance should essentially be to reduce environmental impact of the building which can include some or all of the above mentioned factors, while maintaining or improving the indoor environmental qualities of the project (Petersen and Svendsen, 2010). To have a positive impact on how buildings are designed, it is important that these evaluations should also relate to the design process and inform design decisions by providing credible results at different stages of the design process (Hopfe et al., 2013). However, inspite of numerous developments in literature, techniques, software and technology, two major issues affecting the transition to performance-driven design are: discreet & individual, linear analysis methods where one aspect of the performance may be analyzed at one time, often different software being limited to a select few aspects of the study. And the second being, a lack of direct linkage between architectural and energy/performance models to carry out BEP assessments through the various stages of project development (Palonen et al., 2013).

In practice, it is not uncommon to find Net-zero energy buildings today that are designed depending on performance-based decisions containing various aspects of energy use, daylight autonomy, comfort levels, HVAC, passive design measure as well as renewable energy installations, which are also considered, in addition to other innovative technologies and solutions (Attia et al., 2012). As defined by Kalay (Kalay, 1999), a performance-based design process aims to unify forms and functions into qualitative solutions with specific combinations than in a process-based design. Complicated analysis process therefore makes it necessary to rely on multi-criteria, multi-objective and multi-disciplinary performance evaluation processes (Shi and Yang, 2013). This emphasis on the combination and optimization of the diverse design factors as well as measurable building performance metrics are essential to facilitate holistic future high performance-low emission buildings.

Building Information Modelling (BIM) has evolved as a platform that incorporates information and means of communication that can integrate the complicated aspects of the architecture, engineering and construction (AEC) processes. It is a means to generate a representational 3D model of the building, which also includes information regarding project life-cycle, material quantity, costs, HVAC and other technical aspects, among other things. It supports the development of this information through various stages of the building design process, often employed by the architects as well as other consultants, and contains (or has the capacity to contain) adequate information that may also be suitable for current building performance simulations (Utkucu, 2020). It is a suitable approach to develop the architectural aspects of the building and its ease of carrying information that enables integration with the performance assessment is essential to solve the complex requirements of architecture model development and building performance assessment.

Although the challenge is not new, it has been an evolving process that is still limited in tackling this gap. However, with new developments in software, there is an opportunity here to utilize newer these tools & plugins that can be exploited to connect BEM tools with capacity for multi-criteria BPE analysis with the BIM. This would facilitate interoperable analysis, drawing geometry from BIM and performing analysis in a visual scripting environment. This thesis has attempted to study the challenges and possibilities of utilizing these new solutions as a meant to solve the BIM-BEM linking process, understanding what can be currently solved and what other possibilities exist that need to be addressed. For a case study to evaluate the effectiveness of this tool, solar façades have been selected due to their complex nature of being an aesthetic as well as a functional element of the building.

This would be beneficial to the AEC Industry, including Architects and Building Performance Consultants, making the BPE process much faster and removing the hassle of copy models and the digital ambiguity of lost information which is quite common in the conversion of file formats (Nguyen et al., 2014). This also enables the AEC software industry to exploit new possibilities of scripting directly linked plug-ins for environmental analysis, that automate the process of preparing BIM geometry for performance studies. This would further support the development of performance driven design.

1.1 Research Context

Buildings are responsible for nearly one-third of the global energy consumption, which makes them the second most energy-intensive sector of the market (IEA, 2020). There is now a global effort towards reducing building energy usage. In case of Norway, nearly 80% of the electric use is for buildings, which inspite of being sourced through renewable hydropower is still a high percentage (SSB, 2012). Among the building stock, the issue of energy efficiency has been considered for all the typologies to some extent, at different scales. In practice, Office buildings are more likely to be designed keeping high performance requirements in mind, owing to the nature of their operation, location, rent as well as operational requirements, and may be responsible for high operational emissions, if these strategies are not considered. In Norway, for example, service sector buildings, which consist of 40% by floor area of office and shops, accounts for just 30% floor area of the total built stock across all sectors, but accounts for 40% of the energy need (Sartori et al., 2009). Added to that, office buildings are more likely to adapt high performance measures and are thus considered as a typical case study in this thesis.

A sign of the increase in efforts towards making high performance, efficient buildings is reflected in the growing trend for issuing and implementation of green building certification systems such as LEED in the US, BREEAM in the UK and other variants of these certifications, such as BREEAM Nor in Norway etc (Zhuang et al., 2021). The EU has been especially proactive, with its Green Tagging strategy which provides means for European Green Financing to include options for net-zero-energy buildings and green renovations. (Conti et al., 2016)

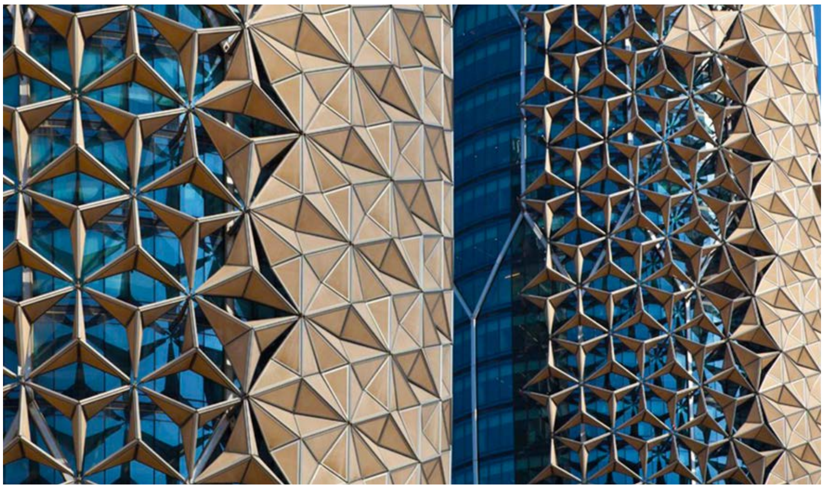


Figure 1.1 Multifunctionality of building facades (source-google)

Building façades, on the other hand, are an integral part of the building envelope due to, both, their aesthetical value as well as their contribution to the BEP and indoor well-being. Facades have traditionally been means of architectural expression as well, often carrying the style, material and expressive construction techniques of that era. Great emphasis was laid on making them geometrically balanced and incorporating symbolic icons, scriptures, motifs, emblems, statues etc. With the coming of the industrial age and the availability of industrial materials, as well as more practical considerations, façades began to have a more transparent expression, with large windows and ribbon window strips. Over the years, this has now translated to entire segments of glazed façade systems that wrap around the building structure, providing outward views across almost the entire floorplates and bringing in ample daylight. Added to that, an emphasis on 'high-tech' or 'high-tech' appearing aesthetics has driven up the use of glazed facades, which has in a way become a global trend unrelated to their actual benefits. This may be useful for buildings located in certain climate but quite detrimental to the BEP of buildings located in other regions & climates.

Apart from reducing the operational emissions, there is also a great emphasis towards on-site energy generation, which is practical at the building scale with the use of the Solar PVs. In this context, in EU all newly constructed buildings after 2020 have to be nearly zero energy (EPBD, 2010). Norway has taken a step further and is now focusing on research towards making Zero-emission buildings (ZEB) which aims to have net-zero emission buildings over a lifetime of 60yrs. In the ZEB approach, building performance as well as materials are all accounted for in terms of their respective GHG emissions as a means of defining the amount of on-site energy production (Hestnes and Eik-Nes, 2017). Therefore, the more materials a building consumes, and especially high emission materials such as steel, concrete and glass, the higher would be the demand for on-site energy generation. This works in two major ways: the first being promoting the use of low emission materials (such as CLT and low-carbon concrete) where possible, while reducing the consumption of these materials where they cannot be replaced without compromising structural integrity (such as in foundations, which are generally required to have some degree of concrete). The second is to consider on-site production as much as possible. This can be achieved in many ways, two common ones being - local on-site generation using renewable sources such as PVs or energy-generation from waste, such as from composting household/sanitation waste or incinerating garbage.

For Building green performance, three primary categorizations of sustainability can be considered: environmental criteria, economic criteria and social criteria. Most BPE which aiming for optimization articles are dual objective optimization, amounting to 65% of the cases, primarily focusing on the environmental and economic criteria as optimization indicators. (Hashempour et al., 2020)

In terms of BPE concerning optimization, studies indicate 3 categories as important areas into which variables for optimization can be divided in the early design stage: Building form, façade form and façade construction. Building form would consist of the building orientation, building shape, floor plan and controlling parameters in the digital building form as variables. Façade form variables consist of the single window size, shading component size and the window-wall layout. Whereas the façade construction includes the variables – glazing insulation parameters, glazing light transmission and opaque insulation parameters. (Zhuang et al., 2021)

In this context, the building-integrated Photovoltaics or BIPV development becomes an essential solution. Of the ZEB test projects in Norway, three base strategies were considered for renewable on-site energy generation: Photovoltaics, wind power and CHP systems. While wind power was not feasible in any of the projects, PVs were used in eight out of the nine pilot projects (Hestnes and Eik-Nes, 2017). Solar PVs were initially add-ons to existing buildings either over the roof or just as a separate element. Since their functional performance depends primarily on their geometric placement with respect to the sun, more often than not, solar PVs were in contrast to architecture or building aesthetics. However, with advancement in building design as well as construction techniques, BIPVs have become more popular, as not only were they integrated into the building envelope, but they were also able to replace existing 'non-productive' building parts.

In buildings, facades act as the weather envelope, controlling heat transmission, solar gains, internal heat gain as well as letting in daylight and ensuring views. Transparent envelopes or the transparent elements in a façade often have lower insulating properties as a consequence of their material property. They directly affect the building performance, leading to higher heating/cooling demand, more so depending on the extremity of the weather compared to the average acceptable comfortable indoor conditions. In this respect, BIPVs such as façade-integrated solar PVs are integral to on-site energy production to help these buildings meet as much of their energy demands off-grid as well as to lower material and operational emissions. In denser urban settings, which pushes for taller structures with less roof area to offer for adequate PV placement, BIPVs are almost the only solution maximizing the façade generation, when aiming for a net zero balance. BIPVs, especially of transparent and semi-transparent type have become relevant for some architectural typologies, such as offices or public buildings in general, due to the use of vast glazing façades (Bizzarri et al., 2011).

1.2 Research Problem

The process of designing a building and doing its performance evaluation are two very interdependent but also distinct and complex tasks. In the industry, these tasks are handled by different software, and the models transition through different structures of data handling & ontologies. For architects, Building-information models (BIM) are the commonly used platforms for developing, organizing and coordinating architectural models through the life cycle of the project design development. Consultants associated with the project development are also likely to use BIM or BIM-viewers due to the use of co-ordination facilitated by BIMs. Similarly, building performance simulation can be carried out in a number of dedicated software (such as eQUEST, DOE2 etc) or in parametric platforms, handled by different plugins.

However, a gap exists in the façade design process where the lack of BIM-BEM linkage limits performance driven design decisions through the different stages of the façade design development. The research question for this thesis is:

What are the possibilities and limitations in developing a dynamic BIM-BEM workflow for multi-domain environmental analysis of solar facades?

1. *This concerns identifying what are the essential BIM elements (3d elements and/or information) that need to be included in the workflow which can facilitate dynamic performance testing through the different aspects of façade design & development?*
2. *What aspects of parametric design approaches and environmental performance studies can be integrated to form a holistic tool?*

1.3 Research Goals

- To develop a workflow combining BIM platform (as 3d-modelling/construction software) and BEM platform (for running energy simulations)
- To deploy the workflow on transparent façade-integrated PV systems as a case-study for performance analysis
- To document the modelling and control steps of the workflow, to analyze challenges and possibilities and future developments

For the purpose of this study, Autodesk Revit has been used as the BIM platform, while Ladybug-Honeybee, which work in EnergyPlus, OpenStudio and Radiance, alongwith other plugins running within the visual scripting Rhino-Grasshopper environment have been used for the BEM aspects. The live-link for interconnectivity was established using Rhino.inside, a new Rhino plugin that enables running Rhino-Grasshopper within Revit's memory.

1.4 Research Design

As described by Zhuang et al., in their research, a BIM centred performance analysis can be divided into four categories, namely: Building Ontological data, external related data, simulated performance data and monitored performance data (Zhuang et al., 2021). This thesis focuses on developing on the 'simulated performance data' aspect as its focus. For enabling this, a basic model will be developed in the BIM environment and a live-link will be established with a parametric/BPS platform. This will be done using existing plug-ins, tools and work arounds in a graphical programming environment. The thesis interest lies in finding possibilities and challenges in forming a seamless and automated exchange of information between the BIM-BEM, instead of the typical practice of exporting copies of the original BIM in compatible formats. The dos, don’ts, scope and gaps of this process would be documented in the process, at the different stages of file exchange.

1.5 Purpose and potential benefits of this research

Connecting architectural building models developed in BIM with performance simulation is not new and has been a challenge for improving integration between these two aspects, over the years. Through developments in software, design requirements and energy standards, both the building design and management process as well as building performance criteria and evaluation techniques, have become increasingly complex. Owing to the unique requirements of both, the platforms have also developed with distinct data structures, file formats and ontologies for organizing this essential building information. For BIM, this can be material information, project cost, project phasing, material quantity, 3d visualization and general co-ordination. For BEMs, it can vary depending on the type of analysis, but often includes simpler geometry with physical and thermal properties of the materials. A live-link connecting BIM-BEM can help in reducing this gap, giving wider access to BPS throughout the different stages of BIM and architectural project development. It would also reduce the chances of error, confusion, data misappropriation, data loss and the general lack of flexibility that occur whilst working with copies of the BIM models. Another issue that can be avoided is the lack of options to reintroduce tweaked BEM models back into the BIM environment. At the same time, it would enable more dynamic simulation studies, flexible design with comparative analysis for a range of components and overall promote the integrated design processes for performance-driven design for future architecture (Samuel et al., 2017). The beneficiaries would include architects, building physicists, environmental analysis consultants as well as industries such as envelope & façade developers, HVAC equipment industry, BMS etc. Academia would also benefit from being able to study more realistic environmental performance assessments that work coherently with the non-linear process of architectural project design & development.

2 Literature Review

2.1 Building Information Modelling (BIM) and Building Energy Modelling (BEM)

2.1.1 The integrated design processes

The integrated design process, as enabled by software platform connectivity, is a need today. Buildings have become extremely complex, not just in their design approaches but in the number of different components and sub-systems that exist in them. To make aesthetically-interesting building that are also required to meet high performance criteria, while also providing for the best of essential building equipment for fire, lighting, HVAC, IoT etc, it becomes increasingly important to start the dialogue at the earliest stages of the project between the different consultants. This early initiation of dialogue helps in the best inputs from the project consultants, which if incorporated into the early design phases helps avoid unnecessary complications at the later stages of the design. The Integrated Energy Design, also called IED, as described in the ZEN book, mentions the following primary characteristics (Hestnes and Eik-Nes, 2017):

- A different approach from the very early stages of design
- Requires a high level of general skills (energy knowledge in a broad sense) as well as communication within the team of architect, client, consultants and users as well
- Leads to a high level of integration and synergy of systems
- Involves modern simulation tools, for performance evaluation, wherever suitable

Existing studies have primarily evaluated the conceptual performance in the early design stage, for example sun-shadow, daylight access, solar radiation, whereas evaluation of overall environmental indicators is yet to be realized in BIM (Jin et al., 2019). Existing literature for BIM centred data-driven green building designs mention issues of missing performance data, of centre platform separation, local supply chain fracture etc. This is a challenge in the development of integrated design of whole life of green buildings, based on the BIM platform, with its comprehensive data management and application framework. (Zhuang et al., 2021)

BIM and its extensions provide excellent communication and co-ordination tools between a number of project attributes and their respective consultants. The challenge for high performance projects, especially performance driven design, is, however, difficult owing to the fact of the independent nature of energy simulation platforms, and their disconnect from the BIM system of working, using BIM native elements and following BIM ontologies (Utkucu and Sozer, 2020).

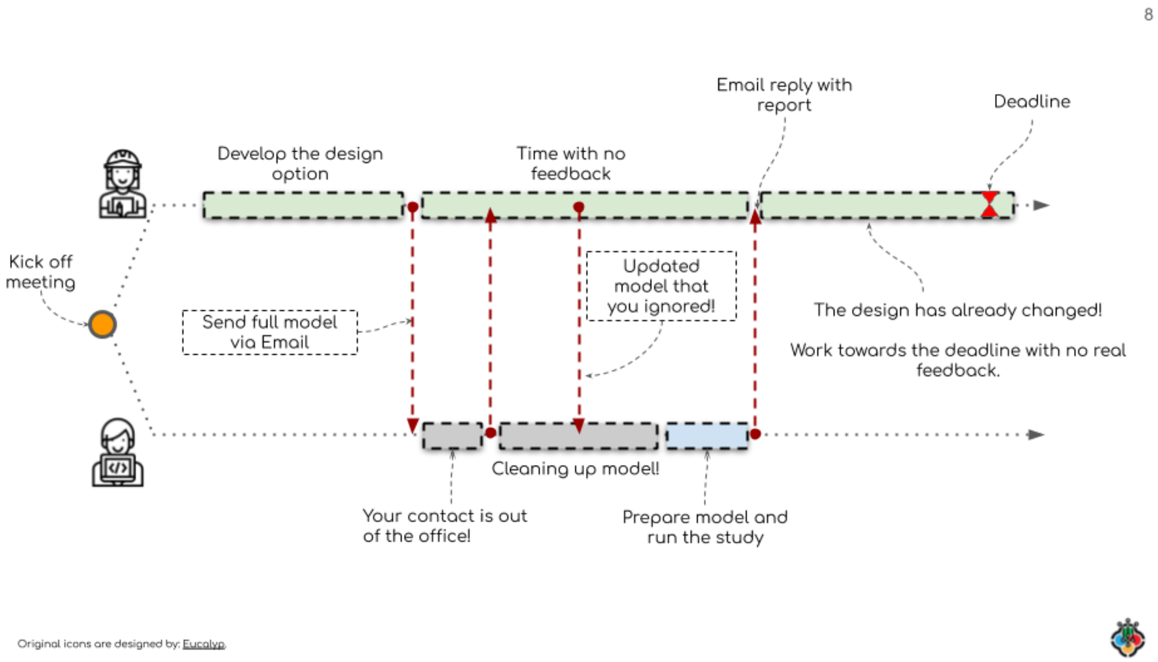


Figure 2.1 An image by Mostapha Roudsari explaining the issue with current approach (Roudsari, 2021)

This is described aptly in this diagram from the Pollination.Cloud blog. Pollination is a paid platform currently in development by the developers of the Ladybug-Honeybee toolset as a solution for interlinking Building architectural modelling and Energy Simulation. In this article, discussed under the title of ‘the Two-week Turn-around Problem’, which states that between developing the design ideas and simultaneously verifying them, the challenge lies in all the intermediate processes and steps that need to be performed before the BIM exported model can be analyzed for performance. However, architectural design is a dynamic process that may or may not follow a linear, predictable trajectory, which means that often by the time the exported BIM model is ready for simulation, the project has already moved ahead. This is the difficulty of the ‘two-week turn-around’ which is a tentative time gap between receiving, preparing and analyzing a design option for its energy performance (Roudsari, 2021). This time can also vastly vary depending on the complexity of the projects, the choice of the used platforms and the nature of analysis being performed.

According to a study by Sanhudo, where software data exchange was studied in the building industry, three generation of exchange models were defined. In the first generation of data exchange, the focus was primarily on the building geometry data. In the second generation of data exchange, an extended model was introduced in the programs to integrate domain-specific performance information. The current generation, which is the third generation of data exchange, schemes such as IFC and gbXML have been developed, which provide a greater potential for coverage through the entire life cycle. However, there are still many limitations in sharing all the information of a building (Sanhudo et al., 2018).

In practice, a complex model today also needs to transform differently for different simulations, even in cases where it is being performed in the same platform. A typical performance evaluation can range from a simple energy demand study, which itself required very precise inputs for accurate calculations, to more elaborate studies, that can include energy, daylight, windflow/CFD, ventilation design, LCA/LCC, acoustic modelling and so on. Typical workflows for these simulations are designed based on a single simulation approach where a single aspect, such as energy or daylight performance, is being studied at one time, therefore relying on very specific modelling inputs. For example, to perform an energy simulation in LB-HB and LCA using Bombyx, both running within the Rhino-Grasshopper environment, each would rely on a different starting model, which makes it a challenge to also perform multi-criteria analysis. Visual programming platforms such Rhino-grasshopper, through their plugins, can be used to generate an integrated performance analysis workflow which can perform multi-criteria or even multiple, unrelated analysis simultaneously, considering the base model and inputs are provided. As a result of this gap, in typical project timelines, the energy performance simulation is performed for much limited design options for attributes such as energy performance or comes in at a very late stage as some analysis, such as LCA, rely on the extent of model detailing for accuracy.

