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IMPLEMENTING BUILDING PERFORMANCE MODELLING THROUGH BIM METHODOLOGY AND ITS IMPLICATION ON BUILDING DESIGN PROCESS

VPLIV UPORABE ZMOGLJIVOSTNEGA NAČRTOVANJA V POVEZAVI Z BIM METODOLOGIJO NA POSTOPEK NAČRTOVANJA STAVB

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Izvleček:

Gradbeništvo 4.0 zahteva nove pristope in metode za dosego primarnih ciljev industrije, kot so trajnostna mesta in skupnosti, odgovorna potrošnja in proizvodnja, podnebni ukrepi ter inovacije. Čeprav zmogljivostno načrtovanje (PBD) ni nov pristop, je v primerjavi s tradicionalnim načinom načrtovanja stavb inovativen pri soočanju s temi cilji. Študija obravnava koncept oblikovanja, ki temelji na zmogljivostnem načrtovanju. Pregleduje metode in orodja, ki podpirajo uporabo PBD v zgodnji fazi načrtovanja.

Namen tega magistrskega dela je osvetliti glavne razlike med konvencionalnim in PBD pristopom, v začetni fazi načrtovanja stavb. Opredeljuje prednosti, omejitve in težave zmogljivostnega načrtovanja, v praksi. Na podlagi ankete pri kateri je sodelovalo 43 anketirancev iz 21 držav so bila opredeljene ključne težave in prednosti uporabe PBD v praksi. Na hipotetičnem primeru poslovne stavbe v Mengšu je bila preučena tudi možnost in primernost PBD pristopa, kot nadomestilo za klasično načrtovanje.

Rezultat študije primerov je strategija in predlog delotoka za uporabo pristopa PBD v zgodnji fazi načrtovanja stavb. Strategijo je mogoče uporabiti neodvisno od orodja za modeliranje in analizo ter za stanovanjske, poslovne in javne stavbe. PBD pristop omogoča razmeroma hitro raziskovanje ogromnega oblikovalskega prostora, ter olajša identifikacijo ukrepov z največjim vplivom na zmogljivost stavbe.

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Construction 4.0 requires new approaches and methods to achieve primary goalsset for the industry, such as sustainable cities and communities, responsible consumption and production, climate actions, innovations. Although the performance-based design (PBD) approach is not new, it is innovative in how it faces these goals compared to the traditional approach. The study discusses the concept of performance-based design in general. It reviews the methods and tools that can support the PBD application in the early design stage, such as Integrated Design Process, Building Information Modelling and others.

This master thesis aims to clarify major differences between the conventional and the PBD approach when applied in the initial design stage. It identifies the benefits of the new approach and the limitations and difficulties when applied in practice. It identified issues of using PBD in practice throughout a survey of 43 respondents from 21 countries. Finally, it examines the ability and readiness of the PBD method to substitute the traditional design approach. It compares the two approaches with a practical hypothetical project of an office building in Mengeš, Slovenia.

The case study results are the workflow and a strategy proposed to apply the PBD approach in the early design stage. The strategy can be used regardless of the modelling and analysis tools and for the residential, commercial and public projects. It helps to explore vast design space relatively quickly to understand design trends and options with the greatest impact on future building performance.

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AEC – Architecture, Engineering, and Construction

AECO – Architecture, Engineering, Construction and Operation

AIA – American Institute of Architects

ASHRAE – American Society of Heating, Refrigerating and Air Conditioning Engineers

BC – Before Christ

BIM – Building Information Modelling

BPS – Building performance simulation

BREEAM – Building Research Establishment Environmental Assessment Method

CIB – International Council for Building Research Studies and Documentation General Secretariat

COP – Coefficient of Performance

DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council)

DGP – Daylight Glare Probability

DHW – Domestic hot water

EPBD – Energy performance of building directive

EU – European Union

EUI – Energy use intensity

GA – Genetic algorithm

GBPN – Global Buildings Performance Network

gbXML – Green Building XML

GHG – Greenhouse gas

GIGO – Garbage in, garbage out

HVAC – Heating, ventilation, and air conditioning

IDP – Integrated design process

IFC – The Industry Foundation Classes

ISO – International Organization for Standardization

LCA – Life cycle assessment

LEED – Leadership in Energy and Environmental Design

LPD – Lighting power density

PeBBu – Performance Based Building Network

PBB – Performance-based building

PBBD – Performance-based building design

PBD – Performance-based design

PD – Performance design

PHI – Passive House Institute

PNNL – Pacific Northwest National Laboratory

PO – Parametric optimization

PV – Photovoltaics

sDA – Spatial Daylight Autonomy

SDF – Shading device factor

SDG – Sustainable Development Goals

SFP – Specific fan power

SHGC – Solar heat gain coefficient

SHW – Solar hot water

USGBC – United States Green Building Council

WCED – United Nations World Commission on Environment and Development

WorldGBC – The World Green Building Council

WWR – Window-to-wall ratio

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1 INTRODUCTION

1.1 General approach

Performance-based design (PBD), generally speaking, is an approach that intends to create a high-performance building that will be energy-efficient, comfortable for the occupants, as cheap as possible to construct, low-cost and easy for maintenance, etc. In other words, it is an approach that is goal-oriented in opposite to the conventional method of design. The traditional (conventional) method focuses on the shape and beauty of a building and functionality and compliance with building codes that prescribe what and how it shall be built and not how it should perform. Not by chance in recent decades all around the world, many building certification systems, such as BREEAM (UK), PassiveHaus (Germany), Green Star (Australia), HQE (France), CASBEE (Japan), have emerged that are focused on the performance and not on just a “better design” in the traditional sense of the word. In addition to certification systems, political and social commitments were made, such as Agenda 2030 (Sustainable Development Goals) proposed and supported by the United Nations and the 2030 Challenge issued by non-profit organization Architecture 2030 and adopted by the American Institute of Architects (AIA).

The main objectives of building codes and standards are to keep people safe and prevent unpleasant consequences of different levels of accidents. However, this is not enough now, when the construction industry faces new challenges such as significant changes in the global climate, public consciousness in human well-being, development of technologies. Today we build a new Paris per month and a new Japan per year (GBPN, 2021). The construction velocity grew amazingly, as we can construct a one-family building in less than 4 hours (Ganninger, 2020) and a skyscraper in 19 days (Ganninger, 2020). While we construct based on the outdated norms, we are doing ourselves and our future generation a huge disservice. Accumulated knowledge stored in standards does not correspond to today’s challenges, such as decrement of CO_2 emission, cutback of energy consumption, use of passive energy generating systems. Another drawback of relying entirely on standards and codes is that they can accumulate much wrong or simply not the best options in terms of performance (Szigeti & Davis, 2005).

International Organization for Standardization (ISO) defines the building performance requirement as the minimum acceptable critical property level (ISO, 2020). Any property could be considered critical as far as it is aligned with the final goal of the design. Furthermore, this set of performance requirements can be different for every building, depending on the type of building, geographic coordinates, investor’s needs, special requirements like comfort, appearance, etc. In modern society, one of the first official documents (standard) where the minimum set of the performance goals was fixed was the Building Regulations in 1965 in the UK (Design Buildings Wiki, 2017), still with the prescription of how it should be built.

Therefore, we realized and began to emphasize the importance of transition towards the performance-oriented buildings by the time we introduced PBD into use, the last decades have brought us new ways of designing. Another factor that has given significant impetus to the PBD approach is the rapid development and replacement of the traditional design method with Building Information Modelling (BIM). Furthermore, BIM technology facilitates the inclusiveness of stakeholders and closer communication between professionals during the entire design process. Moreover, to ensure a smooth process and provide essential data for decision-making at an earlier stage, BIM is a crucial element.

The new era in construction that brings innovative technologies, sophisticated performance codes and certification systems requires new approaches and methods for all the processes starting with an idea and finishing with maintenance & operation and disposal. Moreover, it requires a holistic view, which means engaging diversified expertise as early in the project as possible to assess the project and all its outcomes entirely.

1.2 Main focus

This study intends to get a whole picture of the current use of the performance-based design approach at the beginning of a project, its benefits in comparison to the conventional method of design, as well as highlight present limitations and obstacles for the full and smooth inclusion and consolidation into the Integrated Design Process (IDP). As one of the methods to achieve high-performance, sustainable buildings while avoiding rising costs, IDP plays a vital role in shifting the traditional design practice towards the new approach. As written in Roadmap for the Integrated Design Process (2007), "*it is an approach to building design that seeks to achieve high performance on a wide variety of well-defined environmental and social goals while staying within budgetary and scheduling constraints*" that is fully aligned with the goals of PBD approach. Moreover, IPD relies on the multi-domain team throughout the entire project life from pre-design through occupancy and into the operation phase, making it the best possible framework for the PBD implementation.

Despite the general recognition by professionals of the PBD method as progressive and promising for the initial design phase, it is not yet used enough to speak of its widespread use in practice. Therefore, another objective of this study is to review the workflows, methods and tools offered in the literature and test selected ones on a simple project to validate theories identified through the literature review. In addition to the practical test, the thesis surveys companies worldwide to confirm our conclusions and findings presented in the literature.

The structure of the thesis is as follows:

The first part is an introduction to the topic where the main focus of the work is set together with the study's objectives while discussed problems are highlighted.

The second section introduces outlines of the PBD approach and different methods, tools and standards supporting it found in the scientific papers and other resources. Furthermore, the benefits and limitations of the PBD reported from investigated sources together with knowledge gaps and challenges met during the application and execution of the PBD approach in the early stage.

Chapter three describes the methodology used for a versatile understanding of the research problem. Three strategies were utilized during the study: literature review, a survey of companies and a case study. Each of them works with different levels of perception. While the literature review gives a general view of the subject, the survey collects its personal opinions. The case study allows a high level of control for a researcher and goes deeper into details.

A survey of companies was used to support the data collection and verify hypotheses introduced in chapter two. A survey approach was exploited in a digital form through “Google forms”. It was sent to companies worldwide to get a general view on the application of the PBD approach in different parts of the world, together with the opinion of the experienced users on the PBD approach benefits and disadvantages.

Subsequently, the methodology of practice experiments in order to compare two approaches is described. Prerequisites and requirements for the design and goals are introduced together with a workflow and tools selected for the test explained. An exploratory case study as a logical continuation of a literature review and a survey aims to investigate research questions in-depth and confirm or deny the findings of previous parts of the work.

Chapter four presents and discusses the survey results of 43 companies, which shows the current level of PBD implementation in the initial design phase. Finally, we compared the results of the computational implementation of the PBD approach with the traditional practice used in the conceptual design stage in terms of time spent on modelling and performing the analysis and the results obtained.

Chapters five and six elaborate the findings of the research, survey and experiment together, and further application and execution of the PBD approach.

1.3 Problem discussion and research questions

According to the World Green Building Trends 2018 report, *“ability to conduct analysis as early as possible in the design process”* was recognized as one of the key sustainability trends in technologies that have been improved in the previous five years and will advance the industry shortly. However, despite the good preconditions, such as widespread use of BIM technology, development of new analysis tools, and integration of these tools into modelling ones, the appearance of the IDP approach and a bunch of performance ratings and certification systems, practical application of the PBD approach is limited as the review of the literature and survey showed.

One of the reasons that are preventing widespread use of PBD in the initial phase of design is the absence of suitable analysis tools, their complexity or unreliable results, together with the interoperability issues between modelling and analytical software (Jung et al., 2018). Typically, different analyses, such as structural, thermal, energy efficiency, are carried out in the later design stages to support and validate project decisions. When the cost of changes is unreasonably high, some changes cannot be implemented as it affects the overall project's decisions. The PBD approach, on the opposite, suggests not waiting for the detailed design but running the analysis earlier to make all prudent decisions, supported by reliable data at the beginning of the project to prevent unnecessary changes later. Although the method seems reasonable, some limitations and obstacles appear here, such as minimum input data on the initial stage of design reported by Petrova et al. (2017) as a result of which rapid changes in design occur. Besides, Liu et al. (2015) argue that traditional analysis methods cannot easily handle the enormous amount of analysis data produces during the design process.

The main research questions that this academic work is addressing are:

- What are the advantages of the PBD approach in comparison to the conventional one?
- What are the limitations of the PBD approach when applied in the early stage of design?
- Which workflows, norms and tool(s) can support using the PBD approach in the early stage of design?
- How widely is the PBD approach used in the early stage of design by design companies, and what is their opinion about it?
- What parameters and key performance indicators of the building should be decided on at the early design stage?

This work was carried out to address the above issues and promote the use of PBD in the early design stage.

2 LITERATURE REVIEW

This part introduces key findings and milestones that show prerequisites and background for the general changes in the building and construction industry and the development of new approaches in building design in particular. The main emphasis is made on the PBD approach and its application in the early design stage, together with the benefits and limitations of the method. Key events that promote its appearance and development, different principles, and frameworks developed and used are reviewed.

2.1 Background

2.1.1 From Brundtland report to Sustainable Development Goals

Since the beginning of the 21st century, humanity has begun to think about the future of our planet seriously. Every year, major and smaller organizations and projects arise worldwide to come to a sustainable, better future on the planet.

The starting point of the international community's involvement in solving environmental problems can be considered the United Nations Conference on the Human Environment in Stockholm in June 1972 and the following United Nations Environment Program (UNEP) established by Maurice Strong (Wikipedia, 2001). The program was focused on developing a green economy, solving ecological issues related to climate change and natural resource depletion.

In 1987 the Brundtland Report, published by the United Nations World Commission on Environment and Development (WCED), introduced the "sustainable development" term and suggested how it could be achieved. "*Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs"*. It has increased the importance of interconnection between an economy and ecological problems on the distant horizon (Ravago, Balisacan & Chakravorty, 2015) and greatly influenced the future development of this subject (Jarvie, 2014). The Earth Summit followed it in Rio de Janeiro in 1992, where the emphasis was done on the global partnership and local actions for achieving sustainable goals. As a result, Agenda 21 was proposed, where cities were recognized as the main focus of efforts to address ecological and sustainable issues (Chiu, 2012).

In 1993, soon after the Earth Summit, a non-profit organization World Green Building Council (WorldGBC), appeared in the United States. At the same time, the global network of national green building councils evolved, which proposed their primary mission as promoting sustainability-focused practices in the building and construction industry. Since its foundation WorldGBC has grown into 70 Green Building Councils worldwide (WorldGBC, 2021).

In 2001 European project that research Performance-based Building Design (PBBD) was funded by European Union (EU) in order to explore the performance-based approach in application to the building (PBB) and construction sector and completed in 2005 by publishing the final report Performance-based Building: Conceptual Framework (Szigeti & Davis, 2005). This report described the PBB approach and developed a comprehensive framework to apply into different stages of the project, supported with Compendium of Statements and Requirements Report that illustrates the development and application of the framework in case studies (Szigeti, Bourke & Prior, 2005). This work now serves as the basis for understanding the approach of PBB and using it for developing new frameworks, tools and projects in the area of construction.

In April 2002, in Melbourne, Australia, the ten "Melbourne Principles" for sustainable cities were developed that aimed to describe how a sustainable city would function and provide a framework for action (UNEP, 2002). Almost simultaneously in 2003 One Planet Living framework was developed by Bioregional with ten principles for future sustainability (Fig.1); among them are sustainable water, material and products, zero-carbon energy. One of four major projects of Bioregional is Creating Sustainable Homes and Communities during which BedZED was built, the first principal zero-carbon village in the UK (Bioregional, 2016). The main principles utilized for the design and construction of the village beyond zero-carbon emission are energy efficiency and zero energy consumption, water efficiency and low-impact materials (Wikipedia, 2007).

In 2006 in the United States of America, non-profit organization Architecture 2030 issued the 2030 Challenge to adopt zero-emission movement in the building sector (Architecture 2030, 2021). Soon after that, AIA created a framework called 2030 Commitment to help architectural companies shift to the holistic, performance-oriented practice (AIA, 2021). Together, these measures aimed to rebuild the current approach by prioritizing energy performance, sharing knowledge and best practices for designing zero-carbon buildings.

In 2010 Energy Performance of Building Directive 2010/31/EU (EPBD) was established as a part of the European Green Deal (European Commission, 2021). The European Green Deal project aim"*to reduce net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels*" (European Commission, 2019). The largest energy consumption source (about 40%) and greenhouse gas emission (about 36%) in Europe is the building and construction industry (European Commission, 2021) that makes them the area where the most significant changes are needed.

Some of the major aspects of this directive are (EUR-lex, 2010):

- adoption of a methodology for calculating the energy performance of buildings;
- the setting of minimum energy performance requirements;
- calculation of cost-optimal levels of minimum energy performance requirements;

- new buildings shall meet the minimum energy performance requirements;
- since 31 December 2020, all new buildings shall be nearly zero-energy buildings;
- establishment of a system of certification of the energy performance of buildings.

Figure 1: The ten principles of One Planet Living.
Source: (Bioregional, 2003).

The Paris Agreement was signed and adopted internationally in 2015 to reduce greenhouse gas (GHG) emissions and limit the global temperature increase (key aspects of the Paris agreement) to address climate change and its negative impact. The urban built environment is responsible for 75% of GHG emissions, and only buildings account for 39% (Architecture 2030, 2021). This agreement directly touches the construction sector. Figure 2 shows the built environment's impact on the climate and resource use, health, and well-being in the last ten years from 2010 to 2020 (WorldGBC, 2020). The graph shows that GHG emissions increased by 9%, while energy consumption increased by 4%, and solid waste streams from construction and demolition in developed countries grew by 10%. The population that lives in air polluted areas is about 91%, which shows the importance and urgency of the changes in the industry related to ecological and sustainable issues.

Figure 2: Impacts of the built environment on three sustainable development goals (SDGs) of the Paris agreement.
Source: (WorldGBC, 2020)

The Sustainable Development Goals (SDGs) (Fig.3), *"a blueprint to achieve a better, more sustainable future for all people and the world by 2030",* is a central element of the Agenda 2030 (United Nations, 2015), that the United Nations General Assembly introduced in 2015 (United Nations, 2016). Nine are directly related to the building and construction sector from seventeen SDGs, as presented in Figure 4 designed by WorldGBC.

Figure 3: Sustainable Development Goals (SDGs).
Source: (United Nations, 2018).

Figure 4: How Green buildings contribute to the SDGs.
Source: (WorldGBC, 2017)

2.1.2 Green building and energy performance certification systems

Meanwhile, methods and approaches for assessing the environmental impact of buildings and cities and establishing sets of benchmarks for building performance began to emerge on the global stage. Since there are different benchmarks and goals to achieve in construction and different markets that require different approaches, over 600 sustainability certifications for products and buildings have appeared and existed together (Jensen et al., 2018). Certification systems allowed measuring the building performance with qualitative and quantitative values and documentation and further exploration of the actual case studies to ensure the progress and support an integrated design approach. A timeline in Figure 5 provides a bigger picture of what and when was developed, on the top standards and documents marked up, and on the bottom, labelled green-building certification systems. In the following paragraphs, a brief overview of the major green building certification systems will be presented.

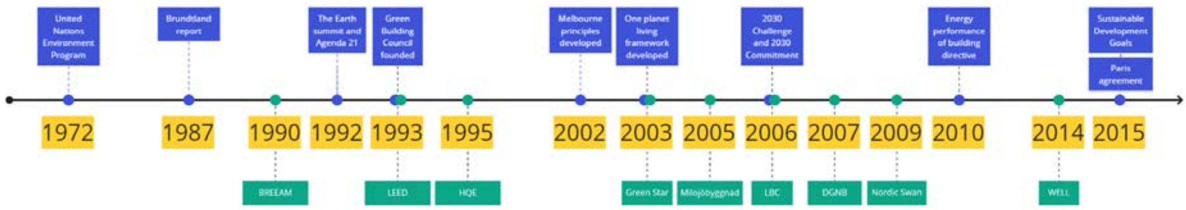

Figure 5: The timeline of key events and documents related to green building construction and green-building certification systems.

The first sustainable building certification can be considered the Building Research Establishment Environmental Assessment Method (BREEAM) launched in 1990 at the Building Research Establishment in England (McPartland, 2016). An international version of the standard was launched in 2008. By now, it has been implemented in over 50 countries (BRE Global, 2017). BREEAM system has been a template for many of the following certification systems (Jensen et al., 2018).

In parallel with BREEAM, the Leadership in Energy and Environmental Design (LEED) certification system evolved in 1993 by the non-profit United States Green Building Council (USGBC). In 1998, the USGBC presented LEED version 1.0. In 2003, the first LEED-certified building appeared, and by the end of 2004, this number increased by 100. In 2005, the PBD approach arisen under the LEED v4 and continued developing in LEED v4.1 (U.S. Green Building Council, 2021) This system covers different parts of the building lifecycle, from design and new construction to operation and maintenance (Jensen et al., 2018).

Haute Qualité Environnementale (HQE) in France was developed in 1995 and is used in France along BREEAM and LEED. It is based on principles of sustainable development formulated during the Earth Summit in 1992. The international operation started in 2012, and unlike BREAM or LEED, it accepts local codes and practices as alternative benchmarks for building performance (Jensen et al., 2018). Through the 2000s, Asian national building certification standards started to appear, such as Green Mark (Singapore), Green Building Evaluation Standard (China), Green Standard for Energy and Environmental Design (G-SEED) (South Korea), BEAM Plus (Hong Kong), The Comprehensive Assessment System for Built Environment Efficiency (CASBEE) (Japan) etc. (Shen, 2016). Deutsche Gesellschaft für Nachhaltiges Bauen (DGNB, en. German Sustainable Building Council), founded in 2007 by the German Sustainability Council (German Sustainable Building Council, 2021), is widely used in Germany and neighbouring countries as its framework allows to adopt it quickly to the local standards and different building types. The main focus is on sustainability together with good technical and process quality; inclusion of the economic aspect distinguishes this system from others (Jensen et al., 2018). In 2008, the first system in South America was launched, called Processo AQUA later was merged with HQE certification in 2014 (A Fundação Vanzolini, 2020). In 2008 concurrently in South Africa, the Green Star SA certification appeared based on the Australian Green Start system (IEA, 2017).

The first building standard that focuses primarily on building impact, on human health and well-being WELL was launched in 2014 by WELL building Institute and used worldwide. It assesses the building performance in terms of sleeping quality, mood, and performance of people inside the space. The certification system is used worldwide, mainly in the USA and China, where most WELL-certified projects are located. It was aligned from the beginning with LEED and constantly improved to work well together with other systems, such as BREEAM and Green Star (Jensen et al., 2018).

The above-exposed systems do not represent a comprehensive list of projects, documents and agreements but major ones that show the importance of the immediate actions and the measures already done to address the environmental and climate issues. Moreover, the building and construction sector has a great potential to meet these challenges and provide sustainable cities and communities since it is one of the primary goals for humanity today. In order to do it, the industry has to change drastically, as it is the only way to make a difference. The buildings themselves have to become more sustainable, lean and eco-friendly. Among the solutions offered, the PBD approach shows a high potential for changes, mainly when applied in the early design stage. This goal-driven approach focused on the future performance of a building rather than the construction process. Applied in the early stage, it provides sufficient data for decision-making that is unavailable in the traditional approach.

2.1.3 Principles of sustainable design

The main objectives of sustainable engineering formulated by Abraham (2005) strongly impact the development of current technologies and methods employed in design in general and on the PBD approach in particular. The principles themselves are not prescriptive, but they create a new foundation for sustainable design development, holistic, focused on safety and well-being, lean, innovative and inclusive. The principles are (Abraham, 2005):

1. *Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools.*
2. *Conserve and improve natural ecosystems while protecting human health and well-being.*
3. *Use life cycle thinking in all engineering activities.*
4. *Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible.*
5. *Minimize depletion of natural resources.*
6. *Strive to prevent waste.*
7. *Develop and apply engineering solutions, while being cognizant of local geography, aspirations and cultures.*
8. *Create engineering solutions beyond current or dominant technologies; improve, innovate and invent (technologies) to achieve sustainability.*
9. *Actively engage communities and stakeholders in development of engineering solutions.*

2.2 PBD approach overview

The performance-based design approach has many definitions; Kalay (1999) defined PBD as a holistic approach that considers ecological components and functional, economic and aesthetic. Spekkink, in the Performance-Based Building Network (PeBBu) report (2005), defined PBD as a design that is based on a set of performance requirements that can be evaluated.

2.2.1 Development of PBD approach

In general, if we look at how architects created projects for their buildings in antiquity, the Middle Ages, modern history, and how architects create their projects now, we will see that the process has practically not changed. Tools, architectural vision, materials have changed, but the process has not. Modern architects research and understand the project's site context, detect constraints, review precedents and case studies, and then create multitudes of sketches and simple models to find the best shape and layout. Furthermore, all this is based on her or his own experience, experience or examples of others and his imagination. There is little place for the informed and data-driven decisions in this approach. Now, it is time to shift from the "form-making" paradigm towards "form-finding" (Oxman, 2008).

PBD approach is not a new concept at all, and the first mentioning was at the time of Hammurabi (1900 BC) (Szigeti & Davis, 2005). Building performance was the main goal of the construction at the beginning, later after achieving a stable result in the utility of the building, building codes and norms emerged prescribing not how the building should perform but how it should be built. A new wave of interest in building performance occurred in the 1970s and 1980s, with building physics development as a discipline. “Phillips Experimental House” (1975), DTH zero-energy house (1975, “Lo-Cal House” (1976), “The Sas-katchewan Conservation House” (1976), “Leger House” (1977), are among the top examples of energy-efficient projects of that time (Ionescu et al., 2015). In 1995 the Passive House standard was developed. A year later, the Passive House Institute (PHI) was founded by Dr Wolfgang Feist and is constantly developing and improving knowledge in the field of building energy efficiency, as the whole system and its parts, such as engineering systems, components and materials (Passive House Institute, 2015).

One of the first comprehensive studies of the performance approach in the building was done by International Council for Building Research Studies and Documentation General Secretariat (CIB) Working Commission W60 from 1971 until 1982 when the CIB Report “Working with the Performance Approach in Building” was published (Gibson, 1982). The report describes the essence of PBD and guides the definition of performance requirements and their implication to the design.

Based on Gibson’s study in 2005, Performance-Based Building: Conceptual Framework, the final report of the Performance Based Building Network (PeBBu), was published. The report introduces a developed framework based on the case studies presented in a separate document, Compendium of Statements of Requirements Report. It discusses the critical criteria for the more straightforward implementation of this method. Moreover, the report highlights the importance of the PBD approach in the early stage of design when *“the information about the “gap”* between demand and supply requirements can support investment decisions (Szigeti & Davis, 2005). The main focus of the study was on how to reconcile user requirement (demand) and performance asset (supply) to obtain the best possible result in building performance. Results of this study were the definition of the PBD concept in relation to the construction industry sector, a template for data collecting and case studies of projects where the PBD approach was utilized, terms and definitions for both “*demand*” and “*supply*” sides (Szigeti, 2005).

2.2.2 Key characteristics

One of the first identified differences of PBD from the conventional approach was that PBD is **not prescriptive**, accordingly to Szigeti (2005) and Gibson (1982). It focuses on the “*required performance in use*” rather than methods and quality of the construction, in other words, not how good it is but how good its end-performance is. Codes and regulations which guide the traditional design method are based on the experience of what works and what does not, and they try to prevent unnecessary accidents that happened in the past (Szigeti & Davis, 2005). The PBD approach does not cancel all the knowledge and experience gathered; moreover, it adds a new value to live in a space that is not only safe but also comfortable and aligned with our needs.

