ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

BUILDING PERFORMANCE SIMULATION IN DESIGN PHASE: A CASE FOR CONSTRUCTION CONSULTANTS IN ADDIS ABABA

By

Michael Teshome Tekleyohannes

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University
in Partial Fulfillment of the Requirements for the Degree of Master of Science
Civil Engineering (Construction Technology and Management Stream)

Advisor: Abraham Assefa Tsehayae (Ph.D.)

May 2022

ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

Building Performance Simulation in Design Phase: A Case for Construction Consultants in Addis Ababa

Michael Teshome Tekleyohannes

May 2022

Approved by Board of Examiners

Abraham Assefa Tsehayae (Ph. D.)		07/08/22
ADVISOR	**SIGNATURE**	**DATE**
Biruktawit Taye (Ph. D.)		July 11, 2022
INTERNAL EXAMINER	**SIGNATURE**	**DATE**
Aychiluhum Sileshi		July 11, 2022
EXTERNAL EXAMINER	**SIGNATURE**	**DATE**
Mebruk Mohammed (Dr.-Ing.) Dean, School of Civil & Environmental Engineering		
COMMITTEE CHAIRPERSON	**SIGNATURE**	**DATE**

Addis Ababa University Addis Ababa Institute of Technology Director of Postgraduate Program

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been submitted nor presented for a degree at any other university. All sources of materials used for this thesis have been duly acknowledged.

Name: Michael Teshome Tekleyohannes

Signature: ____________________________

Place: Addis Ababa University

School of Graduate Studies

Addis Ababa Institute of Technology

School of Civil and Environmental Engineering

Date: May 22nd, 2022

DEDICATION

I want to dedicate this thesis to my late mother, Etenesh Zeleke, and my father, Teshome Tekleyohannes.

ACKNOWLEDGMENTS

Without whom nothing would be possible, I would like to thank God Almighty for his endless blessing and courage throughout my journey.

I would like to express my utmost and heartfelt gratitude to my advisor Dr. Abraham Assefa Tsehayae, for his invaluable support and guiding me throughout this project. I am grateful for his thorough, detailed review and consultations throughout this thesis work.

A special thanks to the Ethiopian Roads Authority (ERA) and Addis Ababa Institute of Technology (AAiT) for their collaborative efforts in making this Master's program possible, sponsoring my studies, and financing this research.

A debt of gratitude is owed to Mr. Bisrat Kifle, Mr. Daniel Getachew, and Mr. Kaleab Teshome for allowing me to pick their thoughts and get insight regarding this thesis, Mr. Aychiluhum Sileshi, and the professionals at the Ethiopian Construction Project Management Institute for their contribution, officers at Addis Ababa City Administration Construction Permit and Regulatory Authority for providing the data required to carry out this research. I would also like to express my gratitude to all of the professionals who took the time and effort to complete the questionnaire for this study, which are far too numerous to list here.

Finally, I would like to thank my entire family and friends for their continuous support, which has sustained me this far. I am indebted to you all.

ABSTRACT

Building performance analysis at the design stage enables assessing the building's performance and the variables that influence it. Simulating the performance of a building by visualizing how the building will react in response to excitation in a virtual environment provides designers and respective stakeholders vital information in the decision-making of buildings.

Nonetheless, a common practice in Ethiopia indicates that an emphasis is placed on how the building appears and is constructed in the project's design phase rather than how the building will accomplish its intended function and performance requirements. Despite the longevity of buildings, analysis of how the building will operate and perform its intended function is seldom.

This research aims to study the existing practices of building performance simulation for buildings in the design stages for the case of consultants in the architecture, engineering, and construction industry of Addis Ababa. The research design employed a questionnaire as a data collection tool. It gathered information from consultants about their approach to design, their tools, use of building performance simulation tools, consideration of uncertainties in their design, and sustainability approaches. For further validation, semi-structured interviews and documentation reviews were used for the case study analysis.

It is found that there is a disparity and underlying lack of understanding of building performance fundamentals and analysis methods. For existing simulation practices in building projects in Addis Ababa, it is found that local consultants do not do them. Moreover, with the infancy of BIM practices in the city’s consultants, capitalizing on the possible BIM-based building performance simulation of buildings is not foreseeable under current circumstances.

As a result, this research recommends essential education and training regarding building performance to realize its potential in developing buildings with improved performance and applicable standards and rating systems for sustainability in the local context.