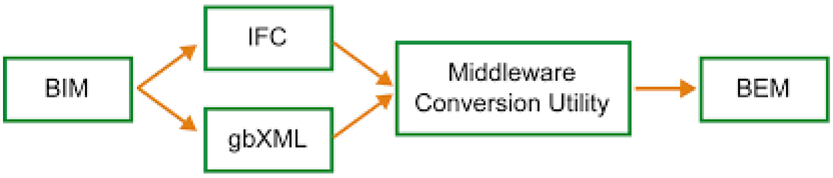


Figure 2.2 Typical BIM-BEM links rely on middleware conversion tools, enabled by protocols such as IFC or gbXML (Bertrand Lack, 2019)

Another challenge of integrating BIM-BEM for performance driven design is cleaning up of the existing model. As models are extremely detailed, detailing in BIM increasing through the different stages of the LoD/LoI, the model tends to be increasingly difficult to 'clean' as the project progresses. Then, whereas an energy performance study is easier to do in the early phase, but an LCA is very tentative, on the opposite end, it is more relevant to do LCA at a latter stage, but the performance study would be tentative and difficult. This can lead to gross generalization or simplistic assumptions and extrapolation of data, which may not reflect real world performance. The responsibility of cleaning up the model is also a question of 'who should do it?'. To begin with, the energy consultants work on a copy and not an actual file of the project, which means there are chances of loss of information in the data transfer. Moreover, the model needs to be cleaned, but whereas the architects understand the design & zoning of the project more accurately and are in sync with the HVAC consultants for example,

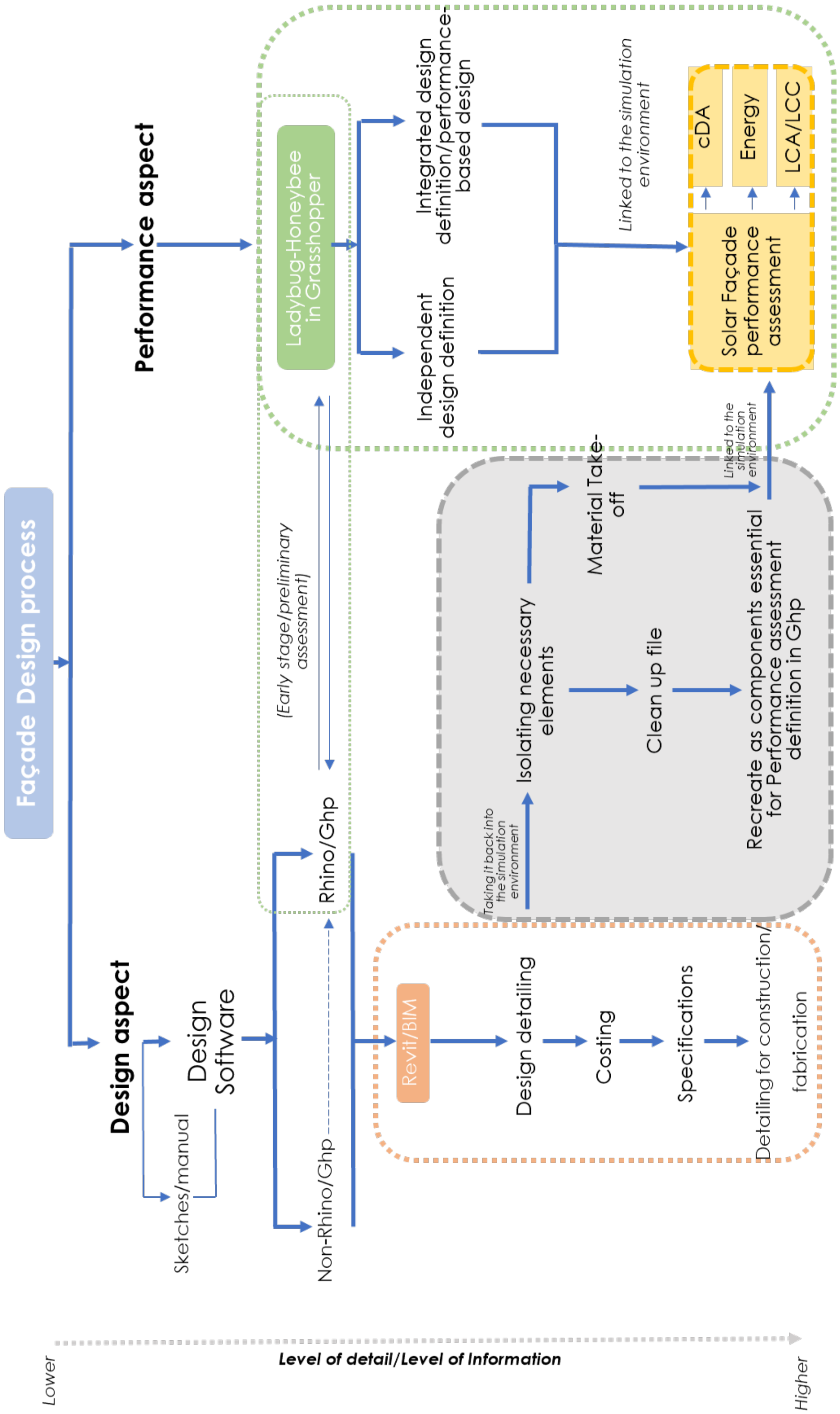


Figure 2.3 A generalized schema depicting the typical workflow design process in Revit and Rhino-grasshopper. The ambiguity of the steps represented in the grey box is what can be solved by having interoperability and BIM-BEM linkage

have the latest information about the zoning and sizing for Indoor Environment Comfort. The energy consultants, on the other hand, would prefer to clean the model as best suits to the simulation modelling and if not provided with adequate information about the Indoor Environment strategies, for example, before beginning the 'model' cleaning up, might eliminate important inputs for the environmental performance simulation. This is also not helped by the fact that buildings today are becoming more multi-dimensional, where multiple building usage are juxtaposed. Modern academic buildings are a good example, with studios, classrooms, libraries, laboratories, auditoriums, canteen and open areas, all very different in design, daylight requirements, ventilation and heating-cooling strategies, all inside a single or inter-connected buildings.

This is called interoperability, which can be defined as the ability of exchange of data between atleast two platforms, and communication between them. This makes the need for duplication of data redundant, while increasing the ability to use multiple tools with same set of files, for different aims (Sanhudo et al., 2018). As the blog article also states, that 'instead of emailing the consultant a copy of the design model, how much more convenient it can be if a Rhino/Revit plugin can be used to create an analytical model, that can pass a QA/QC by both the architects and consultants, before running the simulation – in the same platform' (Roudsari, 2021).

Therefore, a live link between BIM-BEM not just reduces the chances of losing information but also improves the scope of communication. This thesis is attempts to create a simplified workflow using Revit as a BIM platform, linking it to Rhino-Ghp and its many tools as the BEM platform, using Rhino.inside.Revit as tool to facilitate this interoperability between the different models and simulations.

2.1.2 Building information Modelling

Building Information Modelling, also known as BIM, is a broad concept that could possibly have many names: Building Information model, Building Information management etc. BIM is one of the most defining developments in the architecture, engineering, and construction (AEC) industries. BIM technology helps in developing a digital 3D model of the building which is accurate. While BIM may sometimes be misunderstood as a 3d digital store of only building or architectural data. In practice, this model through the various stages of the project, contains the most precise geometry and necessary information that may be essential to facilitate & realize the building, such as construction, fabrication, and procurement activities.

For this research, the considered definition is as by the US National Building Information Modelling Standard, which defines BIM as (Beetz et al., 2018):

Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition. A basic premise of BIM is collaboration by different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the BIM to support and reflect the roles of that stakeholder.

BIM, in its concepts, approaches and methodologies has existed for nearly 30 years. It is however, through the past one-half decade or so, BIM has evolved to be in its present form where it is influencing the way planning, design and construction of building and other infrastructure is carried out. Its global acceptance and widespread application have grown exponentially in the recent time as it offers excellent control over various project aspects of a project and also facilitates communication and interdisciplinary work. Another useful aspect of BIM is that it provides the essential tool and the digital environment to model the lifecycle of a building, providing a base platform for new construction capabilities as well as accommodating changes in roles and relations among a project team. This integrated design control and efficient communication, therefore helps in making better quality or complicated buildings, at relatively lower costs and possibly shorter project timespans. (Kjartansdóttir et al., 2017)

There is much evidence that defines the consequence of widespread uptake in the industry of BIM technologies. According to the WEF 2016 report, the errors caused due to the difficulties in communication, coordination and standardization can be minimized by the adoption of Building Information Modelling (BIM). This technology-led change has the chance to deliver a significant impact in the construction sector. Likewise, wider adoption of BIM in the construction has been predicted by FIEC to unlock 15-25% savings to the global infrastructure market by 2025 (Kjartansdóttir et al., 2017). Also, reports indicate that with BIM adoption across Europe a 10% savings will be benefitted by the construction sector, generating of an additional €130billion in savings. (BCG, 2016)

The high popularity and reliability of BIM is a result of being a single platform (or workflow/work system) that is optimized for the AEC and the architectural as well as related services to go methodically through the different stages of the project. BIM, being an evolving technology, with an ever-increasing application in the building industry, the variety of information carried by the BIM platform/system has continually expanded during the past few decades (Ding et al., 2014). Not only is this well-organized for the professionals, but being a 3d, graphically interactive platform, it can also be used to communicate design or design-related aspects of the project to clients or non-professionals as well. Therefore, for most innovation in the AEC Industry, there is a beneficial advantage in making it BIM Compliant (Akanbi et al., 2018)

2.1.3 Design process and collaboration in BIM

Traditionally, architectural, and structural practices relied primarily on 2d drawing formats as a means of design documentation and communication. This included drawings for the design, for plans, elevations and sections, often at different scales depending on the level of details. This can be accompanied by information about the construction, structure, door-window schedule etc as notes in the sheets or as accompanying reports. Therefore, following suite of the accepted practice, the initial digitalization tools were also 2d software, which transitioned the 2d manual draughting process into a digital one. Autodesk AutoCAD and its many variations over the years are an excellent example of this practice.

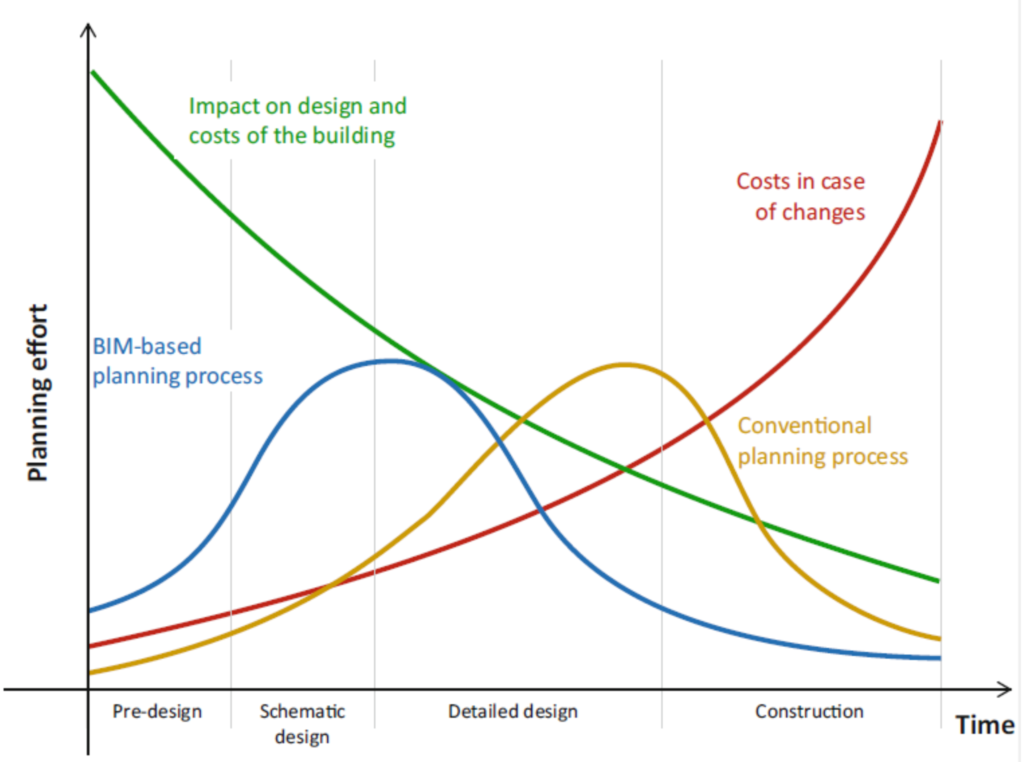


Figure 2.4 Design process and advantages in utilizing BIM (Beetz et al., 2018)

However, buildings and the AEC industry works on a complex overlap of information from various consultants that help define buildings or infrastructure construction projects in general. This can result in various communication gaps, intentional or unintentional, that can affect the construction process. BIM solves this by introducing a structured platform and an interactive 3d interface for managing the 'draughting' process. This leads to consistent 2d drawings generated automatically avoiding errors in the technical drawings as a result of discrete workmanship unlike in the traditional processes. Moreover, the option of adding information to the building elements enables overlapping and clash detection of the inputs from different disciplines: structure, HVAC, fire etc. As indicated in fig xxx above, BIM helps in shifting planning efforts and design considerations to earlier phases of the project development, therefore making it much more convenient to do essential analyses in the earlier stages of the design leading to higher impacts and lower costs.

A selection of the most widespread use cases for BIM has been documented in the table below (Beetz et al., 2018):

Use Case	Description
Technical Visualtization	Visualization of the 3D model as basis for project meetings and for public relations
Coordination of the specialist disciplines	Merging of discipline models into a coordination model at regular intervals, collision detection and systematic conflict resolution
Derivation of technical drawings	Derivation of the major parts of the design and construction drawings
BIM-based simulations and analyses	Use of the BIM model as input for various simulation and analysis tools, including structural analysis, energy performance simulation, daylight analysis, computational fluid dynamics, etc.
Cost estimation	BIM-based quantity take-off as basis for cost estimation
Tendering	BIM-based quantity take-off for creating the Bill of Quantities required for tendering construction works
Construction process modeling (4D modeling)	Linkage of individual components of the BIM model with the corresponding processes of the construction schedule
Simulation of the cost progress (5D modeling)	Linkage of the 4D model with costs for fabricating and/or purchasing the corresponding building components
Progress monitoring	Creation and update of a 4D model for reflecting and monitoring the construction progress
Billing and controlling	Billing and controlling based on the progress monitoring BIM model
Issue and defects management	Use of the BIM model for documenting construction defects and tracking their removal
Building operation and maintenance	Handover of BIM data to the client and subsequent take-over into facility management systems for operation and management

Table 2.1 Different applications of a BIM Model

In the construction phases of the design, past the design phase, BIM offers the advantages of preparing architectural and technical drawings that can be issued to the construction team. The digital 3d model may also be provided as part of the tender to enable accurate calculation or estimation of costs and for the contractors for reference as well as for billing at various stages of the project. In some case, Code compliance may also be done using the BIM model.

The digital 3d model may also be used like a Digital Twin of the actual project even after the period of planning, design, and construction is over. It carries important information about the spatial and technical aspects of the project which can later be reviewed and updates to the original structure can thus be performed. It can also be used for simulations of various aspects such as energy performance, evacuation strategies etc as well as used for maintenance cycles and warranty library of the various appliances installed on the project. Finally, at the end-of-life stage, it can be used as a planning and estimation tool, so as to enable responsible demolition and environmental recycling or disposal of the non-recyclable construction waste.

2.1.4 BIM Models and Level of Development

BIM Models offer numerous options of integrating information into a basic 3D model. The basic 3D model as it is interacted by different consultants and going through the various stages of a project can evolve with information about time, cost, FM etc

Model	Utilities
3D	Model walkthrough
	Clash Detection
	Project Visualisation
	Virtual Mock-up models
	Prefabrication
4D (time)	Construction Planning and management
	Schedule visualisation
5D (cost)	Quantity take-offs
	Real-time' cost estimating
	Whole-life cost and life-cycle cost
6D (facilities Management)	Improved Space management
	Streamlined maintenance
	Energy use planning
	Renovations
	Life-cycle management
7D (green)	Energy
	Life-cycle assessment

Table 2.2 Showing the different types of 3D Models based on utility (Barnes and Davies, 2015)

Although this is a generalized outlook as the BIM models are very project specific, sometimes in practice they may be referred to as 3D, 4D, 5D and so on. Although, it is getting common to refer these additions as simply XD models, a common notion is represented in table 2.2.

The BIM model is more commonly defined as per its LOD – Level of development/detailing. The American Institute of Architects' publication "AIA E202-2008: Building Information Modelling Protocol Exhibit" refers to this as the "Level of Development (LOD)" which specifies the accuracy and reliability of the model elements.

This classification may also be unique to different countries. For example, UK uses 'LOD' as 'Level of Definition', which combines a geometrical aspect called 'Level of Detail' and an information aspect of the graphical attributes of the project, called 'Level of Information'. Often in a project, the models have to go through different stages of LODs, as listed out below Table 2.3 (Kjartansdóttir et al., 2017):

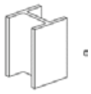
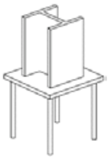
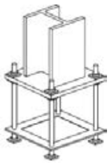
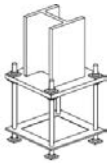
Level of Development	Definition	
LOD 100	Themodel element is represented graphically by a symbol or a generic representation. Information specific to the element such as costs per square meter can be derived from other model elements.	
LOD 200	The model element is represented graphically in the model by a generic element with approximate dimensions, position and orientation.	
LOD 300	The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation.	
LOD 350	The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation as well as its interfaces to other building systems.	
LOD 400	The model element is represented graphically by a specific object that defines its size, dimension, form, position and orientation along with information regarding its production, assembly and installation.	
LOD 500	The model element has been validated on the construction site including its size, dimension, form, position and orientation.	

Table 2.3 Showing the different Levels of detail as defined by the AIA (AIA, 2013)

2.1.5 Building Energy Modelling (BEM)

There are many different tools available today that can be utilized for Building performance simulation (BPS). Multidisciplinary Building design approach, which aims to combine various categories of performance aspects, requires inputs from various professions that each utilize a different building simulation program (Hong et al., 2000). Depending on their, graphical user interface (GUI) and simulation engines, Kamel and Memari categorized BEM tools as follows (Kamel and Memari, 2019):

Energy simulation GUI Only	Energy simulation engine	Independent energy simulation engine with the graphical interface
OpenStudio	EnergyPlus	Ecotect
DesignBuilder		TRYNSYS
Hevacomp		IDA ICE
Simenergy		ApacheSim (used in IES VE)
BEopt		EDSL Tas
GBS	DOE2	Modelica language
eQuest		
RIUSKA		

Table 2.4 Categorization of BEM tools on the basis of GUI and simulations engines

However, owing to the limited ability of customization in these BEM software, other visual programing software have been used in this study. In the parametric environment, tools such as Rhinoceros 3D, developed by David Rutten and Rover McNeel & Associates in 2007 are popular for working NURBS surface and complex geometry in a free modelling environment. Its Plugin, which enable parametric as well energy performance scripting, Grasshopper, is the platform used in this study for the BEM aspects.

2.1.5.1 Grasshopper

Grasshopper, an open-source graphical algorithm editor based on Rhinoceros 3D, is an excellent plug-in for parametric development. Based on a visual programming based input, it enables designers to interact with the algorithms of parametric design without prior programming language. The layout is interactive, the connections are flexible and it offers options to control data flow patterns with options to split, merge, inverse and so on. Different components can be dragged onto a 'canvas' and connected to add parametric controls to the generated forms. These parametric controls imply a real-time change of the geometry, that can be visualized in the Rhinoceros display as a 'preview' and the desired outcomes can be baked to form a 3D model with edges, vertices and surfaces that can either be interacted in Rhino or exported to other software in appropriate formats (Eltaweel and Su, 2017). This is good example of a 'computational design decision support tool.' Grasshopper is mainly used in this study for it offers the possibility of performing multi-criteria analysis while also helping interact with geometrical inputs and outputs. Simple controls can be designed to enable the users, with very basic or no programming skills, to run the simulations.

2.1.5.2 Ladybug Tools

Grasshopper, being an open-source platform, has led to the development of many additional plug-ins that widely expand its capabilities. Initially developed to simplify a rather fragmented workflow of different simulation engines under a single plugin, Ladybug has grown into a full-fledged BPS tool, since its start in 2012. This comprehensive solution enables to use simulation engines in a flexible and user-oriented visual programming environment (Ladybug, 2020). This is the BEM environment used in this study.

Ladybug tools has two major components that were used in the transparent solar façade case study here. First Ladybug, that is used to extract data from standard EnergyPlus Weather files (.epw) and a range of 3D interactive data charts can be created. It is useful for doing initial design stage and supports in the decision-making process, The second one, Honeybee is connected to four validated simulation engines: EnergyPlus, Radiance, Daysim and OpenStudio and can be used to evaluate building energy, daylight and internal comfort (Roudsari et al., 2013).

2.1.5.3 Bombyx

Bombyx is a free license Grasshopper plug-in that has been designed to perform a simplified whole building Life Cycle Assessment (LCA) of buildings during design. The current version is a work in progress platform that focusses on the assessment of embodied impacts using the Swiss LCA database for building materials (ETH, 2022). This tool has been used to explore the LCA aspect of the transparent solar façade case study in this thesis.

Bombyx is based on the approach of combining the principles of parametric design with a simplified LCA method, which is referred to as the parametric LCA (PLCA). The workflow divides the environmental performance of a building into 3 major categories: geometry, materials and heating, ventilation, air-conditioning (HVAC) systems, each with its separate input parameters. The geometrical inputs (areas) are taken from a 3D geometry in Rhino, similar to a thermal model. It, however, contains more details, modelled as surfaces, compared to a typical energy model as this detailing is essential for getting embodied impacts. The building is structured into eleven essential building elements, each consisting of a number of components. This categorization is based on the Swiss structure, cost estimation as per e-BKP-H SN 506 511 and reference service life (RSL) according to SIA 2032 (Basic et al., 2019).

The building material input is a manual step, giving control to the modeler/ analyst to determine the construction type of the extracted 3D geometry from Rhino. This may be done in two level of details: 1. From typical pre-defined components, where pre-defined layers have been put together as is standard or 2. Defining layers and selecting each material separately. Depending on the stage of the project, either of the approaches may be used as suitable. For the technical equipment, the energy reference area (ERA) of the building, which equals the heated gross floor area, is used at a component level. In case of Energy demand (ED), which consists of space heating, hot water demand and electric demand for appliances and lighting, the results are based on the Swiss standard SIA 380/1. However, the ED can also be calculated using other tools such as Honeybee/Energyplus or HIVE, and manually added to the overall emissions. This allows for complex calculations (such as for HVAC, on-site generation etc) and is the method used in this study.

Bombyx being a visual programming-based plugin for Grasshopper, is open-source. It is designed currently for the Swiss context but is also available on GitHub2 for personalization, open to new ideas and customization to other contexts. The database can also be tweaked by guest users for their own directories using accessible SQL scripts, managing their own SQL server on their systems (Basic et al., 2019). This gives enormous growth and customization potential to the platform without being a priced product (which is the case for other advanced LCA tools such as One-Click LCA) and is useful for further research.

2.1.5.4 Colibri Aggregator

Colibri is a grasshopper addon that enables Grasshopper users to turn their definitions into a Design explorer. It is an open-source project, started as part of the 2016 AEC Technology Hackathon in New York. CORE studio developed the project further and officially released it.

The goal of this project was to make it easier to generate Design Explorer-compatible data sets in Grasshopper. Although it has been done so far, the experience was complicated and error-prone. Colibri lets users iterate over some sliders in their Grasshopper definitions and uses a bunch of data recorders and an Excel writer to create a .csv file. Images (screenshots) as a result of this analysis can also be generated, named and linked to the .csv file.