The two essential characteristics of the PBD concept, according to Szigeti and Davis (2005), are:

- **the two languages** from the side of demand and the side of supply. Figure 6illustrates the difference between the two of them, where the main question is how a supplier can correspond on the needs of a client;
- **verification of the results** for compliance with the requirements to confirm that we reached the required end-use performance. It can be done in many ways, such as tests, measurements, audits, etc.

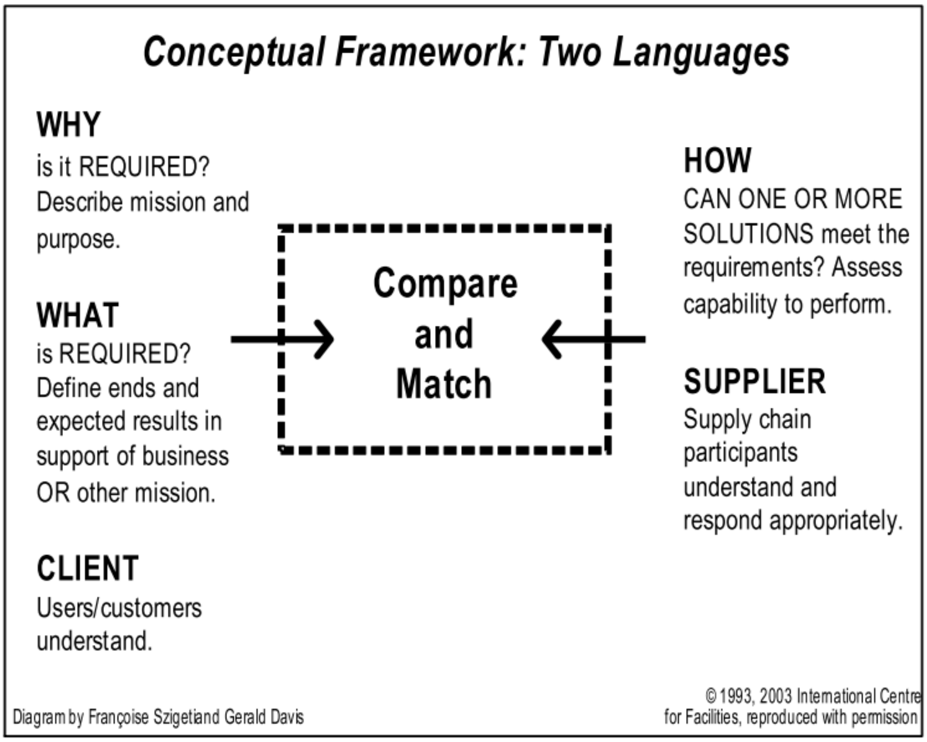

Figure 6: Conceptual framework: two languages.
Source: (Szigeti, 2005).

A holistic view is another characteristic of the PBD approach that differentiates it from the conventional. It requires focusing on the entire building life-cycle and not only on the construction stage (Becker, 2008)**.** Considering the entire building life-cycle, looking further than only the design and construction phase is essential. This approach allows achieving high-performance, challenging goals and realizing a better-integrated solution. Østergård et al. (2016) emphasised that the holistic approach is fundamental when it is necessary to assess the vast range of often contradicting requirements and objectives; they also stated that this approach enables to overcome uncertainties (Østergård, Jensen & Maagaard, 2016).

As we have spoken about the importance of building evaluation throughout its life-cycle, **early involvement of various domains**, such as owners, end-users, manufacturers (Becker, 2008) and facility managers, is required as architects do not have sufficient information about how the building will be used and what the end-users necessities are. There is a potential of bringing broad expertise early into whole-system thinking and decisions influenced by a wider team. It enables the necessary data and knowledge in the various fields to make informed decisions and provide better design (Sibenik & Kovacic, 2020). Szigeti and Davis (2005) agreed with Gervásio et al. (2014) and Abualdenien et al. (2020) that the most fundamental decisions affecting building performance are made in the early design stages. The conventional method is characterized by the involvement of experts when at least the concept design is already done. It means the decisions about shape, height, position, glazing distribution, and sometimes the construction system and materials have been made. In these cases, experts can evaluate the design but cannot implement drastic changes, so only minor improvements can be made, or an extensive rework needs to be done. In the PBD approach, we do not just evaluate the design we have, but we have got more – information on the dependence of performance on the parameters of the building. Suppose we understand efficiency as the quality of doing something well with no waste of time or money. In that case, this approach allows us to do less or even no rework when its cost is higher and get the best possible design in terms of performance.

Hollberg (2018) stated that the only way to find the optimal design option is to generate and compare variants. That brings us to another distinction of the PBD approach from the traditional one – the **multiplicity of design iterations.** The conventional approach employs analysis to assess how good the design is in terms of standards and requirements; it is not desired to know how it could be better and what could be improved. Contrasting, the PBD approach uses analysis to investigate the possible performance the design can reach while applying different solutions.

Although the PBD approach differs from the conventional, it is not required to replace one with the other; they can work together. An example of a balanced system that includes both traditional models based on codes and standards and the new PBD approach is presented in the diagram in Figure 7. From the diagram, it is clear that these two approaches were applied at different levels: the right part represents fields (safety, health, fire, structure, sustainability) where regulations and codes provide measurable requirements in order to prevent risks; the left part works on the level of user needs (comfort, well-being, health) and may differ from the project to project.

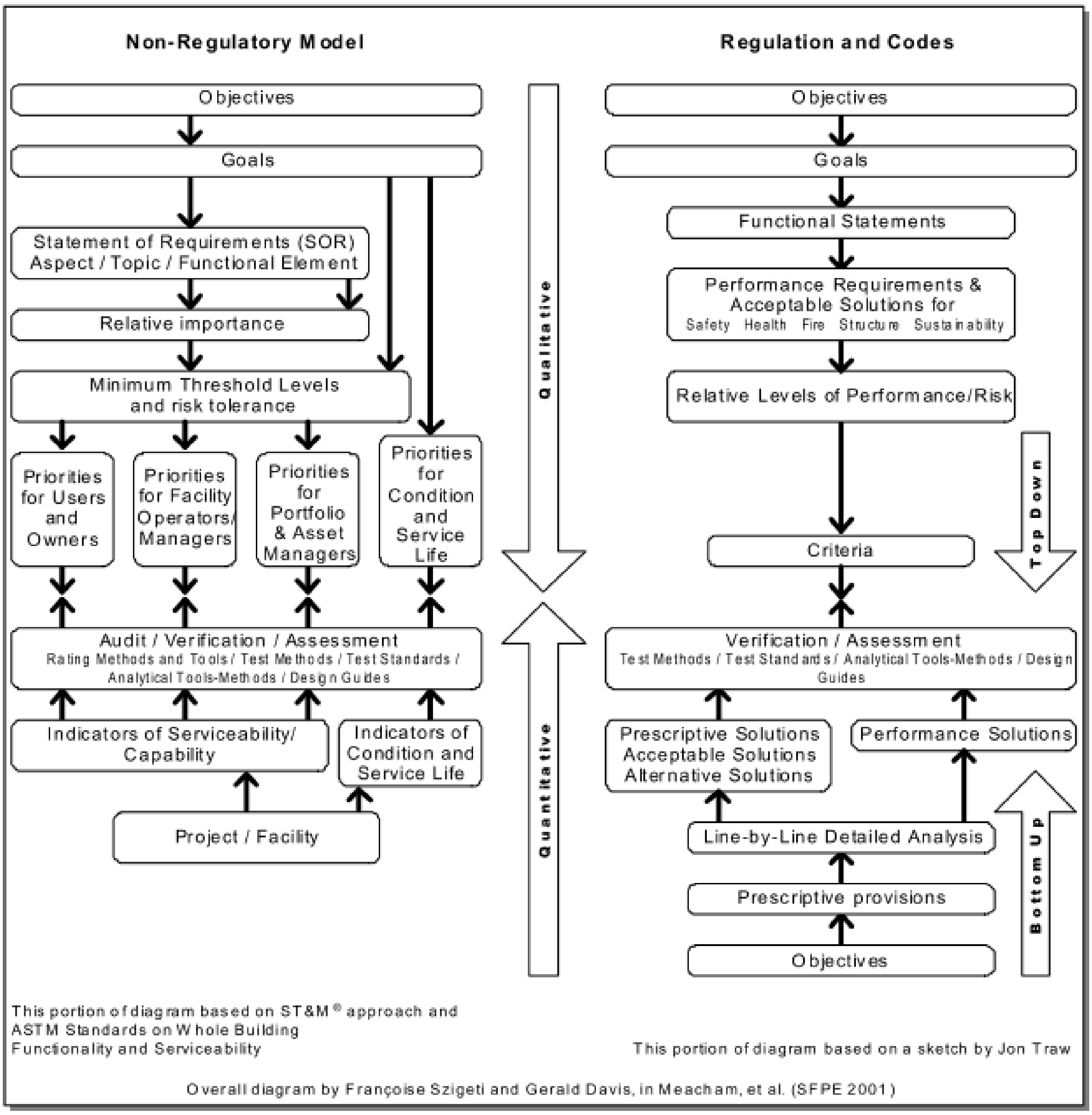

Figure 7: Total Performance system model: A Framework for Describing the Totality of Building Performance.
Source: (Szigeti, 2005).

2.2.3 Tools and methods supporting the PBD approach

BIM and Integrated Design Process (IDP)

PBD approach is a framework, which defines the concept but not an application. BIM as a technology and as a "*process of information management*" (RICS, 2020) involving and connecting professionals, collecting, storing and exchange data, utilizing new methods and cutting-edge technologies in order to produce better buildings is a "Construction 4.0" core (Vite & Morbiducci, 2021). The term came from a more general "Industry 4.0" and highlighted the importance of merging physical, digital and biological aspects (RICS, 2020). BIM used to be defined within seven dimensions (Charef, Alaka &

Emmitt, 2018) illustrated in Figure 8. Every dimension is like an additional layer of information and is related to a specific area of application (Sertyesilisik, Sertyesilisik, Çetin & Ocakoglu, 2021):

- 1D, 2D, 3D – related to three dimensions of space; area of application – visualization, clash detection, prefabrication.
- 4D –dimension of time; construction planning and management.
- 5D – dimension of cost; whole life-cycle cost.
- 6D – sustainability; energy and lifecycle analysis.
- 7D – facility management; space management, efficient use of resources, lifecycle management.

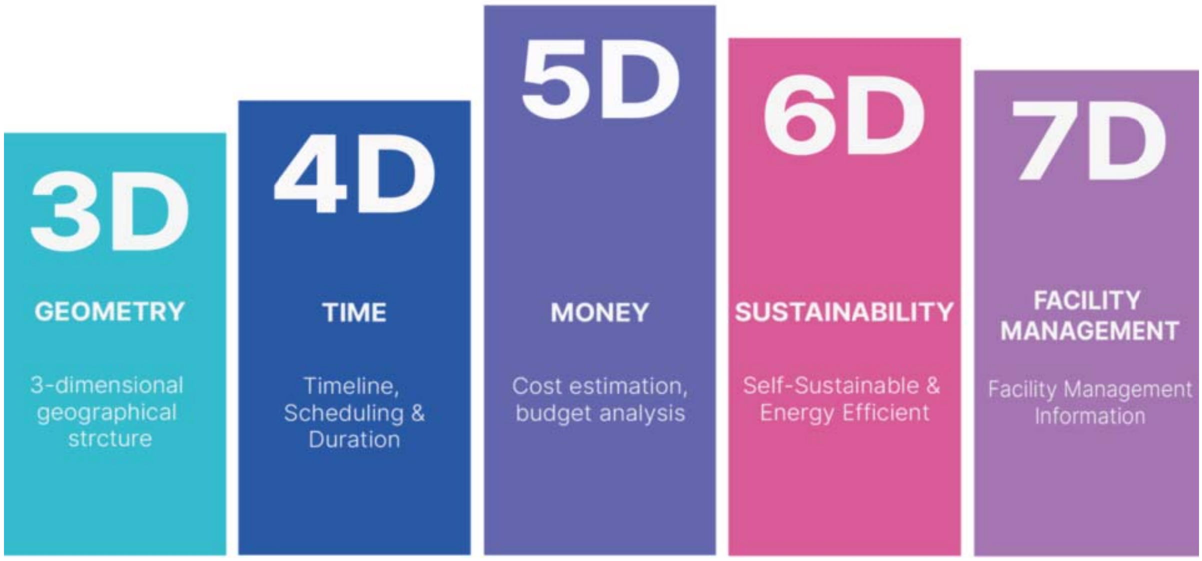

Figure 8: BIM dimensions.
Source: (bimspot, 2021)

BIM has all prerequisites to address sustainability challenges; however, in the traditional approach (even with BIM), sustainability aspects used to be addressed late, when all the vital decisions had been already made (Vite & Morbiducci, 2021). Hence, just the use of BIM is not enough; the approach, method of work has to be changed if we want to reach sustainable goals, which were set.

Integrated design process (IDP) is an intentional way of approaching sustainable building (Amann, 2010) with distinctive features such as goal-driven, inclusive, holistic, iterative (Zimmerman, 2006), front-loaded (time and energy invested early) (Busby Perkins+Will and Stantec Consulting Ltd., 2007). This description is consistent with the PBD approach that allows us to use IPD when the PBD approach needs to be applied. IDP naturally makes a workload shift towards an earlier stage (Amann, 2010), as illustrated in Figure 9. It means more time spent at the beginning of the design process will pay off at the end as the cost of rework grows progressively towards the end of design and construction implementation, as is shown in Figure 9. Another benefit of shifting work load towards the beginning of the process lies in the higher potential to influence the performance in opposite to later stages (Zimmerman, 2006). Tian et al. (2015), together with Bogenstätter (2020), stated that the 80% of final energy performance of the building are the result of 20% of design decisions made in the early stage.

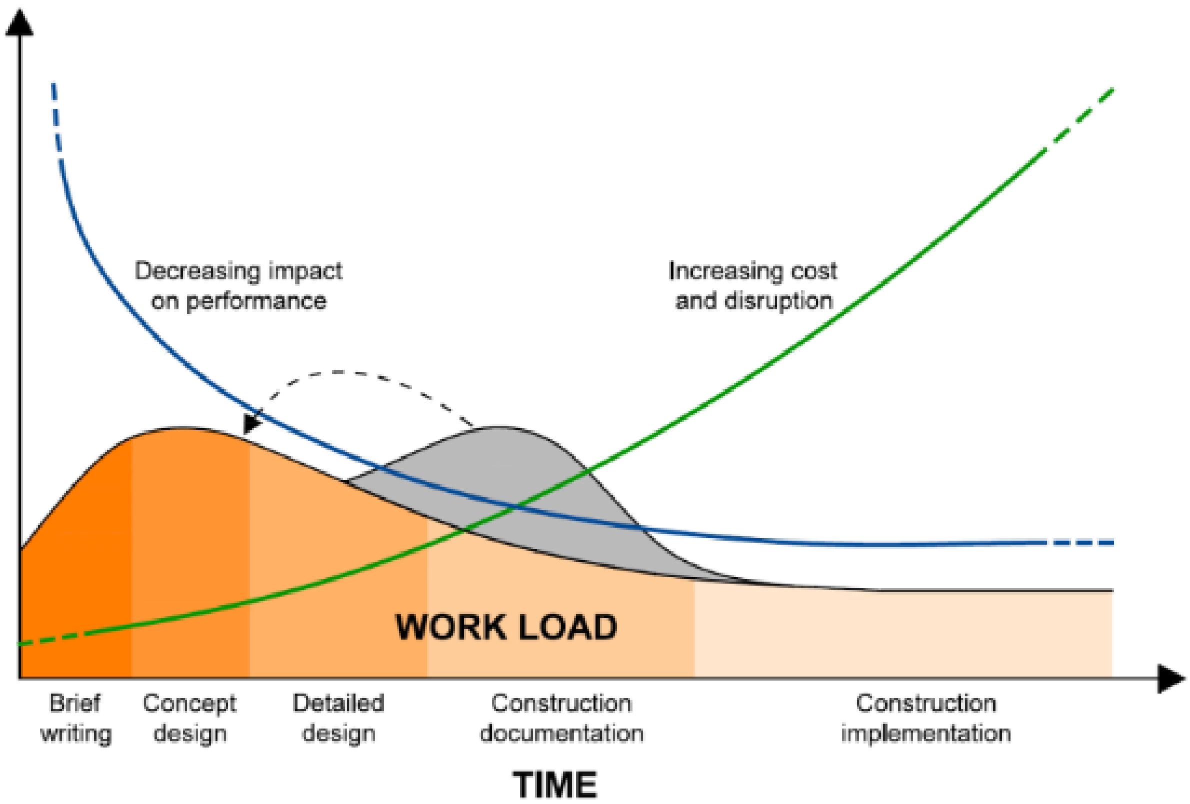

Figure 9: Workload shift due to IDP approach.
Source: (Amann, 2010).

Unlike a conventional linear approach, when decisions are often made by a smaller group of people once and are not reexamined later, an iterative process IDP with regular feedback and involvement of a broad expertize team since the very beginning of the design process allows for informed and proven decisions (Busby Perkins+Will and Stantec Consulting Ltd., 2007). Figure 10 illustrates the process starting from the kick-off meeting and exploring a vast space of design options iteratively, coming to optimal design options and constantly improving even during the maintenance phase. The holistic view of IDP is granted by regular meetings (all team workshops) where specialists of each discipline and stakeholders, procure managers and maintenance managers can and should take part. Otherwise, it can easily be a situation where mechanical engineers are dealing with too high cooling loads, installing expensive air conditioning systems, when architects can solve it, adding shading or changing glazing characteristics.

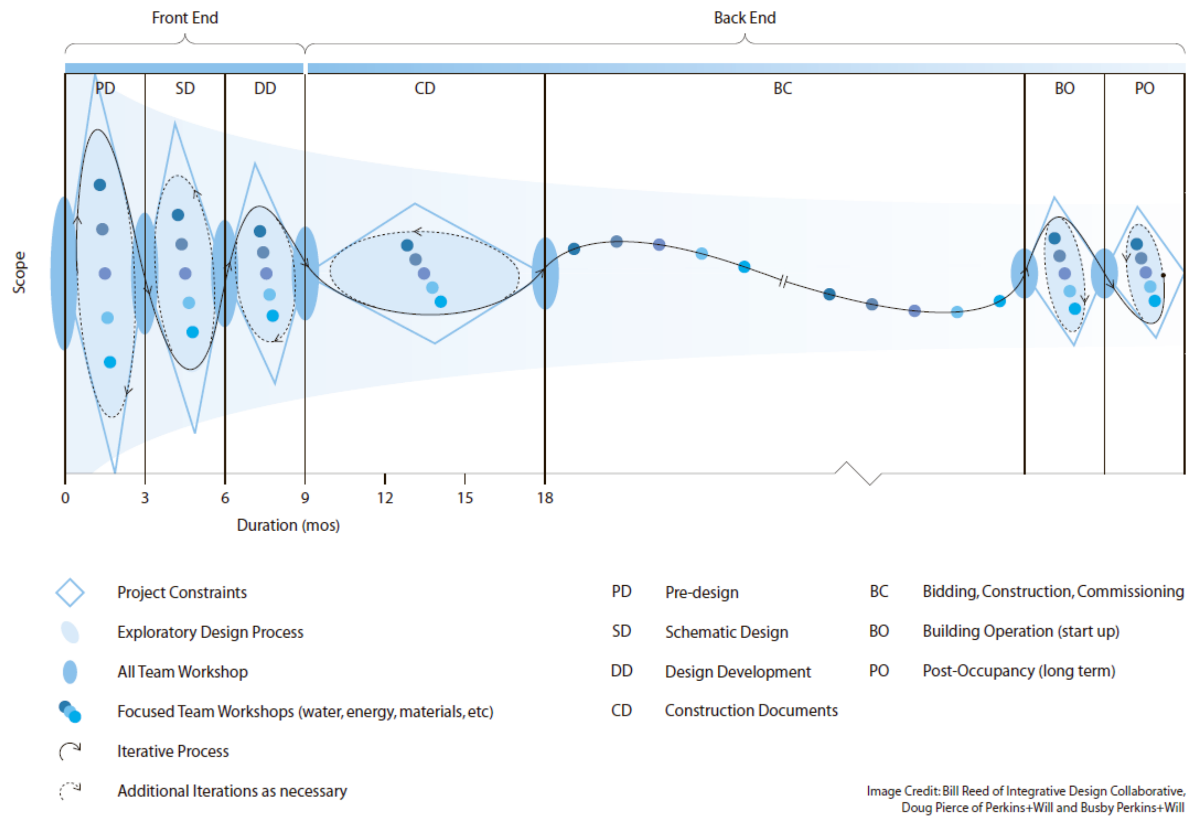

Figure 10: Integrated design process (IDP).
Source: (Zimmerman, 2006).

Building Performance Simulation (BPS) tools

Building performance simulation is the approach when simplified mathematical models are used to imitate the building behaviour in order to understand the future performance of the building (De Wilde, 2018). There are different types of BPS identified: energy performance, environmental performance, indoor air quality, lighting, acoustics (Jung et al., 2018) and others. Østergård et al. (2016) classified BPS tools accordingly to the degree to which they are integrated with BIM tools:

- Integrated – simulations that can be processed inside modelling tools (e.g. solar analysis, system analysis in Revit).
- Run-time interoperable – used plugins or API to transfer data from the model to BPS (e.g. SketchUp + Sefaira, Revit + Green Building Studio, Revit + Cove.tool).
- File exchange – used standard or proprietary file formats for data exchange (exchange file formats examples: IFC, gbXML, DWG, RVT, OSM).
- Standalone – user input data manually into BPS software (EnergyPlus, Radiance).

BPS tools are widely used by engineers at the end of the design phase when they need to obtain the result and compare it with certification system benchmarks (Attia et al., 2009). BPS tools usually require well-developed models with additional information regarding systems characteristics, materials, etc. Moreover, it is a stumbling block for the early design stage as the information at this stage is insufficient and can change rapidly. Although the number of BPS tools available is enormous, there are still numerous limitations and barriers for application of BPS tools in the early design stage identified by researchers (Attia, 2011) (Østergård, Jensen & Maagaard, 2016) (Jung et al., 2018). They are long learning curve periods, unclear results representation, interoperability, absence of optimization strategies, etc. (Attia et al., 2009). Traditional BPS tools have been developed on a request to evaluate the final decision and not to optimize it. It is the recognized issue among researchers (Østergård, Jensen & Maagaard, 2016), (Attia et al., 2012) – an insufficient number of tools, which can not only assess the quality of design but guide designers towards an optimal solution in accordance to the design goals. While "*pre-design informative*" BPS (Attia et al., 2012) (Østergård, Jensen & Maagaard, 2016) are not developed enough in optimization and decision support, another technique – parametric optimization – began to develop.

Parametric optimization (PO) method

Parametric optimization is used when a multi-objective approach takes place (Fu, 2018). In other words, when the space of possible variants and the number of variables is large, checking and comparing them manually is just impossible. This method is highly compatible with BIM modelling tools (Zhuang et al., 2021) through the use of visual programming interfaces (e.g. Dynamo for Revit or Grasshopper for Rhino) and genetic algorithms for design option generation. **Parametric BIM models** in this approach supply genetic algorithms with the variables, which come from the parameters of a model and its components (Rohrmann, 2019). **Visual programming interfaces** are connecting links between parametric BIM models and genetic algorithms. These visual programming interfaces allow specialists unfamiliar with programming to create algorithms using an extensive library of nodes (simple blocks of codes) by easily combining them. **Genetic algorithm (GA)** produces design variants based on the variable inputs; selects several best solutions based on the objectives and goals of optimization; and produces new variants based on previously selected, so the next generation of solutions will be closer to the desired result. The number of generation cycles and best solutions in each cycle can vary from study to study (Lim et al., 2018). Examples of such genetic algorithms can be Pareto Archived Evolution Strategy (PAES), Strength Pareto Evolutionary Algorithm (SPEA) or Nondominated Sorting GA (NSGA) (Rohrmann, 2019). Examples of such algorithms can be Octopus and Galapagos in Grasshopper and Generative design in Dynamo.

Although it is a promising option for the early-design stage PBD approach, it has some substantial obstacles (disadvantages) obstructing its implication and widespread use. Among the disadvantages of this method, Zhuang et al. (2021) highlighted the following:

- It is not a universal (multi-type) method, so the optimization algorithm has to be developed from scratch or updated from previously used for each project or at least a building type.

Different types of buildings utilize different key performance parameters and different design goals, e.g. school building aims to better daylight and lower EUI (energy use intensity) when sports complex has higher requirements for air quality and costs.

- There is no one method of assessing multiple objectives in general and in parametric optimizations. Depending on the user, optimality criteria or metaheuristic methods can be implemented (Sahab et al., 2013), so the comparability of different PO is low.
- Some of the PO methods use external databases of local materials and building components, which are the inputs for variables. The problem is that the small number of regional and specific databases and their occasional updates exist.

2.2.4 Challenges when PBD approach applied in the initial stage of the design

Szigeti (2005), Oxman (2008) and other authors agreed that the implementation of the PBD approach is far from the desired level; despite the number of researches done and the papers and reports published, still, there are several concerns regarding the use of PBD approach in the early stage of design. Reviewed challenges illustrated in Figure11 concerning the benefits determined and proposed solutions.