Keywords: Performance-Based Design, Building Information Modeling, Building Performance Simulation, Sustainability

Contents

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

CHAPTER ONE

INTRODUCTION

1.1. Background

The construction industry has continuously evolved from the days of building with brick and hand-made designs. Throughout the history of civilization, humans developed the tools to construct structures to fulfill a specific need or service. These structures included buildings for worship, commerce, transit, dwelling, etc.

Going back to early human development, humans have dwelled in caves, in burrowed stones for specific requirements and importance; shelter and protection from the elements. Humans have excelled in further development and built buildings throughout continents. Some examples of the many structures built, as depicted in figure 1.1, include the hewn Rock churches in Lalibela in Ethiopia (12^{th} century AD), Chichén Itzá in Mexico (7^{th} – 8^{th} Century AD), Acropolis in Greece (5^{th} Century BC), the Caves of Petra in Jordan (4^{th} Century BC) and many examples. These structures are said to have been built as a form of star representation in astronomical alignment, a stronghold against foreign occupiers, temples of worship, and protection from the elements. These early buildings have socioeconomic significance for their realization's effort, purpose, and contribution. For whatever purpose these structures and many other buildings were constructed, they have been made of a quality that has enabled them to last through the test of time. These buildings are labeled as early high-performance buildings (De Wilde, 2018).

Whether they have addressed it consciously or not, humans have been concerned with the performance of structures. The purpose and requirements these buildings have to fulfill are essential. In his book, De Wilde defines building performance as being related to either a building as an object or a building as a construction process with three main views; engineering, process, and aesthetics. These three views concern how well a building performs, how well the construction process delivers the buildings, and the success of the building as a form for presentation or appreciation.

Figure 1.1 – Lalibela (Saliko, 2018) [top left], Chichen Itza (Daniel Schwen, 2009) [top right], Acropolis (Steve Swayne, 1978) [bottom left], Petra (Bernard Gagnon, 2010) [bottom right]

With cities' increased population and urbanization, further infrastructure development is required. A research done by the United Nations Department of Economic and Social Affairs (UNDESA) in 2018 states that 55% of the world’s population resides in urban areas expected to increase to 68%. In this data, 90% of the population growth is projected in Africa and Asia. Despite the contrast of the African population (57%) living in urban cities compared to the rest of the world, the number is expected to increase in the coming decades. With this, the urban density is expected to increase as well. The energy consumption is expected to increase substantially to meet the projected population growth. Given the limited resources available, it is also imperative that the proposed buildings for construction be sustainable, cost-effective, and enhance human well-being.

In many countries, Ethiopia included, the construction industry is a significant part of the economy; the country’s Gross Domestic Product (GDP), employment rate, and trade balance. Since 2012, the value-added to Ethiopia’s GDP has increased significantly. According to the World Bank collection of development indicators, Ethiopia's industry (including construction) value-added percentage of GDP was reported to be 23.11%. A large workforce and significant budget are allocated to this industry to develop various infrastructures. Therefore, the expectation of stakeholders in the sector must be met to minimize the performance gap. This concept will be discussed in a later chapter.

Within the lifespan of a building, performance varies with time, with a progressive increase at the start and a gradual decline after the facility is in use. Through restoration and maintenance, the functional performance of the building can be brought to its initial level. These buildings will lose their performance level with rapid degradation with extended exposure to the climate and its elements and the passage of time. The speed with which buildings lose their performance value depends on the engineering quality and construction process.