The Colibri workflow can be divided into two stages: Iteration and Aggregation, where Colibri provides a component of same name for each stage. When it is run, it goes through every step in the user's slider and therefore, it becomes important to carefully select the sample size. The iterator loops over the connected slider inputs in a similar way to Galapagos. While the Iterator iterates upstream, the Aggregator component is responsible for collecting all of the data downstream that Design Explorer needs from this Grasshopper definition. The Aggregator therefore gathers the inputs from the iterator, outputs (performance metrics) from the Grasshopper definition, takes cares of generating images, naming images and Spectacle files, and writing all of that data into a data.csv file. Another application for the Aggregator may be to record optimization runs with Galapagos or Octopus (CORE, 2017).

In this project, Colibri is used to generate the result variations for different layouts, WWR, combinations of opaque and transparent PVs to find the defining parameters and useful combinations.

2.1.5.5 Rhino.Inside®.Revit

Rhino.inside is a new plugin/addon that bridges the gap of combining BIM and parametric platforms. Developed by Robert McNeel & Associates, the same company that developed Rhino, it embeds Rhino 7 into a Revit environment. This means that when running Rhino.inside in Autodesk Revit, Rhino 7 is loaded into the memory of Revit, similar to other Revit add-ons (Associates, 2021). One of the most useful functions is the ability to run Grasshopper inside Rhino.inside thus connecting parametric visual programming directly into the Revit environment, making the best of parametric modelling and BIM features. This capability also extends to other Grasshopper plugins such as Ladybug-Honeybee, Bombyx, etc to also be able to directly interact with Revit elements. With Rhino.inside.Revit, apart from grasshopper running inside Revit, Revit geometry can be extracted as well as new geometry can be created into Revit.

For this, the grasshopper running inside RIR has added Revit-aware components that help in identifying different actions that the component performs. These actions can be either – Query, Analyze, Modify, Create and a few others, that are represented by a visually intuitive colour scheme. These actions respond to a typical set of interaction choices with Revit, through the different tools of Grasshopper running inside RIR. This is also represented by a series of badges that have been applied to icons, that show the Type, Identity or other similar aspects of data that the component is designed to work with, as shown in the image below.

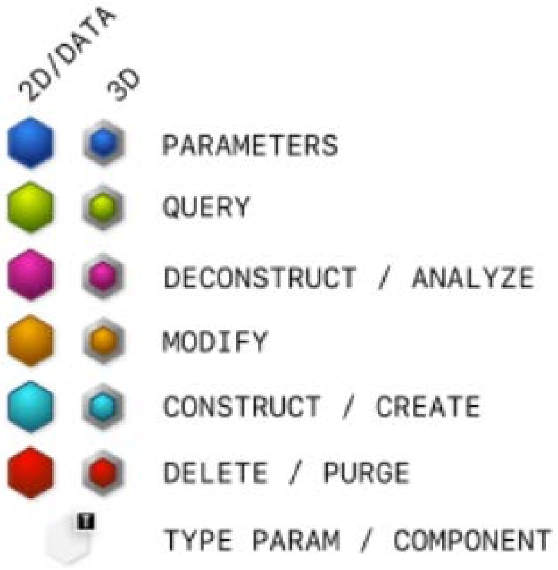


Figure 2.5 The series of badges applied to icons, that show the Type, Identity or other similar aspects of data that the RIR component can handle (Associates, 2021)

In addition, RIR can be used to extract Revit geometry or generate Revit elements, which can be further divided into numerous other options that provide the same functionalities through different grasshopper and RIR tools. Apart from that, using RIR and Grasshopper, it is possible to interact with essential elements such as Revit: Elements & Instances, Revit: Parameters, Revit: Types & Families, Revit: Documents & Links, extending both ways, from Revit to Rhino as well as Rhino to Revit. In terms of modelling, there also exist options for generating Basic & Stacked Walls, curtain walls & systems, Spatial elements, Openings, Structural Elements, Extracting or generating Revit Materials as well as Modifying geometry.

RIR also goes beyond basic geometrical linkage concerning Revit elements, and extends to Documentation, comprising of Drafting, views, schedules & reports. It can also interact with Worksets and Design Options which are essentially Container elements as well as Project settings and styles & patterns which are Revit settings. Further options also extend to scripting Python component in Revit or scripting into Revit API with its base development language - C#.

Apart from this, there may be many other solutions that can be found using RIR, one of which is also the possibility of running energy and performance simulation with Ghp plugins such as LB-HB inside the Revit environment. Rhino.inside.Revit is, thus, a very new technology with the official release announcement being made in August 2021 by Scott Davidson of McNeel (Davidson, 2021), although the Beta version was available nearly a year prior. Therefore, it is a relatively new platform and is an essential element helping address the BIM-BEM live-linking in this thesis project.

2.1.6 BIM-BEM Linkage and its advantages

Although BIM is a vast platform, its application for energy efficiency and building performance optimizations is not convenient as the BIM data framework makes it difficult for integration with building performance information and data. This is due to lack of necessary data standards and high technical difficulties that result in data loss during interactions (Gerrish et al., 2017). BIM platforms in the industry today are complex software with an information logic that cannot be tweaked easily by developers. For this reason, the extension of the ontology information network is mostly realized using standard exchange formats such as IFC and gbXML for BIM based green building design (Zhuang et al., 2021). Further linkages and editability to the exported files might be facilitated using Revit API, through Dynamo etc, to tweak and control the exports. However, this is a one-way interaction only, as the adjusted files after being processed in external design or analysis tools cannot be fed back to the BIM platform. Therefore, that is still an existing a gap in the BIM-BEM workflow that needs to be addressed for integrated design processes (Utkucu and Sozer, 2020). Addressing this gap would help in developing various types of building performance evaluation models that can be constructed with the proposed energy performance (BEM) tools, that are also highly integrated with the BIM platform and model. This would support flexibility, strong universality and operability (Zhuang et al., 2021).

By linking the original geometry from Revit (BIM), the intent is to keep the process close to practice as Revit is a preferred platform used for BIM in many architectural and infrastructure firms (Mistry, 2021). The Revit is linked to the Rhino using a software plugin – Rhino.inside.revit, that allows the user to run Rhino inside the Revit space, extending Rhino and Grasshopper, as well as Grasshopper plugins to Revit. This direct linking works as a live link establishing the foundation for a BIM-BEM connection.

This BIM-BEM connection is tested out on a solar façade case study. The intent is not on optimization due to the time constraints and lack of sufficient information; it is rather on understanding the potential of what can or cannot be done, with the already existing tools. Another benefit, of working with existing or familiar tools is that if the individual (or a company) has a license for them, they can continue working with the same tools without having to invest in a completely new platform. This also solves the problem again for avoiding more complicated platforms, as well as eliminates the need of training new professionals, handling new licenses, updating older libraries and other operational challenges that accompany shifts in software platforms in the work environment.

2.2 Solar PV Technology

2.2.1 Solar Photovoltaics and technology applicability potential

Photovoltaic Panels (PV) are an assembly of PV Cells that exploits freely available sunlight as a source of energy to generate direct current electricity. Often also called as Solar Cell Panels, Solar Electric Panel etc, the first working PVs were innovated around the 1950s and have been in production since the late 1960s. The initial PVs were innovative products but were unpopular as a reliable sources of energy generation due to low efficiency, performance issues and high purchase and maintenance costs. Over the years, the technology has seen significant improvements, not just in the panel technologies but also in the infrastructure and services based around the panels. With higher emphasis on cleaner sources of energy, PV has come out as a reliable, accessible and easy-to-use source of clean energy generation. The modular nature of panel gives it immense flexibility to not just be grouped together in huge solar farms away from the cities, in otherwise barren or non-productive pieces of land, but is also simple and easy enough for a homeowner to upgrade their local energy production capacity by installing it onto their roofs.

Added to that, there has been an almost steady decrease in the costs, with a notable increase in the PV efficiency and thus, an increase in the solar conversion potential of the PVs. Buildings, on the other hand, being accessible spaces in the Urban setting have always been popular spots for application of Solar PVs (Hestnes and Eik-Nes, 2017). Initially, PVs were mostly put up as technology demonstrations or sometimes, as a mark of a company’s sustainability commitment. Buildings have lately been pointed out as major polluters, due to their materials as well as energy dependent operations and the challenge has been taken up by the AEC industry as well as large and small building operators to push for state-of-the-art technologies and high operational efficiency. Wherever possible, Solar PVs are now being actively integrated into the buildings as well to even further their net operational energy demand, by the introduction of on-site production. Not only is this clean energy, but it also detaches the buildings from the grid, which inspite of being from renewable sources (off-site, such as wind or hydro) are still not the most efficient due to grid losses.

PVs were initially added as bolt-on or on a simple framework to the building roof, often as an add on measure. Due to their technical nature, with the maximum performance depending on proper orientation and placement (free from adjacent shading), it was often a compromise between below par performance with aesthetic integration with the building or the opposite scenario of optimum performance but unintegrated with the building form. As a reliable technology, when PV integration was prioritized in the initial project stage itself, there was much better possibility of an integrated building design where the building form and the optimum PV performance was considered at the design stage. This led to further developments in both, design integration approaches as well as development of PV systems designed to be seamlessly integrated into the buildings. BIPVs, or Building integrated Photovoltaics are the example of such systems.

BIPVs are PV cells that are designed specifically for building integration, by replacing parts of a traditional building envelope, such as the roof, skylights or façade with PVs. This provides a clear advantage for the integrated PVs over traditional practice of add-on solutions, is that eliminates the extra cost of material, construction and maintenance of two different systems – building envelope and PV cells with a single functional envelope system that has PV cells embedded. For this, a variety of PVs are available in the market today that can be incorporated into roofs as well as skylights, windows/glazing, sun-shades, louvres and the building façade in general (Bizzarri et al., 2011). This not only eliminates traditional energy-redundant building construction, but is also better for LCA, LCC and Building emissions as well.

2.2.2 Transparent PV systems

Transparent PV systems are the PVs designed to be incorporated into the transparent parts of the building envelope. These can include anywhere from windows, glazing, transparent roofs to entire transparent façades, that are now being employed in many mid- and high-rise structures. Building glazing, being an essential functional component of a building are more challenging than a conventional opaque BIPV. Being a key element for indoor illumination, directly influencing the indoor thermal environment and solar energy utilization and control, Transparent PVs have to function without significantly compromising these roles(Lai and Hokoi, 2015). As done in previous research, it has been a challenge to illustrate and optimize the performance of different building glazing types, which would include balancing heating, cooling and lighting related energy performance considering the U-values, solar heat gain coefficient (SHGC) and visible transmittance (VT) of these components (Lee et al., 2013). Having Transparent PVs as a component of the glazing adds the additional challenge of carefully balancing energy conversion, as current TPVs in the market have lower efficiency that traditional opaque PVs, and their power conversion potential is inverse in nature to their Visual transmittance, that is, TPVs with higher power conversion tend to have offer lower access to views and daylighting. While this may be acceptable in certain regions with high glare, it may not be necessary at times of the day and may even lower the overall performance of the building by increasing the need of lighting due to lower daylighting admittance into the building.

2.2.3 Performance factors for PV systems

The global performance of PV systems primarily depends on two aspects – the climate aspect and the PV system total efficiency aspect. The initial relates more to finding the potential of PV application as PV systems may or may not be suitable for peak performance in every location. This depends on the location-related solar potential. This can be calculated as a preliminary check considering the hourly global irradiance data of the location on an inclined place (W/m^2), and for different possible façade considerations, considering orientation (azimuth angle) and slope (tilt angle). From this data, the total solar irradiation (kWh/m^2) can be estimated (on average) per month and per year. With this aspect, the façade integrated PV is suitable for only certain zones where the sun is not vertical (closer to equator) and not too low in the sky (closer to poles) but is at an intermediate height that gives maximum solar access on average, round the year, as shown in fig xxx below (Mohammed and Alibaba, 2018). For example, in case of Budapest, considering a theoretical availability of around 100kWh/m^2 per month between March and October, whereas this value drops to 60kWh/m^2 in the winter months. For a transparent solar PV, assuming a conservative global (total) performance efficiency of 5% in standard façade placement, the energy conversion is 5kWh/m^2 and 3kWh/m^2 expressed in converted electricity per m^2 of the façade, per month average during summer and winter respectively. This can be an initial check for the feasibility of this solution for a typical building of a particular typology (especially if the energy demand is known) in a certain location.

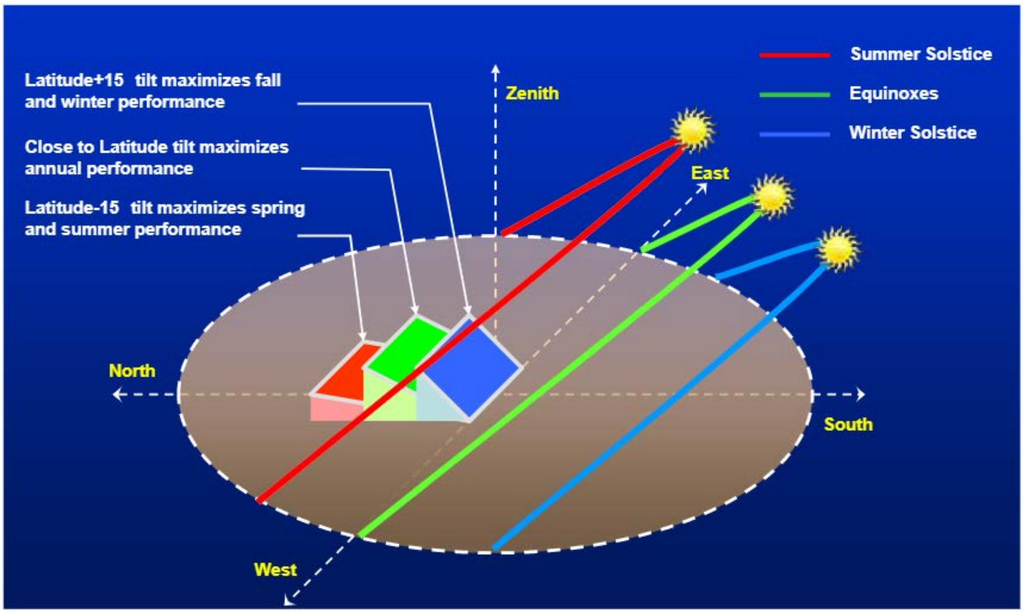


Figure 2.6 Seasonal performance variation (also applies to variation along the latitudes) (Brooks and Dunlop, 2012)

Apart from the climate and location aspect, the conversion of solar potential to electricity also depends on a number of factors which represent the second aspect – PV system total efficiency aspect.

To find the final (converted) electrical energy output of the façade-integrated PV, the total efficiency of the PV system needs to be considered, including, apart from the PV module efficiency (typically declared by the PV manufacturer), the total PV power conversion system upto the final electricity output to be delivered to the consumer. This number also relies on the PV system properties, such as – area of the solar cells, solar radiation energy received on the surface of the solar cells, spectral distribution of solar radiation, the solar incident angle, dust collected on the PV surface among other things (Lai and Hokoi, 2015). In realistic conditions, the PV module efficiency can be further reduced due to the following reasons (ABUD, 2020):

- Real boundary conditions, i.e. temperature and irradiation levels
- Partial shadows from surrounding buildings
- Maintenance of the PV surface, i.e. difference between a perfectly clean surface (at STC) and a surface exposed to real environment
- Connection of multiple PV modules
- Inability to extract maximum power continuously
- Inverter power losses, responsible for converting the electrical power extracted from DC to AC
- In case of façade PVs, this can also be accentuated due to contextual shading from adjacent structures

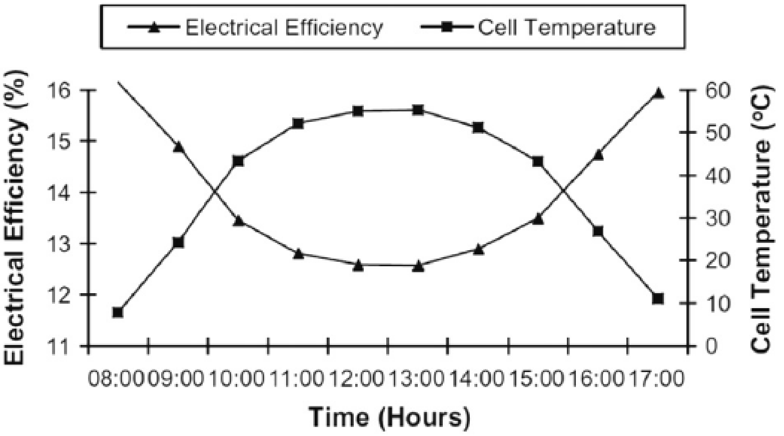


Figure 2.7 Variation in cell temperature and cell efficiency for a typical summer day (Lai and Hokoi, 2015)

Apart from these, the electricity conversion efficiency of PV is also affected by the temperature of the solar cells. The conversion efficiency of the PV module decreases with increase in the temperature of the solar cells. A self-heat dissipation mechanism therefore needs to be included in the design during the development of the BIPV to mitigate this (Lai and Chen, 2011). Therefore, all these factors need to be taken into consideration for truly maximizing the PV potential and to ensure functional on-site generation.

2.3 Façade Systems

2.3.1 Types of Façade Systems

Façade or elevation or envelope are the study focus for this thesis. This topic attempts to discuss the various types of façade systems commonly available today and briefly summarizes the advantage and disadvantages between these different typologies. Two basic façade categories can be: the single-skin façades (SSFs) and the double-skin façades (DSFs).

	Single Skin Façade	Double Skin Façade
Definition	Single layer of glazing	Double layer of glazing
Complexity	Relatively less, due to a single layer that can be directly engaged with the envelope/façade behind it	Higher complexity due to an additional layer which requires a dedicated system to mount it (and operate if operational)
Ventilation	Not individually ventilated	The air volume between the layers can be ventilated using natural, mechanical or a combination (mixed more/hybrid)
Shading Device	Can be mounted on the exterior or the interior of the SSF	Has the option of mounting the shading devices between the layers of glass
	Provides no additional protection to exterior mounted shading devices	Can provide additional protection to shading devices mounted inside the layers (from weather or external elements)
Acoustic	Provides no additional acoustic advantage	Can provide an additional layer of acoustic damping, especially when used in noisier environments
Maintenance	Can be a challenge, especially in mid-/high-rise buildings largely due to the challenge of accessing the façade and all of it elements from the floor level	Easier to access for maintenance as the DSFs often have an access way between the two facades
	Higher challenge in case of closed SSFs, that are completely sealed with no openings	Even with a closed envelope, the inner layer can have openings/access hatch without compromising the performance or aesthetics
Energy Performance	Have limited role due to the single skin, which has both aesthetic and performance roles	DSFs may have higher energy performance due to the presence of dual layer skin, which provides additional insulation
		There is a possibility to utilize the space between the two glazings for solar heating, or ventilation or physcial phenonema induced as a result of one or both, possibly leading to better performance
LCA/Emissions	Lower due to less material intensive nature	Higher due to the second layer of glazing as well as the added structural and material need for mounting it
Cost	Depends, but generally lower for SSFs due to lower material cost	Generally higher due to more material intensive nature of the DSFs

Table 2.5 Single Skin Facade Vs Double Skin Facade

Single-skin facades, abbreviated as SSFs, typically consist of one glazed layer, with one or more glass panels whereas Double-skin facades (DSFs) consist of two glazed layers (ABUD, 2020). Their differences are as have been listed out in table 2.5.

2.3.2 Types of Windows and glazing systems

Based on the design and placement of windows, the façade can be further divided into 3 broad categories; although in practice, designs can be a combination of two or more of these as well:

1. Traditional windows
2. Ribbon windows
3. Curtain Wall (with highly glazed surfaces)

The advantages and disadvantages of each type has been elaborated in the table below based on the basis of their - Construction and maintenance, Thermal Performance, Daylighting performance and Building-integrated photovoltaics (BIPV), as defined below:

	Traditional Windows		**Ribbon windows**		**Curtain Wall (with highly glazed surfaces)**	
	Advantages	Disadvantages	Advantages	Disadvantages	Advantages	Disadvantages
Construction and Maintenance	Easier to manufacture, transport and assemble, as well as maintain and replace	May prove inefficient for large façade surfaces	Relatively easy to manufacture, transport, assemble, maintain and replace	Limitied design, layout and sizing flexibility (especially in case of rooms with varied functions)	High performance systems, with flexibility in design, especially pre-manufacturing and assembly	Require higher degree of engineering, maintenance and construction skills
	Allows maximum design flexibility while requiring less engineering		More efficient design solution for larger façades while requiring less engineering	Need for outside cleaning can be challenging in some cases	Relatively lighter and better engineered as a system solution, compared to the other options	Almost always require exterior cleaning and maintenance
	Have the possibility for unit replacement		May have the possibility for unit replacement			Lack the option for unit replacement
Thermal Performance	Better balance between Opaque and transparent parts	Large opaque parts generally provide better insulation	Better balance between Opaque and transparent parts	May require shading control	Thermal bridges are usually well-solved	Customisation at later stages is generally a challenge
	Possibility of integrating shutters and other shadind devices, even in the later stages of the project	Challenge of Thermal bridges	Possibility of integrating shutters and other shadind devices	Border effect needs to be considered for daylight performance	Homogeneous behavior and little percentage (%) of frame	Natural ventilation needs to be designed

Thermal Performance	Openable for Natural ventilation	Increased frame percentage (%) might lead to worse performance	Openable for Natural ventilation	Customisation at later stages is generally a challenge	Possibility of integrating shutters and other shadind devices	Opaque parts of high-performance curtain walls have relatively worse thermal performance
			Fewer wall-window connections reduce thermal bridges		Option for natural ventilation, if considered early	A fully transparent façade in general would have a worse thermal performance
Daylighting Performance	Easy to control Daylighting performance by selecting glazing units and attachments	Might lead to insufficient daylight if not designed properly	Relatively more abundant daylighting with homogeneous distribution of illuminance	Might require daylight control elements due to control visual discomfort	Relatively more abundant daylighting with homogeneous distribution of illuminance	Might require daylight control elements due to control visual discomfort
		Might also lead to non-homogeneous illuminance distribution, increasing discomfort		Might also lead to non-homogeneous illuminance distribution, increasing discomfort		
Building Integrated PV (BIPV)	Possibility of combining higher performance Opaque PVs on the non-glazed surface with transparent PVs in the glazing	Not (or little) suitability of integration of transparent PVs (windows need to be large enough)	Possibility of combining higher performance Opaque PVs on the non-glazed surface with transparent PVs in the glazing	Best performance would depend on a combination of Opaque and Transparent, therefore needs to be carefully designed	Most suitable for integration of Transparent PV Panels	Not (or little) suitability of integration of opaque PVs (opaque parts need to be large enough)

Table 2.6 Comparison of advantages between Traditional Windows, Ribbon Windows and Curtain Walls (with highly glazed surfaces) (ABUD, 2020)

2.4 Solar façade analysis

2.4.1 Overview of the project

The solar façade analysis definition used in this project was developed to analyze the potential of integrating transparent solar facades into windows and curtain walls. Developed as the Rolla smart façade (SF) solution at ABUD & commissioned by ERON, the project initially aimed to develop an aluminium-framed smart façade system, that has the ability to measure the external environmental conditions of the building where it is installed, produce electricity by the integration of PV on the building façade and control the HVAC system, addressing environmental and economic needs, especially in terms of CO_2 emissions.