These challenges can be grouped in the way they relate to the part of the PBD approach:

1. Requirements formulation.
2. Modelling and software issues.
3. Results assessment.

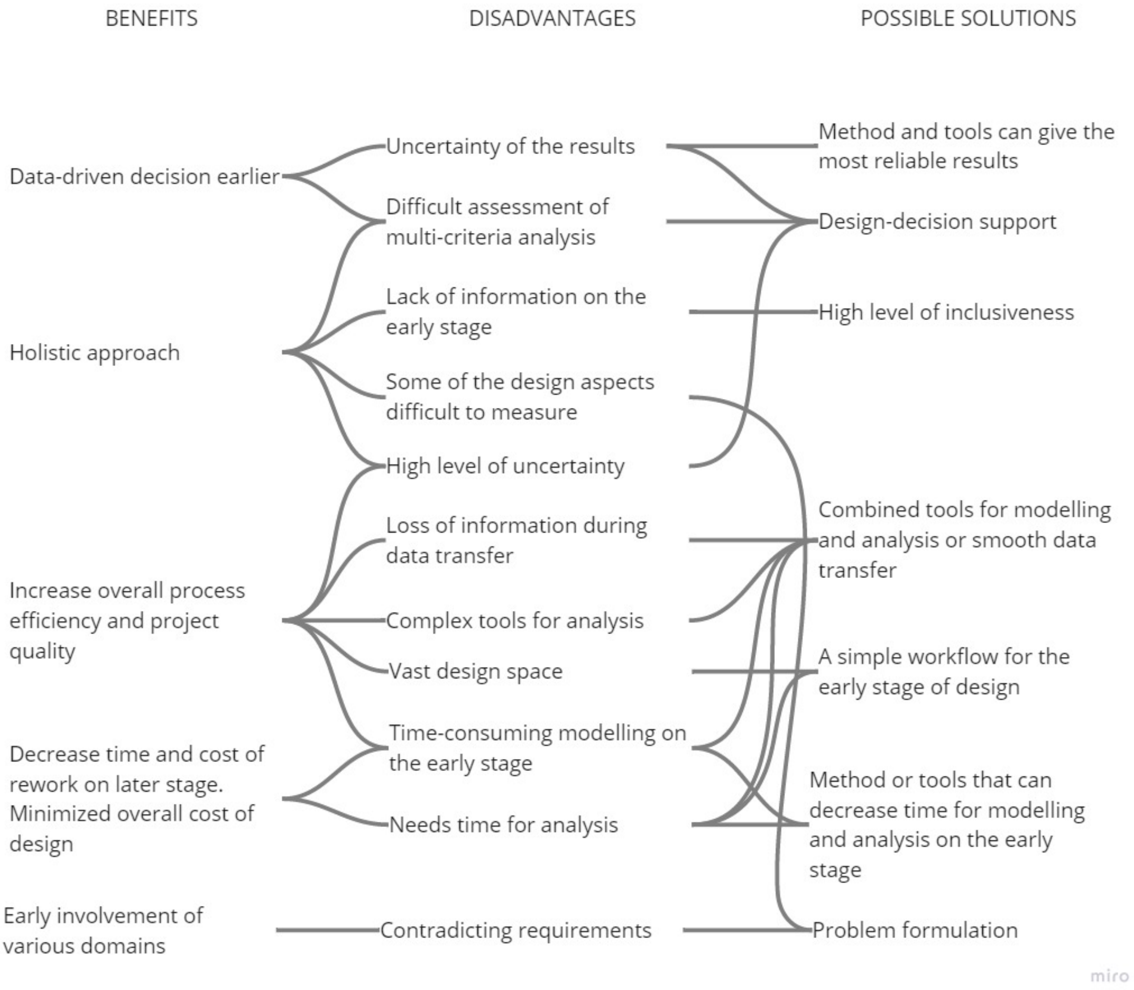

Figure 11: The reviewed benefits and their relation to different challenges of PBD in the early design stages and possible solutions.

Requirements formulation

One of the PBD approaches features is the early involvement of various expertize that comes to a problem on the requirements gathering stage (Khemlani & Kalay, 1997), such as **contradicting requirements**. The list of criteria building has to fulfil (requirements) starting from various codes and standards and complemented by the specific condition from the list of professionals involved. For instance, architectural needs might confront the requirements of a structural engineer, or in order to provide more natural light on the working places, the overheating of the space or glare can occur. As we use a holistic approach, we have to consider design aspects and parameters regarding the requirements we receive from the stakeholders. Moreover, we came to another issue, which states that some **design aspects are difficult to measure** (Rohrmann, 2019). Some building parameters can be measured and described easily; others can be translated to countable scores through secondary aspects. Such parameters that are quantifiable are easily incorporated into the PBD design approach. However, parameters like view quality, occupant sensations, architecture (i.e. aesthetic) qualities, etc., are too subjective and cannot be quantifiable. Therefore, their inclusion into the PBD paradigm is almost impossible, although such parameters are sometimes crucial for the success of a particular project (Jensen et al., 2018).

Our experience as architects confirms that all necessary data related to the building in the environmental, economic, and social spheres is quite difficult to obtain at the very beginning of the project. Figure 12 illustrates the idea "garbage in, garbage out" (GIGO), which means complete and trustworthy input data is needed to obtain reliable analysis results; if this data is unavailable, the result will be imprecise and inaccurate or even impossible to get.

Figure 12: Garbage in, garbage out (GIGO) concept.
Source: (Sykes, 2013).

Another concern about input data is that BIM models used for analysis require more initial information than traditional 2D drawings. Information insufficiency (Kolltveit & Grønhaug, 2004) can lead to significantly false assumptions (Abualdenien et al., 2020), which can, in turn, affects design decisions. With contradicting requirements and uncertainty of the design, lack of information on the early design stage might give results far away from the final actual performance that can cause decisions based on wrong information. One of the consequences of this issue is that buildings rarely perform and often consume 20-30% more energy than was predicted (Pinheiro, Corry & O'Donnell, 2015).

Modelling and software issues

Modelling itself is a time-consuming task compared to 2D drawings; however, each type of analysis requires specific information to be present in a model to conduct the analysis.BPS software often requires a specifically prepared model that differs from the original, created into modelling tools. The consequence is **increased time for modelling** at the beginning of the project (Attia et al., 2012). In case we want to collect all necessary information in one model properly, it is an even more challenging task, as sometimes different types of analysis require different levels of maturity or model's Level of Development (LOD) (Abualdenien et al., 2020). Abualdenien (2020), in his work, presented the concept of the Multi-LOD model to manage information of multiple LODs in one model that can help to overcome this issue but still needs to be tested and put in practice. Time-consuming modelling issues also occur when iterative modelling needs to be done during a series of systematic analyses (Østergård, Jensen & Maagaard, 2016). Another challenge, highly related to the time-consuming modelling, is a **vast design space** together with the **rapid change of design** inside one project as well as in a sequence of projects when project configuration changes from one project to the next, or different software and modelling standards are used (Østergård, Jensen & Maagaard, 2016).

Tian et al. (2015) discuss another issue related to tools compatibility – simulation tools are not always ready to consume the BIM model, so it needs to be updated in line with specific tool requirements or remodelled inside the BPS software if there is a possibility. One option to get over this issue is to use a modelling tool that supports early-stage analysis within it; unfortunately, there is still an insufficient number of such tools (Østergård, Jensen & Maagaard, 2016). Therefore, exchange formats, such as the Industry Foundation Classes (IFC) or Green Building XML (gbXML), are widely used for data transfer between modelling and BPS tools. Nevertheless, Sibenik and Kovacic (2020), in their study, reported about the geometry interpretation problem during the data transfer via IFC format; as well as Jung et al. (2018) described issues with the transfer of mechanical systems data for dynamic simulations to IFC; Petrova et al. (2017) stated information loss during data transfer as an actual problem.

Despite the increasing number of PBD tools evolving in the last decades, some designers report the **complexity of tools** (Gratia & Herde, 2002) or inconsistency to the standards and methods used (Aksamija, 2012). The complexity of tools explains their initial purpose – to conduct the later stage analysis and achieve precise, detailed and accurate results. The tools require a more complex and accurate model as an input than a conceptual building model. Despite the high accuracy and reliability of results, these tools are usually not suitable for assessing a wide range of different performance indicators together, so the comparison and evaluation of multiple analyses is another challenge here (Østergård, Jensen & Maagaard, 2016). These tools utilize more sophisticated analysis methods that bring us to the next challenge highlighted in the literature – **it takes time to run the analysis.** One type of analysis (one simulation) may take relatively little time; however, it rarely needs to run one simulation or one type of analysis, so the time consumed increases significantly. By the time the result has been obtained, it may be late as new design options have already evolved (Østergård, Jensen & Maagaard, 2016). Lately, specific BPS tools for the early-stage analysis started to evolve, such as Cove.tools, Sefaira, Green Building Studio (GBS), etc. These tools incorporate multi-criteria analysis with the ability to consume raw data from the conceptual BIM model; however, these tools suffer from unreliability and low accuracy of results.

Results assessment

Due to the reasons discussed above (insufficient information, vast design space, etc.) and imperfection of simplified BPS tools, the risk of obtaining **inaccurate results** increases (Negendahl & Nielsen, 2015). It is one of the disadvantages of simplified tools being flexible and giving fast feedback on the one hand and giving unreliable results on the other. Moreover, an architect should know how to interpret results obtained from the tools to optimize the design (Østergård, Jensen & Maagaard, 2016). Besides, there is **not only one criterion** for assessing future building performance and no one way to measure different aspects of it (Iwaro et al., 2014). For multi-criteria analysis, it is not clear what option is the best – e.g. is it better for a building project to be better daylighted or to have lower transmission thermal losses due to smaller area of glazing? According to the research about "architect friendly" BPS tools made by Attia et al. (2009), only a few tools provide guidelines and support in this process.

Nevertheless, it is critical to have **competent guidance in understanding the results** as decisions made in the early stage have the highest effect on the final design. Informative support for decision making was identified by Attia et al. (2012) as one of the barriers to integrating BPS during the early design phase together with results interpretation (Fig.13). It is rarely only one type of analysis used, or it is done in one cycle; more often, multiple iterations must be done to explore all possible solutions the design might have. At this point, another barrier – **informed iteration** (Fig.13) – comes out. Informed iteration also requires architects to understand building physics and the relations between different parts of building systems. Previously the analysis was not done as a part of the form-finding procedure when there was no need for special knowledge (Attia et al., 2012). Furthermore, there is no single methodology on how to approach the simulation result's evaluation should be executed.

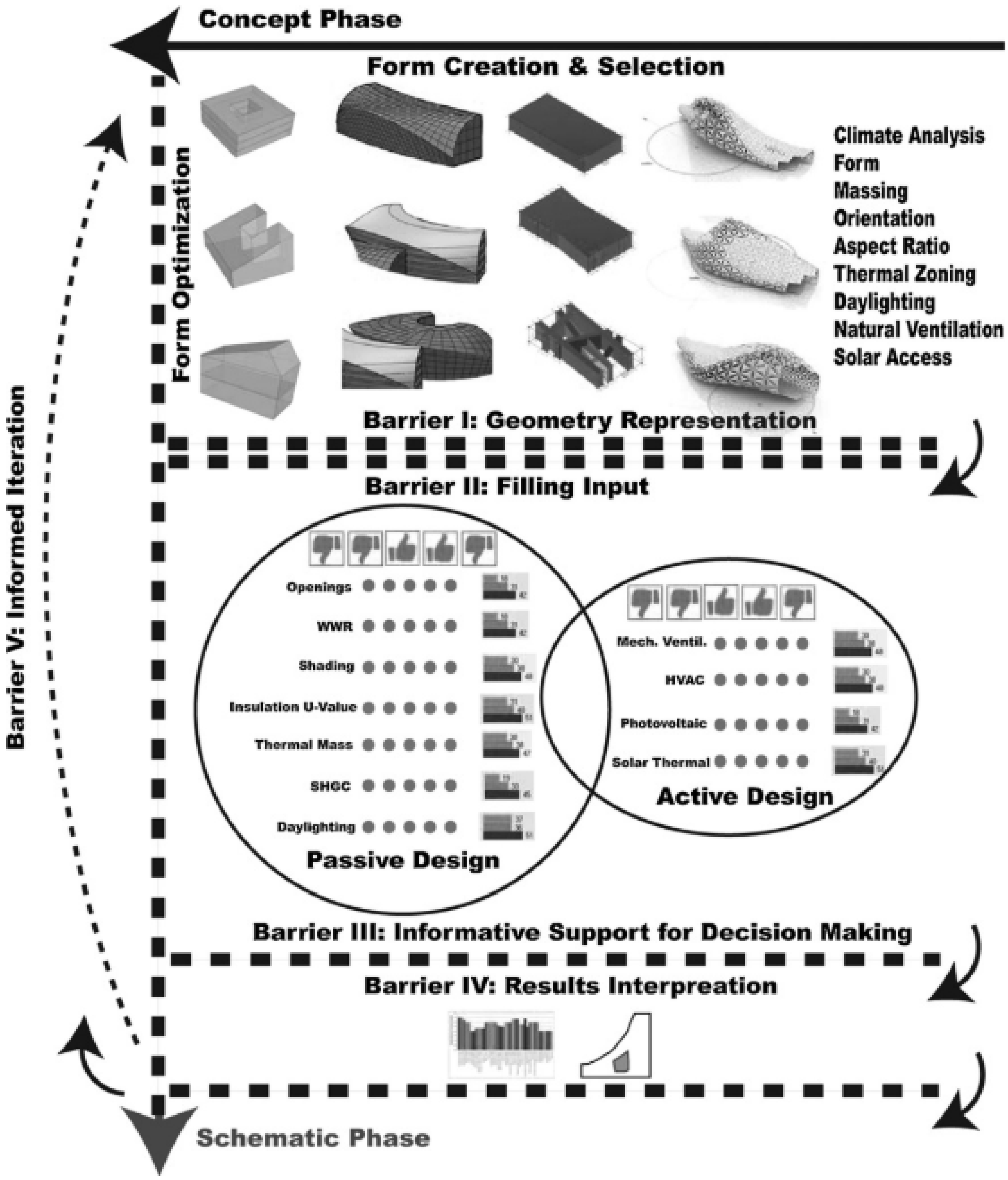

Figure 13: Barriers to integrating BPS during early design phases.
Source: (Attia et al., 2012).

2.2.5 Knowledge gaps

The identified knowledge gaps were:

- Absence of a clear and straightforward system of objectives for the early design stage.
- Absence of the reliable methodology (strategy) for the performance analysis in the early design stage.
- Absence of one simple methodology for multi-criteria assessment.

3 METHODOLOGY

Two primary approaches were selected to address the exposed objectives of the thesis. A comprehensive online survey was conducted to support the data collection and to understand the acceptance of PBD from the design participants (architects, engineers, etc.) point of view. Secondly, a practical experimental application of PBD on a hypothetical project was accomplished with a selected early design stage performance evaluation tool that can be integrated or linked with BIM tools. The practical application was intended to identify issues with the application of PBD in BIM from the designer's point of view and compare its approach to a conventional one.

One of the biggest challenges during the practical case study was an absence of a tried and proven methodology for PBD analysis on the early stage of design and standard workflow for the overall process of modelling and analysis. The conventional approach usually involves one cycle of design: modelling – analysis – improvement, while the PBD approach implies more than one such cycle. In order to develop the strategy that could support the workflow, the following questions were asked:

- What is important to measure at the early stage of design? What are the goals of the design?
- What features of the building cannot be changed easily later (shape, orientation, glazing, etc.) and should be decided earlier?
- In what order to run the analysis to obtain reliable results?

The first question helps to identify requirements for the design and translate it to measurable metrics; for instance, visual comfort could be translated into Spatial Daylight Autonomy (sDA) and Daylight Glare Probability (DGP) (Atzeri et al., 2016). The second question aims to pick only those features of the building that are basic on the one hand; however, their change at later stages leads to global rework in the project on the other hand. The third question was necessary in order to build a system for conducting tests. As discussed previously, the PBD approach involves more than one analysis cycle, and there is usually more than one parameter to check.

3.1 Explanation of research methods

3.1.1 Survey

As the research attempts to investigate the application of the PBD design approach at the early stage of the design process, a questionnaire was utilized to collect information from practitioners using BIM technology, as this is one of the prerequisites for applying this approach.

The proposed survey (Annex 1) was prepared and disseminated online using Google Forms to gather as much data as possible among large and small architectural and engineering companies worldwide.

The questionnaire consists of 20 questions, and the estimated time to complete a survey was 5 minutes or less; an example of a survey questionnaire can be found in Annex 1.

The survey consists of two parts:

Demographic information: collecting data about the company type, size and experience and selecting out those respondents who use performance-based design approach in their practice.

PBD acceptance information: verifying statements about performance-based building design approach made based on the literature review. The first part of the survey has ten questions with one or multiple-choice answers, while the second part has another 10 Stapel scale type questions where respondents indicate agreement or disagreement with a statement on a scale from 1 (disagree) to 5 (agree).

The survey was sent by email directly to the companies' addresses and disseminated indirectly through LinkedIn, Facebook and WhatsApp groups. Seventy-five direct messages were sent, and five indirect posts on social media platforms were created in 3 weeks.

3.1.2 Practical part

The study was focused on the concept phase of design and conducted in two different ways: applying the conventional approach and the PBD approach. At first, the conventional approach test was done intentionally to exclude the influence of the knowledge gained during the performance-based approach. Both methods utilized the same tools that are described below. The comparison of methods was made based on the time used for the particular step – i.e. modelling, preparing the analysis and the analysis itself, and the subjective judgment of the quality (i.e. performance) of the final product.

Tools

As BIM is not a new technology, the number of tools developed, especially for modelling, is enormous. It was not the goal of this work to make a comprehensive list of the software present on the market or to compare all of them and select the best modelling tool; that is why the selection was made based on how extensively the tool is used. The chart below (Fig.14) illustrates the top 3 BIM modelling software tools in 2019; among them are Revit, AutoCAD & AutoCAD LT and ArchiCAD (NBS, 2019). As the most widely used BIM software (46%), Revit (version 2021) was selected for the current study.

Autodesk Revit is a multidiscipline design collaboration software that supports:

- conceptual design with a particular set of tools;
- interoperability through the formats like IFC and gbXML;
- architectural, structural and MEP modelling;

- built-in graphical programming interface Dynamo;
- integrated energy analysis and optimization using Autodesk Insight, an online analysis module.

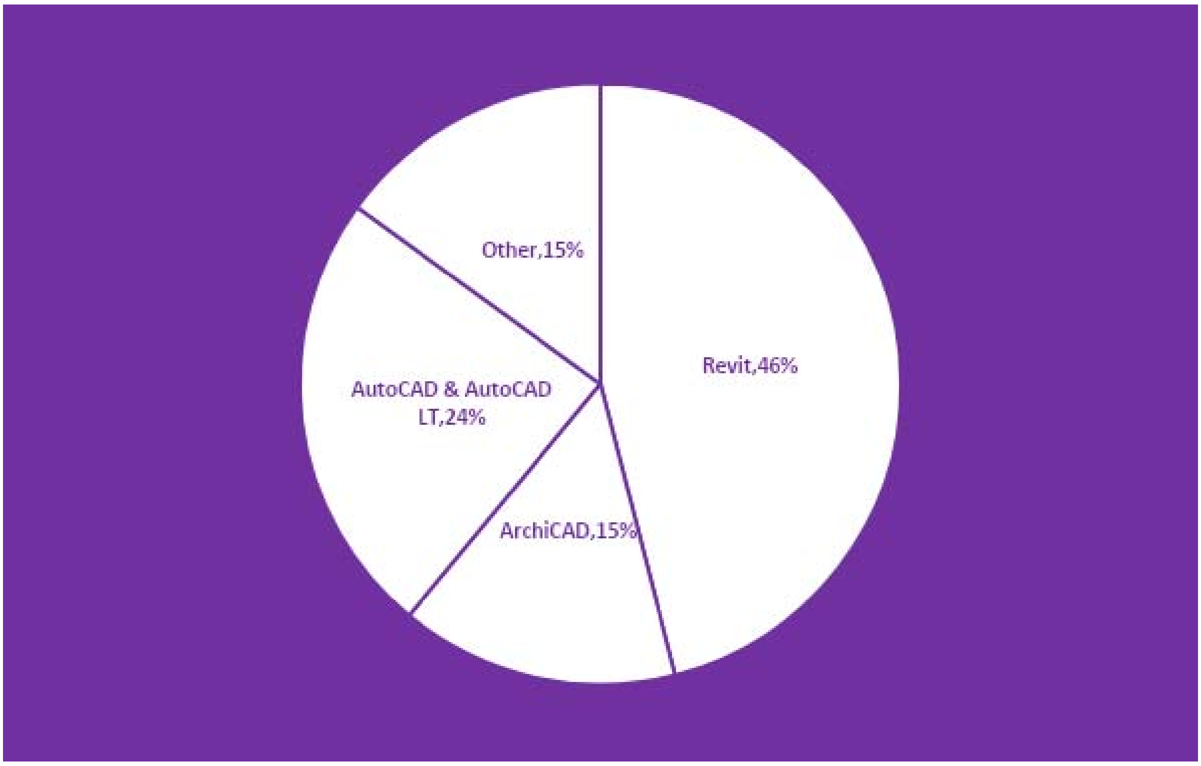

Figure 14: Top 3 BIM software for 2019.
Source: (NBS, 2019).

One of the objectives of this work was to check the ability of analysis tools that currently exist to consume raw (semi-structured) data from modelling tools as one of the issues identified in the literature review and survey. Among the solutions offered, we pre-selected tools intended for analysis at an early stage of design due to their relative simplicity and readiness to consume simple conceptual models:

- Insight 360 and Green Building Studio (GBS) (Autodesk) - a cloud-based service for building performance simulation and energy efficiency optimization. It can obtain data directly from Revit and FormIt via plugin and other modelling tools via gbXML file format (Autodesk, 2021).
- Sefaira (Trimble) is a web-based early-stage analysis tool that directly connects with SketchUp and Revit via plugins (Trimble, 2020).
- ClimateStudio (Solemma) - plugin for Rhinoceros 3D that provides the performance analysis.
- Cove.tool - a web-based platform for modelling, an early stage performance analysis and parametric optimization. It accepts geometry from a range of the most popular modelling

tools, such as Revit, Rhino, SketchUp, ArchiCAD, and allows creating a simple geometry inside the tool (Cove.tool, 2021).

Another option that can be applied for the PBD analysis early is a parametric study that can be created directly inside a modelling tool with an additional graphical programming interface, such as Dynamo for Revit and Grasshopper for Rhino. This method has not been considered since it requires additional knowledge in programming, which is another obstacle for applying the PBD approach at the early design stage. It is also a more time-consuming method.

After a quick comparison of the above-described options, the **Cove.tool** was selected for the current case study because of the following advantages:

- it has a simpler workflow and is less demanding for the model used for analysis comparing to GBS;
- it has plugins for smooth workflow for more modelling tools than any other of explored software alternatives have;
- it has an internal modelling tool that allows creating a simple model without using third-party software.

The following features are not specific to Cove.tool but are an essential part of the analysis engine:

- it provides 3D visualization for daylight, glare, shadow, radiation, view quality, COVID occupancy assessment score, and site-context studies;
- it does automated energy modelling with preloaded templates, energy codes, and engineering inputs;
- it has indoor, outdoor, stormwater management, and cooling tower water use calculator;
- it has carbon emissions and embodied carbon calculator;
- it calculates parametric cost and provides energy optimization options;
- it creates an automatic report.

An integrated process of transferring geometry from Revit to Cove.tool was provided by the Cove.tool plugin for Revit, making the process faster and easier than the workflow with file exchange (IFC or gbXML). Only geometry was transferred from Revit to Cove.tool app, while other settings, like materials, occupation schedule, building system setting, etc., were controlled from the Cove.tool. Below is the comprehensive list of inputs for Office building, presented in the way they were grouped in the Cove.tool with a short explanation of each from the Cove.tool (Chopson et al., 2021) unless otherwise specified:

- Envelope

- Roof U-value (Thermal transmittance) [W/m² K] – *the rate of transfer of heat through a roof structure, divided by the difference in temperature across that structure* (Lymath, 2015).
- Wall U-value [W/m² K] – *the rate of transfer of heat through a wall structure, divided by the difference in temperature across that structure* (Lymath, 2015).
- Glazing U-value [W/m² K] – *the rate of transfer of heat through glazing, divided by the difference in temperature across that structure* (Lymath, 2015).
- Glazing Solar Heat Gain Coefficient (SHGC) [-] – *the fraction of the total incident sunlight that is being transmitted through the glazing material.*
- Envelope heat capacity [J/K] – *the ratio of the heat added to an object to impact the resulting interior temperature.*
- Blinds/Curtains/Shades *are used to determine the shading device factor (SDF), a factor that directly impacts the solar transmittance of all the windows.*
- Wall emissivity [-] – *the fraction of energy being emitted relative to that emitted by a thermally black surface.*
- Ground floor area [m²] – *the total area of the floor that is in contact with the ground*
- Ground floor U-value [W/m² K] – *the measure of the overall rate of heat transfer through the ground floor of the construction.*
- Below grade area [m²] – *the area of the total walls that lies below the ground of the building* as illustrated in Figure 15.
- Below grade depth [m] – *the distance from the ground floor (Below grade) to the first floor (Above grade) of the building* (Fig.15).
- Below grade U-value [W/m² K] – *a measure of the overall heat transfer for the walls below-grade of your construction* (Fig.15).

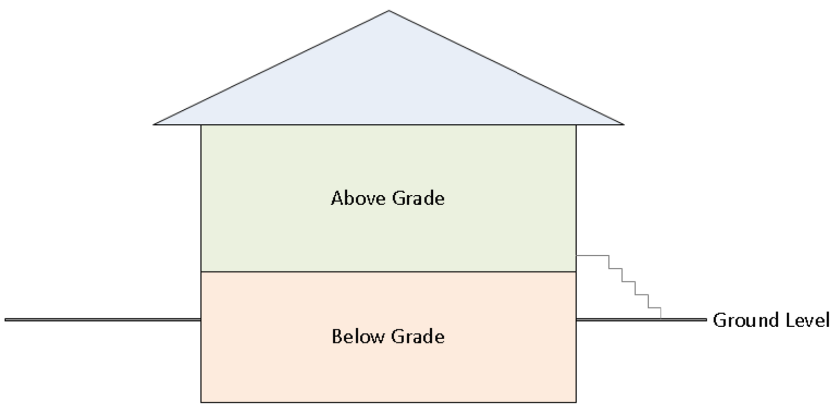

Figure 15: Illustration of the terms above and below grade.
Source: (Padwal, 2021).