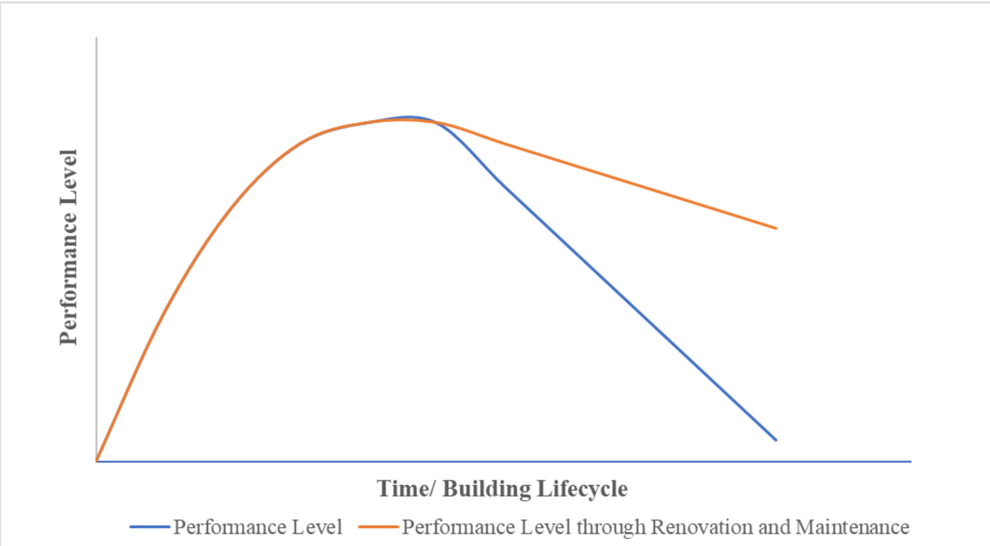

Figure 1.2 – Building performance level with respect to lifecycle (Adopted from De Wilde, 2018)

The project's design stage tends to influence, for better or worse, the project's short- and long-term success of the project and the performance of the building. A time to implement the best solutions for efficient, better performing, and sustainable buildings is during the design stage, where the cost to implement changes is the lowest.

Evaluation of building performance helps express how well the building is carrying out its intended function. Key performance indicators include energy efficiency, thermal comfort, indoor air quality, and lighting.

The remainder of this research will establish how the performance of a building in terms of crucial parameter indicators is measured and analyzed and how it can contribute to the improvement of buildings.

1.2. Statement of the Problem

The design approach to buildings in the Architecture, Engineering, and Construction (AEC) industry of the country focuses mainly on the stakeholder's envisioned requirement and aesthetics with the architectural aspect, the integrity of the structure to withstand imposed loads, and the services installed with respective engineering systems such as plumbing, ventilation, lighting, and other systems depending on the type of building. In conclusion of this, an estimation of cost and material is established.

More emphasis during the design phase is given to how the building looks and how it is constructed—with most practices in the country, predicting how the buildings will perform with the performance requirements during design stages is not given much consideration. In his research on Building Information Modeling (BIM) in improving building design and process, Getachew B. (2016) states that the critical assessment information about a proposed design, including cost estimates, energy-use analysis, and structural detail, is done last when it is too late to make meaningful changes. Analyzing how the building will operate and perform its intended function is seldom.

Running simulations on buildings and analyzing their performance during the early stages of design provides the design team with practicable knowledge about how well the building fulfills its functions. Therefore, it is essential to consider the performance of the building through building performance simulation from various measurement parameters such as energy use, thermal heat and comfort, air quality, acoustics, and so on. A lack of attention to a building's performance makes it more unfavorable to ensure comfort, user and tenant satisfaction, and an awareness of the building's influence on the environment.

1.3. Research Questions and Hypothesis

The hypothesis for this research is as follows;

"There is a significant gap of understanding in building performance analysis in the AEC of the country and utilization of building performance simulation tools. Its practice is not fully understood and limited to few intrinsic options."

To study the problems identified, the following questions are stated for the study

i. What is the current practice with regards to building performance?
ii. What is the extent of awareness regarding building performance analysis and simulation and the tools utilized?
iii. How will performance simulation benefit buildings' design, construction, and operation?
iv. Which key stakeholders in the AEC can influence incorporating building performance simulation, and how will this benefit the industry?

1.4. Brief Methodology

This research has taken primary data sources through semi-conducted interviews and a questionnaire and secondary data sources through a literature review of journals and publications. Many publications were used as an essential tool in studying the concept of building performance analysis and its potential, challenges, and current practices with different types of performance quantification.

The data analysis method included a descriptive statistics method using a frequency distribution approach where tables and charts were used for data visualization. Further validations of the qualitative research were based on four industry case studies selected through purposive sampling regarding building design described briefly.

- Case study for Hidassie Telecom S.C. Headquarter building,
- Case study for Addis Ababa City Library building,
- Case study for Meskel Square and Palace Heritage underground parking building,
- Case study for Center of Excellence for Sustainable Construction Engineering and Management building.

1.5. The Objective of the Study

1.5.1. General Objectives

The main objective of this research was to study the practices of building performance analysis through simulation by consultants in Addis Ababa in the initial stages of design to predict the performance of the building for decision making.