The study that was done in the this Project can be divided into two broad stages (ABUD, 2020):

Phase I: Feasibility study

In the 1st phase of the study, the feasibility of SF and BIPVs was checked for a range of different locations and climates where the developed SF had a potential to be used and an analysis of the climatic potential of solar building-integrated PV was performed. This study resulted in more favorable outcomes for balanced climates of Budapest, Barcelona and San Francisco, compared against relatively challenging climates of Helsinki, Dubai or Miami, considering all other physical variables of the PV (different orientation, tilt angles) remained same. In more detailed analysis, different other factors can also contribute to varied results, such as the effects of temperature on PV efficiency, including the presence of cooling systems or heating systems to avoid snow-soiling.

The study also considered the possibility of combining the different integration options between the smart façade and the building management systems (BMS), mainly consisting of sensors, controllers and actuators, leading to a number of possible façade configurations. The ultimate direction for the project depends on the final market and other specifics, but the study intended to explore the range and scope. A final aspect was a hypothetical case study of a building in Budapest, that demonstrated the significant difference when comparing the potential building-integrated PV conversion to a 'conventional' free-standing fixed PV plant conversion.

Phase II: Digital Twin Development Modelling & Simulation: Annual energy demand and annual energy conversion potential

The aim for this stage was to assess façade/façade module in its global performance which included not only electricity converted by the PV Layer, but also the total net energy used in the room /building that the façade is a part of. The method used for this analysis was to establish a co-simulation (thermal, daylighting, energy conversion) workflow in combination with a parametric modelling approach that can be utilized to explore the impact of a range of domains on the possible configurations for the façade module. This study is further detailed out in the subsequent section. The thesis attempts to explore further the potential of this analysis by extending its interoperability with a realistic model, thus facilitating a BIM-BEM integrated workflow.

2.4.2 Structure of the solar façade study

This project was eventually steered towards a research project to simulate in detail the thermophysical and optical behavior, and the energy conversion potentials of a series of façade (or façade module) configurations The broad aim was to understand how the performance of the façade was affected by different constructional features, so as to best quantify the impacts of the selection of one or another technology on different domains. An important aspect of this study was to evaluate the potential and limitations of transparent systems, characterized by the possibilities to convert solar energy into electrical energy (PV glazing), focusing on finding out to what extent a PV-based glazing solution can compete with alternatives (ABUD, 2020).

The main research question for this study was broadly: To what extent can PV glazing configurations represent a suitable and competitive solution for an advanced façade module?

This was further broken down into more detailed sub-questions as follows:

i. What is the global energy and daylighting performance of the façade solutions that integrate PV glazing systems?
ii. What is the performance gain provided by façade solutions that integrate PV glazing systems compared to alternative options (such as facades without any PV layer or facades that incorporate opaque, conventional PV layers)?
iii. What is the impact of the current characteristics of PV glazing solutions on the overall performance of a façade based on these solutions?
iv. What could be the development trends and potential areas of interest for PV glazing-based solutions?
v. What is the configuration that, in a global perspective, provides the best performance in terms of energy use, energy conversion, and daylighting exploitation?

These questions are essential to understand the nature of this performance assessment workflow and the KPIs chosen which have been customized specifically to answer these questions. This was an explorative exercise where the reliability of transparent PV systems as a major on-site generation was being verified. In this study, in the initial phase, the research focus was primarily placed on the solar to electric energy potentials of PV glazing technologies compared to conventional PV modules. In the second phase, this was broadened as research for the assessment involving the overall behavior of the façade systems, as the total impact of the system in the indoor climate.

This study was designed entirely using the Grasshopper environment to analyze various essential KPIs (discussed later) utilizing the Ladybug-Honeybee tools package. The standard case was designed for a representative room so as to extract information with general value that went beyond the specific case-building/-room simulation, so as to answer the research questions. However, the same workflow definition can also be extended to a variety of rooms, representing realistic spaces of existing, refurbished or upcoming projects to perform an analysis of the potential of Façade BIPVs (transparent, Opaque or combination). This aspect of the study is the potential add-on for this thesis project as a case study to understand the challenges and the potential of using a BIM-BEM live-linkage for an integrated performance assessment.

3 Methodology

3.1 Research design

The aim of this thesis is to generate a suitable workflow to connect a BIM model (from Revit) to a BEM model (using Rhino-grasshopper and plugins) and to document the steps as well as the possibilities and challenges experienced in this process. The intent was not optimization *per se* for this analysis but it was to keep the processes as wide as possible, using a variety of plugins to show the possibilities of this workflow. The steps followed for this were as follows, also shown in the figure 3.1:

- Construct a model in Revit
- Establish live-link and extract the Revit geometry & material information using Rhino.inside
- 'Clean' the model, reconfigure the geometry/materials as suitable for the next steps of the simulation, in this case, one for Energy-Daylight simulation using Ladybug-Honeybee and the other being LCA using Bombyx
- For Energy-Daylight, set up the energy model, including schedules and loads as per the case (Closed office in this study). This study was conducted with WWR (defined from Revit geometry), 3 types of glazing – 2 with TPVs and 1 without any TPV and considering Opaque PVs on the remaining South façade in different proportions (5 options considered)
- For the LCA, the extracted geometry was 'baked' into Rhino in Bombyx specific layers. The material area was extracted by Bombyx, material values assigned by User and Operational Emission values extracted and cumulated
- Multiple simulation runs were conducted using the defined variables and the performance was documented using a design exploration tool – Colibri, to find the best scenarios

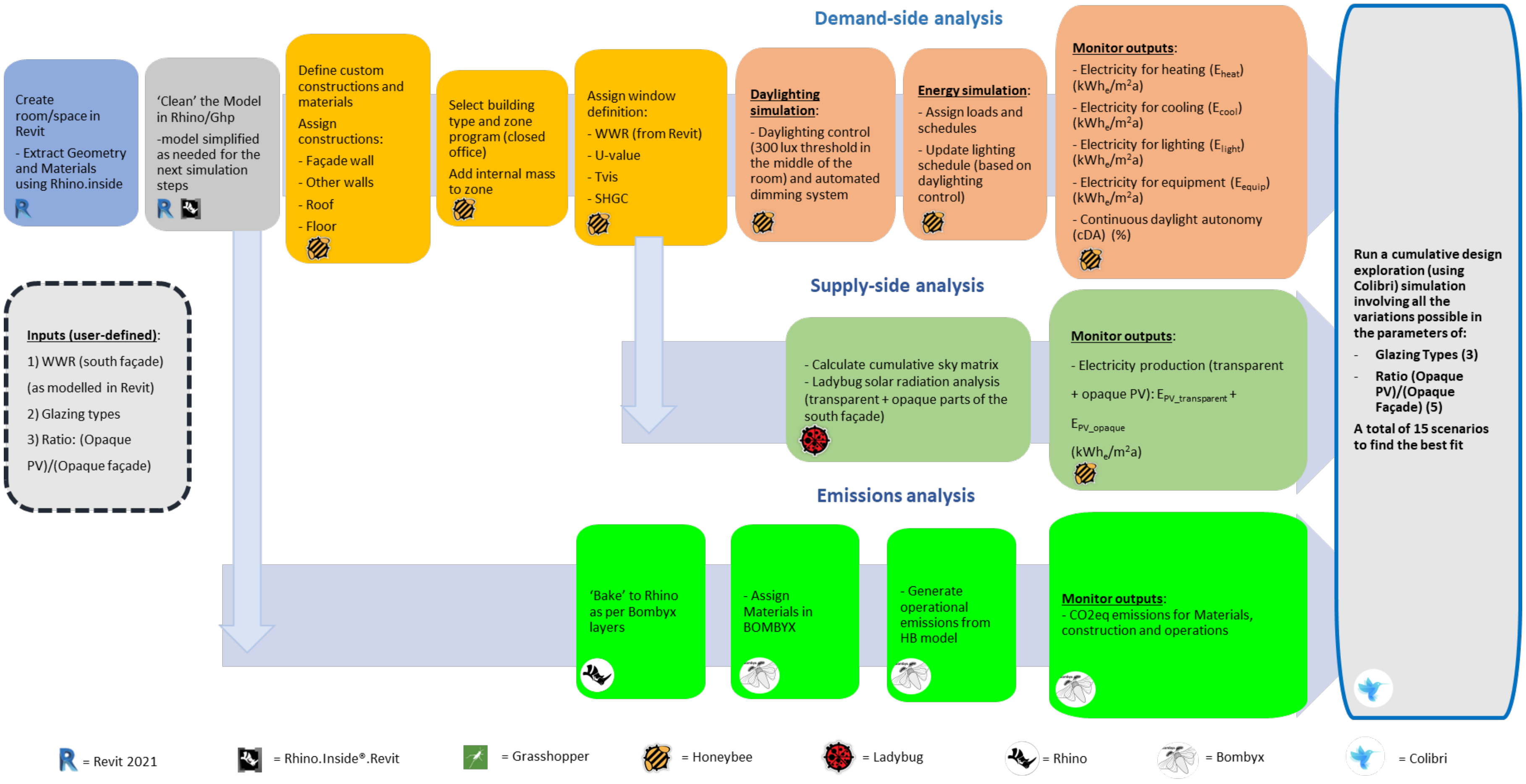


Figure 3.1 Simulation workflow between BIM-BEM

3.2 Energy and Daylight simulation

3.2.1 Geometric specifications

The geometry under consideration has surfaces exposed to all the directions, surrounding an indoor area with windows facing south. This is a simplified development on the solar façade study defined previously. The South orientation which has the SF, comprising of the transparent and opaque façade can be changed easily, or developed to represent multiple facades with window, for this study it is limited to South only. Being located in the northern hemisphere, the South façade provides for the highest solar conversion potential, the highest solar load/gains as well as the highest daylight availability, making it a relevant case study for this analysis.

To maximise the results of such a study, approach is to parametrically sample a variety of façade configurations whereas the workflow can also be used for single factor case studies where different aspects are selected as desired/designed. The façade configuration analyzed in this study consists of a combination of transparent zones, derived from Revit in this case and opaque areas which may or may not have conventional PVs. The factors considered are:

- Glazing technology of the façade, including transparent PV glazing as well conventional glazing
- Window-wall ration (WWR) either extracted from the Revit geometry based on the windows used in the model, or parametrically generated in the grasshopper environment over the derived geometry. This is also decided using the proportion between the glazed surface and the opaque surface of the façade, as a numerical input
- The amount of opaque surface covered by conventional (opaque) PV modules, as an optional layout to test the effectiveness of using combinations to maximise the impact of the façade BIPVs. Here, the transparent PV and the opaque PV can be simultaneously or alternatively applied

Window-to-wall ration (WWR) (%)				
BIM	As extracted in the geometry			
BEM	20	40	60	80

Table 3.1 WWR for the simulation

Ratio: Opaque PV/Opaque Façade (%)					
PV Efficiency = 16%					
Permutations	0	20	40	60	80

Table 3.2 Ratio of Opaque PV-to-Opaque Facade (%)

Glazing Types				
Permutation		PV Glazing		Conventional Glazing
Parameters	Units	Onyx Solar GL.01	Onyx Solar GL.02	Double Glazing with selective coating
U-value (thermal transmittance)	W/m2K	1.2	1.2	1.2
Visible Light Transmittance (Tvis)	%	10	16	62
Solar Heat gain coefficient (SHGC)	%	12	16	30
Transparent PV Cell efficiency	%	4.14	3.51	N/A

Table 3.3 Glazing types used in the study (comprises of 2 TPVs and 1 conventional glazing)

In the table 3.3, are the glazing types used in this study. It includes a pair transparent PV solution as well as one example of a conventional glazing, standard products currently available in the market. The selected PV glazing types (Onyx Solar GL.01 and Onyx Solar GL.02) represent the two contrasting scenarios, one with higher visible transmittance and the other with higher PV Cell conversion, while the conventional glazing is selected considering relatively higher visual transmittance with no energy conversion characteristics.

Considering these factors, leads to a combination of study for 3x4x5 = 60 scenarios in case of WWR not derived from the Revit glazing, or 3x1x5= 15 scenarios when the Revit glazing geometry is used directly. This gives the possibility to see the implications of a variety of façade combinations providing excellent inputs for decisions that maximise environmental as well as cost performances. Further details of the exact simulation settings can be found in Appendix A. (Building Energy and Daylight simulations) and Appendix B. (Simulation workflow).

3.2.2 Key Performance Indicators (KPI)

KPIs or Key Performance Indicators are the outcomes that are used to compare and analyze the performance of the selected combinations. The KPIs used in this study are used to convey the overall environmental performance metric of the façade (or the façade module). This is based on three domains that are derived from the monitored outputs of the numerical simulations discussed before. They are:

Total Electricity Demand – which is calculated as the energy demand for the building climatization, omitting the electricity demand for electrical equipment/plug loads. Here, the energy demand for ventilation air movement is excluded as it is a quantity independent from the façade configurations:

$$E_{tot\_demand} = E_{heat} + E_{cool} + E_{light}\ (kWh_e/m^2a) \qquad \text{………} \quad (1)$$

The Total electricity production, including both the transparent PV and the opaque PV:

$$E_{PV} = E_{PV\_transparent} + E_{PV\_opaque}\ (kWh_e/m^2a) \qquad \text{………} \quad (2)$$

Combining both (1) and (2), the total electrical energy balance can be calculated:

$$E_{tot} = E_{tot\_demand} - E_{PV}\ (kWh_e/m^2a) \qquad \text{………} \quad (3)$$

The four KPIs adopted in this study are as below:

E_{tot} (kWh_e/m^2a) – is the annual total electrical energy balance referenced to the floor unit of the building (per m^2), which includes the difference after considering the contribution of the energy generated from the façade PVs

E_{pv} (kWh_e/m^2a) – which is representative of the annual electrical energy converted by the façade per unit area of the building (includes both transparent and opaque PVs)

cDA (%) – The annual continuous daylight autonomy (cDA) which describes the number of the occupied time across a year when the indoor space is illuminated using natural daylight. This is decided for a specific point of the indoor space meeting or exceeding a specified illuminance level (300lux in this study), and although there is no minimum value, >50% is considered as a minimum value for this metric in scientific literature.

CO2 (CO_{2eq}/m^2) – Which is the LCA aspect of this study, considering the materials and the operational emissions considered for the chosen type of façade layout in this study. The materials are recreated in Bombyx with specifications closest to the BIM or the energy model as is suitable, while the emission from the operations is defined based on the E_{tot} (kWh_e/m^2a), calculated as a product of the grid emissions.

This case study intends to merely demonstrate what kind of complexity can be included into a performance workflow and is not in itself an optimization exercise. However, it is interesting that a performance assessment of such multi-domain complexity can be performed directly with working BIM models for a project, as a result of availability of the models *via* a real-time linkage between BIM-BEM.

3.3 BIM-BEM Linkage

Shown below are the different components of the Grasshopper workflow of the multi-domain workflow that was developed for this study. This setup runs inside Rhino, which in-turn is running inside Revit, using Rhino.inside. Therefore, all tools from the RIR toolset are available and are used to automatically extract from Revit (BIM) geometrical and material properties into the Grasshopper BEM environment:

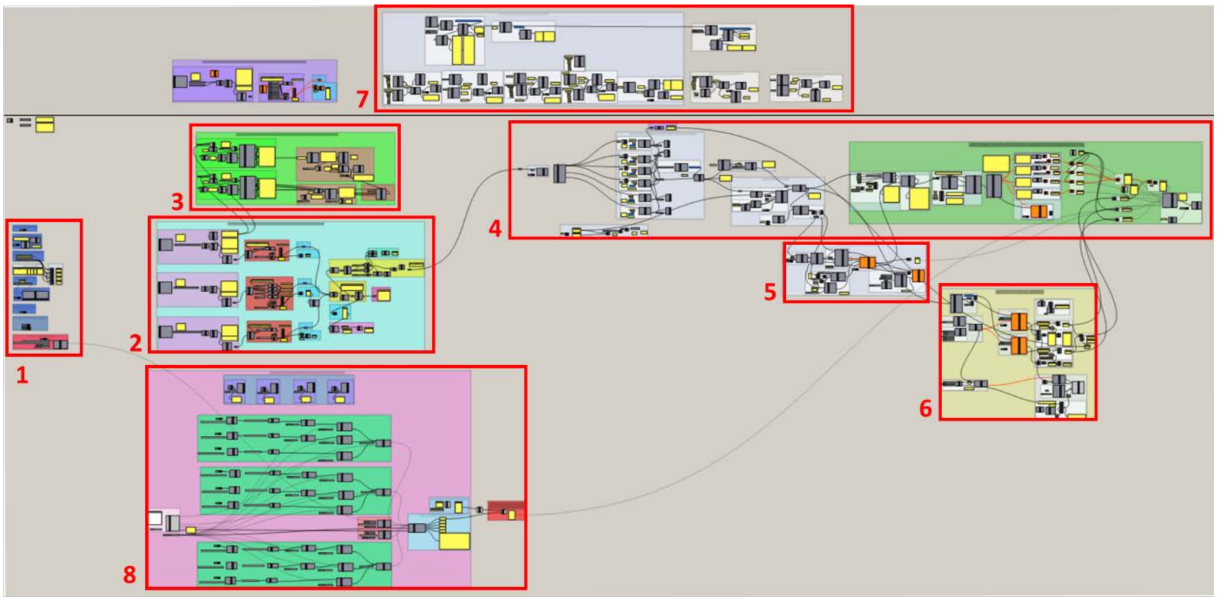


Figure 3.2 Grasshopper canvas showing the different components of the multi-domain workflow

1. Combined Control Panel

2. Revit Geometry to Rhino using RIR
3. Revit Material to Rhino and then for making Honeybee materials for energy simulations
4. Energy analysis using Honeybee which uses the EnergyPlus engine, which relies on geometry extracted in 2.
5. Daylight Analysis in Honeybee using Radiance/Daysim, which relies on geometry extracted in 2.
6. PV power generation calculations from both Transparent and Opaque PVs, both or single, as and where applicable
7. Honeybee Custom Material creation panel. These are the materials utilized in this case study, where they were custom created but this can also be linked to the materials from 3.
8. LCA Workflow using BOMBYX toolset, relying on geometry extracted in 2. and Operational emissions from energy demand in 4.

3.3.1 Extraction of Geometry from Revit

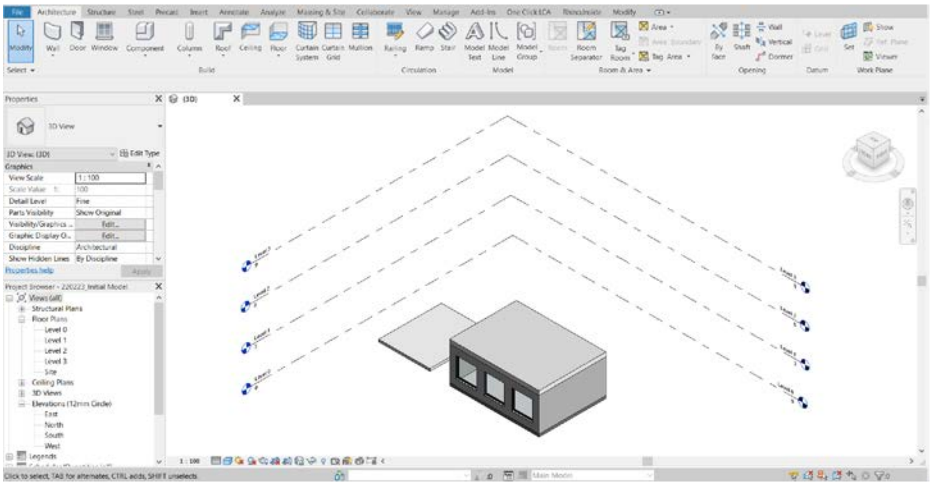
For the solar façade study discussed before, to explore the generalized answers to the research questions, a typical scenario of an office space was considered. The basic geometry for the study was kept the same in this case study, except this that the geometry was created in a BIM environment using Revit as the base platform. The choice for a simpler model was: 1. To develop a simple but objective method for extracting the BIM model into the BEM environment, 2. To perform all the possible analysis that can be done using the developed performance assessment workflow with minimum changes. This can be scaled up for a future case as the method of extraction is irrespective of the scale of the BIM model, employing steps that would relate to the general base components of any architectural BIM model. The decreased complexity of the analysis saves on time while providing results that can be extrapolated with general validity.

The flow chart in image xxx describes the typical steps involved in the process of taking a typical room (or a small cluster of rooms) in a standard architectural BIM format, made with BIM elements and converting it into a geometry that can be read by HB to create a thermal model suitable for energy performance calculations.

These steps, though charted out here sequentially, were the result of many hit-and-trial exercises, addressing the different challenges presented at the various steps of this process. This workflow was also developed with the intention of being an automated definition that needs minimal input. A few parametric controls may be needed to be provide input depending on the complexity of the geometry.

However, these inputs are controlled by intuitive graphical controllers that do not require the knowledge of programming or the input itself.