- Usage and schedules
    - Daylight sensors – *a photo-cell detecting device that reads available light in a space and sends a signal to the control system.*
    - Occupancy sensors – *an indoor motion detecting device used to detect the presence of a person to control lighting, temperature, or ventilation systems automatically.*
    - Lighting [W/m²] – an automated input by Cove.tool based on the maximum Lighting Power Density (LPD) value. This value varies based on the building type and the energy code version.
    - Lighting (Unoccupied hours) [W/m²] – *an automated input by Cove.tool which is determined after the calibration of the models with respective Pacific Northwest National Laboratory (PNNL) building prototypes.*
    - Exterior lighting power [W] – *base allowance of illuminated areas.*
    - Appliance use [W/m²] – *appliance intensity during occupied hours. These can include things that turn on after the occupants arrive, like computer monitors, coffee machines etc.*
    - Appliance use (Unoccupied hours) [W/m²] – *appliance intensity during unoccupied hours. These can include things that do not turn off after the occupants leave, like servers, refrigerators etc.*
    - Metabolic rate [Btu/h] *is used to describe the amount of heat given off by people within a space.*
    - Heating set-point [°C] – *the temperature that the building will be heated to during the occupied hours.*
    - Heating set back [°C] – *the temperature that the building will be heated to during the un-occupied hours.*
    - Cooling set-point [°C] – *the temperature that the building will be cooled to during the occupied hours.*
    - Cooling set back [°C] – *the temperature that the building will be cooled to during the un-occupied hours.*
    - Total occupants (Occupied hours) – *total number of people during occupied hours.*
    - Total occupants (Unoccupied hours) – *total number of people during unoccupied hours.*
- Building system
    - System type *defines the heating, ventilation, and air conditioning (HVAC) system used in the building.*
    - Integrated part-load value – *chiller type.*
    - Heating system coefficient of performance (COP) [-] – *the ratio of useful energy versus the input energy, describes a systems energy efficiency.*

- Cooling system COP [-] – *the ratio of useful energy versus the input energy, describes a systems energy efficiency.*
- Heat recovery system *defines the type of Air Side Heat Recovery used.*
- Fan flow control factor [-] *describes how the fans within a building will operate.*
- Specific fan power (SFP) [W/(l/s)] – *the measure of how much power is required to move a given amount of air with a fan system.*
- Ventilation type *defines the type of ventilation system (mechanical, natural or combined).*
- People outdoor air rate [l/s/Person] – *the supply air flow rate.*
- Infiltration [$m^3/h/m^2$] – *the flow of outdoor air into a building through unintentional openings, such as cracks and exterior entry or exit doors.*
- Building energy management system *refers to the standard EN 15232 for simulating the effect of Building Energy Management Systems.*
- Ventilation control – *ventilation control strategy (on-demand, consistently on or off during unoccupied hours).*
- Exhaust recirculation [%] – *the amount of heat energy recovered from the exhaust air stream.*
- Domestic hot water (DHW) generation – *the method of generating hot water used for handwashing, dishwashing, showers and other similar purposes.*
- Hot water distribution system – *type of hot water distribution system.*
- Domestic hot water demand [m^3/yr] – *yearly consumption of DHW.*
- Pump control for cooling – *cooling system type.*
- Pump control for heating – *heating system type.*

- Energy generation
  - Solar panel surface area [m^2] – *the total array area for photovoltaic (PV) panels.*
  - Solar panel angle [°] – *the angle in degrees between from a horizontal plane and the collector as it is installed.*
  - Solar panel module location – *the installation location of the panel, varying between 'cladded on the roof' versus 'on a frame'.*
  - Solar panel module type – *the material characteristics of the module.*
  - Solar hot water (SHW) collector surface area [m^2] – *the total surface area of the exposed absorber plate. The SHW collector is a solar thermal panel, similar to a photovoltaic (PV) panel, but instead of transferring sunlight into usable electricity, it transfers the radiant heat to the water.*
  - SHW collector angle [°] – *the angle in degrees between from a horizontal plane and the collector as it is installed.*

    - SHW collector efficiency [%] – *the percentage of efficiency for the heat generation is used versus lost specifically to the type of collector for the selected SHW system.*
- General
    - 2030 building type – *a factor used in energy modelling software to differentiate commercial buildings into categories of buildings whose uses share similar energy usage data. In Cove.tool, eight categories are accessible that control the benchmarking information provided via the 2030 Challenge.*
    - Primary energy domestic hot water *controls the primary energy source for DHW in a project.*
    - Primary energy heating – *the source of heat for the project.*
    - Building location type *informs details about the wind behaviour and therefore infiltration for the building.*
    - Electricity utility rate [€/kWh] – *the cost of electricity used for calculating the yearly energy cost of the project.*
    - Natural gas utility rate [€/kWh] – *the cost of natural gas used for calculation the yearly energy cost of the project.*

These settings could be determined manually by the user, and another option was to select one of the templates prepared by the Cove.tool team of professionals. Manual input requires some knowledge and understanding of all the parameters used for analysis (at any stage of design) and how they influence the overall building performance and the feasible values for each. Not all architects and engineers know how to make the correct inputs; not all parameters are determined at the early stage of design; that is why these templates were a great help and a starting point, especially at the initial stage of design. In our study cases, we used the template for an office building with the values presented in Annex 2.

Prerequisites and requirements

Prerequisites and requirements of a hypothetical project were set the same for both methods:

- Location (Fig.16, 17): 46°09'59.4"N 14°34'11.5"E (Mengeš, Slovenia).

Figures16, 17: Location of hypothetical project, Mengeš, Slovenia.

Source: (Google Maps, 2021).

- Key target parameters:
  - Energy use intensity (EUI) [$kWh/m^2/yr$] – *an annual measure of the total energy consumed in a building* (Energy budget). It calculates accordingly to the ISO 13790 Heat Balance Engine (Understanding the automated report) using the inputs described in the previous section and the information about the climate on the location of the project. As discussed previously, reducing building energy consumption is one of the significant current global challenges; therefore, EUI was chosen as one of the key target parameters. The lower this parameter, the better performance of the building is.
  - Spatial Daylight Autonomy (sDA) [%] – *a yearly metric that describes the percentage of space that receives sufficient daylight. In particular, it means the percentage of floor area that receives at least 300 lx for at least 50% of the annual occupied hours on the horizontal work plane* (Understanding the automated report). The legend (Fig.18) retrieved from the Cove.tool app illustrates the scale where the yellow part just meets the requirement. The left part does not have enough or even at all natural light in opposite to the right part. The higher this parameter, the better performance of the building is. It is the metric that is utilized by LEED certification in combination with the Annual Sunlight Exposure (described next) to evaluate the daylighting quality in LEED-certified buildings.

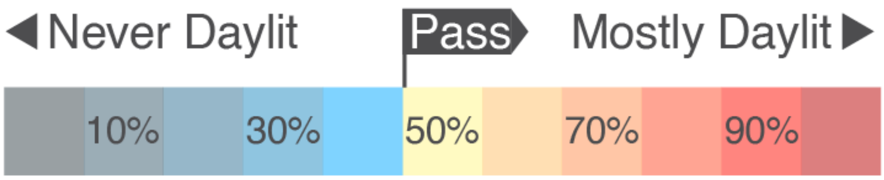

Figure 18: Legend for sDA metric used in the Cove.tool app.
Source: (Chopson et al., 2021)

  - Annual Sunlight Exposure (ASE) [%] refers to *the percentage of space that receives too much direct sunlight (1000 lx or more for at least 250 occupied hours per year)*, which can cause glare or increased cooling loads (Understanding the automated report). Figure 19 shows the scale used for this metric in the app, where the green fragment is 0 to 250 hours per year with indoor horizontal illuminance above 1000 lx under direct sunlight conditions. All the higher values mean increasingly worst performance. This metric desires to be as small as possible; however, it is connected to the previously discussed sDA metric. In general, higher sDA means higher ASE. However, high values of ASE can be reduced by the introduction of appropriate shading, while sDA is dependent on the area of windows, building geometry and optical properties of glazing.

Figure 19: Legend for ASE metric used in the Cove.tool app.
Source: (Chopson et al., 2021)

- Utility cost –is *estimated yearly electricity and natural gas cost for the project*. It is calculated based on the estimated electricity and natural gas consumption for cooling, heating, lighting, equipment consumption, water heating, etc. This metric is related to the EUI, but it is not the same as it also depends on the price of the source of energy at the particular location. It is essential to consider this metric beside others as maintenance costs (including utility costs) are about 85% of the overall cost of the building, as is illustrated on Figure 20.

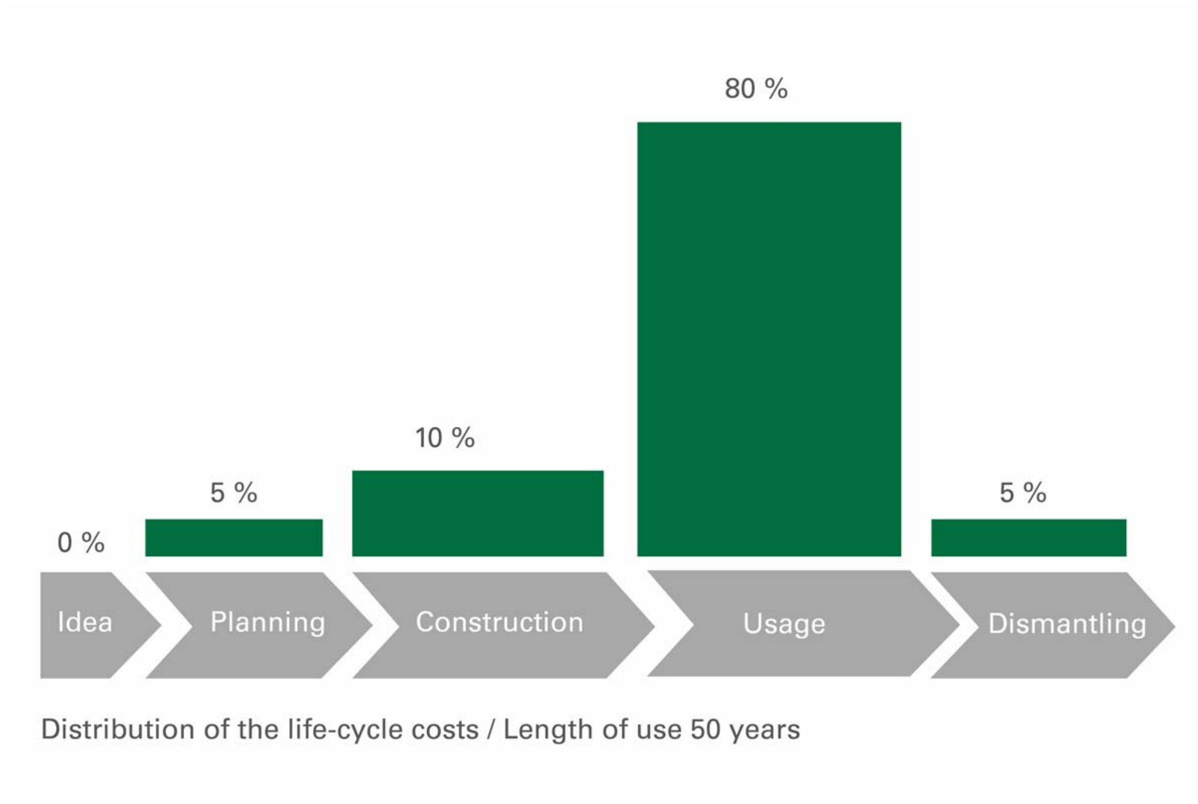

Figure 20: Distribution of the life-cycle costs over 50 years.
Source: (ALHO, 2021).

Workflow for the conventional approach

In the conventional approach, after collecting requirements, several design options were developed and assessed in terms of aesthetics, useful floor area, etc. Despite this, only one design option was developed in a conventional approach in the current case study as it was a hypothetical project. The simplified workflow presented in Figure 21 shows the steps used in the conventional approach. The design option was developed, starting with the shape of the building placed on the plot and then the development of the building storey layouts; after that, the glazing was distributed according to the layout of each floor. The model has only elements of the following categories – walls (internal and external), floors, roofs, windows, curtain walls and zones, which were transferred via a plugin to the Cove.tool for the performance analysis. Inside the Cove.tool, the location, type of building and orientation was set. All inputs described in the part Tools were set automatically from the template for building type Office and can be seen in Annex 2.

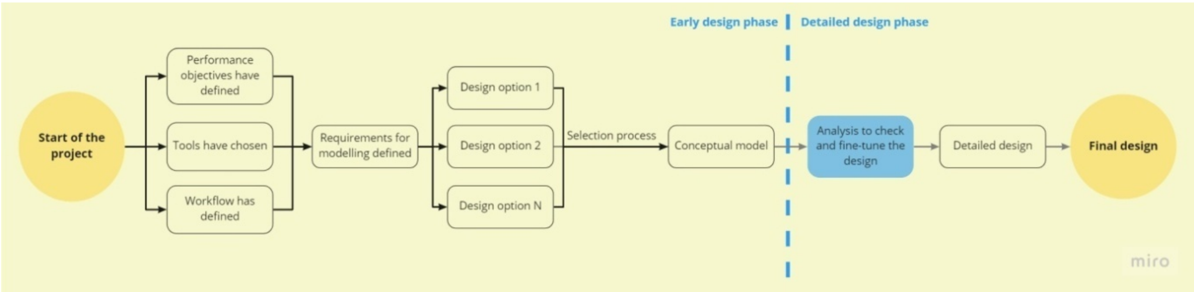

Figure 21: Conventional workflow.

Workflow for the PBD approach

The second part of the study was done on the same plot and prerequisites but in several cycles, where every cycle one of the building variables was examined while others were locked. The modelling was also done in Revit and then transferred to the analysis tool via the plugin. Only external walls, floors, roofs and windows were modelled to decrease the time for modelling and reduce model complexity as much as possible to prevent problems with the geometry transferring. At the first cycle, all the settings (Annex 2) inside the Cove tool were the same as for the conventional method. The general workflow is presented in Figure 22 and includes an additional block at the early stage, called the analysis loop, that includes initial modelling - analysis - remodelling in several cycles that can vary depending on the requirements set and the complexity of the design. The flowchart presented in Figure 23 demonstrates the particular strategy that was exploited during the case study.

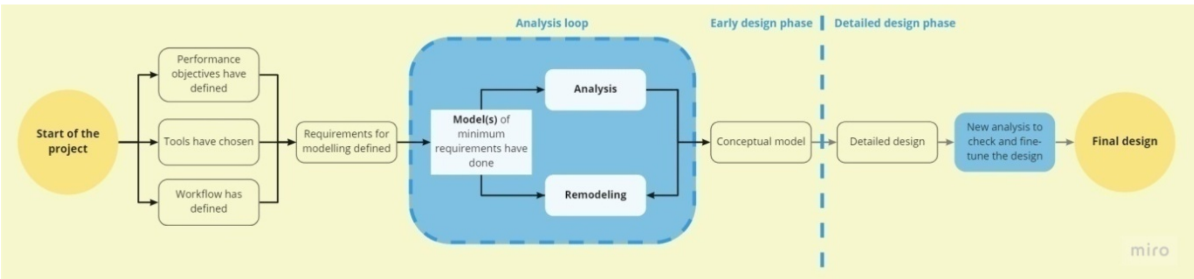

Figure 22: PBD workflow.

The first column, “Initial inputs” of the flowchart (Fig.23), shows the initial modelling inputs, such as total floor area, location, orientation, glazing ratio and glazing distribution that were the same for the first design options. The second column, “Outputs”, presents the best results selected after each cycle of analysis. The feature of modelling was the cumulative effect, which means that after each cycle, the best option was the input for the next cycle of analysis. The conditions for selecting the best option were defined in the diamond shapes, such as the lowest EUI and lowest utility costs.

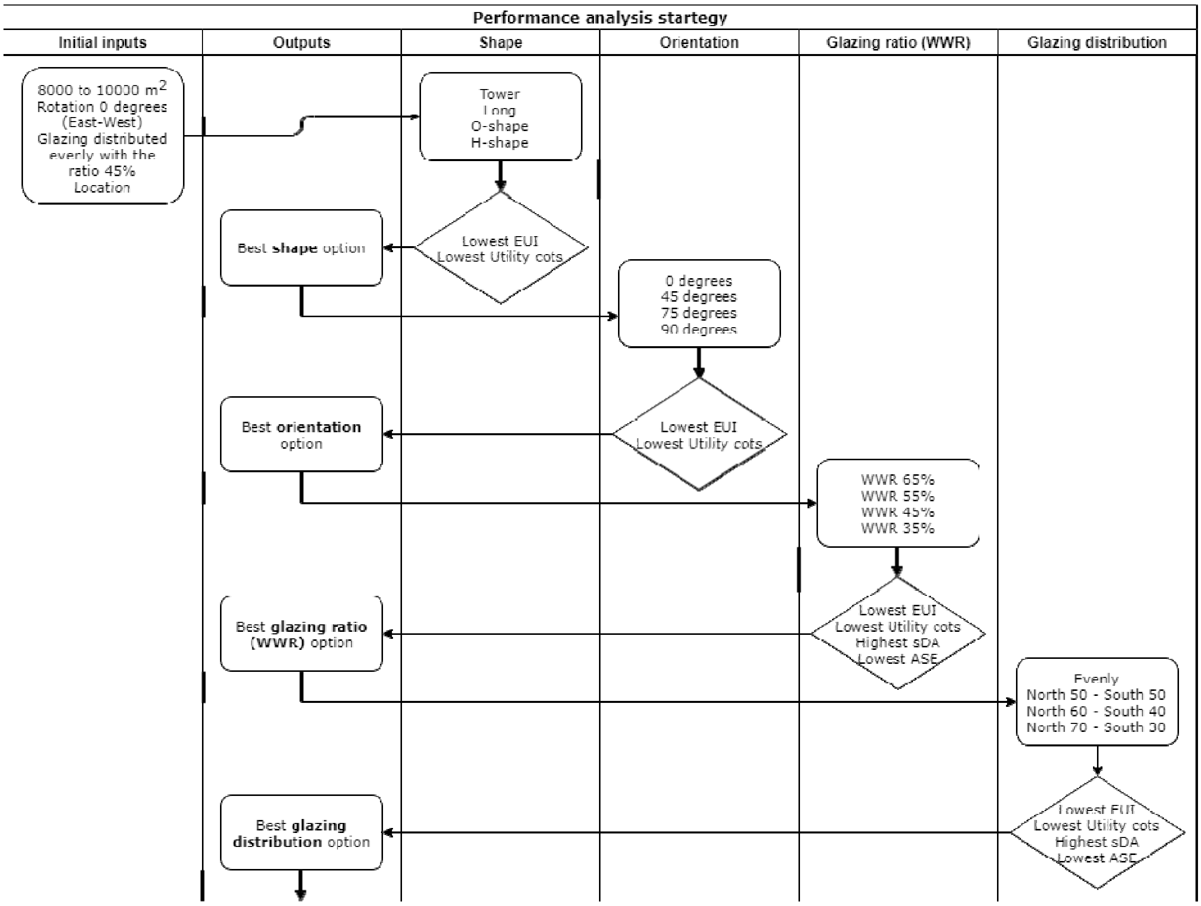

Figure 23: Flowchart of early-stage PBD analysis strategy for stages one to four.

Descriptions and peculiarities of each cycle presented in Figure 23 are given below:

1. **Shape.** As the most difficult to change in the later stage, the shape parameter was selected as the first variable. Four models of different masses were created with approximately the same total floor area (8000 to 10000 m^2) and glazing distribution evenly on the facades with WWR of 45% – tower, long, H-shape, O-shape buildings were defined (Fig.24). After the analysis run, all the options were compared according to the EUI and cost of utility parameters. At this stage, the best option was selected with the lowest EUI and lowest utility costs.

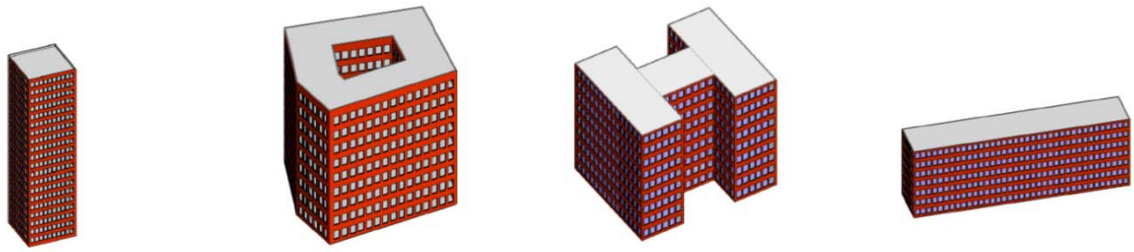

Figure 24: Tower, O-shape, H-shape and long buildings modelled in Revit for the first cycle of PBD analysis.

2. **Orientation** was evaluated in the next cycle with the shape selected previously. The same strategy was applied here – 4 models in the same shape, same total floor area, even glazing distribution with WWR of 45% but rotated by 0°, 45°, 75° and 90° relative to the north-south orientation (Fig.25) were analyzed, and the results of the analysis were compared according to EUI and utility costs. The best option at this stage was again with the lowest EUI and the lowest utility costs.

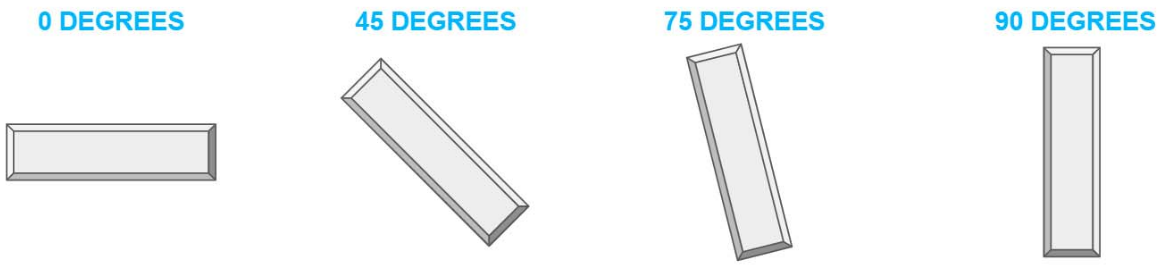

Figure 25: 4 different positions rotated differently for the second cycle of PBD analysis.

3. **Window-to-wall ratio (WWR)** on the first two cycles was set as 45% and equally distributed across all facade surfaces, therefore for the understanding of lighting performance and impacts on EUI; three additional WWRs were investigated - 35%, 55% and 65% distributed equally. The goal of this analysis loop was to find the design option with the optimal relation between sDA and ASE. The best option here was the one with the highest sDA and the lowest ASE.
4. **Glazing distribution** also significantly influences the overall (energy) performance of the building. In the previous stages, the distribution was presumed as uniform across all facade surfaces, so at this stage, additional options were examined - distributed by two sides 50/50%, 60/40% and 70/30%. The EUI, utility costs, sDA and ASE, were compared as glazing distribution can improve or worsen any of these metrics; the target outcome for this stage was the lowest EUI, utility costs and ASE and the highest sDA.
5. The next **group of parameters** analyzed during this study does not have such an impact on the early design stage; however, they might give pointers for the design at later stages. The

parameters are *shading, heat recovery option, exhaust air recirculation, domestic hot water generation system and energy generation options were investigated*.

4 RESULTS

As the central question of the overall study was the practical application of the PBD approach on the early stage of design, the survey aimed to validate the ideas formulated based on the knowledge gained from the academic literature and other sources such as books, websites, and knowledge bases. The survey examines practitioners' points of view on the issues detected in scientific papers. The focus group was not limited just to the European market and was conducted worldwide. However, the focus was on the companies that use BIM as it is one of the prerequisites for successfully implementing PBD.

The goal of the practical part was to compare the conventional way of work with one that utilizes PBD to understand the difficulties architects face in trying to use PBD. The practical case study was also a way to test the current development level of tools available on the market to approach early-stage analysis in the way architects need. Another goal was to clarify some gaps and uncertainties in the PBD application on a case study identified even among practitioners who use this approach in their work. The results of both parts will be given in separate subchapters, while overall implications of results will be dealt with within the Discussion section.

4.1 Survey results

4.1.1 Demographic part

From 75 direct requests and five non-direct through LinkedIn, Facebook and Whatsapp groups, the survey was filled in by 43 respondents from 20 countries from 5 continents. The countries from which responses were received are marked in Figure 26. At the same time, the number of responses per country is evident from Figure 27. The maximum number of responses was obtained from Slovenia - ten, five from Russia and Brazil, three from Spain, two from Germany, Belarus and India, and International (the countries were not specified) with the remaining responses equally distributed among other countries. Figure 28 (left) represents the proportion of the number of answers per country. While Figure 28 (right) represents the proportion of responses per continent. Most of them were received from Europe – 30, another six from Asia, five from South America, one from North America and Africa.

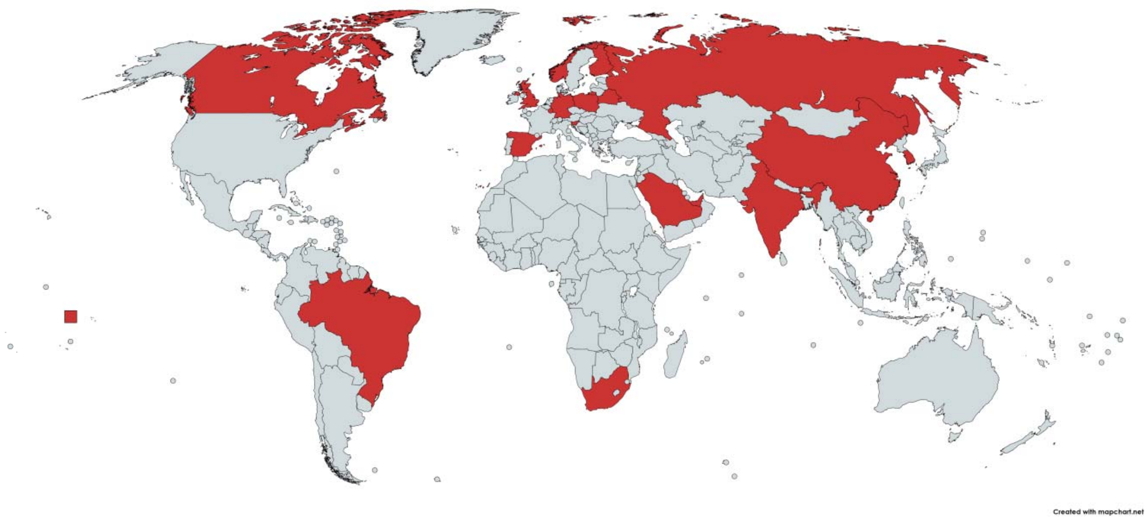

Figure 26: The map with the countries that participated in the survey.

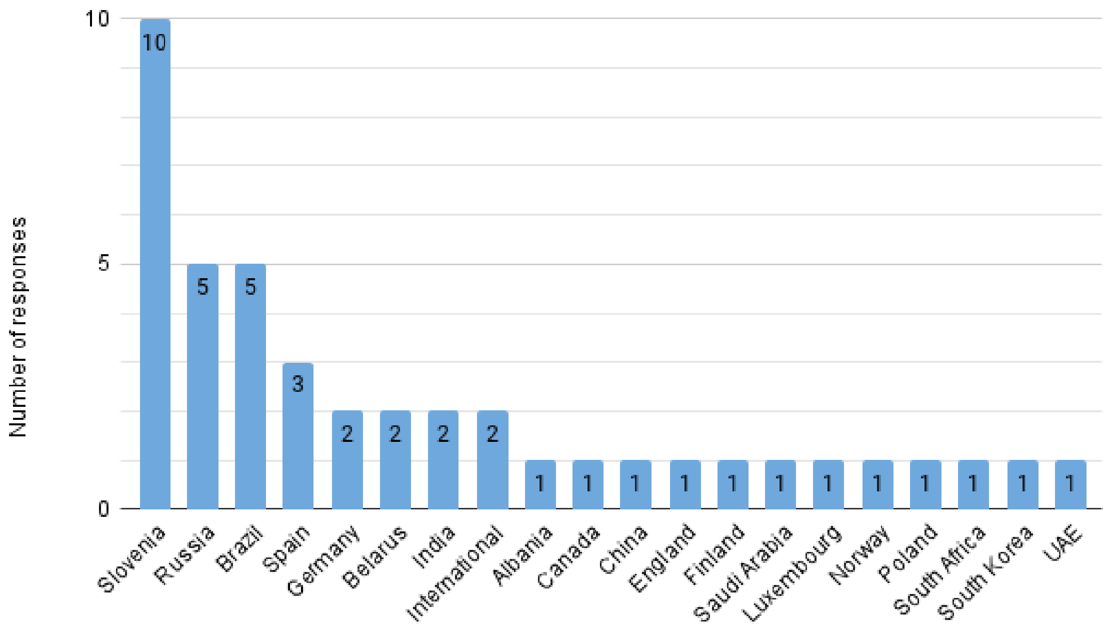

Figure 27: Number of responses per country.