1.5.2. Specific Objectives

The specific objectives of this research included

i. Study the principles, measurements, and types of building performance analysis,
ii. Study the concept of sustainability with building performance,
iii. Study the challenges of building performance simulations,
iv. Study the potential of Building Information Modeling (BIM) based building performance analysis/simulation

1.6. Limitations of the Study

The interaction between a building as a system and its functions determines a building's performance. As briefly stated in the introduction, the performance attribute of a building is dynamic and changes throughout the life cycle of buildings illustrated in Figure 1.3.

Clarke (2015) mentions a need for further efforts towards positioning in the design process, abstracting building performance design problems, and developing performance criteria, metrics, and project performance assessment. Due attention here is crucial as this is the stage where buildings and their performance are emanated. The following points bind the scope of this thesis:

- Building performance is studied in only the design phase of buildings,
- The geographical study area is bound to the city of Addis Ababa,
- Consultants who are registered and licensed under the Addis Ababa City Administration Construction Permit and Regulatory Authority and operating under the 'Building' category.

The following are limitations of this study:

- Limitations in previous research done about building performance in Ethiopia's AEC industry context,
- The infancy stage of BIM implementation in the country, i.e., conventional practice (without BIM)
- Data collection is solely done through questionnaire,
- Due to the selection of non-probabilistic sampling, i.e., quota sampling, the extent of representation of the sample to the overall population may be subjective.

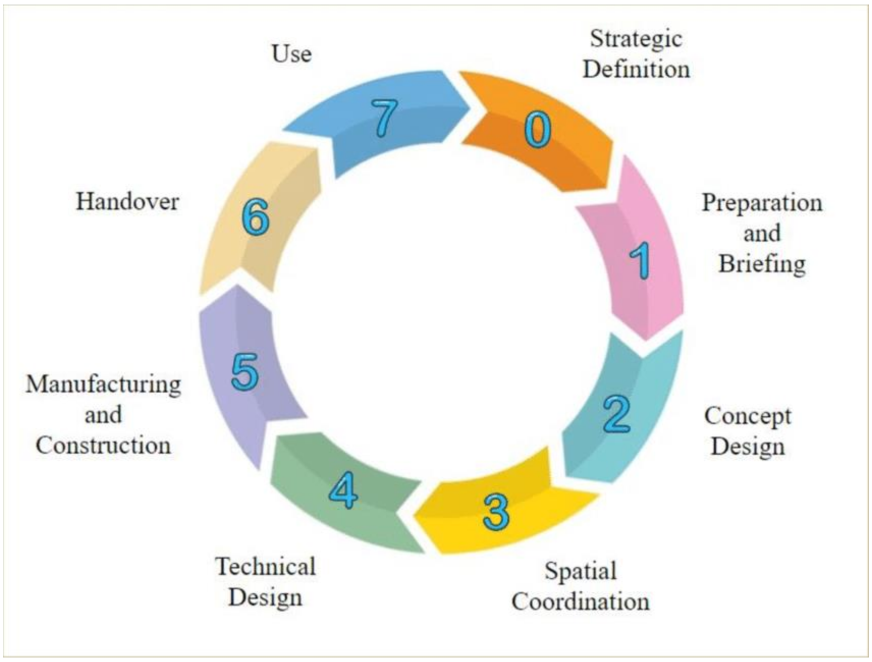

Figure 1.3 – Building lifecycle, (Alani et al., 2020) (Adapted from RIBA 2020)

1.7. Research Significance and Beneficiaries

The significance of this research is to observe building performance practices and test the research hypothesis. Building performance plays an essential role in the architecture, engineering, and construction industry in which prominent performance aspects such as energy use modeling and efficiency, thermal comfort, and building sustainability assessment for future infrastructure development.

The construction sector is a significant part of Ethiopia's development in which key stakeholders invest their resources. Entrepreneurs, owners, and developers can benefit from saving operating costs and improving comfort conditions and dwelling conditions. Architects, designers, and engineers can significantly impact the industry by creating an efficient and sustainable approach to designing buildings. Regulation authorities, too, can influence the performance of buildings through set standards to be achieved in the construction of buildings.

Overall, joined efforts among the stakeholders can significantly aid in achieving one of the four strategies of Ethiopia's Climate Resilient Green Economy (CRGE) in the use of appropriate advanced technologies in the industry, transport, and buildings on a local scale and achieve one of the Sustainable Development Goals (SDG) (The 2030 Agenda for Sustainable Development) making cities and human settlements inclusive, safe, resilient, and sustainable in the global scale.