1. Developing the BIM Model:



3D View: (3D)

Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Fine
Parts Visibility	Show Original
Visibility/Graphics ...	Edit...
Graphic Display O...	Edit...
Discipline	Architectural
Show Hidden Lines	By Discipline

Project Browser - 220223_Initial Model

- Views (all)
  - Structural Plans
  - Floor Plans
    - Level 0
    - Level 1
    - Level 2
    - Level 3
    - Site
  - Ceiling Plans
  - 3D Views
  - Elevations (12mm Circle)
    - East
    - North
    - South
    - West
- Legends

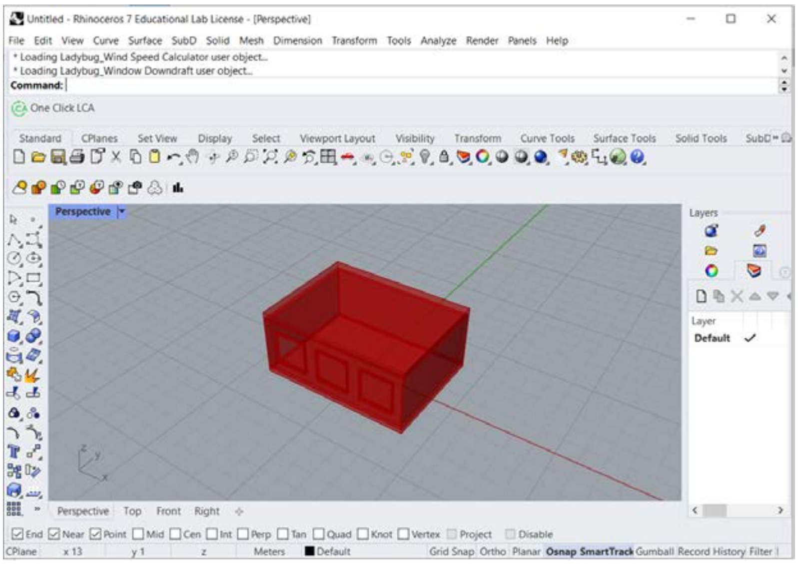
Click to select, TAB for alternates, CTRL adds, SHIFT unselects

Figure 3.3 Revit Study Model

The model used is the BESTEST case, which is representative for many different cases in energy modelling. This is a simple one-zone building model of exterior dimensions 8x6x2.7m with four facades, a floor and a ceiling. The ceiling and floor dimensions add extra height to the model, with the internal dimension being approximately 2.775m. It consists of the typical Revit elements: Floors, walls, Roof and Windows on the South façade. The windows here are representative of design choice in realistic projects and have been placed assuming this model was considered after the Façade designer’s inputs for the glazing was considered.

2. Extracting into the Rhino-Ghp environment using Rhino.inside.Revit:

The BIM model can then be extracted into Rhino using Rhino.inside.Revit plugin in Grasshopper. This tool is essential to facilitate this live-link as it enables running Ghp inside the Revit environment directly interacting with the Revit elements as presented in the model. All the elements that are brought into the Rhino-Ghp environment generate new challenge as, unlike in BIM, they lack identity as elements in Rhino-Ghp. They get reduced to complex geometrical surfaces, where for e.g., a monolithic Revit wall would just be a cuboid with 6 surfaces, while a complex element such as a window or door assembly becomes a closed/semi-closed object with multiple surfaces (Outer frame, Inner frame, glass, sealants/sliders, hinges, handles etc. all as geometry).

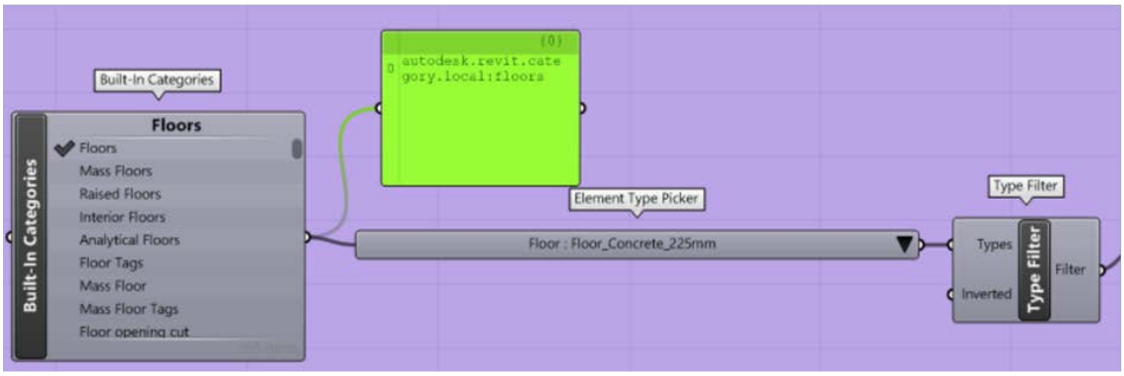


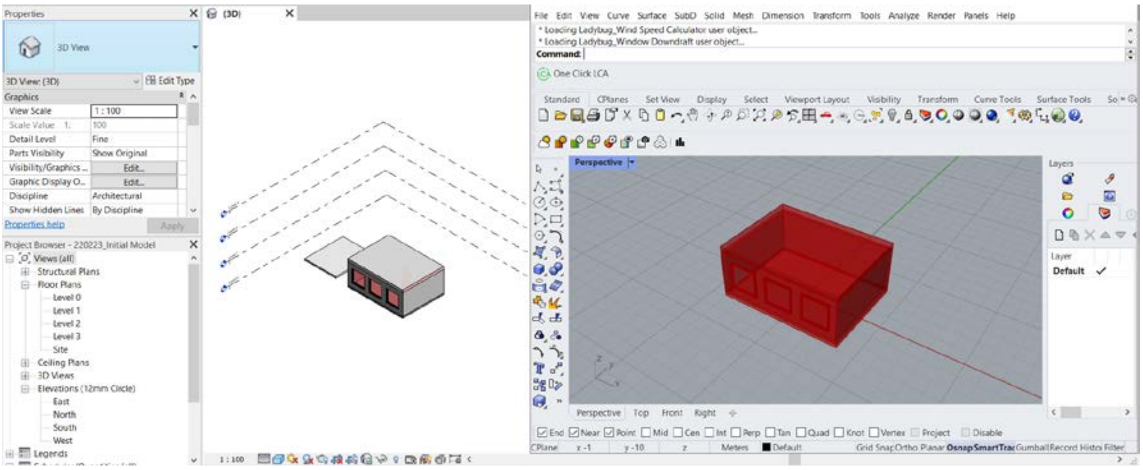
```
* Loading Ladybug_Wind Speed Calculator user object...
* Loading Ladybug_Window Downdraft user object...
Command:
```

Figure 3.4 Revit study model extracted into Rhino. Here, the model looks exactly as the Revit elements, but with no element properties. It consists of geometry only

3. Controlled import of necessary elements:

Another issue is the challenge of isolating only what is necessary from the Revit (BIM) environment into Ghp (BEM) environment. BIM models, depending on the state of detail (or information) can having varying complexity which may or may not be desirable for performing energy performance analysis, which on the contrary relies on simple geometry with different information assigned to these geometrical elements.





Graphics	
View Scale	1 : 100
Scale Value 1:	100
Detail Level	Fine
Parts Visibility	Show Original
Visibility/Graphics ...	Edit...
Graphic Display O...	Edit...
Discipline	Architectural
Show Hidden Lines	By Discipline

```
* Loading Ladybug_Wind Speed Calculator user object...
* Loading Ladybug_Window Downdraft user object...
Command:
```

Figure 3.5 Element Type Picker, one of the RIR tools used to selectively import elements, and shown here being used to selectively extract the required floor from the Revit model

This issue is solved by using the combination of the ‘Element Type Picker’, a standard with the RIR package and the possibility of creating custom Revit element types. The Element Type Picker, based on the chosen type of the ‘Built-in categories’ selected, isolates that particular Revit element out of the pool of available elements. For eg, a selection of Floor_Concrete_225mm would only isolate this type of floor, present wherever in the Revit model, and ignore all the other floor types. This not only helps controlling the elements required to be extracted into the Rhino-ghp environment, but also can be used to isolate parts of complex Revit models by temporarily changing the revit elements there to a custom element. This is essential to avoid unnecessary cleaning up of complex models, which can be time-consuming and might lead to loss of information in certain cases.

4. Isolating boundary surfaces as needed for the simulation:

The next step is to convert the ‘clean’ the Revit import elements now to simpler models suitable for generating a HB-compatible Thermal model format. The HB thermal model works with single surface closed BREPS for constructing the thermal zone, and can identify walls, floors and roofs out of the model. Depending on the complexity of the model, this step can be time consuming as the Revit elements are imported with their entire geometry but lack identity and thus are just surfaces that have to be manually cleaned, one element at a time. To avoid this, the definition was developed to automate this step so as to recreate a closed BREP.

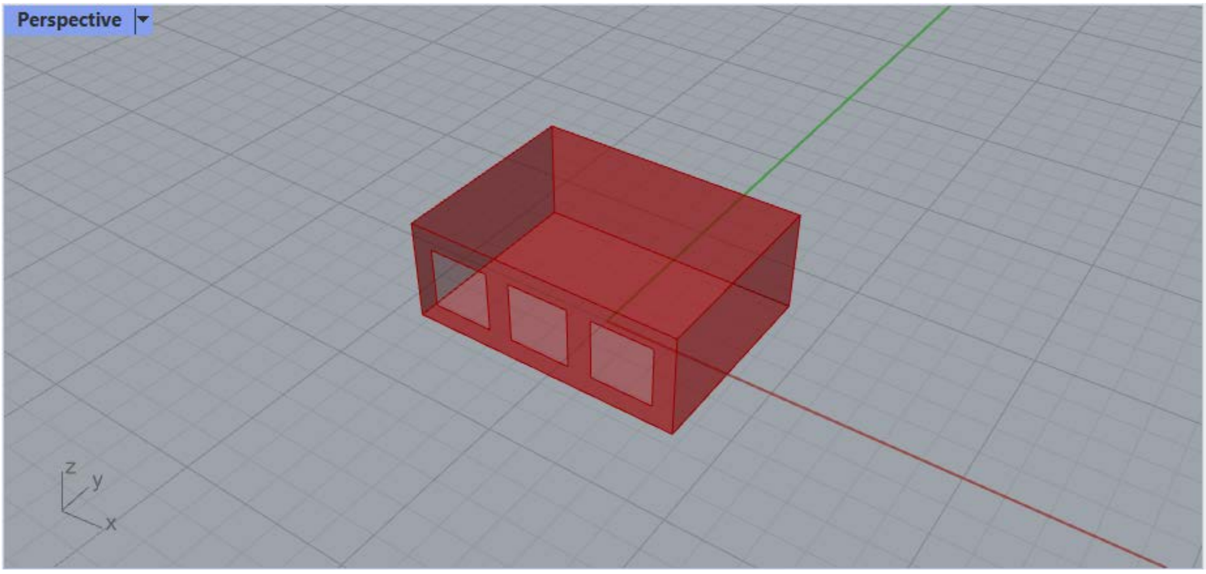


Figure 3.6 Single surface planar geometry extracted from the Revit import

This step leads to a new issue where the windows, which associate with Revit walls as voids, transforms into a non-enclosed model. This step of the definition, thus, works for all elements which are intact and do not have voids, or elements that may be associated with them as voids. Another thing to consider is the Revit modelling requirements may need to be adjusted for the surfaces to isolate in a way suitable for the definitions to conveniently convert them into a BREP with edges touching. For this, all elements in Revit should have the outer extent of their geometries in contact with each other, for eg. Walls may need to extend through the floors to end at the floor's bottom surface rather than top. The walls corners in revit, are also needed to be similarly refined, and the option for 'Mitre' corners and 'Allow join' needs to be enabled in Revit for this step to work.

5. Recreating a closed form:

Since the steps upto the previous step led to non-enclosed models due to voids in the wall, a different approach was considered to avoid this issue. For this step, a set of vertical elements was recreated using the Roof and the Floor as reference elements in Ghp. As a result, as part of the definition, this is still an automated action that required no user input, but can be altogether avoided in certain cases, depending on the level of detail of the model.

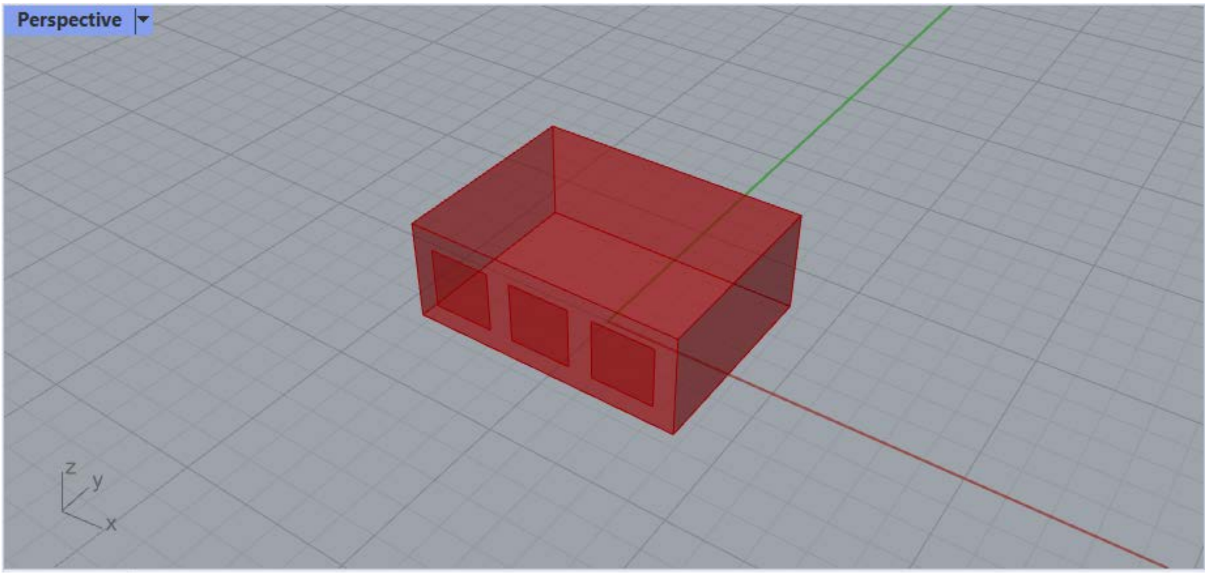


Figure 3.7 Recreated geometry that is suitable for further simulations in Honeybee

It is to be noted here that, as a result of this step, the windows used here, which also need to be single planar surface overlapping the walls has to be recreated from the original window voids. For this step, it is essential that the Revit model, with its walls and windows, need to follow the steps mentioned in the previous section. Eventhough the walls and windows here are recreated within ghp, they still rely on the original BIM model in Revit for their geometry.

6. Final Geometry ready for HB simulation:

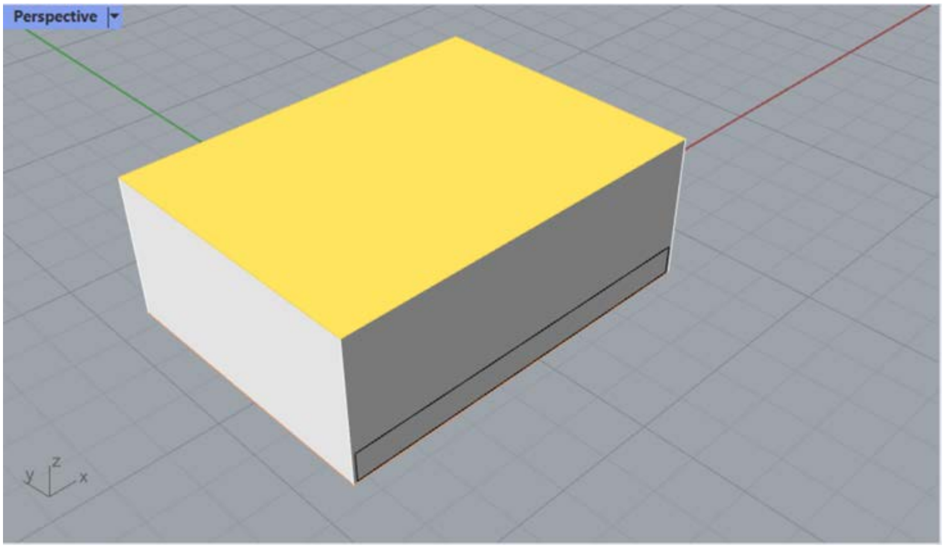


Figure 3.8 Revit geometry, now converted and then created into a Honeybee thermal mass

The model is now ready to be fed into the HB thermal mass definition to create an appropriate thermal zone, with the essential elements: wall, roof, floor and windows which can be detailed further as per thermal zone specifications. These surfaces can now be assigned materials created from the Revit specifications or with custom materials from the HB library. This step is discussed further.

3.3.2 LCA Calculation

The LCA Calculation for this study is performed using the Grasshopper tool, BOMBYX, an LCA Calculation tool developed by ETH, Zurich. BOMBYX relies on an open-source platform which is suitable for local (or organization-wide) customization. The database can therefore be edited or connected to other established databases. BOMBYX relies on a Rhino model with building elements divided into 10 (+1 – Technical Equipment, not modelled) categories. These are also the layers needed in Rhino from which necessary information is extracted into BOMBYX. As the working environment is majorly based on RIR, Ghp and LB-HB, there is no need for a Rhino model until this step here. However, for the LCA, a series of steps need to be followed in a specific sequence (including the Rhino model) as described.

1. Geometry in Rhino:

As BOMBYX relies in a Rhino geometry with windows in window layer, balconies in balcony layer, floors in floor layer and so on, there is a need to generate a Rhino model from the extracted Revit geometry.

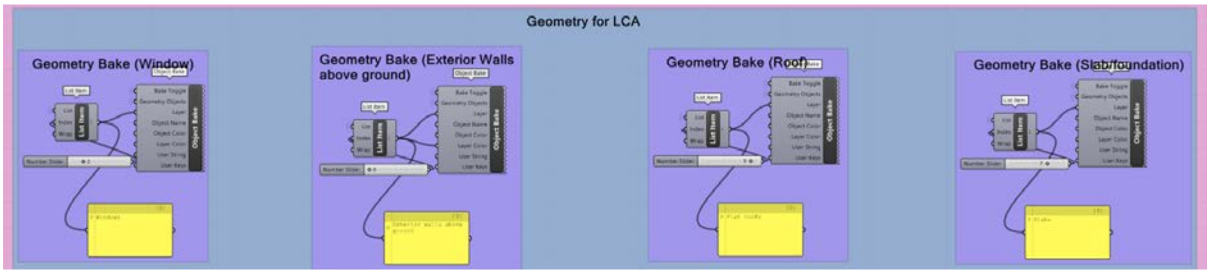


Figure 3.9 'Cleaned' Revit geometry baked into Rhino through grasshopper

However, the geometry requirement for BOMBYX is a single surface planar geometrical models, similar to the recreated geometry for the HB thermal model, in the previous step. This geometry can then be Connected to an 'Object Bake' Ghp tool so as to get the Rhino geometry for the calculations.

This is an important step that decides the quantity of the materials; therefore, a few things need to be considered. For example, the wall from the HB model cannot be used here, as it lacks punctures for window as HB needs a closed model, whereas BOMBYX would require a representative model. Therefore, the wall connected as this stage is from a previous step of the extracting the model (step 4). Similarly, any other differences (such as the presence of balcony, foundation etc) will need to be carefully extracted from Revit, 'cleaned' and used here, apart from the HB definition model, as it is not necessary there, but may be needed here. For simpler geometry, as in this case, it is workable to use almost the same model, keeping check on the accuracy of the information that is being provided by the geometry.

2. Bombyx specific Rhino layers:

As mentioned, BOMBYX required the Rhino model to be in a certain specific layer for it to be able to extract the required quantities for the LCA calculation. It is convenient that BOMBYX provides an option to generate these layers for the users and automatically assign them to the Rhino model. As the layers are colour-coded, it is easy to visually check if the Rhino model building elements are in their respective correct layers after baking. These layers can be generated and updated anytime, however, it was observed that it worked best when the layers were generated before the Rhino model was baked from the extracted and recreated Revit geometry.

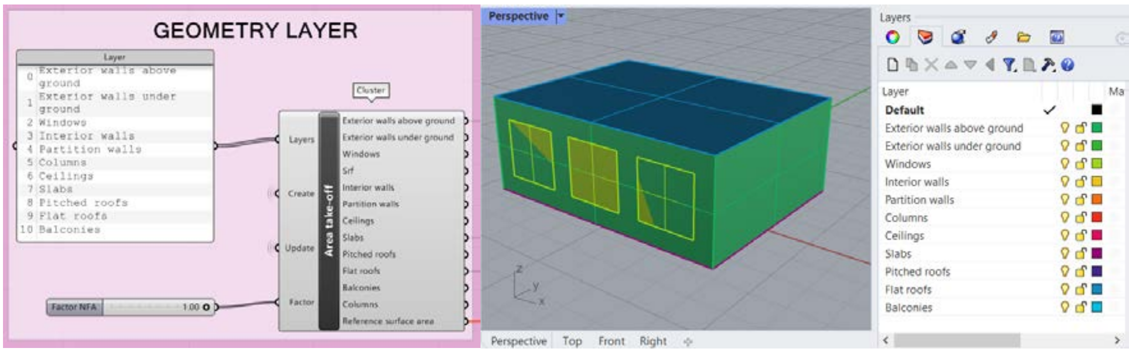


Figure 3.10 Rhino model in Bombyx specific layers that helps Bombyx automatically extract data from the Rhino model

3. Customized Operational Emissions:

Operational Emissions (B6) is an essential part of the LCA and BOMBYX relies on its own custom tools for the calculation of emissions based on the Swiss standards (SIA 380/1). However, in case there is already available information about the operational demand from other sources such as HB, this step can be replaced by calculating operational emission directly (Basic et al., 2019). As for the solar facades study, it is important to account for the E_{tot} , it can be used here by converting the kWh_e/m^2a of the energy demand into its operational emissions using the Grid emission factor. For the sake of demonstration, the value $0.27KgCO_{2eq}/kWh$ has been used here, which is the emissions for the Hungarian grid (Map, 2022). This number can be updated by any relevant number available for the local grid emissions of that particular place. This gives us a value for the emissions by that particular choice of transparent PV as the B6 emissions entirely depends on the net energy demand balance which can be a distinguishing factor between two available options of PV. Considering their material emissions (A1-A3) is more or less similar, unless considered for different window assemblies with differences in geometrical or physical variables.