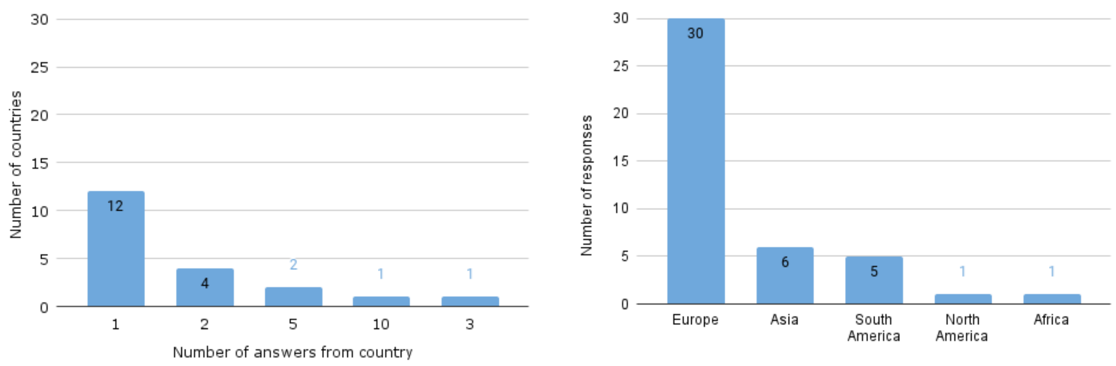

Figure 28: P roportion of the number of answers per country and per continent.

According to the type of company the most represented were architectural design offices (15 companies) followed by engineering company/consultants (12 companies), construction companies (4 companies), university/school/research lab (3 companies), developers/facility managers, and their combination (3 companies) (Fig.29). About 50 % of respondents work in an architectural company or architectural or engineering departments of the design construction companies. 25% of respondents provide engineering/consulting services. About 10% are developers/facility management companies as well as research labs and educational organizations. About 5% work in construction companies.

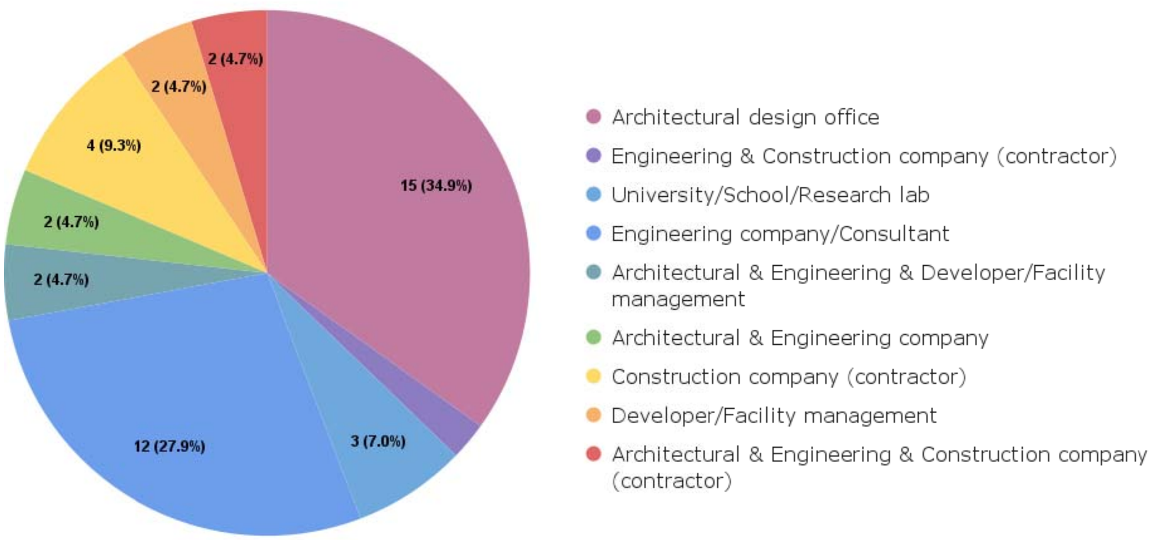

Figure 29: Types of surveyed companies.

About one-third of responses (34.9%; 15 responses) came from large companies with more than 200 employees, 25.1% (11 responses) practitioners work in companies of less than 10 employees, seven (16.4%), six (14.1%), and four (9.4%) responses came from the companies with the number of employees 10 to 50, 50 to 100, 100 to 200 accordingly (Fig.30). The proportion of respondents' occupation and current job position is evident from Figure 31. The largest group of respondents were architects (34.9%) and engineers (30.2%), followed by design managers (18.6%) and BIM specialists from Implementation Coordinator to BIM manager (9.4%). The remaining responses were equally distributed among CEO, researcher and modeller (1 response from each, 6.9% total).

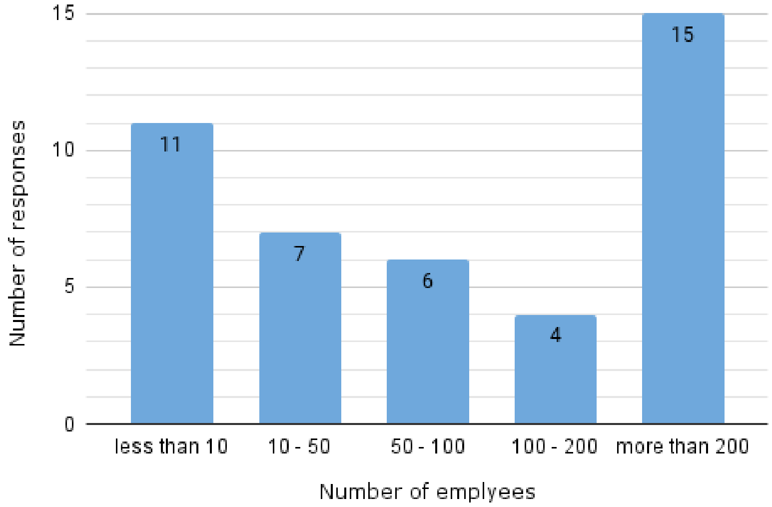

Figure 30: Number of responses by company size.

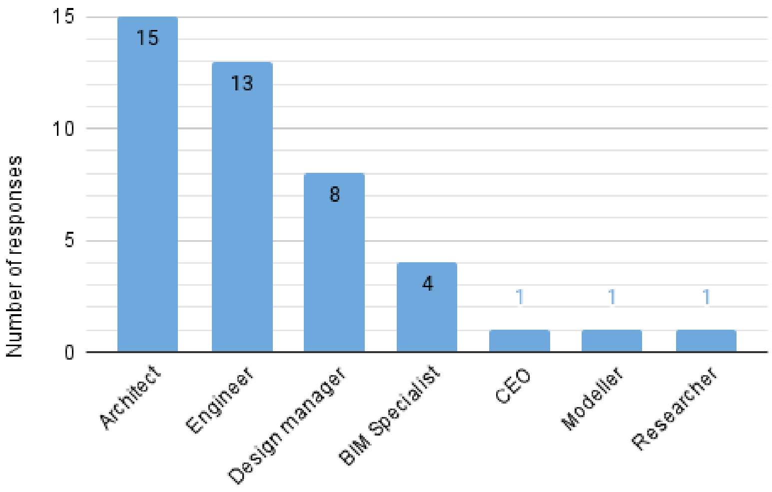

Figure 31: Profile of the respondents.

Additionally, respondents were asked what types of projects are specific for the companies they work for. Interviewee could choose from the proposed list of options more than one type or suggest its type, so the total is higher than the total number of responses. Figure 32 illustrates the proportion of the companies that work on a specific type of project. Residential, commercial and public architectural projects are among the top responses – 55.8 to 67.4% of respondents work in this field. Slightly less than a half of companies (44.2%) take part in infrastructural and industrial projects. 16 (37.2%) and 15

(34.9%) companies have restoration and renovation and interior design projects in their portfolio, and 8 (18.6%) companies reported they work on landscape and urban design.

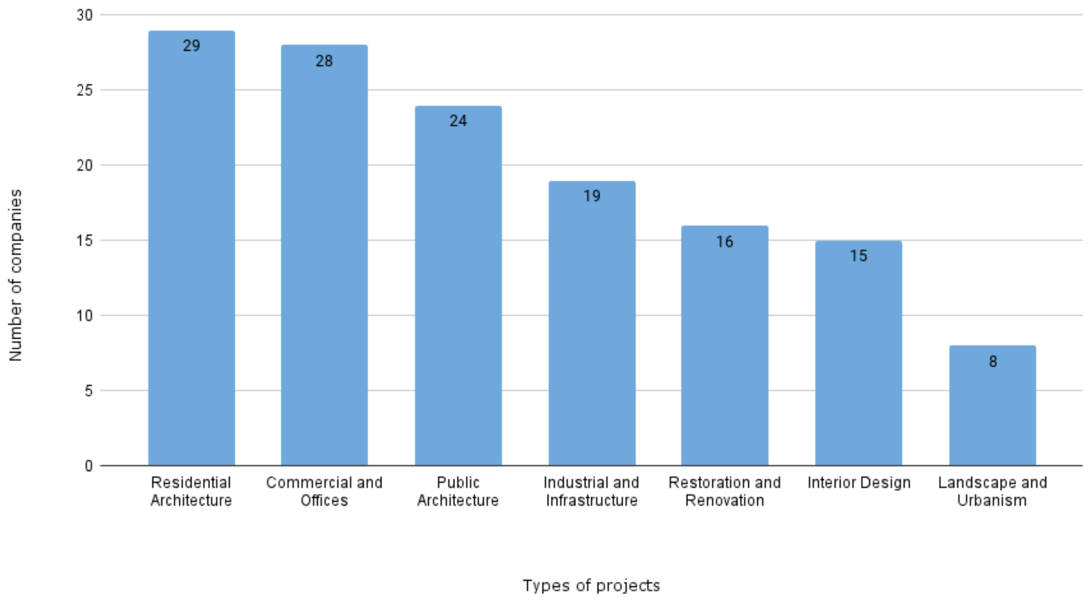

Figure 32: The number of companies per project type.

To understand what software is the most widely used, we asked our respondents to choose from the list of software tools that they mostly use. The results are shown in Figure 33. The majority of respondents selected Revit – 30 responses out of 43, while ArchiCAD and SketchUp were chosen by fourteen and eight professionals accordingly. Tekla had only five votes, while AutoCAD had three. Eight responses were grouped in "*other software*", such as Civil 3D, Infraworks, Unity, Navisworks, BIM360, Dalux, Trimble, Solibri. Most of the companies use more than one software, so the total here is more than 43 (number of responses).

Next, respondents were asked if they use BIM or not in their practice. Figure 34 (left) shows that the majority of respondents (86%) use BIM technology. Only six respondents (14%) reported they do not use it; among them were three construction companies from Saudi Arabia, India and Albania and three architectural/engineering companies from Slovenia, Brazil and China. The critical question of the first part of the survey was if the respondents used the PBD approach. Figure 34 (right) illustrates the result. Slightly less than a half - 21 (48.8%) of the total number of respondents stated they use PBD; another 22 (51.2%) answered they do not use it.

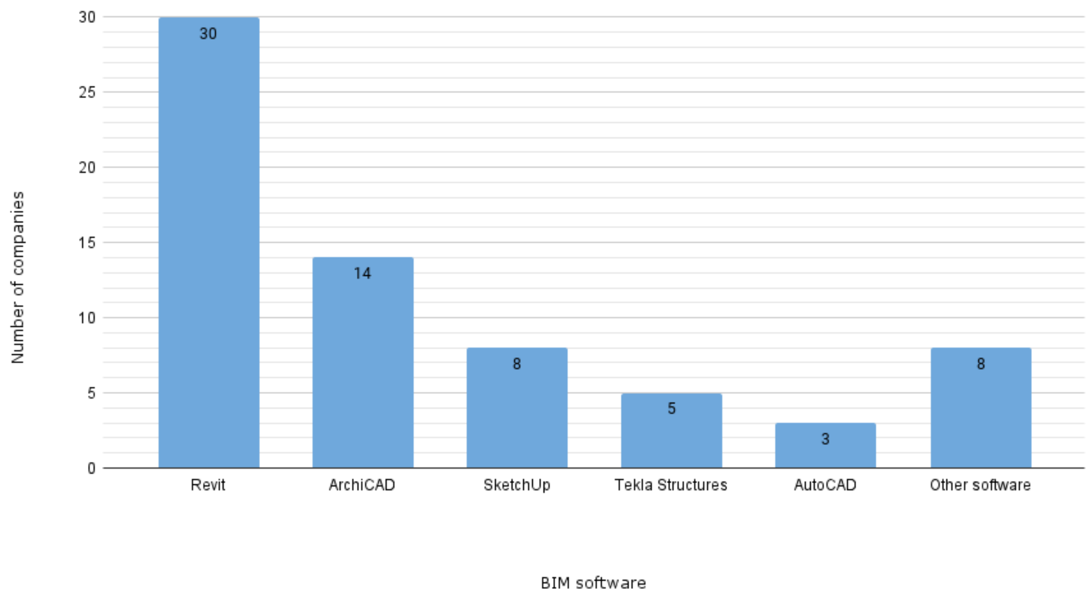

Figure 33: BIM software used by respondents.

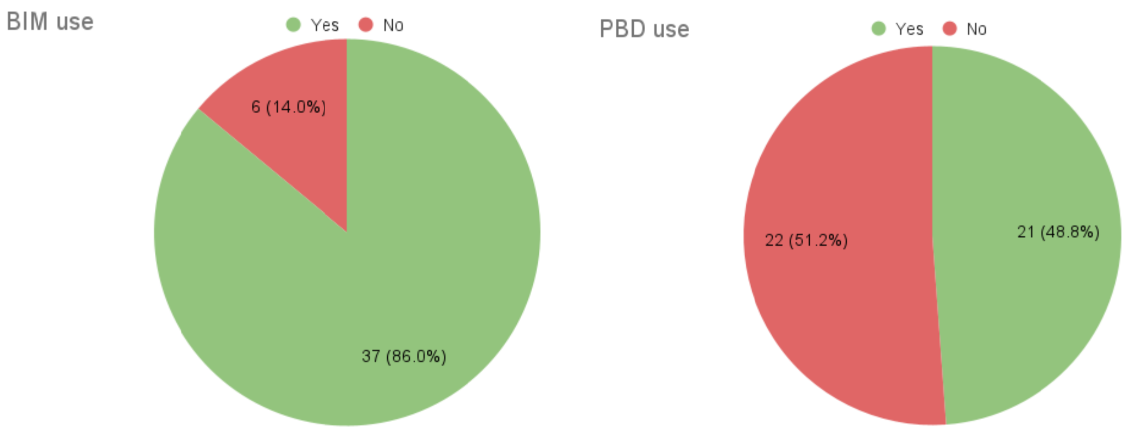

Figure 34: The number of companies that use BIM (on the left) and PBD (on the right).

Those who answered “*No*” on the previous question were also asked to choose why they do not use it, and the answers were the following (Fig.35). Of 22 of them, eight do not know what PBD is; another six answered it is too complex, and four respondents stated it takes too much time. Two more participants do not use it due to no demand from the client, and the last two work on the later stages of design development only, when all the decisions have been already made. The result illustrated in Figure 35 corresponds to reports from the literature about the complexity and additional time needed for the PBD as being the major obstacles in adoption by the practitioners.

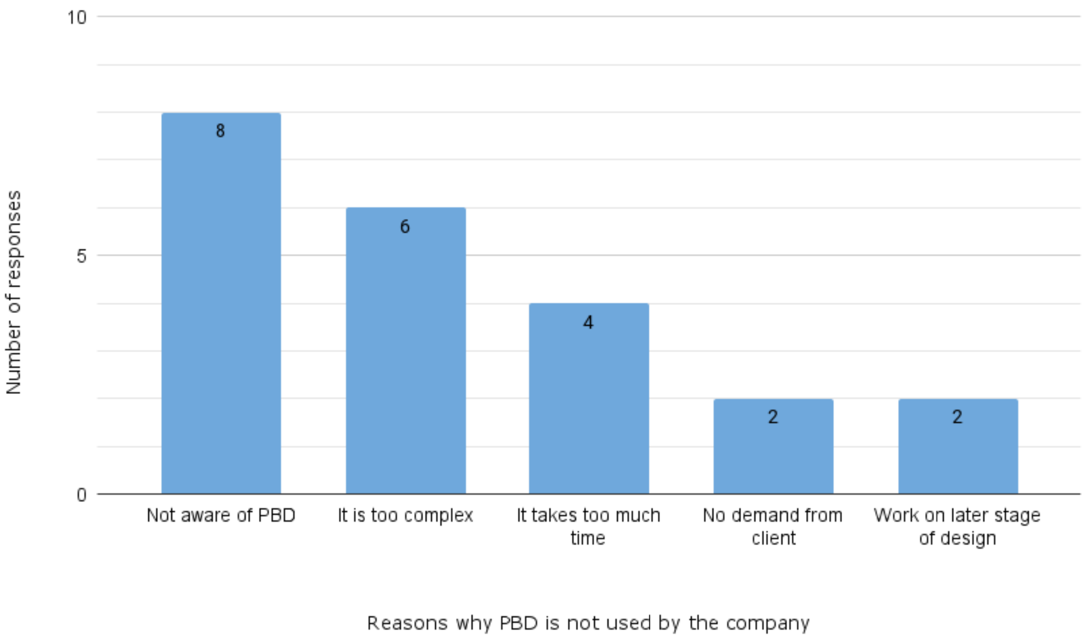

Figure 35: Respond from practitioners about the reason they do not use PBD.

In turn, those who answered they use PBD were inquired about the frequency of use PBD in their work. The result is presented in Figure 36. Seven respondents (33.3%) of those who use PBD answered they use it in every project, twelve (57.2%) indicated they use it in some projects, and only two (9.5%) reported they use it rarely. No one of the respondents did not choose the option ”*I only used it once*”.

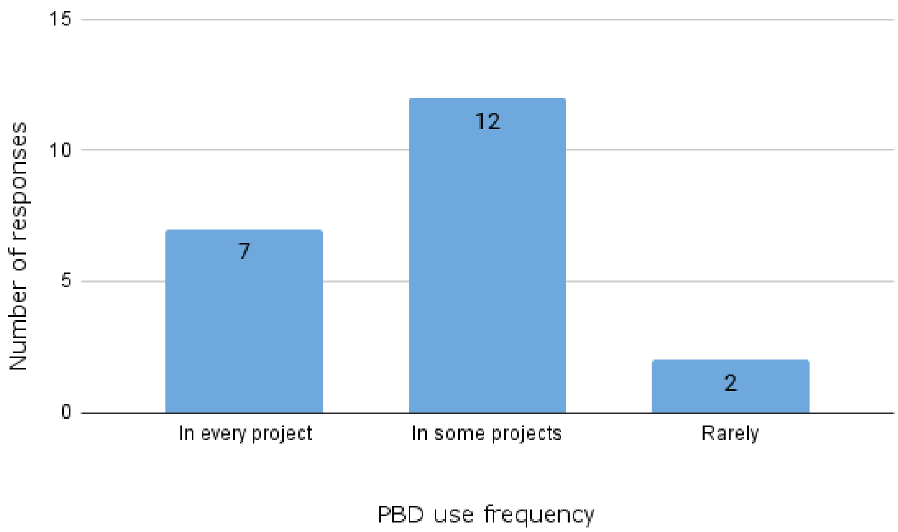

Figure 36: Frequency of PBD use.

4.1.2 PBD acceptance

For the acceptance and better understanding of the PBD approach benefits and disadvantages from the practitioners' point of view, the second part of the survey was conducted with another type of questions. Respondents had to agree or disagree on a scale of one (strongly disagree) to five (strongly agree) with ten assumptions about PBD and its application. The answers are supposed to be done based on the respondent's experience who reported to work or at least know the PBD approach. Only the respondents that indicated in the previous section of the survey that they use PBD and BIM were asked to answer these questions. As a result, a total of 21 respondents were included in this part of the survey. The first five from ten statements presented the benefits of the PBD over the conventional approach. Six to ten statements presented disadvantages or difficulties in the use of the PBD approach. The acceptance of surveyed practitioners of PBD benefits (statements one to five) is presented in Figure 37.

Data processed from the response to the first five statements are presented in Table 1. The first statement we asked for a professional opinion was "*performance-based approach decreases time and cost of rework on later design stages*". 95.2% agreed with this statement, while 4.8% expressed neutrality. Because"*performance-based approach increases the design process' quality and efficiency*", 81.0% of respondents agreed. In comparison, only 76.2% agreed with the assumption that a "*performance-based approach increases the design quality*", and 9.5% disagreed with it. With the assumptions stated that "*PBD helps to make decisions faster*" and "*improves designers expertise faster than traditional practice*", only two-thirds of respondents agreed (61.9% and 57.2%, respectively). In comparison, 23.8% and 33.3% were uncertain and 14.3% and 9.5% disagreed with these statements. In general, the majority of surveyed practitioners agree with the listed benefits of the PBD approach. However, some uncertainty is present regarding the speed of decision-making and faster acquisition of knowledge compared to the conventional approach.

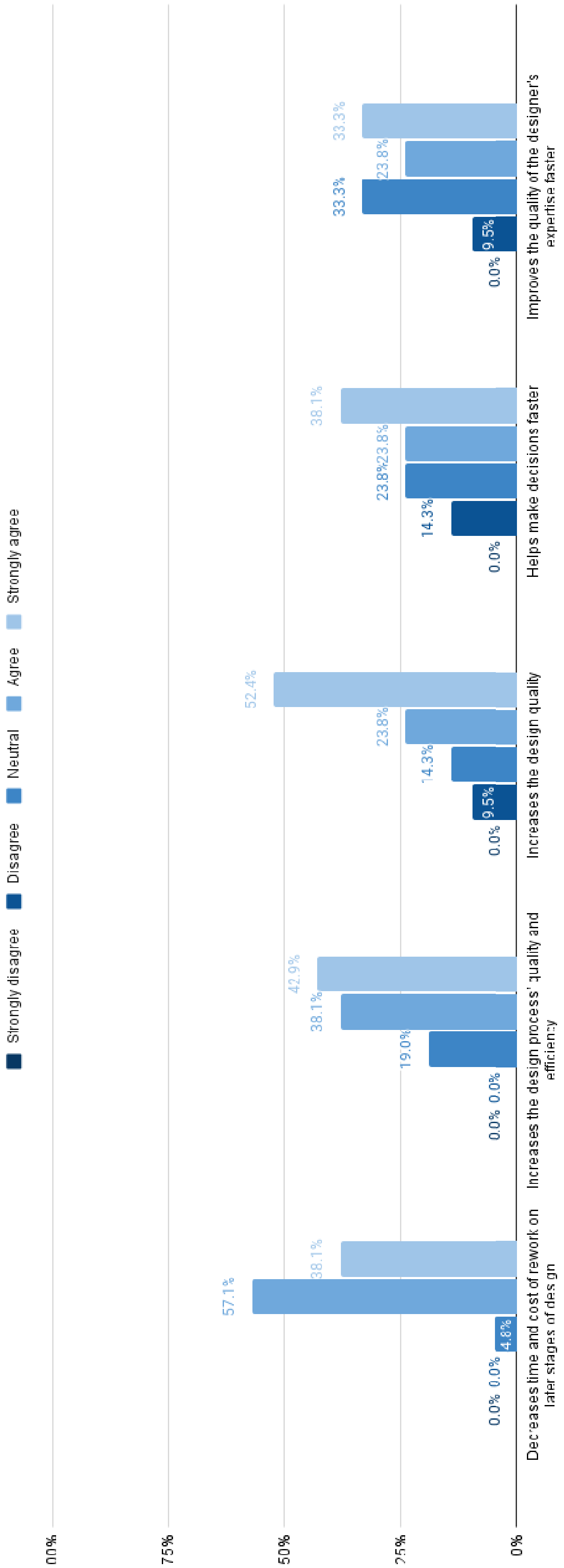

Figure 37: Attitude of professionals to PBD benefits.

Table 1: Data for users acceptance of PBD benefits.

Survey statements about PBD benefits	Number of responses on statements one to five					
	Agree/Strongly agree		Neutral		Disagree/Strongly disagree	
	Number	%	Number	%	Number	%
1. Performance-based approach **decreases time and cost of rework** on later stages of design	20	95.2%	1	4.8%	0	0.0%
2. Performance-based approach **increases the design process' quality and efficiency**	17	81.0%	4	19.0%	0	0.0%
3. Performance-based approach **increases the design quality**	16	76.2%	3	14.3%	2	9.5%
4. Performance-based approach **helps you make decisions faster**	13	61.9%	5	23.8%	3	14.3%
5. Performance-based approach **improves the quality of the designer's expertise faster** than the conventional approach	12	57.2%	7	33.3%	2	9.5%

The acceptance of surveyed practitioners of PBD limitations and difficulties (statements six to ten) is presented in Figure 38. Processed data from the response on the second part of assumptions are shown in Table 2. In general, the opinion of the professional community about the limitations and difficulties of PBD is not clear. The clearest result was obtained only in the case of statement seven, where 71.4% of respondents agreed that "*complex and time-consuming training is needed for successful PBD use*" instead of only 4.8% that disagreed with this statement. In comparison, the rate of uncertainty was 23.8% of respondents. 42.8% agreed that PBD is a "*time-consuming process*", whilst another 47.6% could neither agree nor disagree, and only 9.6% disagreed with this point. The high level of uncertainty highlighted the lack of research or experiments done on this subject. "*Selection of performance objectives*" and "*the final result of the design during the optimization*" are still two strong challenges professionals are facing during the PBD. As a result, this is highlighted by 47.6% (for the performance objectives selection) and 42.8% (for the difficulties in selection of the best design option). In opposite 28.6% and 19.1% testify disagreement with these difficulties. Moreover, a high level of uncertainty 23.8% and 38.1% accordingly show the immaturity of the PBD application. The greatest level of uncertainty caused the final statement, "*the benefits of the performance-based approach are less than the difficulties that appear while using it*", where about a half of respondents (47.6%) was not sure whether the approach has more benefits than difficulties. About one third (28.6%) disagreed or strongly disagreed with this statement, another 23.8% agreed.