1.8. Organization of the Study

This research work is organized into five chapters. The following components will briefly establish how each chapter is constructed to achieve the research objective.

Chapter 1: Introduction – This chapter will include a quick introduction, a statement of the problem, general and specific objectives, a research question based on a formed hypothesis, scope limitations, a brief methodology, and the importance of the research.

Chapter 2: Literature Review – This chapter examines the literature on the research topic and seeks to provide a theoretical context and framework for the study.

Chapter 3: Research Methodology – The methods and approaches used to find, select, process, and analyze information are detailed. It will clarify how data was acquired or created and how it was analyzed.

Chapter 4: Analysis and Discussions – This chapter presents the results and findings of the research and discusses them in detail.

Chapter 5: Conclusions and Recommendations – The research closes with this chapter. It summarizes and explains the findings of the study's conclusions and suggestions.

Finally, references and appendices for the research are included at the end of this thesis.

CHAPTER TWO

LITERATURE REVIEW

2.1. <u>Building Performance</u>

Oxford Dictionary defines a building as a structure with a roof and walls or the action or trade of constructing something. On the other hand, performance is defined as ‘an act of presenting a play, concert or other forms of entertainment: the action or process of performing a task or function: or a task or operation in terms of how successfully it is performed.’

Several definitions of performance have been given with the utilization of different terminologies. International Council on Systems Engineering (2015) defines the performance of any system as a quantitative measure characterizing a physical or functional attribute relating to the execution of the process, function, activity, or task. These characteristics include quantity (how many or how much), quality (how good), responsiveness (how often), and readiness (when under what conditions). Building performance is defined by Almeida et al. (2010) as the behavior of buildings as a product in relation to their usage. Foliente et al. (1998) define building performance as non-performance, which the authors describe as failing to meet a specified performance level. A clear definition of building performance is given by De Wilde (2018) in his book Building Performance Analysis as follows.

“Building performance is a concept that describes, in a quantifiable way, how well a building and its systems provide the tasks and functions expected of that building. Requirements may stem from three main views: an engineering view of buildings as an object, a process view of building as a construction activity, and an aesthetic view. Important performance requirements in the engineering view pertain to building quality, resource savings, workload capacity, timeliness, and readiness.”

2.1.1. <u>Building Performance Expression</u>

Expression of performance has a wide range of terminology with different backgrounds. Some of the expressions are stated as follows.

- Key Performance Indicators (KPI) – Originally used in business and organizational goal measurements, they can also measure the process and buildings in the building sector. They represent performance on some quantitative scale that is not necessarily measured physically.
- Return on Investment (ROI) – This profitability metric is a principal tool used to evaluate how well or poorly the investment has performed in terms of the costs for the building. It is a performance measurement metric used to assess a building's efficiency or profitability.
- Performance Indicators (PI) quantify building performance to represent simulation and actual measurement outcomes.
- Measurement of Effectiveness (MOE) looks at a performance from the owner's point of view; this measures success independent of a specific system.
- The Measure of Performance (MOP) is used to quantify overall performance.
- Technical Performance Parameters (TPM) – This helps quantify the performance of elements or subsystems.
- Key Performance Parameters (KPP) capture the crucial aspects of a system.

2.1.2. <u>Building Performance Criteria</u>

There are many qualitative performance aspects of a building, such as its image, character, or success, which are subject to criteria-based judgment that will resolve whether a building is successful (Blyth & Worthington, 2010). A criterion is a concept or a standard by which something may be assessed, usually by comparing observed behavior to an objective or a goal.

Criteria are absolute or relative values on a scale, and objective functions frequently record them to optimize unbiases for the stakeholder or decision-maker. Criteria can be contextualized in various ways, such as a preference for one design over another. Building performance criteria are needed for each of the performance requirements, such as

- Quality requirements – how good a function must be done,
- Resource-saving requirements – how much of a resource can be used or saved,
- Workload capacity requirements – how much capacity is to be provided,
- Timeliness requirements – how responsive the building is or must be,

- Readiness requirements – under what circumstances the building must be available.

For example, a criterion can be set for how much energy, water, and material is used in constructing and operating a building. These criteria define what level of performance is needed and the frame of reference for setting those values.