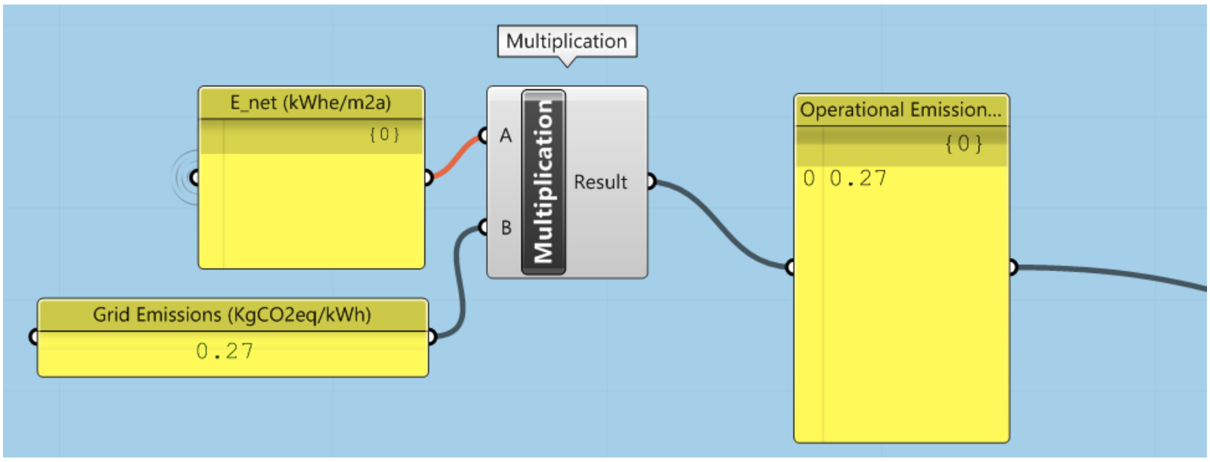


Figure 3.11 Operational emissions calculated directly from HB energy demand studies

4. Net Emissions Calculations:

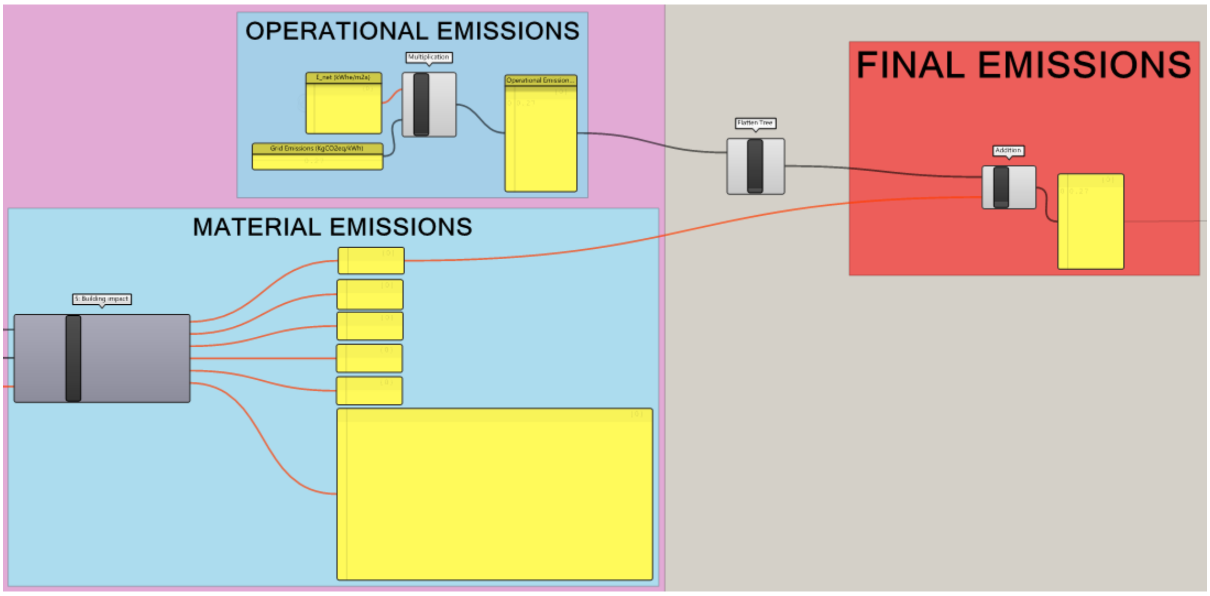
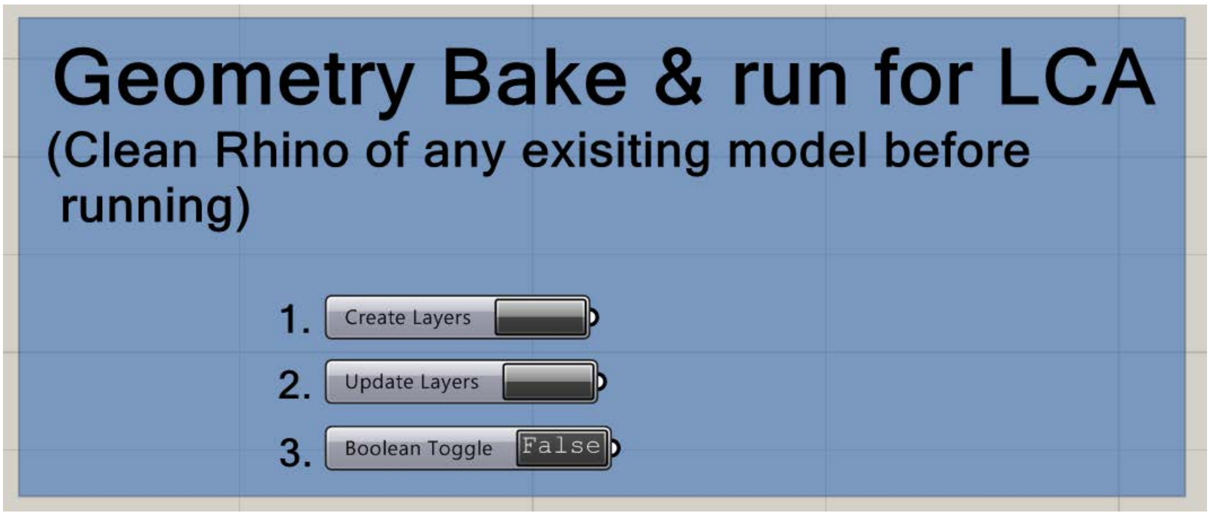


Figure 3.12 Final emission calculations in Bombyx showing the effect of different PV layouts on the energy demand and thus, affecting the operational emissions

The net emissions calculation is therefore a combination of Material Emissions (including transport, maintenance and replacement) as calculated from the Baked Rhino model and the operational emissions calculated from the net energy balance derived from the HB calculation. When choosing between two competing TPV panels or a certain type of PV layout, this can be defining factor, considering the importance of emissions of that choice. As projects become more conscious about their emissions today, this would definitely become a key parameter and has therefore been considered for the demonstration case study here. As mentioned before, not all data may be available in the database (such as PV cells and non-Swiss specific materials) which may need to be manually added into the SQL database from which the emissions data is derived.

5. Control Panel:

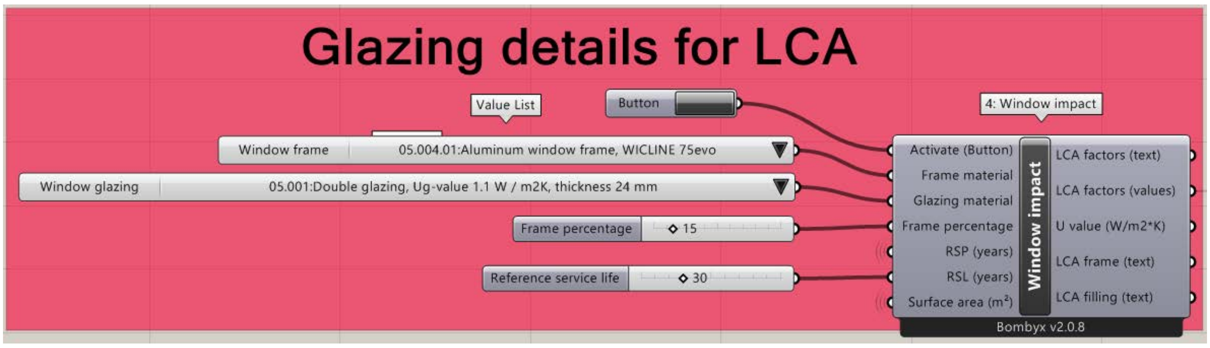
The last step in this process is the user-dependent step of running the steps above, but to avoid errors, it is best to do it in a certain sequence. Firstly, it is important to make sure that the Rhino canvas is free from any geometry and must be cleaned before running these steps. A reminder note is also added to the Control Panel stating the same. The next steps are to create and update the Rhino layers which is best to do before baking the model. The reason for this was that it was observed during this study, that the tool worked either way but if the geometry was baked before the layers were generated, then the building elements did not pick the layer colours which makes it difficult to perform the visual check to ascertain the right elements are identified in the layers. Therefore, it is best to run the 'create layers' and the 'update layers' buttons before starting the LCA calculation process.



Geometry Bake & run for LCA
(Clean Rhino of any exisiting model before running)

Figure 3.13 Bombyx tool panel for the user. The sequence is essential to get accurate data

The next step would be to enable the Boolean Toggle (3.) which is a single switch for all the connected 'Bake Geometry' panels mentioned in Step 1. It is also essential to check if the 'Bake Geometry' is connected to the right sources for these geometries before running this step to avoid discrepancy in the model.



Window frame: 05.004.01:Aluminum window frame, WICLINE 75evo

Window glazing: 05.001:Double glazing, Ug-value 1.1 W / m2K, thickness 24 mm

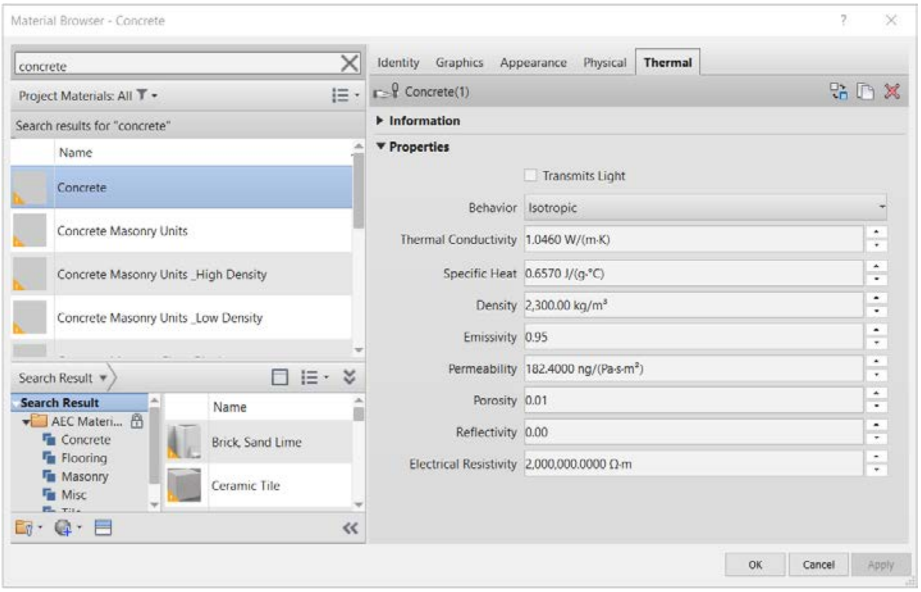
Frame percentage: 15

Reference service life: 30

Figure 3.14 Window/Glazing specification in Bombyx. Areas are automatically extracted from the Rhino model

As this stage, for the LCA, calculation, there is a need for manual inputs and configurations, especially for the materials as BOMBYX relies on its own defined item selector connected to its database that cannot be collect information in the Grasshopper without manual user input. For convenience, an added step can be to place the RIR Element Material Panels beside the Material selection panel of BOMBYX to help the user select the material closest to the BIM material, albeit as a manual user input. If, however, the purpose of LCA is merely for comparative calculation, then only specifying the window material (also a control panel as shown) can be toggled leaving all the other elements default, the final results being indicators to compare the relative differences of their respective emissions.

3.3.3 Material extraction from Revit



☐ Transmits Light

Behavior: Isotropic

Thermal Conductivity: 1.0460 W/(m·K)

Specific Heat: 0.6570 J/(g·°C)

Density: 2,300.00 kg/m³

Emissivity: 0.95

Permeability: 182.4000 ng/(Pa·s·m²)

Porosity: 0.01

Reflectivity: 0.00

Electrical Resistivity: 2,000,000.0000 Ω·m

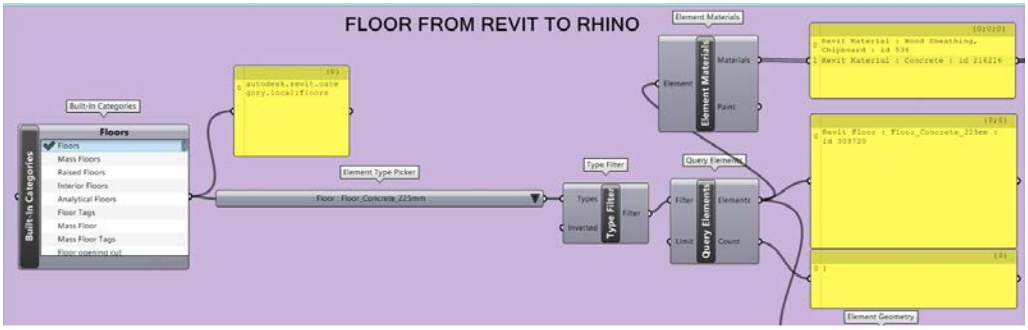
Figure 3.15 Revit material Thermal properties

It is common for BIM to have its predefined materials that have their defined properties. These properties can be divided into 3 major categories: Appearance, physical properties and thermal properties. For the purpose of this study, HB materials are needed to be manually created and defined in the definition. This is essential because in practice, it is often common for offices to maintain a BIM specific material library that is often utilized in their projects. This makes it easier to accurately recreate the actual chosen materials from BIM in HB.

In this case study, the material extraction has been done solely for demonstrative reasons and does not replace the HB material properties defined before. The reason for this was that the Revit library in this project lacked sufficient information to accurately recreate materials in HB that were thermally suitable. The process, nevertheless, holds true for any typical cases. This process can also be automated by using RIR tools with a few customizations as defined below:

1. Identifying element materials:

When extracting the geometry using the 'Element TypePicker', an additional RIR tool called 'Element Materials' can be used to find out the names of the materials and their layering from the extracted Revit element. This is, however, only in a text string listing the material info in the format - *Revit material : Material Name : Id XXXXX.*



```
{0}
0 autodesk.revit.cate
  gory.local:floors
```

```
{0;0;0}
0 Revit Material : Wood Sheathing,
  Chipboard : id 536
1 Revit Material : Concrete : id 216216
```

```
{0;0}
0 Revit Floor : Floor_Concrete_225mm :
  id 303720
```

```
{0}
0 1
```

Figure 3.16 Identifying the Revit materials for the imported Revit elements

2. Segregating the layers:

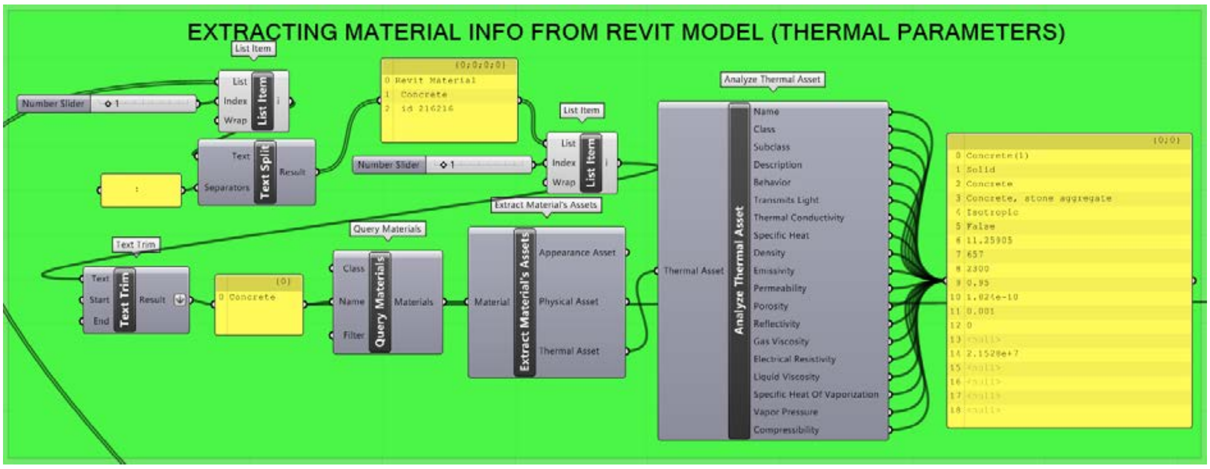
After finding out the layers of materials in the previous step, each layer has to be individually recreated. Therefore, the materials undergo a few automated steps in this definition where the actual text string representing the material name is segregated, for eg. From *Revit material : Material Name : Id XXXXX* , the *Material Name* is separated as it is essential for the following steps. The next steps are independent of the layers until the last step, step 7, where the HB material for an element, such as a floor or wall, is created.

3. Querying the material:

RIR offers a tool called 'Query Material' which, through text inputs of material names can retrieve those materials from the Revit project library. This is essentially the step where the textual name of material from the previous steps gets converted to a Ghp element.

4. Extracting thermal properties of the materials:

As for this study, the material is needed to recreate Thermal models for the HB library with specifications as accurate as possible to the original Revit model. This would typically be a manual process, where each material property would have to be noted and fed back into the HB definition, making it a time-consuming process that is inflexible and prone to errors. However, using RIR tool 'Extract Material's Assets', the Thermal properties of the material can be retrieved with specific outputs for Behaviour, Light Transmittance, Thermal Conductivity, Specific Heat, Emissivity and numerous other properties that can be used.



```
{0;0;0;0}
0 Revit Material
1  Concrete
2  id 216216
```

```
{0}
0 Concrete
```

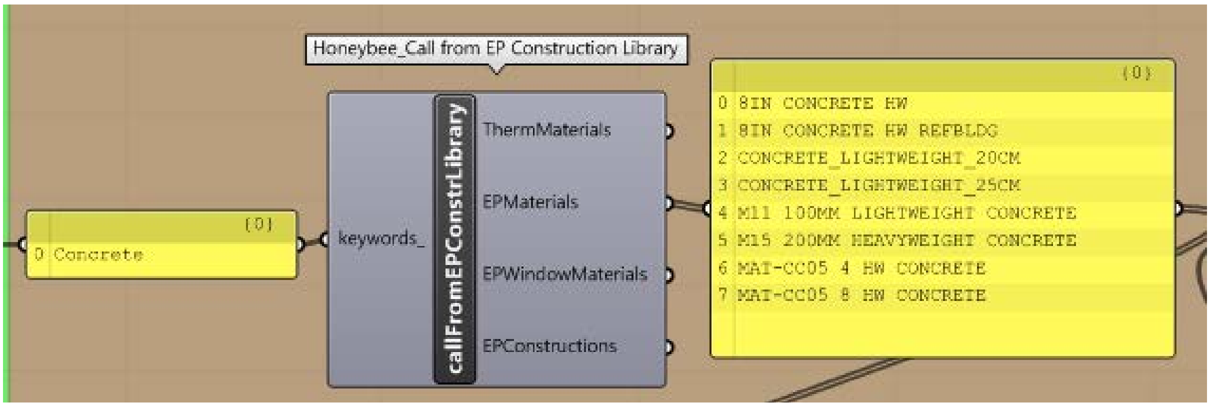
```
{0;0}
0 Concrete(1)
1 Solid
2 Concrete
3 Concrete, stone aggregate
4 Isotropic
5 False
6 11.25905
7 657
8 2300
9 0.95
10 1.024e-10
11 0.001
12 0
13 <null>
14 2.1528e+7
15 <null>
16 <null>
17 <null>
18 <null>
```

Figure 3.17 Extracting the thermal properties of the Revit material

The next step is to recreate these materials in the HB format. Depending on whether a material is already present or not in the HB library, there could be two approaches to the next step as described in 5 and 6.

5. Recreating the materials in HB (using Default HB materials):

After extracting the material name, the HB tool 'HB_Call from EP Construction Library' can be used to first search for the material. It is possible to find more common materials, such as Concrete, directly from this library, that can then be used directly in the HB thermal model. It is important to note that the HB Construction Library may not always have materials that are thermally accurate and its best practice to check the properties before plugging them into an EnergyPlus model.



```
0 8IN CONCRETE HW
1 8IN CONCRETE HW REFBLDG
2 CONCRETE_LIGHTWEIGHT_20CM
3 CONCRETE_LIGHTWEIGHT_25CM
4 M11 100MM LIGHTWEIGHT CONCRETE
5 M15 200MM HEAVYWEIGHT CONCRETE
6 MAT-CC05 4 HW CONCRETE
7 MAT-CC05 8 HW CONCRETE
```

Figure 3.18 Materials such as concrete may not need to be recreated as the HB library contains a default library

In certain cases however, the said material may not be preloaded in the Construction Library and an alternate approach is to be followed as described below.

6. Recreating the material in HB (custom construction):

Certain materials may not be available in the Construction Library due to either limited market availability or different name (which can different at different locations around the globe). In this situation, HB tool 'HB_EP Opaque Material' can be used to recreate this Revit material as a custom material in HB. The thermal inputs of this material can be directly retrieved from the RIR 'Analyze Thermal Asset' tool and after defining a name, can be added to the HB Construction Library.