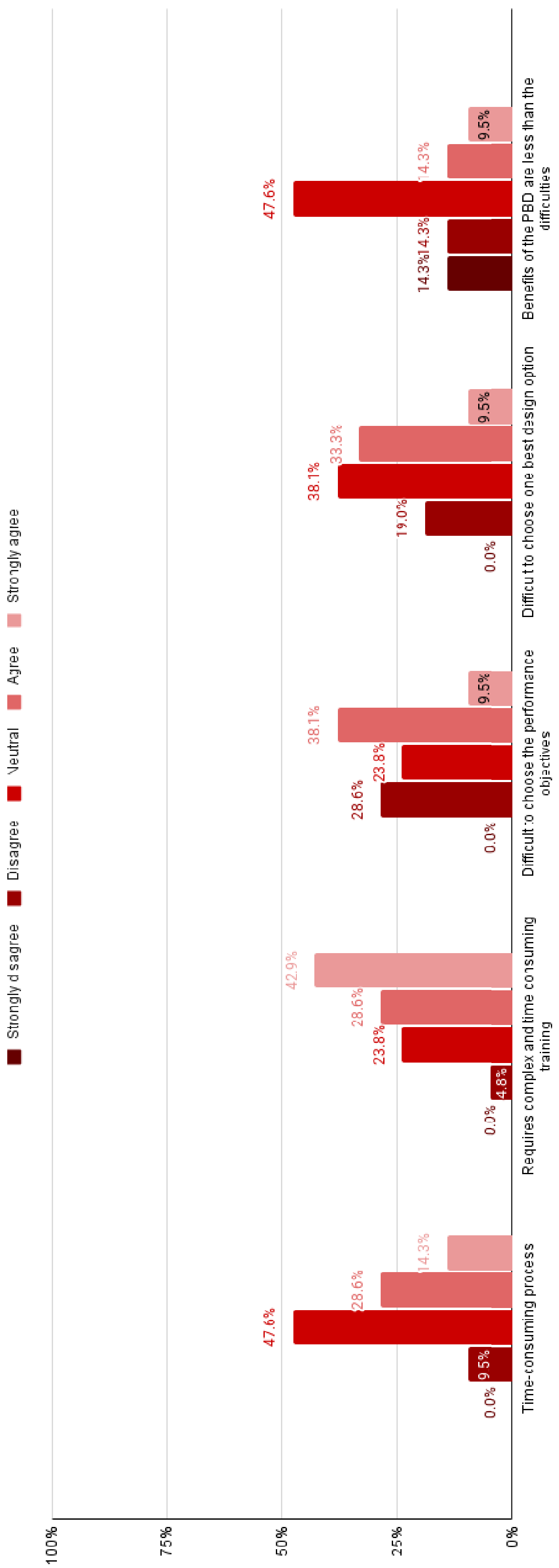

Figure 38: Attitude of professionals to PBD disadvantages and limitations.

Table 2: Data for users' awareness of PBD limitations and difficulties.

Survey statements about PBD benefits	Number of responses on statements one to five					
	Agree/Strongly agree		Neutral		Disagree/Strongly disagree	
	Number	%	Number	%	Number	%
6**.** When dealing with multiple types of analysis and evaluations, this **process is time-consuming**, greatly reducing	9	42.8%	10	47.6%	2	9.6%
7. Performance-based approach requires **complex and time-consuming training** of a specialist to be able to do it	15	71.4%	5	23.8%	1	4.8%
8. It is **difficult to choose the performance objectives** that matter most to the project	10	47.6%	5	23.8%	6	28.6%
9. It is **difficult to choose one bestdesign option** from many based on multy-criteria analysis	9	42.8%	8	38.1%	4	19.1%
10. The **benefits** of the performance-based approach are **less than the difficulties** that appear while using it	5	23.8%	10	47.6%	6	28.6%

In general, presented results highlighted that although many research works were done on this topic, many practitioners are still not familiar with the concept of PBD. Moreover, it is far from the widespread application even among BIM users. However, the results of the second part of the survey showed that architects and engineers, who use this approach, are aware of the benefits it brings to the early design phase. On the other hand, the PBD approach implementation still has multiple challenges, such as methodology for choosing performance objectives or selection process during the optimization; both issues were exposed by the survey.

4.2 Practical part results

4.2.1 Conventional approach

Based on the requirements stated in the methodology and on architectural experience, we created a model of the office building in Revit. Firstly, the decision regarding the height was made – the low-rise building corresponded to the surrounding environment. Therefore, the height from ten to fifteen meters and the three-storey maximum were set as an additional limit for the design. Next, simple 2D layouts were sketched with the Revit zone tool to find the correct dimensions for the building and comply with the area required. The decision about the number of levels was made at this stage based on the layouts done. Further, after the rough layouts were decided, form-finding started using basic

Revit tools as walls, floors, roofs for solid geometry and doors, windows, curtain walls for the glazing. The resulting model with the below-stated characteristics is presented in Figure 39:

- Height – 10 m (two storeys).
- Total floor area – 9600 m^2 (4800 m^2 per one floor).
- Orientation – rotation clockwise 15° about the corner A (Fig.39 bottom left).

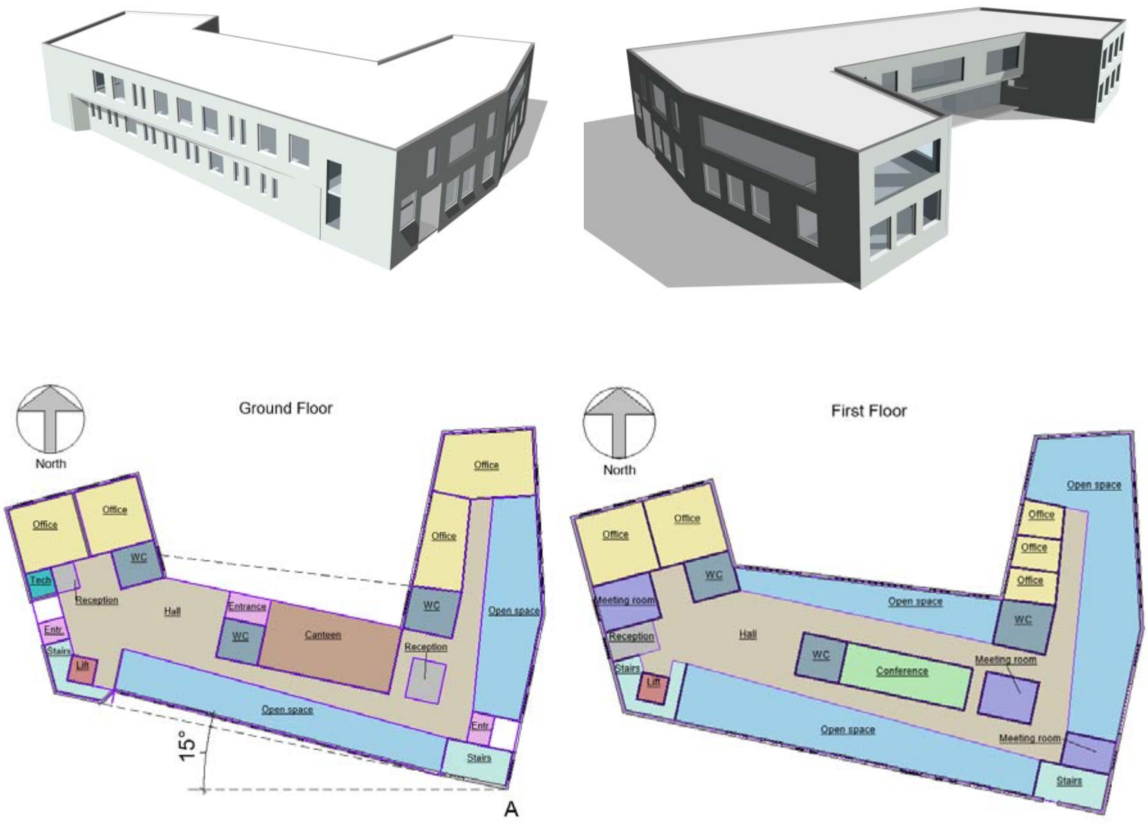

Figure 39: Revit model. Result of the conventional case study. 3D views, plans.

After the geometry was decided, layouts were refined and defined with interior walls. Finally, the analysis was done to assess the performance of the future building. Minor adjustments were made in the model, and several auxiliary views were created before transferring the geometry to the Cove.tool used for the performance assessment. In the Cove.tool, additionally to the transferred geometry, the office type of building was chosen from the template with default characteristics for this type of project (Annex2), project location, and orientation were set. The analysis results are presented in Figure 40.

The whole building EUI was at 125.44 kWh/m^2/yr, lower than the 2030 baseline [296.10 kWh/m^2/yr] but much higher than the 2030 target energy consumption [59.22 kWh/m^2/yr] for this type of building. The baseline is obtained from the database of typical modern buildings and their characteristics in general. The target is set by AIA 2030 and is currently determined 70% below the consumption level of 2015 to 2019 years (Cove.tool, 2021). Utility costs were €39043.59 per year, for electricity - €32785.21 per year, and natural gas – €6258.38. sDA and ASE both were 38% for this approach.

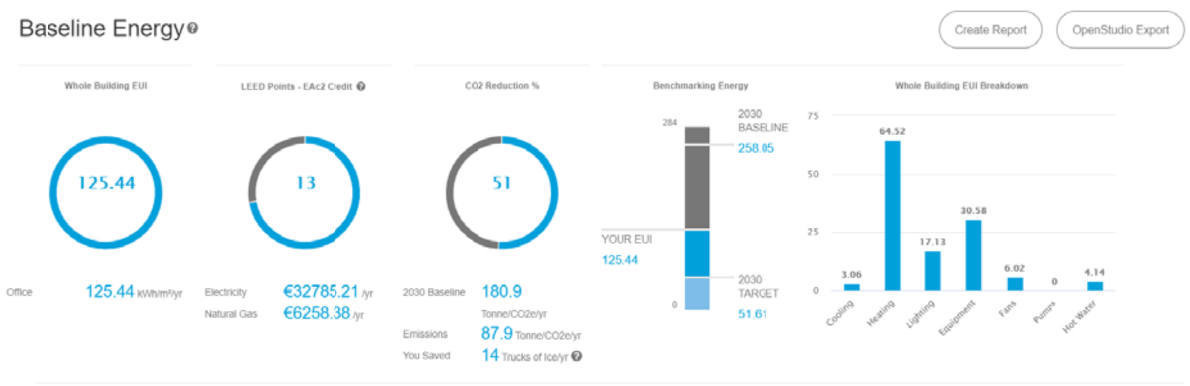

Figure 40: Analysis result dashboard for the conventional method.

4.2.2 PBD approach

Shape

According to the methodology written in chapter 3 of this thesis, the PBD approach was applied to the hypothetical case study of the office building in several repetitive loops. The first step was to generate four simple masses in Revit (in separate files). The In-Place Mass tool was used for masses and Mass floors to calculate the resulting area. After the area was reached, the required walls, floors and roofs were generated based on previously created masses. The last modelling step was to disseminate windows with WWR 45% equal on every façade. The above-described steps are illustrated in Figure 41.

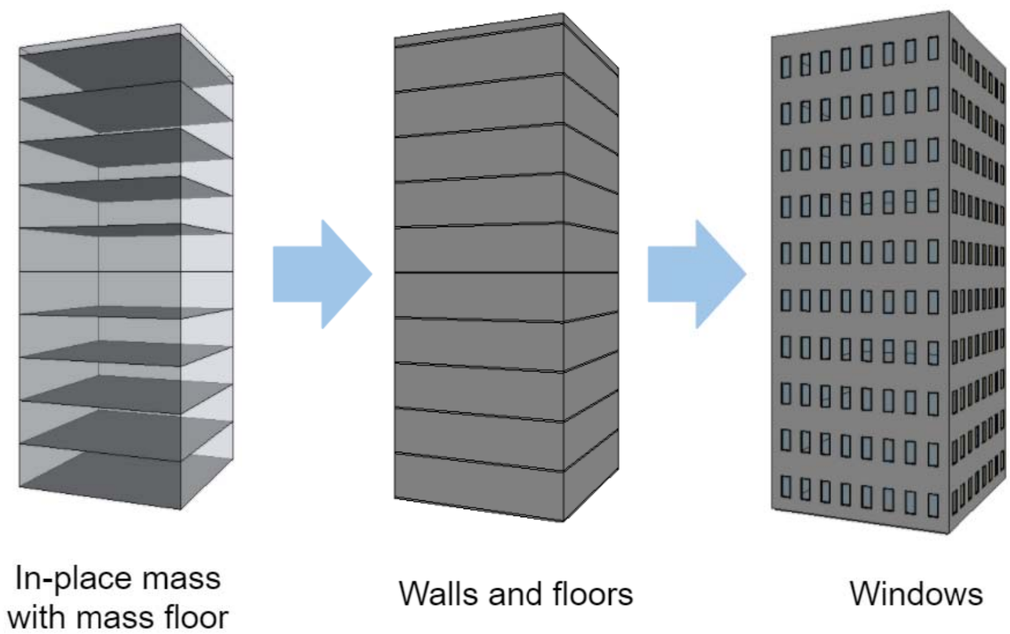

Figure 41: Workflow for creating a simple model for the early-stage analysis.

The resulting four models are presented in Figure 42. Four masses of different shapes – Tower, O-shape, H-shape and long building – were modelled to understand which shape has a better performance in terms of objectives set in the methodology phase. Characteristics of each model are presented in Table 3. The areas of all buildings are comparable, but heights vary from 25 m (7 levels) in case of long shape to 70 m (20 levels) in the tower. For both O and H-shape buildings, the height was the same – 32 m (9 levels). Both performance objectives for the long design option were the lowest, which is the goal for EUI and utility costs. EUI of the following two options, H-shape and O-shape prototypes, were 10.3% and 21.1% higher than EUI of long-shape, and total utility costs were 7.5% and 16% higher, respectively. High-rise building (tower) showed the worst result among the studied shapes, that is 30.6% higher EUI and 16.9% higher total utility costs than for the long building. Detailed results are presented in Table 3.

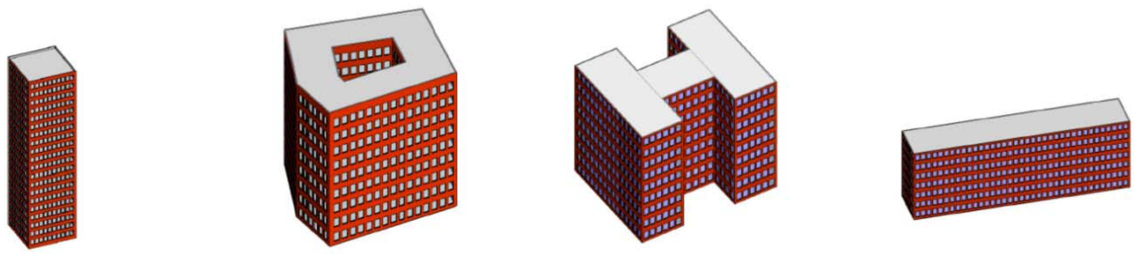

Figure 42: PBD cycle 1. Tower, O-shape, H-shape, long prototypes.

Table 3: Result of the first cycle of analysis – shape.

Objectives	Tower	O-shape	H-shape	Long
		Geometrical objectives		
Total floor Area [m^2]	8835	8885	8640	8390
Height [m]	70	32	32	25
Number of levels	20	9	9	7
		Performance objectives		
EUI [$kWh/m^2/yr$]	134.24	124.54	116.41	102.81
Total utility costs [€/yr]	109557.80	108678.52	100749.30	93745.17

Orientation

To understand how will perform previously selected shape but oriented differently next cycle of analysis was run. Long building from the previous study was rotated by 0° (long side of the building in line with EW axis), 45° clockwise, 75° clockwise and 90° (long side in line with NS axis), as illustrated in Figure 43. Results of the analysis done for each option are presented in Table 4. The results show how the rotation influence the EUI and utility cost indicators. Both objectives grew with the rotation from 0° to 90°, with the difference for EUI in 3.3% and total utility costs in 1%. The difference is small for these two objectives; however, the rotation can influence more substantially daylighting characteristics, such as ASE and sDA.

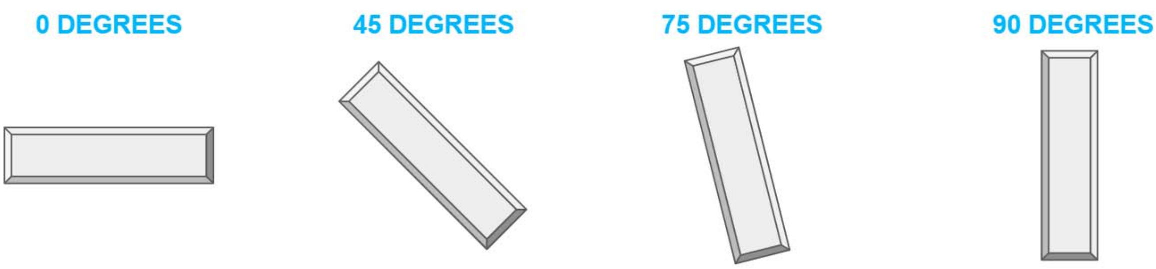

Figure 43: PBD cycle 2. Rotation option 0°, 45°, 75° and 90°.

Table 4: Result of the second cycle of analysis – orientation.

Objectives	0°	45°	75°	90°
		Performance objectives		
EUI [$kWh/m^2/yr$]	102.82	104.95	106.10	106.20
Total utility costs [€/yr]	93745.17	95962.97	94671.14	94673.16

Window-to-wall ratio

Another four options were generated in Revit with different WWR – 35, 45, 55 and 65%. The size of windows was fixed (1.2 x 2.1 m, sill height – 0.8 m), but the number of windows for each option was different. All facades of one option had the same target WWR, so the building in general.

Table 5: Result of the third cycle of analysis – WWR.

Objectives	WWR 35%	WWR 45%	WWR 55%	WWR 65%
Performance objectives				
EUI [kWh/m^2/yr]	98.05	102.82	110.39	116.90
Total utility costs [€/yr]	92413.41	93745.17	97675.41	100892.85
sDA [%]	71	87	88	90
ASE [%]	36	59	62	74

As we can see from the results (Table 5), WWR has dramatically influenced energy consumption and daylighting performance. The EUI and utility costs grew with the increase of WWR, and the difference between WWR 35% and WWR 65.0 % is 19.2% for EUI and 9.2% for utility costs. This rise can be explained by the growing demand for heating in winter and cooling in the summertime with the growing percentage of WWR. For the sDA target is 50% or higher, all results meet this target, with the lowest sDA of 71% in the case of WWR 35% and the highest sDA of 90% for WWR 65%. However, the ASE level is too high for all options and means that from 36% of working surface (WWR 35%) to 74% (WWR 65%) receive too much direct sunlight. It can cause visual discomfort, increase the cooling load, energy use, and costs; it also negatively influences the user's productivity because of overheating and possible glare. We cannot decrease the ASE more, although shadowing devices might be helpful in this case. The option with WWR 35% was selected for the next cycle as one with the best performance.

Glazing distribution

One of four models is the best option from the previous analysis cycle, with windows distributed equally through facades. Three more models were decided differently – they have glazing only on two sides – North and South (Rotation is 0°) with different relations – 50 to 50%, 60 (North) to 40% (South) and 70 (North) to 30% (South). Based on the results of this analysis cycle (Table 6), there is no doubt that the N50 S50 option is the best performance with the results for EUI 97.21 kWh/m^2/yr, total utility cost €92114.32/yr, sDA 71% and ASE 31%. However, the one that has glazing evenly distributed around the facades has slightly higher values of EUI [98.05 kWh/m2/yr], total costs [€92413.41/yr] and ASE [36%], and the same for sDA [71%].

Table 6: Result of the fourth cycle of analysis – glazing distribution.

Objectives	N25 E25 S25 W25	N50 S50	N60 S40	N70 S30
Performance objectives				
EUI [kWh/m^2/yr]	98.05	97.21	99.82	100.35
Total utility costs [€/yr]	92413.41	92114.32	93347.20	94042.24
sDA [%]	71	71	69	62
ASE [%]	36	31	32	25

The general understanding of shape, orientation, and glazing parameters with the best performance profiles in the current project conditions has been defined. The best shape in terms of performance is long and not high, with the rotation approaching 0° and the glazing distributed evenly (N25% E25% S25% W25%) or 50/50% (North to South). However, five more analysis cycles were performed during the current study to get more information for neighbouring disciplines – mechanical, electrical and plumbing engineers. The analysis results of these cycles are illustrated in Table 7. Assessed options do not significantly impact the concept design; moreover, they can be decided later without massive rework. Nevertheless, the time spent for analysis and assessment is relatively tiny compared to the full design process, so this additional data can be beneficial even at this point, e.g., setting a goal for optimization. The final dashboard with the characteristics obtained presented in Figure 44, where whole building EUI is 89.83 kWh/m2/yr, total utility cost per year is €78366.03 (electrisity - €69269.81, natural gas - €9096.22). The final sDA and ASE for this option were 71% and 31% respectively.

Table 7: Result of the fifth to ninth cycles of analysis.

Design options	EUI [kWh/m^2/yr]	Total utility costs [€/yr]
Shading options		
Internal	98.98	88291.34
External	99.89	87403.60
Heat recovery		
Run around coil, no pipes	98.36	88184.66
Off	98.98	88291.34
Exhaust air recirculation percentage		
None	98.36	88184.66
40%	98.23	88151.26
60%	98.16	88139.01
80%	98.09	88126.77

The domestic hot water generation system		
VR-Boiler	98.09	88126.77
Gas-Boiler, HR-Boiler	97.37	87964.52
Co-Generation	96.76	87829.17
Energy Generation		
Off	96.76	87829.17
400 m^2/15° inclination	89.83	78134.99

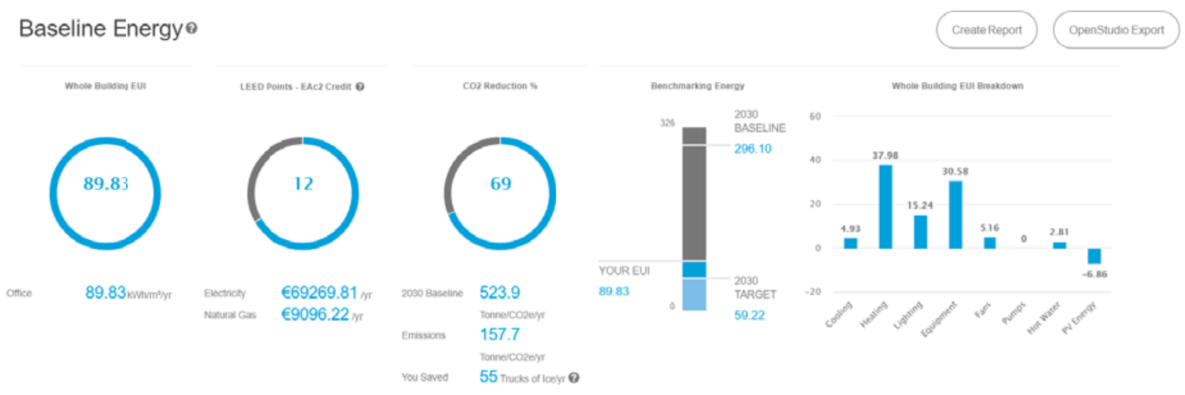

Figure 44: Analysis result dashboard for PBD method.

4.2.3 Comparison of the results of conventional and PBD approaches

First of all, the quality of the design in terms of performance objectives can be assessed. The PBD approach results are significantly better for EUI [89.83 to 125.40 kWh/m^2/yr]; moreover, it is closer to the 2030 target [51.61 kWh/m^2/yr] (Fig.45). If we compare the EUI breakdown for the two design options (Fig.46), we can see that only for cooling energy consumption was slightly higher for the PBD option [4.93 kWh/m^2/yr] than for conventional [3.06 kWh/m^2/yr]. The most significant difference was in the heating category, where the traditional design option consumes 70% more [64.52 kWh/m2/yr] than the PBD design option [37.98 kWh/m^2/yr]. Consumption for lightning [15.24 to 17.13 kWh/m^2/yr], fans [5.16 to 6.02 kWh/m^2/yr] and water heating [2.81 to 4.14 kWh/m^2/yr] was slightly lower for PBD option. The equipment consumption was the same [30.58 kWh/m^2/yr] because the number of occupants was the same for both options. It is evidently from Figures 45 and 46 that the PBD approach showed noticeably better results.

Results for daylighting performance was also compared (Fig.47). Both objectives, sDA and ASE, are better for the PBD design option. The sDA of PBD was 71%, almost two times higher than the sDA of conventional design [38%]. The better (lower) ASE was in the case of PBD [31%] comparing to traditional design [38%]. If ASE could be decreased later with various shading devices, sDA could not be increased without significant changes, e.g., increased windows dimensions.

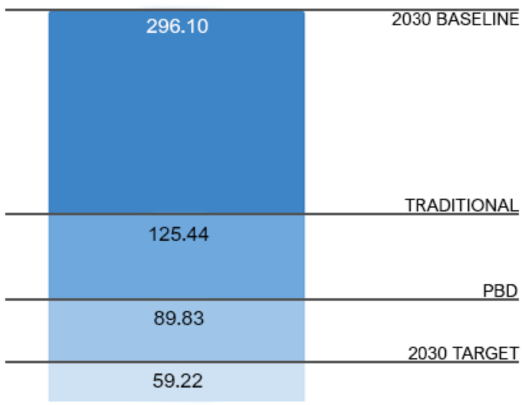

Figure 45: Whole EUI for PBD and conventional design in comparison with 2030 baseline and 2030 target.

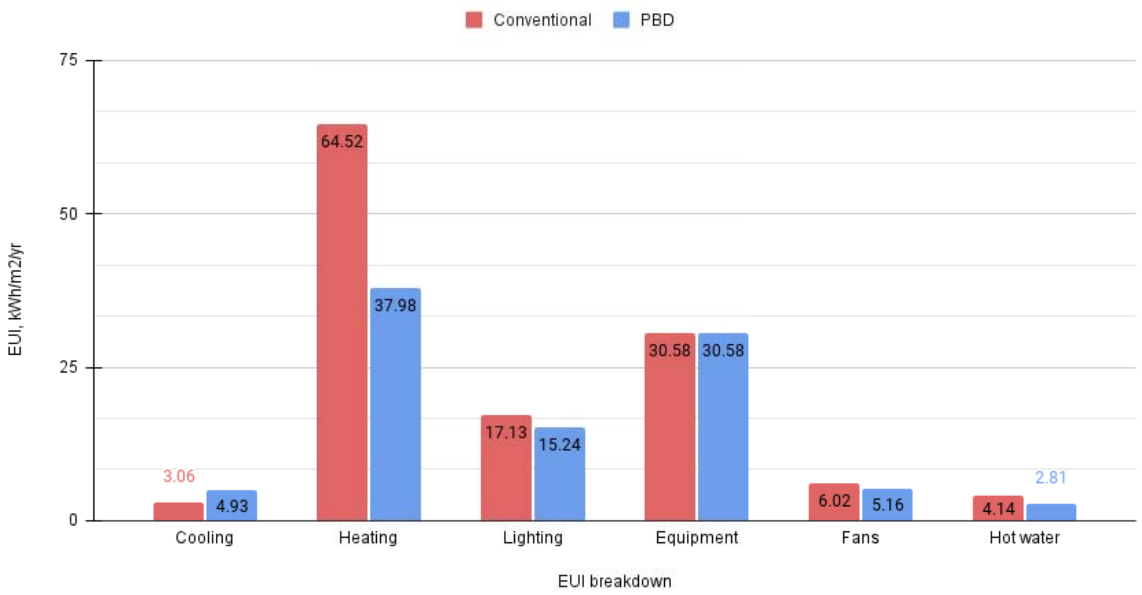

Figure 46: EUI breakdown for PBD and conventional design.