Baseline, a closely related term to benchmarking, is the lowest point for contrast assessment. The process of establishing performance benchmarks can take a variety of forms. California Commissioning Collaborative (2011) differentiates two approaches toward benchmarking

- ✓ Comparison of performance of the building against historical performance
- ✓ Comparison of performance of building against the performance of similar buildings

Deru & Torcellini (2005) list out the benefits of comparison with a benchmark

- ✓ Compare actual performance with the design intent
- ✓ Compare the performance of specific buildings with others
- ✓ Support building ratings

Benchmarks are often constructed using data collected from existing buildings; however, in situations when the measurement is not possible, simulated performance data can be used to generate a benchmark set. Benchmarking can only be successful and valuable if the compared systems or processes are similar. When it comes to buildings, this implies that they must all be of the same type, for example, when evaluating energy use and being exposed to comparable elements. Dedicated benchmarking programs exist to facilitate building energy performance benchmarking, such as EnergyStar, Cal-Arch, EnergyIQ, FM Benchmarking, MSC, and WegoWise.

2.1.3. Building Performance Requirements

In most cases, performance requirements are criteria that specify how things should perform or the standards they must meet in a particular set of conditions. An overview of the primary requirement types with subcategories derived from Gilb (2005) and SEBoK (2014) is explained as follows.

A. **Functional Requirements** – This specifies what the system must do but does not say how well the function is provided. This appears to be prevalent in construction briefs

- Operational requirements
- Usability requirements

B. **Performance Requirements** – This is concerned with how well a system carries out a function; three subcategories are concerned with performance requirements;

i. Quality requirement – how good the system performs its function

ii. Resource-saving requirement – how much can be used or saved

iii. Workload capacity requirements – how much the system delivers regarding a function.

C. **Design Constraints** – These are limitations to the design solution, such as applicable legislation; there may be necessary to link with other systems, reducing choice space; and there may be a space constraint for the material to be employed.

D. **Condition Constraints** – These are limitations that address the factors of time, location, and event; they are constraints that specify when a structure should be operational or not.

Financial or economic restrictions and the subcategories of the primary requirement types stated above play a part in performance requirements. The budget and resources allocated to a building can influence the performance achieved. Stakeholders in a particular building must have adequate finances to meet the requirements.

2.1.4. Building Performance Indicators

Scholars dealing with building performance use common terms as metrics, measures, and indicators as they seldom use measurand, defined as a quantity intended to be measured. Whether metrics, performance indicators, or measures (parameters) are used, this has to be clear and straightforward for comprehension by all stakeholders. These can be straightforward, such as the illuminance or electricity consumption. In other cases, the attribute can be complex and require decomposition, such as the ‘quality of the system’ which is decomposed of availability, adaptability, and usability.

The terms performance metric, performance indicator, and performance measure are all used to describe the measurement and quantification of performance. Adopting Labate (2016) differentiation, metrics, measures, and indicators are explained as follows.

A. Performance Metrics

Metrics represent how performance changes over time or in different dimensions. This is used to capture measurement methods, values obtained through measurement, and calculated. In the building domain, Hitchcock (2003) states metrics must be predicted or measured in relation to the passing of time and must allow the evaluation of meeting particular performance objectives. He distinguishes metrics between performance metrics used for benchmarking and performance metrics used to express a more specific assessment outcome. Further differentiation is made on metric calculation value and database filtering variables. Metric calculation relates to building size, fuel type, occupancy, and location, whereas database filtering variables relate to HVAC, building use, and ownership concepts. These can be measured at a basic level, e.g., electric power consumption, energy use intensity, intermediate level, for instance, electric lighting power, HVAC, to advanced level such as plant operation hours (Gillespie et al., 2007).

B. Performance Measures

A measure is a standard unit that expresses size, amount, degree, extent, or quality. Performance measures are used in a range of fields. Lee Hansen & Vanegas (2003) acknowledge that cost-based measurements are the most common in the literature but recommend that additional factors such as flexibility, aesthetics, accessibility, constructability, maintainability, engineering performance, and environmental friendliness be considered.

C. Performance Indicators

Performance Indicators are combined values used to measure a specific change's performance, achievement, or impact. International Organization for Standardization (ISO) defines an indicator as a 'measurable representation of the condition or status of operations, management, or conditions' (ISO 14031:2021). Performance-Based Building (PeBBu) project state-of-the-art summary suggests these indicators must be quantifiable, well understood, and amenable to computational analysis to enable performance prediction during the generation of design solutions. Augengroe (2019) frames performance indicators as an agreed-upon indicators that can be quantified using an agreed-upon measurement method.