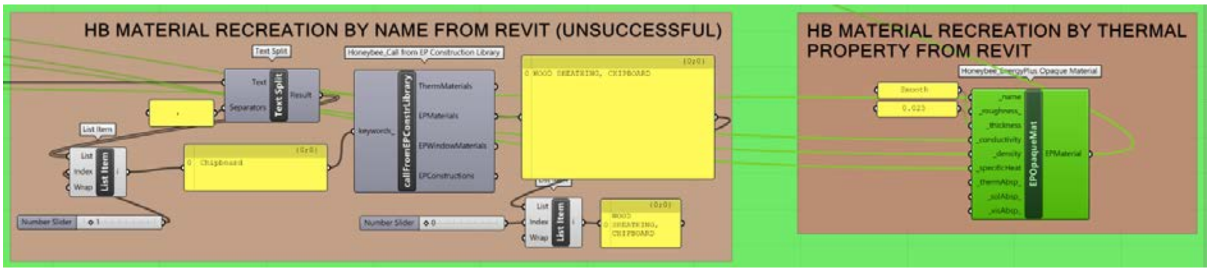
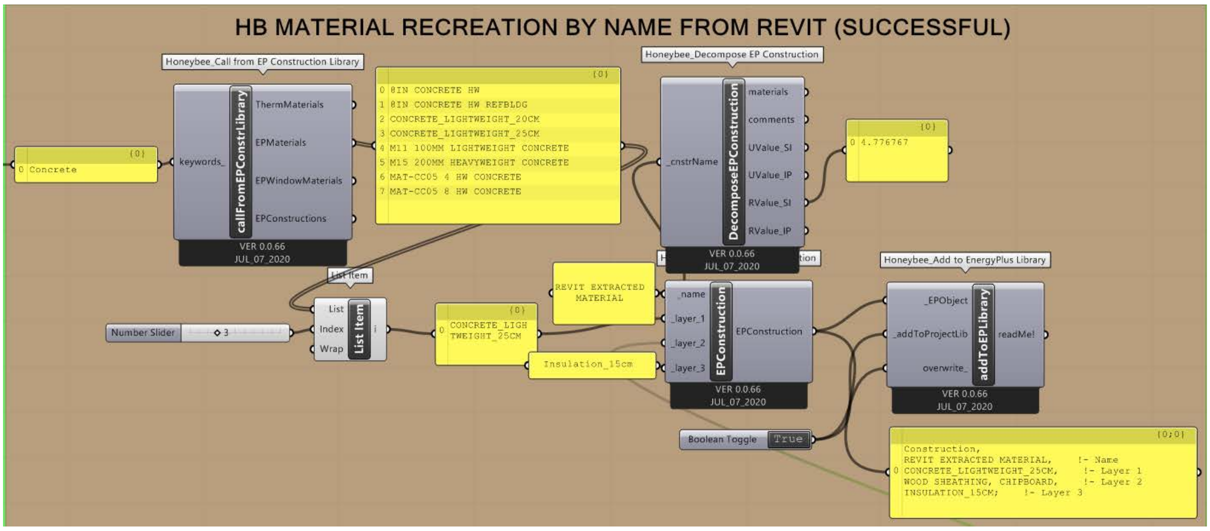


Figure 3.19 Other materials, which are not available in the HB library, can be recreated by directly using the Revit thermal properties

7. Recreating the material by layers in HB same as the Revit element:

The last step in this process is of recreating the element material by layers, which is typical to constructing HB thermal material libraries. Using 'EP Construction' the recreated materials can be put back together to recreate the Revit element, such as for wall or floor. This can then be added to the EP Library and used for performing the energy simulations.



```
{0}
0 Concrete
```

```
{0}
0 8IN CONCRETE HW
1 8IN CONCRETE HW REFBLDG
2 CONCRETE_LIGHTWEIGHT_20CM
3 CONCRETE_LIGHTWEIGHT_25CM
4 M11 100MM LIGHTWEIGHT CONCRETE
5 M15 200MM HEAVYWEIGHT CONCRETE
6 MAT-CC05 4 HW CONCRETE
7 MAT-CC05 8 HW CONCRETE
```

```
{0}
0 4.776767
```

```
REVIT EXTRACTED
MATERIAL
```

```
{0}
0 CONCRETE_LIGH
  TWEIGHT_25CM
```

```
Insulation_15cm
```

```
{0;0}
  Construction,
  REVIT EXTRACTED MATERIAL,     !- Name
0 CONCRETE_LIGHTWEIGHT_25CM,    !- Layer 1
  WOOD SHEATHING, CHIPBOARD,    !- Layer 2
  INSULATION_15CM;     !- Layer 3
```

Figure 3.20 Revit materials recreated for the HB library

4 Results

Façade or a façade module can be high performance based on many variables. Here, various variables & interconnected phenomena can contribute to the performance in terms of the E_{tot}. It is also interesting to note that the variables considered can sometimes complement or contradict other variables. For example, theoretically, a façade can be high performance by simple using passive strategies to reduce the energy demand, without the use of PVs or conversely, have relatively higher energy demand but compensated by the PV's energy generation. This can also be a case for emissions, where low emission materials are used, or conversely, high (relatively) emission, but high-performance materials are used paired with on-site generation with PVs to lower the overall emissions of the space and the façade system. Therefore, from a global perspective, 'the more PV output, the better the system' is a misleading notion as it is oversimplified.

As a result, a multi-domain approach is beneficial to properly assess the environmental performance of a SF that covers the essential performance metrics considered their dependence on other metrics as well. Here, inhomogeneous quantities that cannot be easily converted into a single metric can be solved by using a multi-objective optimization. In such cases, it may be impossible to find a configuration that provides the 'best' performance in each domain without some significant compromises, the result can however be found using the 'non-dominated' solution, which is the best compromise between the different domains. This ensures that the solution presents a feasible solution that maximizes each output without degrading any metric beyond the threshold limit where it may become unacceptable.

The metrics considered here can be:

- minimum E_{tot}
- maximum E_{PV}
- maximum cDA
- minimum CO2

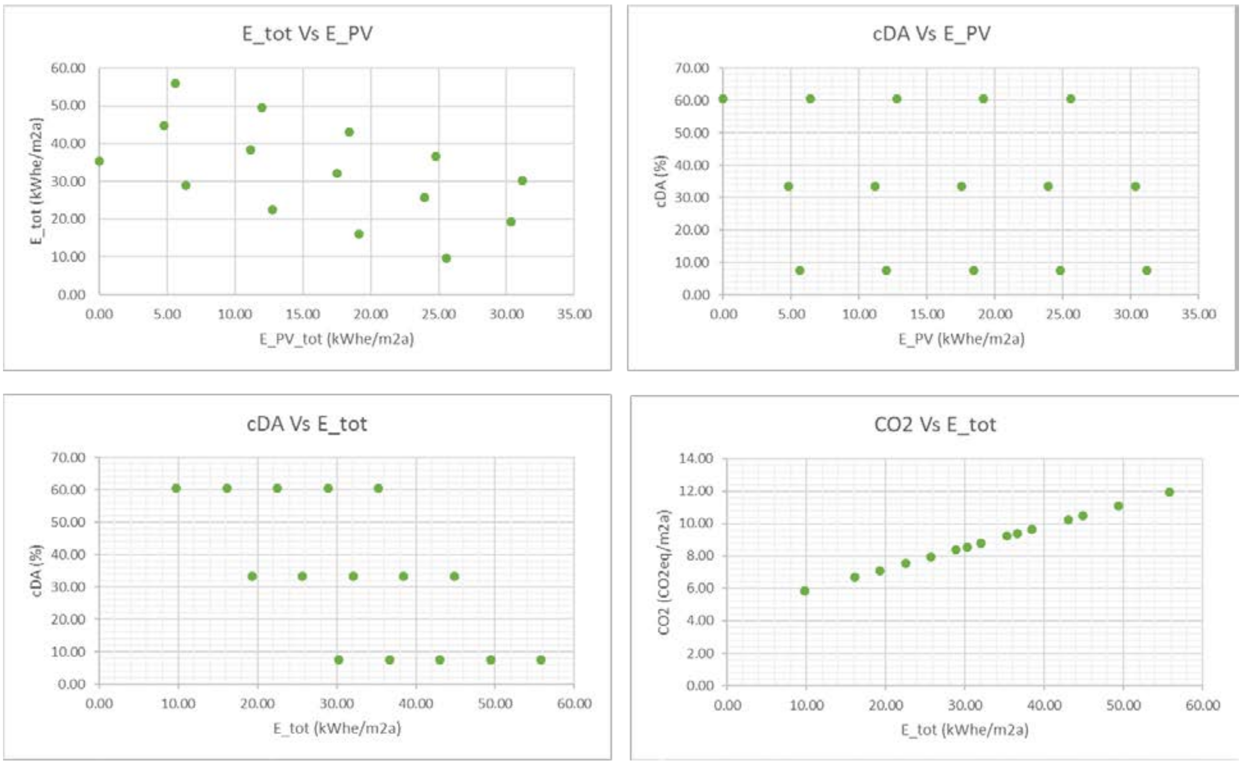


Figure 4.1 Charting out the result of the study that can be used to take further design decisions

Based on the charts shown here, generated from an excel table that is the result of the simulation workflow can be used by designers to take further decisions based on the performance of the selected glazing and the layout. Further details of the results can be found in Appendix C (Data in tabular form) and Appendix D (Graphical representation of all the daylight simulation studies).

Furthermore, any tweaks to the design can also be generated into excel such as here, and then used to compare different options. For example, if mid-design, single window is replaced by a ribbon window, the change in performance can be similarly generated and compared to decide on the design implications.

5 Discussion

This thesis touches upon numerous different aspects from BIM modelling, energy modelling, to PV panels, LCA and so on. The intent of this thesis is again to bring to light the vast opportunities that open up by the being able to establish a live-link, through new software tool developments. The question of seamless connectivity between architectural modelling and energy performance analysis is not new, and there have been many attempts and also industrially accepted workflows that rely on exported models. These workflows typically utilize Revit API and customized scripting to automate the solutions where necessary. However, an issue remains with BIM, especially considering Revit, that it is unable to accept back models that have already been exported in formats other than .rvt and is even unable to import .rvt files made in older generations of Revit. Therefore, there was no efficient way to establish a 'live-link' as feedback, since even using Revit APIs could only be one way, that is from Revit to the exported model. If the software importing the Revit-exported model cannot update on the go with new information, this linkage is severely limited. Apart from that, working with copy of the original file creates various other issues as discussed.

Therefore, with Rhino.inside.revit, a vast opportunity of extension to original Revit (BIM) features opens up. Grasshopper being open source, with many contributors developing customized tools, is an experimental platform that provides opportunities to perform parametrization, simulation and analysis, especially over a live-link. Design development is a dynamic process, passing through many steps of design development, with 100s of design options that may be generated along the way, at various different scales. It is not too far to say that a design might undergo complete change of essential features even in the intermediate stage, which can be a result of external factors (such as change of brief, failure to acquire certain property, budget or time over-runs etc), and the ability to address this drastic change in a simplified manner can still help the project have environmental performance close to its initial analysis. As mentioned before, this would therefore help address the 'Two-week turn-around' challenge which still remains a gap in the industry.

For convenience, this workflow can be further simplified. For example, if the project settings are already defined in the early stages, there is no need to set it up. With a consolidated control panel, as shown in fig. 5.1 a few inputs can run the entire simulation. In such case, the study also can be conducted by someone who is not necessarily proficient in grasshopper or visual programming, thus enabling designers conduct complicated analysis and in taking informed design-decisions.

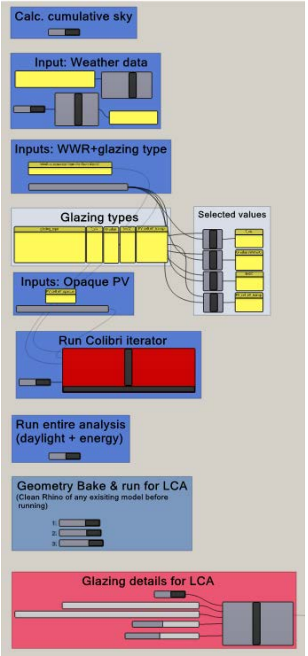


Figure 5.1 Consolidated Control Panel to run the entire simulation with minimum tweaking

Another advantage is that unlike some other solutions, that rely on entirely new platforms or complicated workflows where there is a possibility of file transfer, the process of BIM-BEM linkage might run into issues of file transfer due to Revit's limited capacity for file sharing (input). Added to that, there would be the need of monetary investment in a new software, training the office to understand and then adapt the new tool and maintain issues of licensing and legal documentation, for another platform. However, with RIR, offices that employ Revit for BIM and consultants that work with Rhino-Ghp tools such as LB-HB and Bombyx for performance assessment can quickly switch into this new setup, with minimal investment in additional software costs and training times. This makes it an easy, accessible and a fast way to improve transition towards a performance-driven design norm in architecture, making it more convenient to design aesthetically complex buildings while improving high performance and low emission criteria.

Grasshopper being an open-source visual programming tool also extends the possibility for developing more complex, non-linear performance workflows. In the solar façade performance workflow, utilized as a case study in this project, the Transparent Solar PVs integrated on glazing have two major performance criteria that are contradictory in nature – daylight access and energy performance.

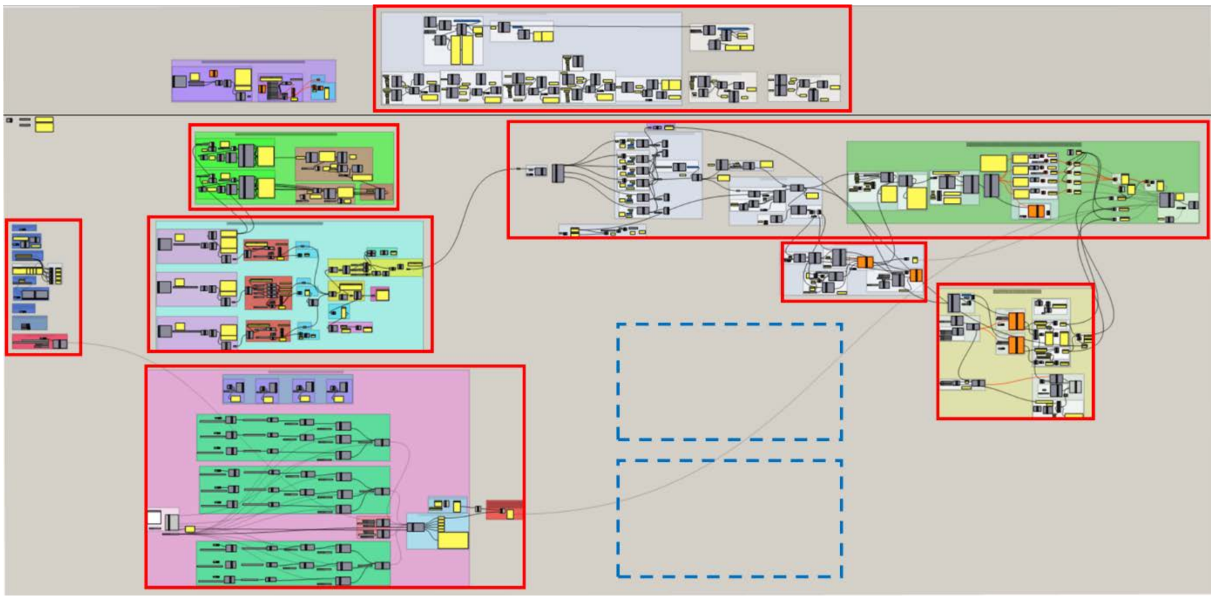


Figure 5.2 Modular nature of the simulation set-up

This makes for a unique problem, where, without solving the metrics into a single functional unit can mislead the results. As the workflow employed in this study demonstrates, that ultimately, Total energy demand was utilized, which meant the workflow was customized to suit the KPIs defined for this study. This is an example of a multi-domain analysis. An advantage using visual programming software such as Rhino-Ghp, is that there will always be the possibility of linking them to other analysis to extend the multi-dimensional nature of the analysis. Here, the base solar façade analysis workflow was extended to incorporating LCA. By its modular nature, the workflow can be further extended in the future (shown in blue dotted outlines, fig 5.2) the future to analyze acoustics, cost, CFD and numerous other parameters that are possible in the grasshopper plugins.

In conclusions, BIM-BEM linkage can be simplified further using currently available software and tool and without the need for scripting. Platforms for BEM like Rhino-grasshopper provide the opportunity for conducting complicated performance analysis, that when connected to BIMs like Revit, will help in shortening analysis time, in making BEP calculation more accessible to architects and ultimately in promoting performance-driven design, which is a necessary step to cut the contribution of buildings to global emissions.

References

ABUD, K., E., BALÁZS, R.D., GOIA, F. 2020. ROLLA SMART FAÇADE R&D PROJECT: Digital Twin Development Modelling & Simulation: Annual energy demand and annual energy conversion potential. Budapest, Hungary.

AIA 2013. AIA contract document G202-2013, building information modeling protocol form. Washington, DC: American Institute of Architects.

AKANBI, L. A., OYEDELE, L. O., AKINADE, O. O., AJAYI, A. O., DAVILA DELGADO, M., BILAL, M. & BELLO, S. A. 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. *Resources, Conservation and Recycling,* 129**,** 175-186.

ASSOCIATES, R. M. 2021. *Getting Started with Rhino.Inside.Revit* [Online]. Robert McNeel & Associates. Available: https://www.rhino3d.com/inside/revit/1.0/getting-started [Accessed 25.02.2022].

ATTIA, S., GRATIA, E., DE HERDE, A. & HENSEN, J. L. M. 2012. Simulation-based decision support tool for early stages of zero-energy building design. *Energy and Buildings,* 49**,** 2-15.

BARNES, P. & DAVIES, N. 2015. *BIM in principle and in practice,* London, ICE Publishing.

BASIC, S., HOLLBERG, A., GALIMSHINA, A. & HABERT, G. 2019. A design integrated parametric tool for real-time Life Cycle Assessment – Bombyx project. *IOP Conference Series: Earth and Environmental Science,* 323**,** 012112.

BCG 2016. Digital in Engineering and Construction.

BEETZ, J., BORRMANN, A., KOCH, C. & KÖNIG, M. 2018. Building Information Modeling : Technology Foundations and Industry Practice. 1st ed. Cham: Springer International Publishing : Imprint: Springer,.

BERTRAND LACK, S. B. 2019. Bridging BIM and BEM: the path forward to more efficient building design and operations. Available: https://damassets.autodesk.net/content/dam/autodesk/www/solutions/building-information-modeling/mep/articles/autodesk-SE-WP-bridging-BIM-and-BEM.pdf [Accessed 20.02.2022].

BIZZARRI, G., GILLOTT, M. & BELPOLITI, V. 2011. The potential of semitransparent photovoltaic devices for architectural integration: The development of device performance and improvement of the indoor environmental quality and comfort through case-study application. *Sustainable Cities and Society,* 1**,** 178-185.

BROOKS, W. & DUNLOP, J. 2012. Photovoltaic (PV) installer resource guide. *The North American Board of Certified Energy Practitioners (NABCEP), Tech. Rep.*

CONTI, J., HOLTBERG, P., DIEFENDERFER, J., LAROSE, A., TURNURE, J. T. & WESTFALL, L. 2016. International energy outlook 2016 with projections to 2040. USDOE Energy Information Administration (EIA), Washington, DC (United States ….

CORE. 2017. *Colibri Release* [Online]. CORE Studio - Thornton Tomasetti. Available: http://core.thorntontomasetti.com/colibri-release/ [Accessed 03.03.2022].

DAVIDSON, S. 2021. *Rhino.Inside.Revit Version 1.0 Released* [Online]. McNeel. Available: https://discourse.mcneel.com/t/rhino-inside-revit-version-1-0-released/128738?u=eirannejad [Accessed 10.01.2022].

DING, L., ZHOU, Y. & AKINCI, B. 2014. Building Information Modeling (BIM) application framework: The process of expanding from 3D to computable nD. *Automation in Construction,* 46**,** 82-93.

ELTAWEEL, A. & SU, Y. 2017. Controlling venetian blinds based on parametric design; via implementing Grasshopper's plugins: A case study of an office building in Cairo. *Energy and Buildings,* 139**,** 31-43.

EPBD 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). *Official Journal of the European Union*.

ETH. 2022. *Bombyx by ETHZ_SC* [Online]. Food4rhino. Available: https://www.food4rhino.com/en/app/bombyx [Accessed 25.04.2022 2022].

GERRISH, T., RUIKAR, K., COOK, M., JOHNSON, M., PHILLIP, M. & LOWRY, C. 2017. BIM application to building energy performance visualisation and management: Challenges and potential. *Energy and Buildings,* 144**,** 218-228.

HASHEMPOUR, N., TAHERKHANI, R. & MAHDIKHANI, M. 2020. Energy performance optimization of existing buildings: A literature review. *Sustainable Cities and Society,* 54**,** 101967.

HESTNES, A. G. & EIK-NES, N. L. 2017. *Zero emission buildings*, Fagbokforlaget Bergen.

HONG, T., CHOU, S. & BONG, T. 2000. Building simulation: an overview of developments and information sources. *Building and environment,* 35**,** 347-361.

HOPFE, C. J., AUGENBROE, G. L. & HENSEN, J. L. 2013. Multi-criteria decision making under uncertainty in building performance assessment. *Building and environment,* 69**,** 81-90.

IEA 2020. World energy balances (Edition 2019). 2019 ed.

JIN, R., ZHONG, B., MA, L., HASHEMI, A. & DING, L. 2019. Integrating BIM with building performance analysis in project life-cycle. *Automation in Construction,* 106**,** 102861.

KALAY, Y. E. 1999. Performance-based design. *Automation in Construction,* 8**,** 395-409.

KAMEL, E. & MEMARI, A. M. 2019. Review of BIM's application in energy simulation: Tools, issues, and solutions. *Automation in construction,* 97**,** 164-180.

KJARTANSDÓTTIR, I. B., MORDUE, S., NOWAK, P., PHILP, D. & SNÆBJÖRNSSON, J. T. 2017. *Building information modelling-BIM*, Civil Engineering Faculty of Warsaw University of Technology Warsaw, Poland.

LADYBUG. 2020. *Ladybug Tools* [Online]. Available: https://www.ladybug.tools/ [Accessed 25.03.2022].

LAI, C.-M. & CHEN, R. H. 2011. Novel heat dissipation design incorporating heat pipes for DC combiner boxes of a PV system. *Solar Energy,* 85**,** 2053-2060.

LAI, C.-M. & HOKOI, S. 2015. Solar façades: A review. *Building and Environment,* 91**,** 152-165.

LEE, J. W., JUNG, H. J., PARK, J. Y., LEE, J. B. & YOON, Y. 2013. Optimization of building window system in Asian regions by analyzing solar heat gain and daylighting elements. *Renewable Energy,* 50**,** 522-531.

MAP, E. 2022. *Live 24/7 CO2 emissions of electricity consumption in Europe* [Online]. Electricity Map. Available: https://app.electricitymap.org/zone/HU [Accessed 05-04-2022 2022].

MISTRY, N. 2021. Developing a Decision Support Tool for minimizing embodied carbon in early design stage facade material selection.

MOHAMMED, M. & ALIBABA, H. 2018. THE EFFECT OF PHOTOVOLTAIC (PV) PANEL TILT ANGLE FOR BEST ENERGY GENERATION IN HOT CLIMATE. 185-196.