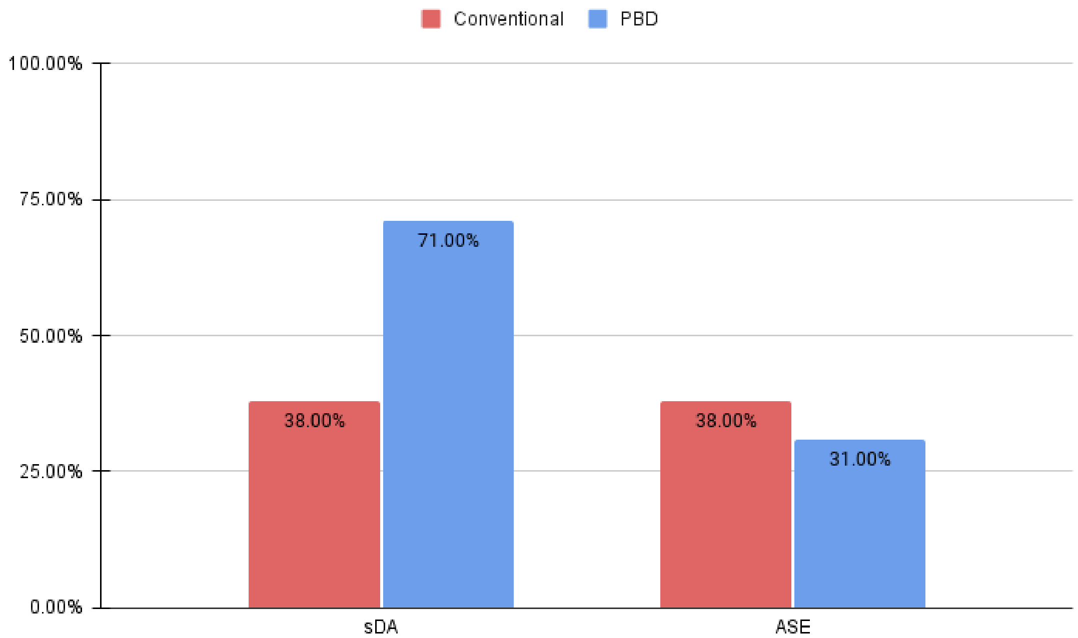

Figure 47: sDA and ASE results for PBD and conventional design options.

The last performance objective that was set as a goal for both design options is utility costs. The absolute values for both options were reduced to values per m^2 per year and compared in the bar chart (Fig.48). In this case, the traditional design option showed better results with a total of 4.07 €/m^2/yr comparing to 9.34 €/m^2/yr for PBD design. Costs for electricity were 58% higher and for gas 40% higher for PBD. The difference is possible because of the different levels of complexity of models, as well as the different geometrical characteristics of both buildings (height, length and width).

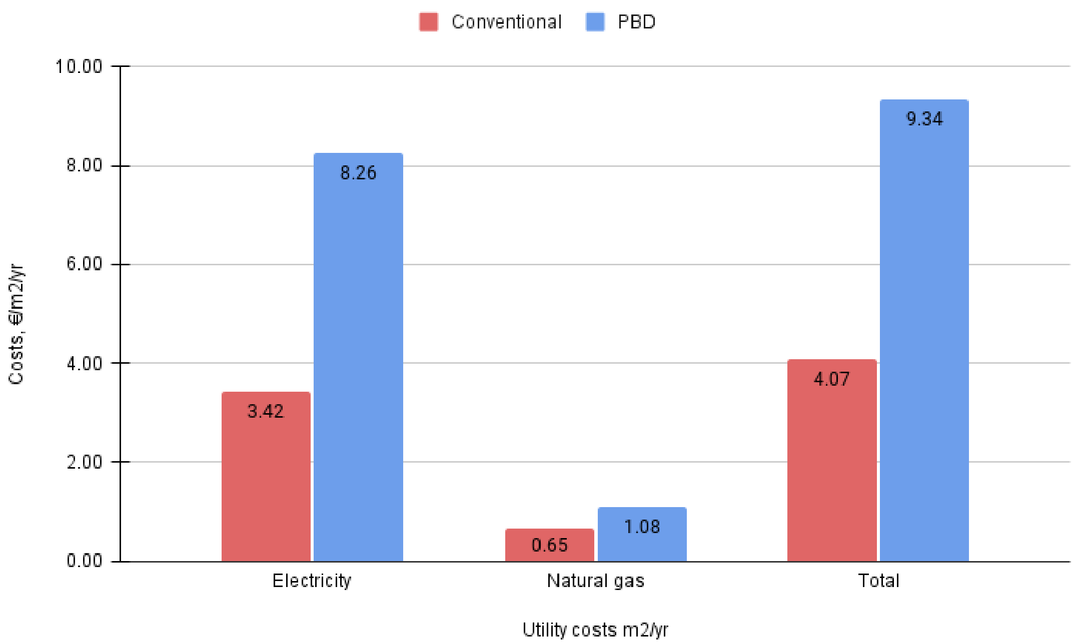

Figure 48: Utility costs per m2 per year for PBD and conventional design options.

The two case studies can also be compared regarding the time spent on different tasks. Table 8 presents the data about the time consumed for each type of work during both case studies. The four tasks were the same for both approaches – modelling, transferring data, setting parameters, analysis, and comparing the results have appeared in the PBD approach only. The time is comparable for the modelling part and slightly more for the conventional method – 4.5 hours and 4 hours for PBD, although the number of models in PBD was ten times higher. So the time per model in the PBD approach is 0.4h per model; however, models are not of the same complexity.

Time for geometry transferring and analysis was four times different – 0.5h for traditional and 2.1h for PBD. Time spent for transferring geometry per model in PBD was 0.21h, which is two times smaller than traditional, but the complexity of PBD models was lower. As the initial settings were the same for both options, the time for setting parameters in the app is the same. For the PBD approach, it was enough to set parameters once and use one project as a template (in Cove.tool platform). Without results assessment and comparison, it was impossible to move from one cycle to another, so the time spent on it is vital. For the conventional method, only one cycle of analysis was done, when for the PBD, there were four major cycles and five additional. If we compare the time spent per cycle in PBD [1.02h] and the conventional approach [0.75h], they are close to each other. Finally, the comparison of results after each cycle was made only during the PBD study – as it is an integral part of this approach. The time spent for it was 3.3h or 0.37h after each cycle. Finally, the time in total differs by a factor of 3 in the case of the PBD approach compared to conventional, but the absolute value is not high – almost 19h and 6h accordingly. For the total duration of the design phase from the beginning until construction, this difference is not significant.

Table 8: Time comparison of results conventional and PBD approach.

Approach	Time spent for [h]					
	Modelling	Transferring geometry	Setting parameters	Analysis	Comparing results	Total
Conventional	4.50	0.50	0,30	0,75	-	6,05
Performance-based	4.00	2.10	0,30	9,20	3,30	18,90

For a comprehensive assessment of the two methods, the final models should be compared. The result of the traditional approach is the concept 3D model with the basic layout, the future performance of which we know. However, we cannot rely on the performance results assessed at this stage because of factors like general uncertainty, simplicity of the design at this stage, unfamiliar software, and assessment methods. Moreover, we do not know how these objectives could change if the design changed. The PBD approach results in a very simple conceptual model that should be significantly improved before the next design stage. Nevertheless, the most significant result here is not a model but the knowledge of how each design feature influences the future building performance. If the design changed in the traditional approach, a new analysis should be conducted to understand how the changes affected building performance. The primary benefit of PBD is in the knowledge obtained about one possible design solution and a wider space of variants.

5 DISCUSSION

All three parts of this work – literature review, a survey among practitioners and practical case study made it possible to research the existing picture of implementation and use of Performance-based design in the early stage in depth.

The results of the survey show that professionals know the Performance-based building design approach. At least 83.0% (29 of 43) of the respondents from 21 countries stated they know about PBD. At least 65.5% (19 of 29) of those use it in their work. Unfortunately, half of the respondents do not use it for now, and 17.0% do not know what it is. The benefits of the PBD approach are highly recognized among those who use it. However, there is still hesitation in its application in everyday design practice, even among users of PBD. Uncertainty in answers to questions four and five of the second part of the survey could be related to the fact that the PBD approach can give different levels of support in different types of projects. For example, like in residential buildings, standards, codes, and prescriptions have already been tested by time and offer the solutions that perform and are demanded by the rules. Of course, these solutions can be improved but to a small extent if the context of the prescription based rules and standards is not changed. Compared with project types like public architecture (educational, healthcare, sport, etc.) or restoration and renovation, the decision-making space is broader, and the design space expands. In these projects, case-oriented support can be derived by PBD. There is more space for improvement in other types of projects like offices, healthcare, sport, and educational buildings where PBD can be used to find a better solution going beyond well-established approaches and solution archetypes.

Learning how to work with the early-stage BPS tools does not take much time compared to the time needed for learning how to work with complex modelling tools, such as Revit or ArchiCAD. Sooner or later, analysis tools will become a part of modelling tools, so the time spent learning them will not be considered extra, but they will be studied altogether. There are already some examples of such tools that exist. The more vital concern is that to read and understand results and be able to compare them, more complex training is necessary, as it is a part of building physics science.

The practical study intended to compare the PBD method with the conventional approach and decide if PBD has more significant advantages than the conventional one. However, in the end, we concluded that the PBD approach could not fully replace the conventional method but accomplish it in the way of obtaining the vital data earlier. The PBD can upgrade the conventional approach significantly with additional data acquired through the cycles of analysis. Moreover, the PBD approach applied to the early design process cannot give a final design, but it can guide architects towards the desired design goal. The PBD approach should be implemented as the first step before architectural design work has started. Determining the best shape, orientation, and glazing options can be fundamental for the performance of design and the process quality. **Before creating the model, it is essential to explore the space of options** as comprehensive as possible to understand roughly the best shape, orientation, glazing options, etc. So the information obtained during this analysis can be used as input for the concept design. It corresponds to everything described previously – the workload shift towards the early stage, holistic view and bringing expertise earlier in the design process. Unfortunately, the intention of this study was not to explore and compare tools but to understand the process and issues that prevent designers from the widespread use of the PBD approach early in design. In the end, the PBD should not be viewed as a substitute for the conventional approach but rather as an additional input of data-driven parameters that should influence the architectural formulation of a specific building.

As the practical part of this work showed, running the analysis is not a stumbling block of the considered approach; it is just a matter of time. However, setting the design goals and understanding the analysis results require more knowledge, time and additional research. To set specific goals for the particular project and decide the strategy for the analysis loop, a specialist (e.g. architect) has to know what are the design options, materials, systems available and how they affect specific performance indicators and cost. Although methods like generative design can help find the optimal solution from a large field of variants, they cannot give a comprehensive understanding of how the design will perform if some of the parameters are changed, so the analysis has to be run again and again if something changes in the design. The current codes and standards should be updated with key performance indicators for different types of projects. It will help architects with the issue of the design goal setting, identified in the literature and confirmed by the survey results.

During the case study, the issue of deciding the best design option was not identified. However, it is still a question if the optimization methods take place. The workflow proposed and utilized in this study has the potential to increase the quality of the conventional approach significantly if applied not for the design but data collection before the design.

6 CONCLUSION

As presented in the literature review, humanity and the construction industry set an important goal of reducing our impact on the environment. The buildings and construction industry is responsible for about 40% of CO^2 emissions. The sustainable approach has already led other industries, such as robotics, mechanical engineering and others. So it is time for the construction to utilize it in order to achieve sustainable goals. As it was presented in the literature review, the PBD approach is the most promising one to support the industry in this primary goal through changes in the design of buildings. The most relevant recourses consulted and the survey conducted shows that the implication of PBD in use is still insufficient, although the approach is not new.

Considering the survey results and the case study, we came to the following conclusion: the PBD approach could not replace the conventional method, even though they are often set in the opposite – which might be a wrong representation and oversimplification of the subject. However, the PBD can significantly contribute and improve the traditional design approach. BIM technology, together with the IPD process, is a good foundation for the implication of PBD. Because they provide inclusion of different domains from the early design stage, integrated process and resulting integrated model with all vital information, holistic view on the design.

Moreover, as previously, Neufert's Architects Data "*took architects away from the fear of the blank sheet*" (About building design, 1995) with all the data collected and meticulously structured, so now the PBD approach can similarly significantly help young architects. Not with the collection of data in general, but retrieving knowledge about the building performance in connection with the design options and parameters.

The professional community is aware of the benefits of PBD application early in design. However, much uncertainty is still occurring when it comes to the limitations and difficulties. The workload shift towards the beginning of design confuses the professionals and does not correspond to the traditional approach. Nevertheless, it is an essential condition to the process and design quality.

It was also understood that the early-design BPS tools imperfection is not an issue if we use them to explore design space and not to assess a particular option. These tools are suitable for guidance and support in the design decision process. They are fast, interoperable with the primary architectural modelling tools, have a user-friendly interface, comprehensive templates and a relatively short learning curve. Moreover, the BIM tools industry works on developing features inside modelling tools. Some types of analysis have already been integrated with it (e.g. system or solar analysis in Revit).

Additionally, two problems in the methodology take place. Firstly, the problem of the requirements formulation was highlighted from the literature and confirmed by survey results. It also refers to the early connection of different disciplines that can cause adverse requests from different domains. It possibly can be solved by improving the current standards with a common set of performance indicators for each type of building. Secondly, the problem of decision making when it comes to the multi-criteria result assessment. The foundation of it is in the previous issue when a set of performance goals is defined. At the analysis and result assessment stage, if the strategy was not set, the decision-making could not be easy.

Based on literature review and survey, this work proposed the workflow and a strategy for the early performance analysis that can fit project types such as residential, commercial and public architecture. The proposed strategy can contribute significantly to the architectural practice as these three design areas are the most extensive. While for other types of projects, like restoration and renovation, interior design, landscape and urban design, and infrastructural, additional research should be done regarding the methods of application PBD.

Finally, to improve analysis methods, the BPS tools used, it is vital to learn how the buildings perform after being constructed. The analysis results are not always accurate and reliable. With more accurate data, the optimization can be more precise and reliable. It has been highlighted by the available research and also through the presented work that in order for the PBD to become an integral part of early-stage building design also the knowledge of the designers has to be expanded. While PBD can provide data about projected performance, its interpretation and the subsequent impact on the building design are solely in the designer's hands (or the head). In other words, data is worth only if it is understood correctly. Therefore, a substantial gap emerges in the current structure of design offices, design processes, and how designers and engineers are educated.

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8 ANNEXES

Annex 1: The annex shows a survey created in Google Forms and distributed online through e-mails and Social media.

Annex 2: The annex shows the Cove.tool inputs that were used in the study case. Cove.tool

Annex 3: The annex represents the analysis results obtained with Cove.tool during the practical hypothetical case study

8.1 Annex 1

Performance-Based Building Design Approach Survey

Here is a short survey in support of my Master's thesis.
It helps me to understand better the limitations of the implementation of a performance-based building design approach in the real design process.

It only takes 3-5 minutes to answer the questions and submit this survey.

Questions about you and your company

Your company is best described by which field *

- [ ] Architectural design office
- [ ] Engineering company/consultant
- [ ] Developer/facility management
- [ ] Construction company (contractor)
- [ ] Other: ____________

In which country is your company based? *

Your answer ____________

Your role in the company *

- ○ designer/architect
- ○ engineer (architectural engineer, structural engineer, etc.)
- ○ management
- ○ public relations
- ○ Other: ____________

Number of employees in your company *

- ◯ less than 10
- ◯ 10 - 50
- ◯ 50 - 100
- ◯ 100 - 200
- ◯ more than 200

Type of projects your company is working on (generally)? *

- ☐ Residential Architecture
- ☐ Commercial & Offices
- ☐ Restoration and Renovation
- ☐ Public Architecture (Educational, Healthcare, Sport, etc.)
- ☐ Industrial and Infrastructure
- ☐ Landscape and Urbanism
- ☐ Interior Design
- ☐ Other: ______

Does your company use BIM? *

- ◯ Yes
- ◯ No

Which BIM software is used in your company? *

- ☐ Revit
- ☐ ArchiCAD
- ☐ Tekla Structures
- ☐ Bentley Open Buildings
- ☐ Allplan
- ☐ SketchUp
- ☐ Other: ______

Do you use performance-based design approach in your projects?

Performance-based design (PBD) is a goal-oriented design approach that specifically addresses performance-related criteria, such as energy use, operating cost, occupant comfort, daylighting, and HVAC size and cost, among others.

Do you use performance-based design approach in your projects? *

- ◯ Yes
- ◯ No

If answer was "No":

Why don't you use performance-based design approach in your projects? *

- ☐ I don't know what is it
- ☐ I used it once but I didn't get any benefit from it
- ☐ It takes too much time
- ☐ It is too complex
- ☐ Other: ______

If answer was "Yes":

Your experience from using performance-based approach

How often do you use a performance-based approach in your design? *

- ◯ In every project
- ◯ In some projects
- ◯ Rarely
- ◯ I used only once

Please indicate your opinion about each of the following statements

1. Performance-based approach decreases time and cost of rework on later stages of design *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

2. Performance-based approach increases the design process' quality and efficiency *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

3. Performance-based approach increases the design quality *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

4. Performance-based approach helps you make decisions faster *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

5. Performance-based approach improves the quality of the designer's expertise faster than conventional approach *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

6. When dealing with multiple types of analysis and evaluations, this process is time-consuming, greatly reducing the design benefits of BIM *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

7. Performance-based approach requires complex and time consuming training of a specialist to be able to do it *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

8. It is difficult to choose the performance objectives that matter most to the project *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

9. It is difficult to choose one best design option from many based on multy-criteria analysis *

	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

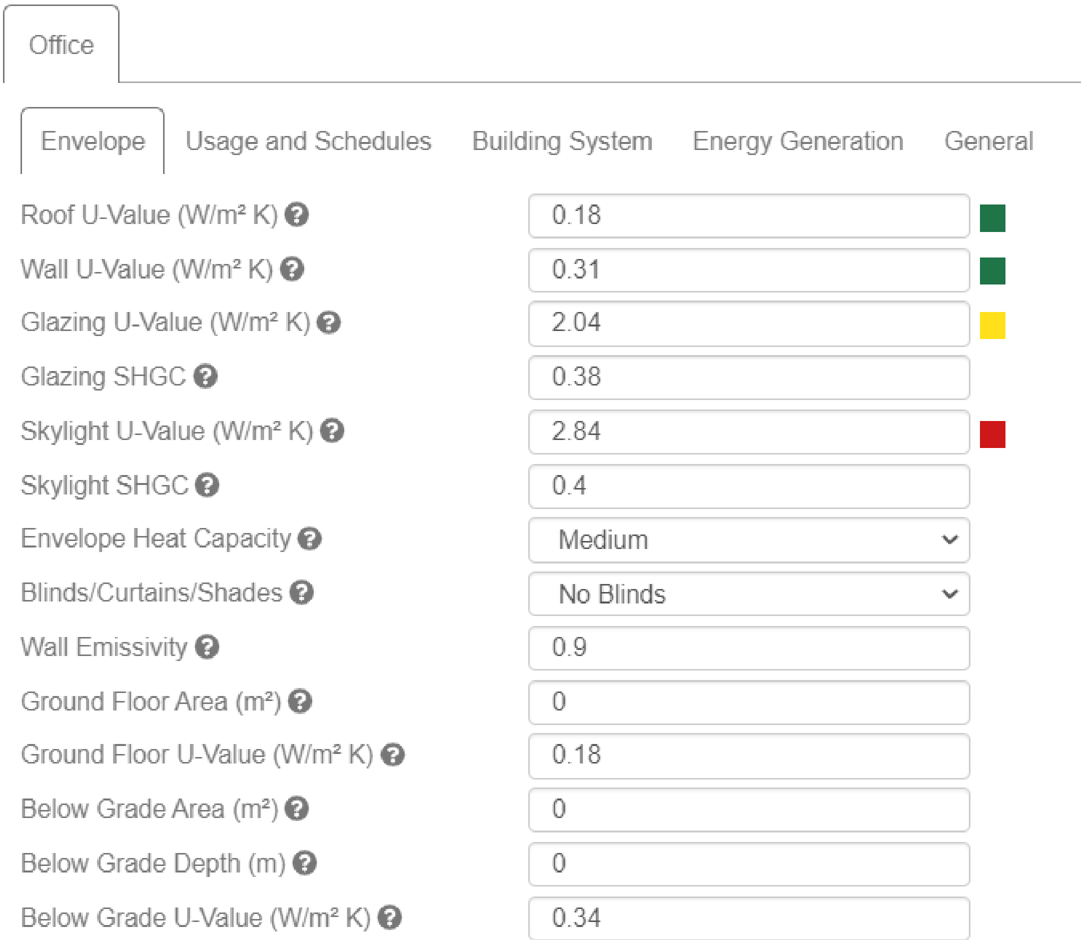
10. The benefits of the performance-based approach are less than the difficulties that appear while using it *

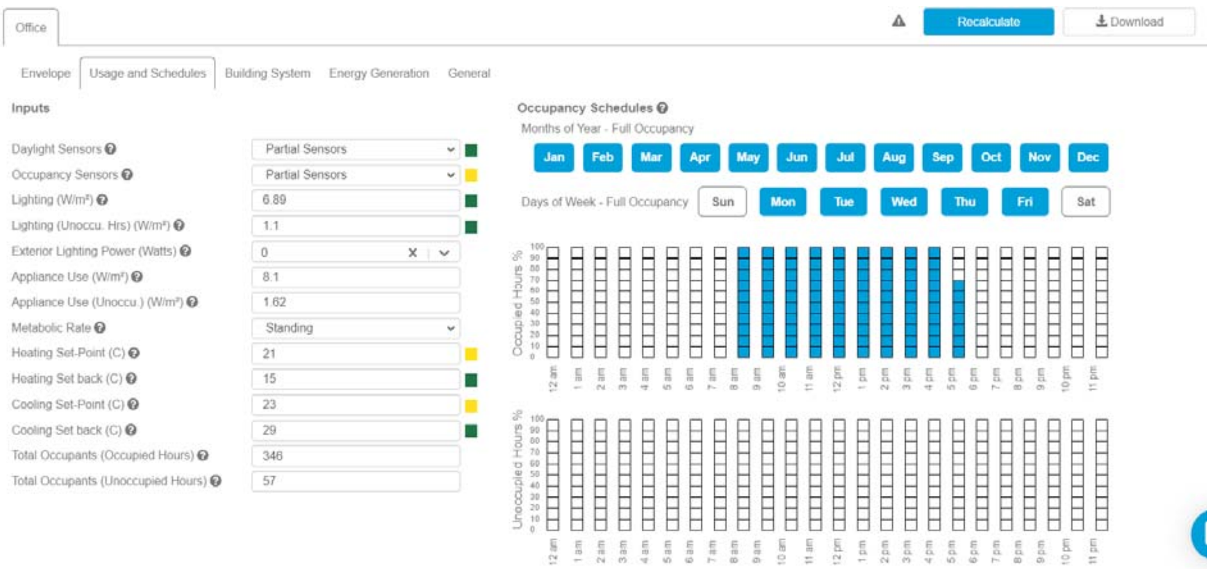
	1	2	3	4	5	
Disagree	○	○	○	○	○	Agree

Do you want to add something else based on your experience?

Your answer

8.2 Annex 2

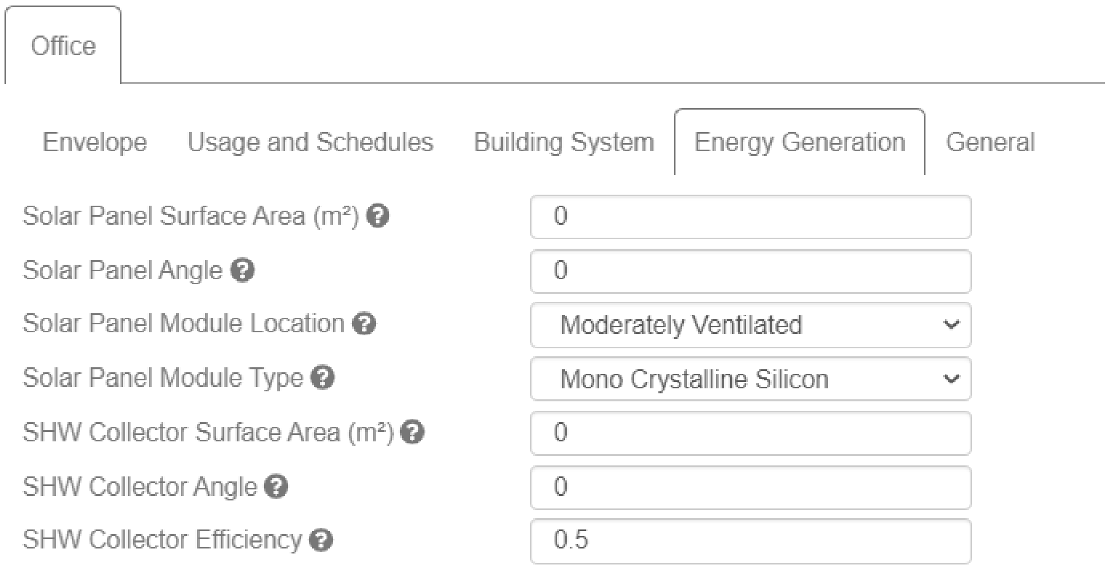

Office
Envelope
Usage and Schedules
Building System
Energy Generation
General
Roof U-Value (W/m² K)
0.18
Wall U-Value (W/m² K)
0.31
Glazing U-Value (W/m² K)
2.04
Glazing SHGC
0.38
Skylight U-Value (W/m² K)
2.84
Skylight SHGC
0.4
Envelope Heat Capacity
Medium
Blinds/Curtains/Shades
No Blinds
Wall Emissivity
0.9
Ground Floor Area (m²)
0
Ground Floor U-Value (W/m² K)
0.18
Below Grade Area (m²)
0
Below Grade Depth (m)
0
Below Grade U-Value (W/m² K)
0.34

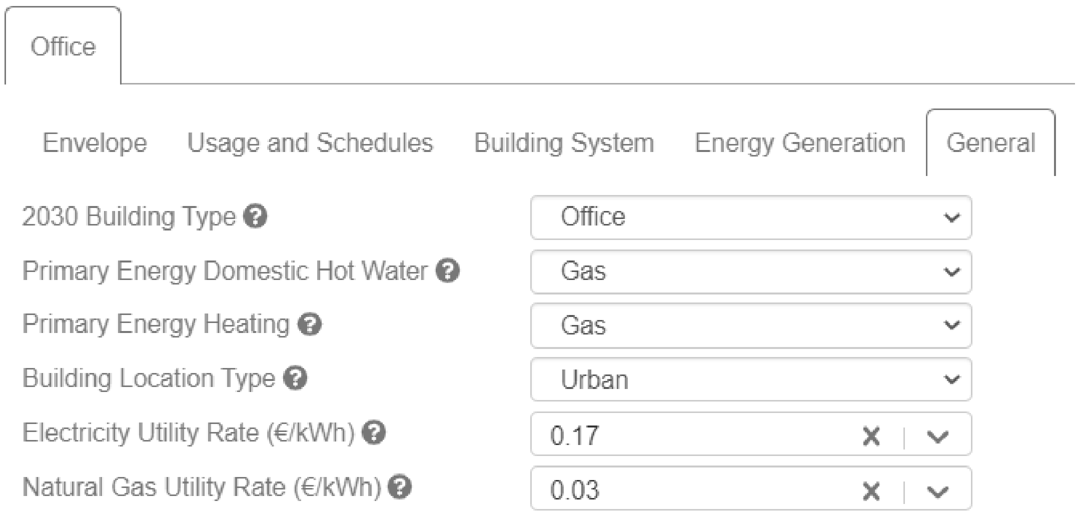

Office
Recalculate
Download
Envelope
Usage and Schedules
Building System
Energy Generation
General
Inputs
Daylight Sensors
Partial Sensors
Occupancy Sensors
Partial Sensors
Lighting (W/m²)
6.89
Lighting (Unoccu. Hrs) (W/m²)
1.1
Exterior Lighting Power (Watts)
0
Appliance Use (W/m²)
8.1
Appliance Use (Unoccu.) (W/m²)
1.62
Metabolic Rate
Standing
Heating Set-Point (C)
21
Heating Set back (C)
15
Cooling Set-Point (C)
23
Cooling Set back (C)
29
Total Occupants (Occupied Hours)
346
Total Occupants (Unoccupied Hours)
57
Occupancy Schedules
Months of Year - Full Occupancy
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Days of Week - Full Occupancy
Sun
Mon
Tue
Wed
Thu
Fri
Sat
Occupied Hours %
Unoccupied Hours %

Office

Envelope | Usage and Schedules | Building System | Energy Generation | General

System Type	CAV w/ Radiant, with Electric R
Integrated Part Load Value	Constant Speed Screw Chiller
Heating System COP	0.8
Cooling System COP	3
Heat Recovery System	No Heat Recovery
Fan Flow Control Factor	Variable Speed
Specific Fan Power	Central Mechanical Ventilation \
Ventilation Type	Mechanical
People Outdoor Air Rate (L/S/Person)	2.5
Area Outdoor Air Rate (L/S/m²)	0.3
Infiltration (m³/h/m²)	0.5
Building Energy Management System	None
Ventilation Control	Demand Control
Exhaust Recirc. %	None
DHW Gen.	VR-Boiler
Hot Water Distribution System	Taps Within 3 Meters Of Heat G
Domestic Hot Water Demand (m³/yr)	186.8
Pump Control for Cooling	No Pump
Pump Control for Heating	No Pump


Office
Envelope
Usage and Schedules
Building System
Energy Generation
General
Solar Panel Surface Area (m²)
0
Solar Panel Angle
0
Solar Panel Module Location
Moderately Ventilated
Solar Panel Module Type
Mono Crystalline Silicon
SHW Collector Surface Area (m²)
0
SHW Collector Angle
0
SHW Collector Efficiency
0.5


Office
Envelope
Usage and Schedules
Building System
Energy Generation
General
2030 Building Type
Office
Primary Energy Domestic Hot Water
Gas
Primary Energy Heating
Gas
Building Location Type
Urban
Electricity Utility Rate (€/kWh)
0.17
Natural Gas Utility Rate (€/kWh)
0.03

8.3 Annex 3

PERFORMANCE-BASED ANALYSIS
FOR THE EARLY STAGE OF DESIGN

AUTODESK
REVIT

cove.tool

PREREQUISITES AND REQUIREMENTS

TYPE OF THE BUILDING

OFFICE

LOCATION

MENGES, SLOVENIA

TOTAL AREA

8000-10000 sqm

WINDOW-TO-WALL RATIO

45%

SITE

ENERGY CODE

ASHRAE 2019 - IECC 2021 Equivalent

ASHRAE Standard 90.1 2019 - IECC 2021 Equivalent
Energy Standard for Buildings Except Low-Rise Residential Buildings

BENCHMARKS

Energy

298
National Average

60
2030 Target

EUI is expressed as energy per square meter per year. It is calculated by dividing the total energy consumed by the building in one year (measured in kWh) by the total floor area of the building. The most common unit for EUI is kWh/m²/year.