NGUYEN, A.-T., REITER, S. & RIGO, P. 2014. A review on simulation-based optimization methods applied to building performance analysis. *Applied Energy,* 113**,** 1043-1058.

PALONEN, M., HAMDY, M. & HASAN, A. 2013. *MOBO a new software for multi-objective building performance optimization*.

PETERSEN, S. & SVENDSEN, S. 2010. Method and simulation program informed decisions in the early stages of building design. *Energy and Buildings,* 42**,** 1113-1119.

ROUDSARI, M. S. 2021. *Our Solution To The Two-Week Turn-Around Problem* [Online]. Pollination.cloud. Available: https://www.pollination.cloud/blog/our-solution-to-the-two-week-turn-around-problem [Accessed 15-01-2022 2022].

ROUDSARI, M. S., PAK, M. & SMITH, A. Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. Proceedings of the 13th international IBPSA conference held in Lyon, France Aug, 2013. 3128-3135.

SAMUEL, E. I., JOSEPH-AKWARA, E. & RICHARD, A. 2017. Assessment of energy utilization and leakages in buildings with building information model energy. *Frontiers of Architectural Research,* 6**,** 29-41.

SANHUDO, L., RAMOS, N. M., MARTINS, J. P., ALMEIDA, R. M., BARREIRA, E., SIMÕES, M. L. & CARDOSO, V. 2018. Building information modeling for energy retrofitting–A review. *Renewable and Sustainable Energy Reviews,* 89**,** 249-260.

SARTORI, I., WACHENFELDT, B. J. & HESTNES, A. G. 2009. Energy demand in the Norwegian building stock: Scenarios on potential reduction. *Energy Policy,* 37**,** 1614-1627.

SHI, X. & YANG, W. 2013. Performance-driven architectural design and optimization technique from a perspective of architects. *Automation in Construction,* 32**,** 125-135.

SSB 2012. Statistisk sentralbyrås årsrapport for 2011.

UTKUCU, D. & SOZER, H. 2020. Interoperability and data exchange within BIM platform to evaluate building energy performance and indoor comfort. *Automation in Construction,* 116.

ZHUANG, D., ZHANG, X., LU, Y., WANG, C., JIN, X., ZHOU, X. & SHI, X. 2021. A performance data integrated BIM framework for building life-cycle energy efficiency and environmental optimization design. *Automation in Construction,* 127**,** 103712.

Appendix

A. Building Energy and Daylight simulations

As the primary concern with using transparent PVs is to understand the trade-offs between the two essential but contradicting properties of the transparent PV system, that is: Daylight access and power conversion. The workflow of this part of the study was used as developed for the solar façade study workflow but customized to include the updates made into the BIM-BEM definition. As mentioned previously, this part of the study was done entirely within the grasshopper environment that was first opened using Rhino.inside.Revit. Using the Honeybee-Ladybug plugins, provided the freedom to develop a customized workflow to study the different aspects of this analysis, in a single holistic definition. As a result, there was scope for parametric design/control of architecture, as well as performing lighting performance analysis and building energy consumption modelling simultaneously and then linking them through a common energy criterion. The EnergyPlus engine was used here for the energy simulations while the Radiance/Daysim enabled the daylighting simulations. The geometry extracted from Revit has been used as was described earlier.

The climatic data for this case study was obtained from EnergyPlus weather files; the location considered was of Debrechen which is the closest available climate of Budapest. This climate can be changed as is relevant to the project, considering data for the closest location which has a .epw file available. In this study, neither a shading system nor a natural climatization control strategy was considered. Although the global performance of the façade might be improved by the use of one or both of the strategies, but in a scenario of comparison, the impact might not be a significant difference in the relative performances. This can, however, be a possibility for further development.

The energy modelling workflow consists of the following steps:

1. Geometry - The basic geometry extracted from the Revit model and cleaned into a format that works for the HB-LB thermal modelling format, constructing a thermal zone
2. Construction - Custom constructions and materials are generated, defined as close as possible to the construction system/specifications chosen in the BIM, and assigned to the South façade, the other facades, roof and floor. Custom windows can also be generated, to get a realistic thermal performance
3. Building zone and type - The building type and zone program were selected, in this case – Closed office.

4. Fenestrations/Glazing - Windows are recreated from the Revit model specification for the south-facing wall (façade) and in the HB model translated into a numerical input, based on the Window-to-wall (WWR) ratio. This parameter is therefore directly dependent on the BIM-BEM live link as the input depends on the Revit model. Therefore, it gives the designer the option to test out the window choice for its energy performance, irrespective of form or shape, as a means of its effective ratio to the façade area. The glazing type, then can be parametrically set from the select options available based on the thermal transmittance (U-value), the visible light transmittance (T_{vis}), and solar heat gain coefficient (SHGC). For the PV glazing later, the transparent PV (TPV) conversion efficiency is also selected as per the input in the glazing specification, in this case, 2 of the 3 glazing types provide an input value for this analysis
5. Daylighting - is performed as an annual grid-based simulation which serves two purposes: monitoring the availability of the continuous daylight autonomy (cDA, %) in the indoor space and also to inform the energy simulation the appropriate electric lighting schedules required, based on an auto-dimming control with switch-off occupancy sensor (defined in the workflow itself). This ensures that the condition of minimum available daylight is never compromised for any of the available glazing types, thus ensuring user comfort and realistic scenarios. This process is called Daylight control, was set to an illuminance of 300lux, measured by 4 sensors placed 20cm from the floor in the middle of the room
6. Annual Energy – For the selected closed office zone, the internal loads (including equipment, lighting, occupancy density), infiltration rates, ventilation rates and the corresponding schedules were assigned, the lighting schedule was updated based on the daylighting control as defined in the previous step. The basic building energy use was solved for the yearly simulation considering the parameters: heating, cooling, lighting, equipment (plug loads), handled by the EnergyPlus engine
7. Outputs – The final outputs were derived in terms of the m^2 of the floor area for the values of electricity for heating (E_{heat}) and cooling (E_{cool}), electricity for lighting (E_{light}), and electricity for equipment (E_{equip}, kWh_e/m^2a), as well as the continuous daylight autonomy (cDA, %).
8. Supply-side analyss – In addition, a supply-side analysis was also performed to estimate the potential of electricity production by the BIPV. After generating the cumulative sky matrix using LB and the weather data from the .epw file, an annual solar radiation is generated. This is used to calculate the potential electricity production by the transparent and the opaque PV parts of the south-facing façade. The outputs were then measured and monitored as per m^2

of floor area, i.e. transparent PV electricity ($E_{PV\_transparent}$) and opaque PV electricity (E_{PV_opaque}, kWh_e/m^2a), for an easy comparison with the demand-side analysis outputs.

B. Simulation Workflow

Added to the previous section presenting the simulation workflow, there can be more specific simulation that may be needed to make a typical performance analysis model. This can include, but is not limited to, information on materials, schedules, setpoints and other typical assumptions. The settings used for this case study are as presented below.

The materials of this case building have been provided in HB, some custom made and rest from the HB library. They have been modelled as defined:

- Façade (R-value=4.29 m2K/W): sandwich panel made of 15 cm insulation material with a thermal conductivity of around 0.035 W/mK and metal sheets on both inside and outside.
- Other walls (R-value=4.60 m2K/W): 15 cm of insulation towards the outside, 10 cm of concrete, and gypsum boards on both inside and outside layers.
- Roof (R-value=4.82 m2K/W): 25 cm of light-weight concrete structure and 15 cm of insulation on the outside of the roof layer, plus a covering layer (roof membrane).
- Floor (R-value=4.82 m2K/W): 15 cm of insulation on the outside, 20 cm of light-weight concrete structure, and gypsum boards on both inside and outside layers

The surfaces were modelled here as externally exposed and subject to the outdoor boundary conditions as derived from the weather data. This can also be customized to internal walls for alternate layouts, for all the remaining walls or selectively, as defined best by the actual settings. These materials can also be recreated from Revit materials as has been discussed later.

For the HVAC Plan, the environment was modelled as always meeting the dual set-point with deadband for indoor air temperature, set to set to 21.11°C (70°F) and 23.89°C (75°F), for the heating and the cooling activation, respectively.

USA's Department of Energy (DoE) provides standardised models for medium office which are derived from the ASHRAE standards. These are used for inputs for the internal loads, occupancy and ventilation schedules that were adopted in this study. Details of the models are as shown in image xxx

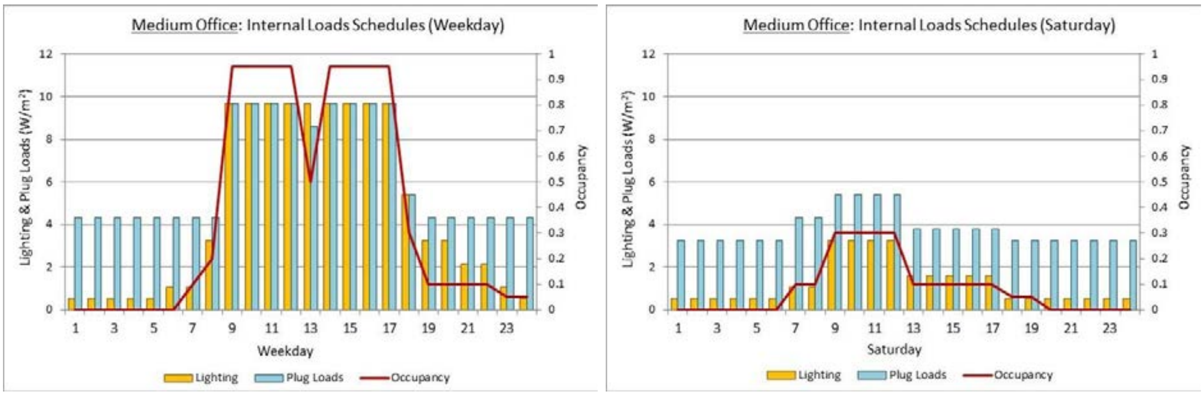


Fig B.1 Schedule of a medium office building by DoE

For the Ventilation strategy, the requirement of fresh airflow was defined as per ASHRAE standards. The energy needed to climatize the ventilation air supply for the indoor space has been included in the energy need for heating and cooling. However, the energy necessary to move the air mass has been excluded as it is independent from the configuration of the façade and depends on the air mass needed for the indoor space. The ventilation plan relies on a Balanced mechanical ventilation with a heat recovery (MVHR) system with 80% operational efficiency, which is more or less standard for modern, environmentally conscious buildings

For the study of illuminance, a connection has been made between having adequate daylight of 300lux, measured with sensors at 80cm from the floor (work desk height) with 4 sensors in the middle of the room. This is then connected with an automated dimming system that matches the requirement illumination set point by adjusting the energy required for the artificial daylight level available at the sensors, for an annual period. This information on the daylighting level is obtained through the high-fidelity, radiance-based simulation. To accurately simulate the realistic implications for choosing one transparent PV option over another, this is an important factor as TPVs with higher production may maximise energy conversion, while also limiting daylight availability leading to higher operational energy needs, atleast for the illuminance. Therefore, this information is fed back to the thermal engineering that computed the internal lighting load at each step.

The thermal simulation engines regulate the heating and cooling loads of the space behind the façade, and for the sake of consistency, rely on a single metric for combining different thermal use with energy from artificial light and electrical conversion from the PVs and TPVs. The assumed global conversion efficiency was set to, COP_{heat} = 3 for the heating plant and COP_{cool} = 3 for the cooling plant.

For the PVs (both transparent and opaque), the available solar irradiation is converted with nominal PV cell efficiency, and also account for system conversion losses due to DC-AC conversion, MPPT performance, partial accidental shading. The losses have been assigned an average annual value of 20% of the converted electricity, therefore making the global PV system efficiency as 80%.

C. Final outcomes of the whole simulation:

in:glazing_type	in:Ratio_Opaque_PV_to_Opaque_Facade	in:WWR as extracted from the Revit Model	out:E_heat (kWhe/m2a)	out:E_cool (kWhe/m2a)	out:E_light (kWhe/m2a)	out:E_tot demand (kWhe/m2a)	out:E_equip (kWhe/m2a)	out:E_transp_PV (kWhe/m2a)	out:E_opaque_PV (kWhe/m2a)	out:E_PV_tot (kWhe/m2a)	out:E_tot (kWhe/m2a)	out:Solar_coverage (%)	out:cDA (%)	out:CO2(CO2eq/m2a)
Onyx Solar GL.01	0	0.405	13.12	6.42	41.90	61.44	47.44	5.63	0.00	5.63	55.82	9.16	7.50	11.94
Onyx Solar GL.02	0	0.405	13.45	5.54	30.63	49.62	47.44	4.77	0.00	4.77	44.86	9.61	33.42	10.49
Double Glz (w/TPV)	0	0.405	12.95	5.87	16.47	35.29	47.44	0.00	0.00	0.00	35.29	0.00	60.58	9.23
Onyx Solar GL.01	0.2	0.405	13.12	6.42	41.90	61.44	47.44	5.63	6.39	12.01	49.43	19.55	7.50	11.09
Onyx Solar GL.02	0.2	0.405	13.45	5.54	30.63	49.62	47.44	4.77	6.39	11.16	38.47	22.48	33.42	9.65
Double Glz (w/TPV)	0.2	0.405	12.95	5.87	16.47	35.29	47.44	0.00	6.39	6.39	28.90	18.10	60.58	8.39
Onyx Solar GL.01	0.4	0.405	13.12	6.42	41.90	61.44	47.44	5.63	12.78	18.40	43.04	29.95	7.50	10.25
Onyx Solar GL.02	0.4	0.405	13.45	5.54	30.63	49.62	47.44	4.77	12.78	17.55	32.08	35.36	33.42	8.80
Double Glz (w/TPV)	0.4	0.405	12.95	5.87	16.47	35.29	47.44	0.00	12.78	12.78	22.51	36.20	60.58	7.54
Onyx Solar GL.01	0.6	0.405	13.12	6.42	41.90	61.44	47.44	5.63	19.16	24.79	36.65	40.35	7.50	9.41
Onyx Solar GL.02	0.6	0.405	13.45	5.54	30.63	49.62	47.44	4.77	19.16	23.93	25.69	48.23	33.42	7.96
Double Glz (w/TPV)	0.6	0.405	12.95	5.87	16.47	35.29	47.44	0.00	19.16	19.16	16.13	54.30	60.58	6.70
Onyx Solar GL.01	0.8	0.405	13.12	6.42	41.90	61.44	47.44	5.63	25.55	31.18	30.26	50.74	7.50	8.56
Onyx Solar GL.02	0.8	0.405	13.45	5.54	30.63	49.62	47.44	4.77	25.55	30.32	19.30	61.10	33.42	7.12
Double Glz (w/TPV)	0.8	0.405	12.95	5.87	16.47	35.29	47.44	0.00	25.55	25.55	9.74	72.40	60.58	5.86

Fig C.1 Results of the overall simulation that is extracted into an excel sheet

D. Daylight analysis:

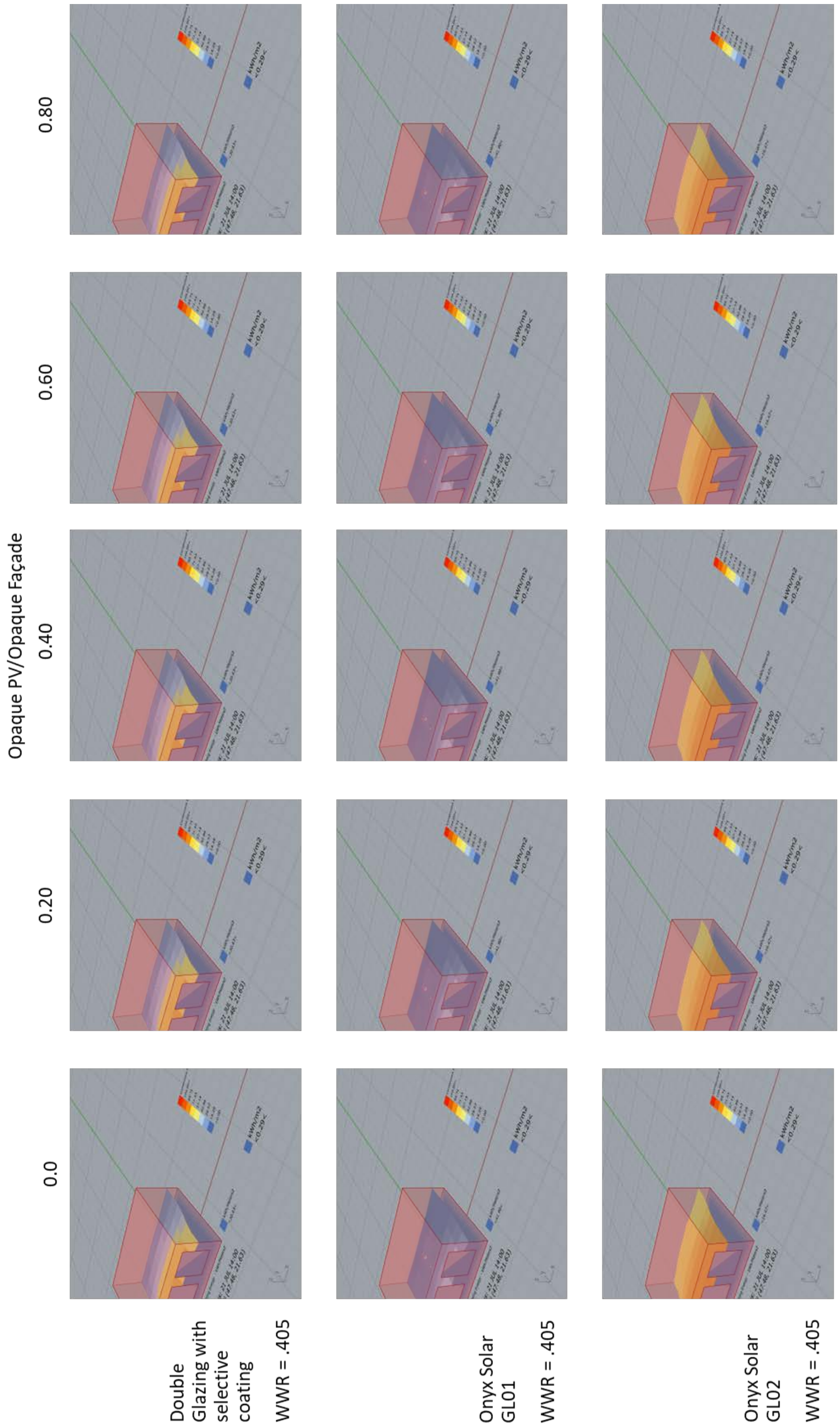
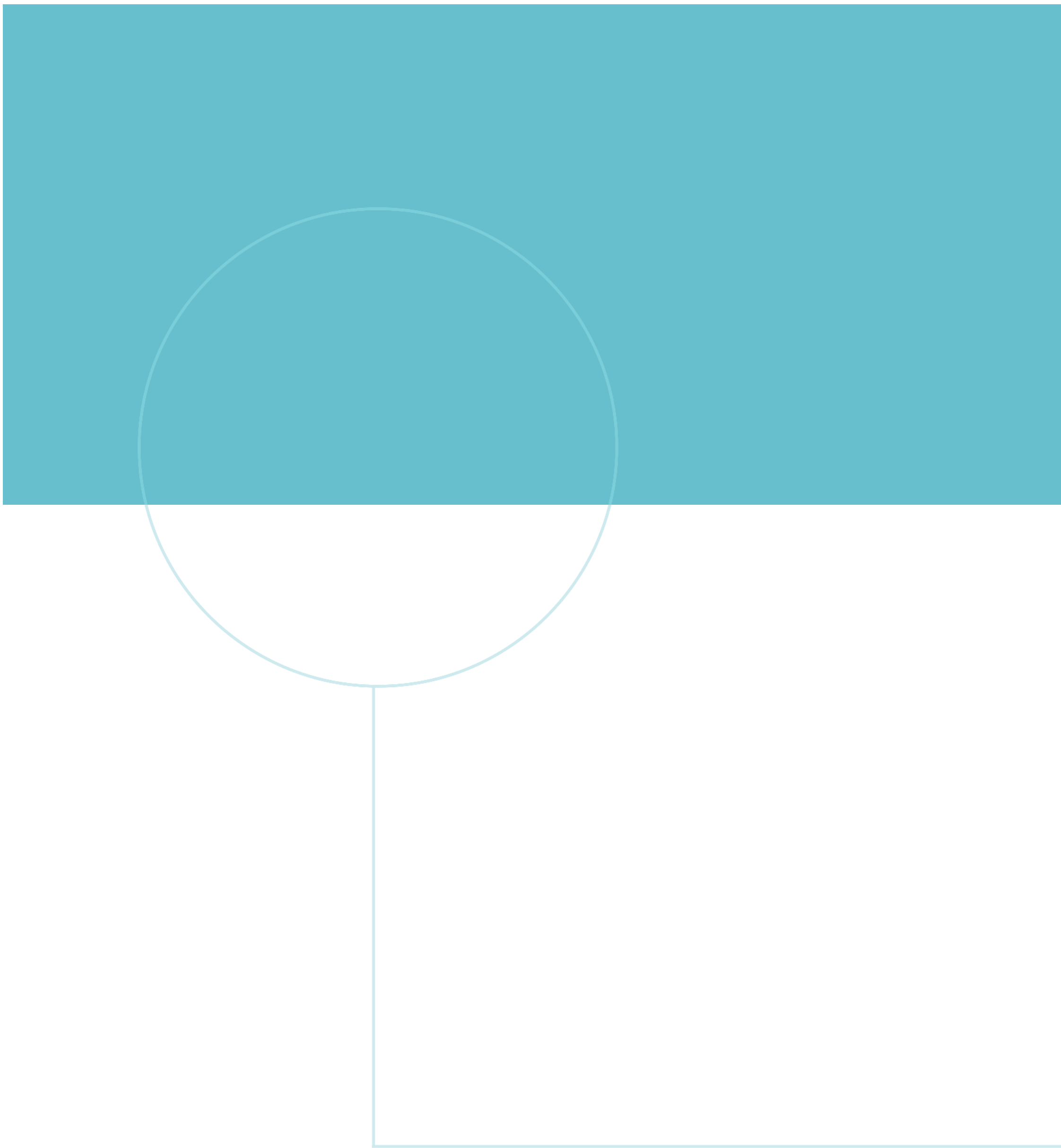


Fig D.1 Results of the daylight simulation for each setting



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