Daylight

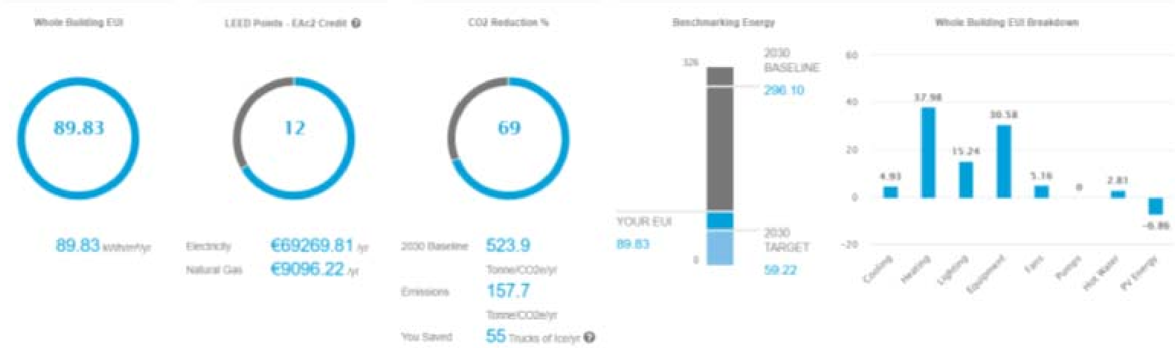
55 %
Daylight

Spatial Daylight Autonomy (sDA) describes the percentage of floor area that receives at least 300 lux for at least 50% of the annual occupied hours.

10 %
Glare

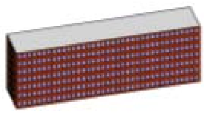
Annual Solar Exposure (ASE) refers to the percentage of space that receives too much direct sunlight (1000 Lux or more for at least 250 occupied hours per year), which can cause glare or increased cooling loads.

BASELINE ENERGY FOR CURRENT OPTIONS



BEST OPTIONS FOR THE CURRENT REQUIREMENTS

SHAPE
LONG



ORIENTATION
WEST-EAST

GLAZING RATIO (WWR)
35-45%

GLAZING DISTRIBUTION
NORTH 50 - SOUTH 50
↘ EUI
↘ UTILITY COST

SHADING
INTERNAL OR EXTERNAL
↗ EUI
↘ UTILITY COST
↗ LEED

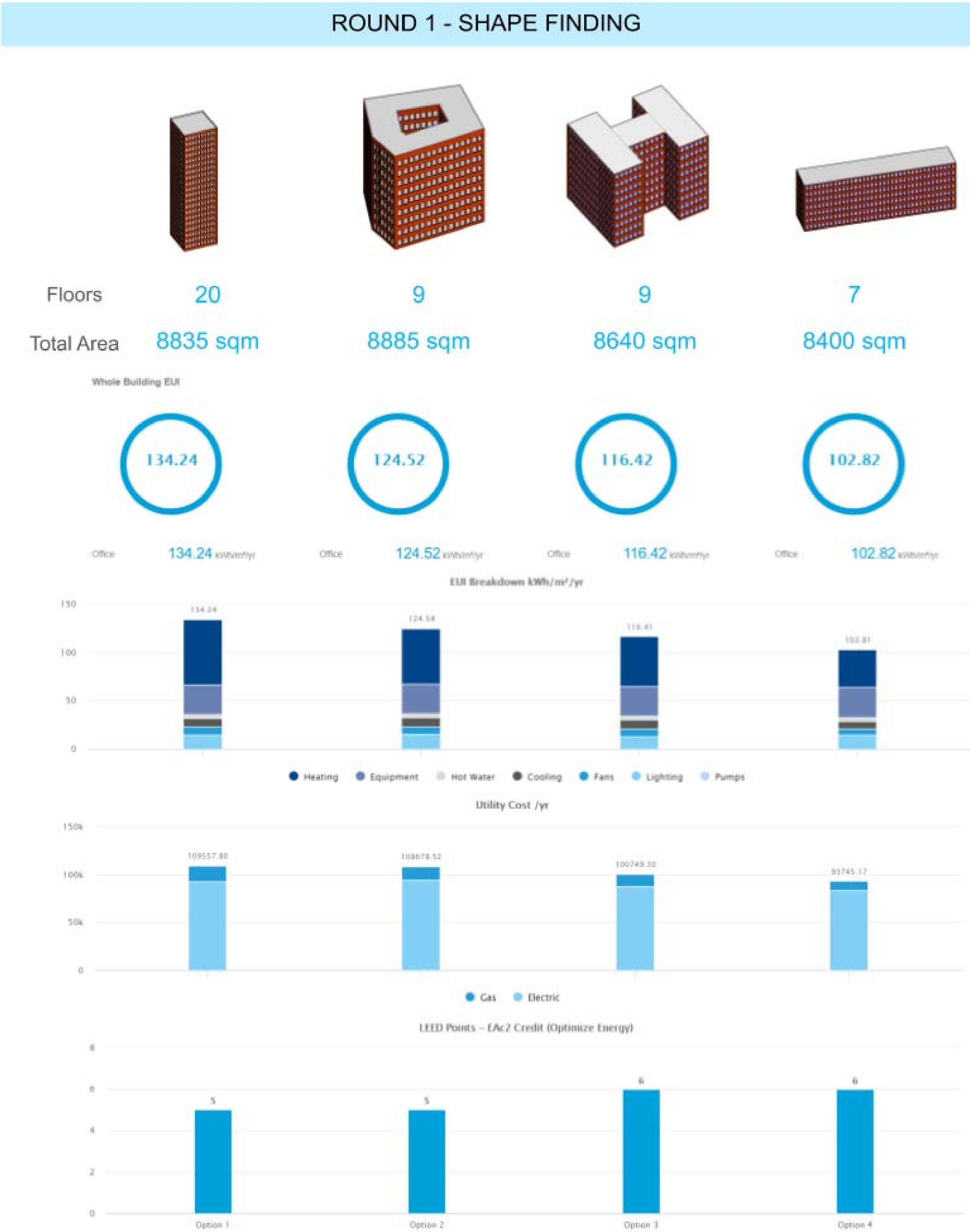
HEAT RECOVERY
↘ EUI
↘ UTILITY COST

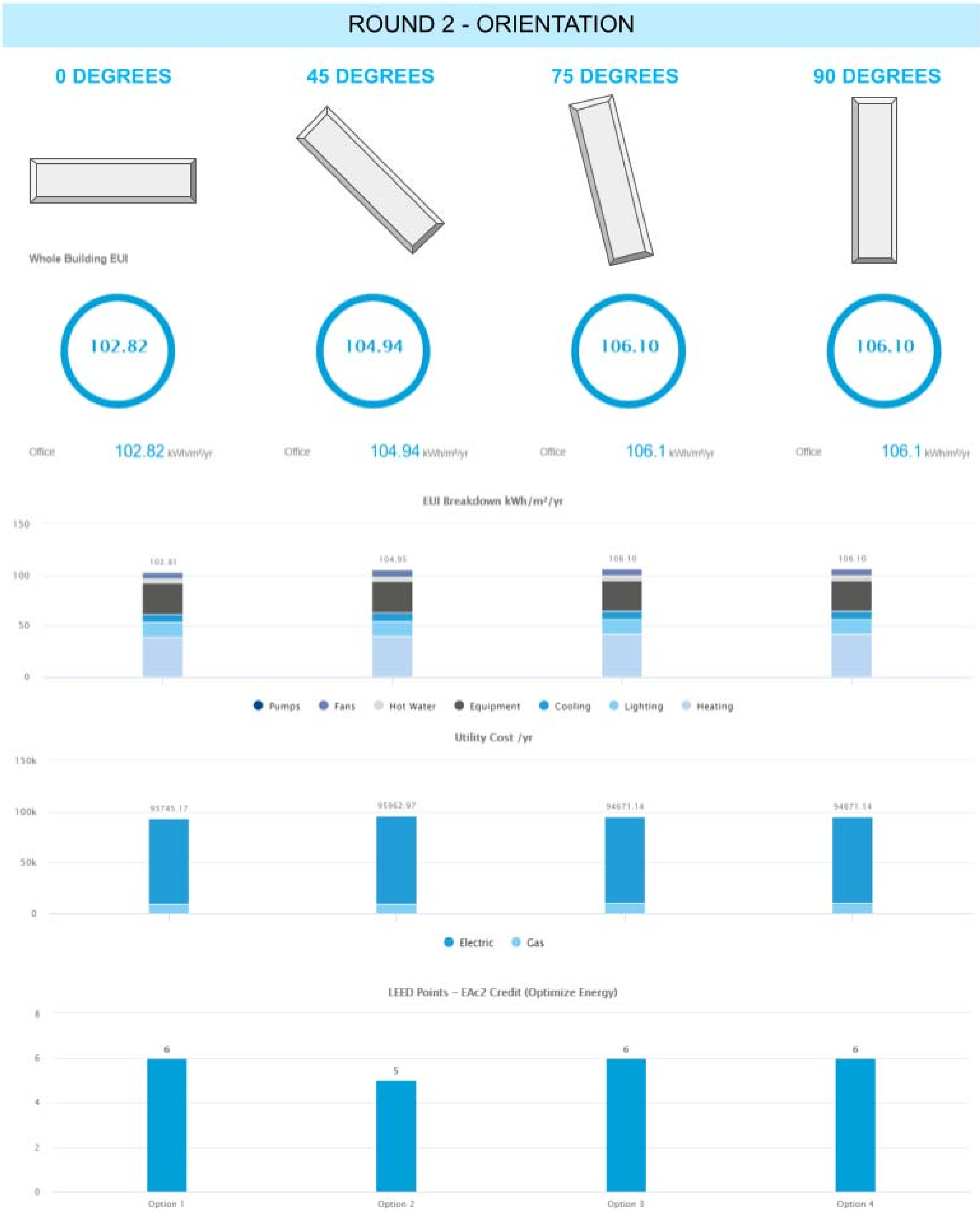
EXHAUST AIR RECIRCULATION PERCENTAGE
↘ EUI
↘ UTILITY COST

DOMESTIC HOT WATER GENERATION SYSTEM
↘ EUI
↘ UTILITY COST

ENERGY GENERATION
↘ EUI
↘ UTILITY COST
↗ LEED

MORE SUBSTANTIAL LESS SUBSTANTIAL


ROUND 1 - SHAPE FINDING
Floors
20
9
9
7
Total Area
8835 sqm
8885 sqm
8640 sqm
8400 sqm
Whole Building EUI
134.24
124.52
116.42
102.82
Office 134.24 kWh/m²/yr
Office 124.52 kWh/m²/yr
Office 116.42 kWh/m²/yr
Office 102.82 kWh/m²/yr
EUI Breakdown kWh/m²/yr
Heating
Equipment
Hot Water
Cooling
Fans
Lighting
Pumps
Utility Cost /yr
Gas
Electric
LEED Points – EAc2 Credit (Optimize Energy)
Option 1
Option 2
Option 3
Option 4

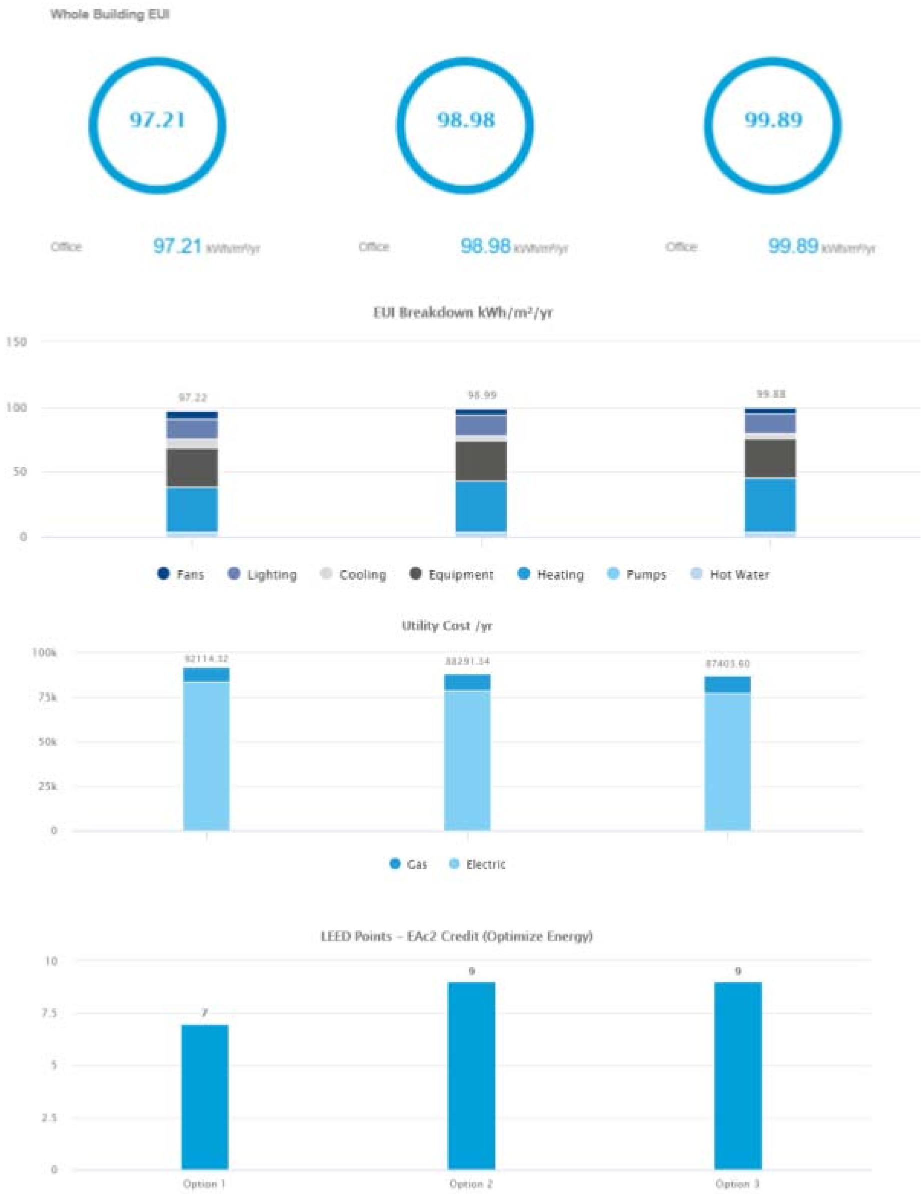

ROUND 2 - ORIENTATION
0 DEGREES
45 DEGREES
75 DEGREES
90 DEGREES
Whole Building EUI
102.82
104.94
106.10
106.10
Office
102.82 kWh/m²/yr
Office
104.94 kWh/m²/yr
Office
106.1 kWh/m²/yr
Office
106.1 kWh/m²/yr
EUI Breakdown kWh/m²/yr
150
100
50
0
102.81
104.95
106.10
106.10
Pumps
Fans
Hot Water
Equipment
Cooling
Lighting
Heating
Utility Cost /yr
150k
100k
50k
0
95745.17
95962.97
94671.14
94671.14
Electric
Gas
LEED Points – EAc2 Credit (Optimize Energy)
8
6
4
2
0
6
5
6
6
Option 1
Option 2
Option 3
Option 4


ROUND 3 - GLAZING RATIO (WWR)
35%
45%
55%
65%
Whole Building EUI
98.05
102.82
110.39
116.90
Office 98.05
Office 102.82
Office 110.39
Office 116.9
EUI Breakdown kWh/m²/yr
Fans
Heating
Hot Water
Pumps
Cooling
Equipment
Lighting
Utility Cost /yr
Gas
Electric
LEED Points - EAc2 Credit (Optimize Energy)
7
6
4
3
Option 1
Option 2
Option 3
Option 4


ROUND 4 - GLAZING DISTRIBUTION
EVENLY
NORTH 50 SOUTH 50
NORTH 60 SOUTH 40
NORTH 70 SOUTH 30
Whole Building EUI
98.05
97.21
99.82
100.35
Office 98.05
Office 97.21
Office 99.82
Office 100.35
EUI Breakdown kWh/m²/yr
150
100
50
0
98.06
97.22
99.83
100.35
Equipment
Pumps
Heating
Cooling
Lighting
Fans
Hot Water
Utility Cost /yr
100k
50k
0
92413.41
92114.52
93347.20
94042.24
Electric
Gas
LEED Points - EAc2 Credit (Optimize Energy)
7.5
5
2.5
0
Option 1
Option 2
Option 3
Option 4

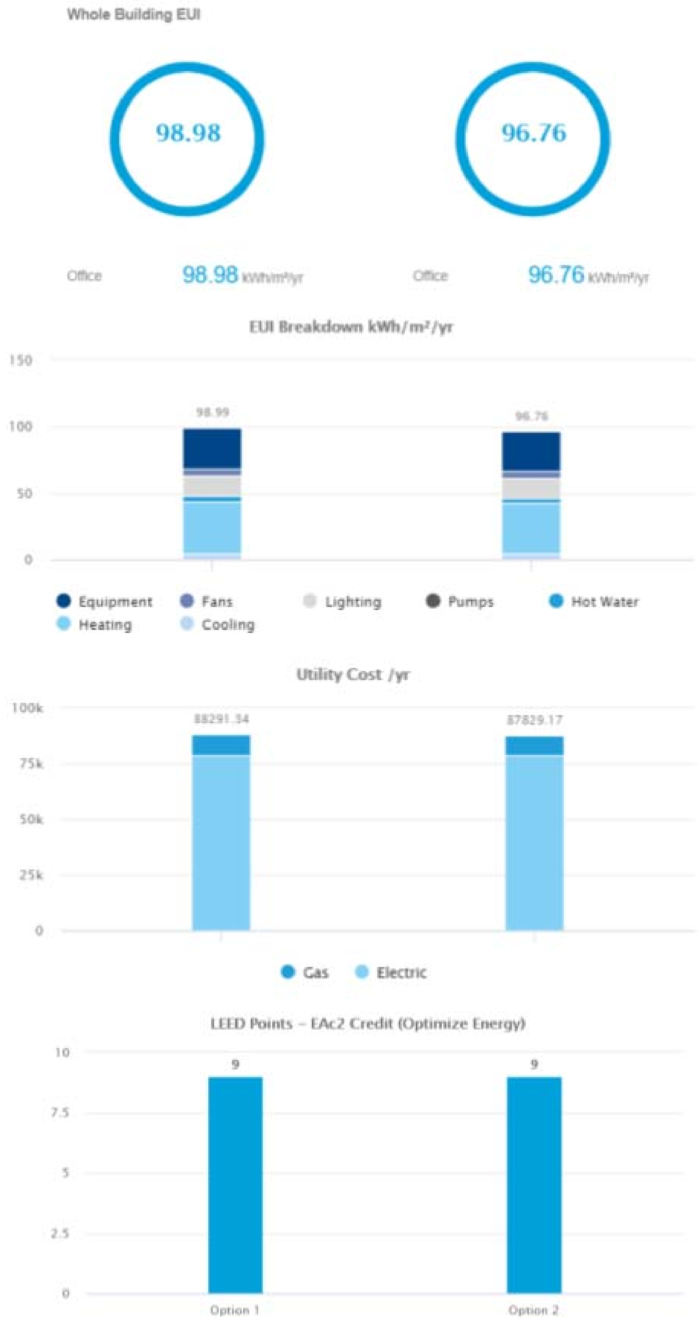
ROUND 5 - SHADING

NO | **INTERNAL** | **EXTERNAL**



ROUND 6 - HEAT RECOVERY

NONE RUN AROUND COIL, NO PIPES

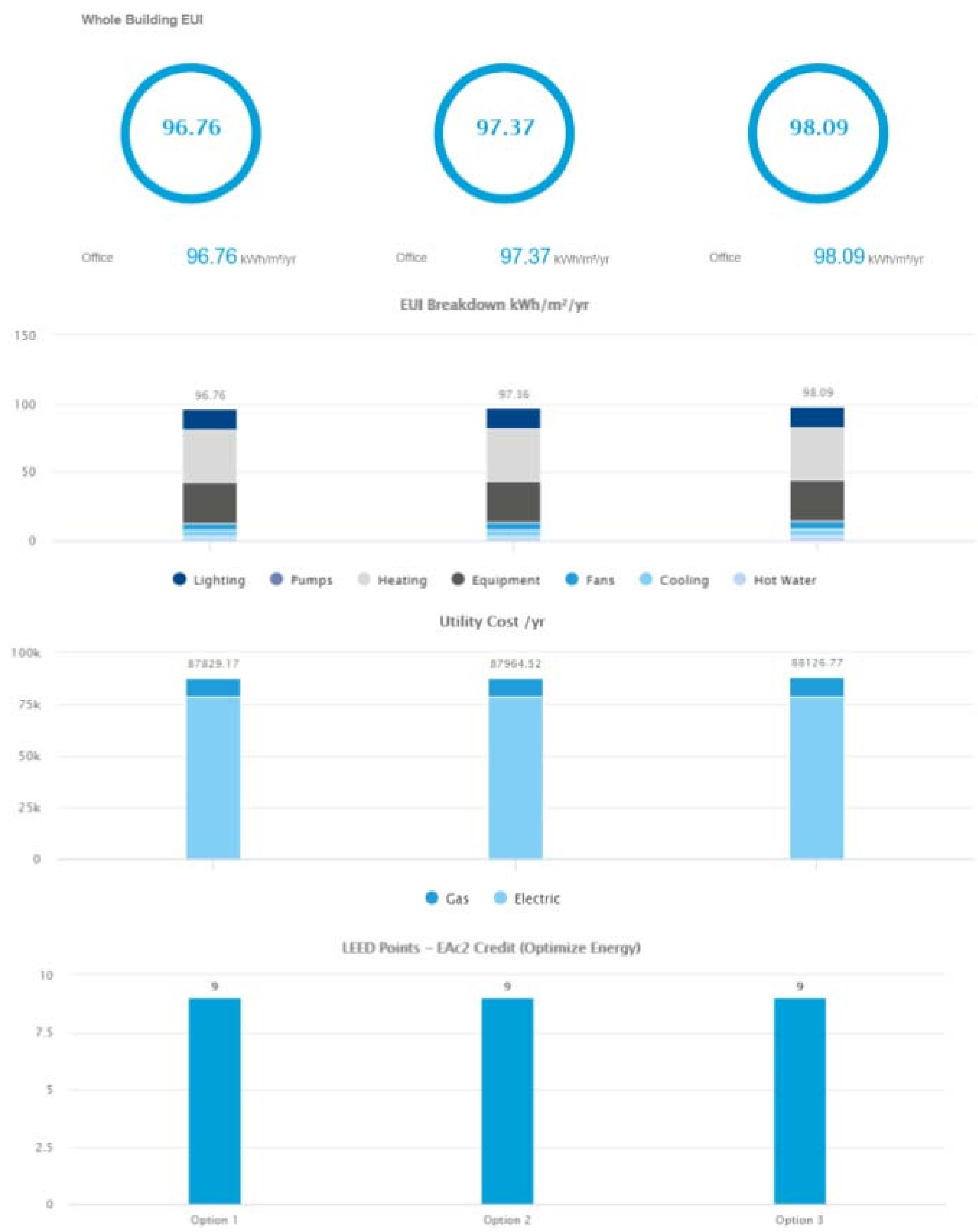


ROUND 7 - EXHAUST AIR RECIRCULATION PERCENTAGE

NONE 40% 60% 80%

ROUND 8 - DOMESTIC HOT WATER GENERATION SYSTEM

VR-BOILER | **GAS-BOILER, HR-BOILER** | **CO-GENERATION**



ROUND 9 - ENERGY GENERATION

NONE 400 m2 ROOF