Despite the distinction between each three terms describing performance, observation is made in building performance which does not necessarily adhere to these definitions, instead of using the terms as synonyms (Keeney & Gregory, 2005). Nonetheless, whatever term performance attributes are given, they must aid in evaluating numerous options and be noted in a clear, straightforward, and unambiguous manner.

2.1.5. Building Performance Quantification and Measurement

Quantifiable targets help the designer judge the building design's failure or success in meeting the stakeholder's needs. Quantifying building performance can be based on testing, calculation using a computational procedure to show required performance, or a combination of both (Foliente G., 2000). Measurement of the performance of a real building is done but quantifying is done by way of simulation for virtual buildings.

There are many terms used to express measurement, as previously stated. Beyond this, subcategories can indicate a specific focus or use. For example, leading indicators monitor tasks/functions' performance that will lead to a result. This relates to a process. In contrast, lagging indicators check whether results are achieved or not. This refers to performance targets.

A requirement for quantification is the use of a properly defined process. This is mainly achieved through technical standards. Some of these standards include the British and European Standard BS EN 15221-7 (2012), the International Organization for Standardization ISO 6241 (1984) and a wide range of building systems and components under the American Society for Testing and Materials (ASTM). Where no standards are available, measurement and quantification need to follow sound science principle, making sure it is valid and accurate.

Consistent performance quantification is seldom straightforward despite a strong foundation of science and the technological domain. There are ranges of assumptions to be made and decisions about performance expression. In the domain of buildings, the phrases verification and validation are used to describe the quality control of experiments. Verification offers objective proof that a system meets its defined requirements and features. In contrast, validation provides objective evidence that the system meets its objectives and stakeholder requirements in the intended operating context.

Regardless of the number of performance variables involved in a given application, the performance approach's effectiveness depends on the building's requirement, the context in which buildings have to meet those requirements, and the predictive measures for modeling the performance of buildings (CIB, 1982).

2.1.6. Types of Building Performance Measurement

Quantification is the expression or measurement of the quantity of something where that quantity is an amount, number, or other property of something measurable. This quantification of performance will serve on how well buildings fulfill requirements. Gilb (2005) defines the measurement in the context of Systems Engineering, which is also suitable for building performance analysis. Through this understanding, there are four approaches in which performance can be quantified: Physical Measurement and Testing, Computer Simulation, Expert Judgement, and Stakeholder Evaluation.

2.1.6.1. Physical Measurement

Physical measurement entails closely examining the actual building or a portion of the building being tested and measured. This strategy's complete control of experiments is unlikely; at best, it will be semi-controlled. Weather and internal and external forces are all uncontrollable. A portion of the structure may be placed inside a lab and extrapolated to the rest of the outside world to counteract this scenario.

Several broad ranges of approaches and instruments are available. Measurement is done for building in German Fraunhofer Institute for Building Physics (GFIBP) in Germany, Building Services Research and Information Association (BSRIA) in the UK and National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), and National Institute of Standards and Technology (NIST) in the United States.

Some of the standards applicable to the physical measurement and testing are established from prominent sources in ISO standards, ASTM standards, CEN standards, NFPA standards, and other organizations such as GB/T, JIS, and ANSI respective to their field of measurement and testing.

Some of the selected physical measurements and tests include

- Air pollutant measurement measures the ambient concentration of ultrafine particles (UFP), black carbon (BC), particulate matter, and trace elements.
- Curtain wall performance-mockup-unit (PMU) testing involves a mock-up of the façade on how it will perform before construction.
- Building system component testing involves testing the building facilities such as HVAC, electrical, and plumbing systems to inspect for product liability investigations.
- Fan pressurization test involves testing whether the establishment of air tightness of the building envelope is maintained.
- Thermography is done using infrared cameras to reveal differences in surface temperatures to indicate whether there is heat loss.
- Indoor climate analysis (IAQ) uses a monitoring platform to measure indoor climate data such as temperature and humidity from an air-conditioned room.
- Sound measurements measure the required acoustic parameters using a sound level meter.

Figure 2.1 – Thermography (top left) (TSI Energy Solutions, n.d.), Acoustics measurement (top right) (Building acoustics measurement set, n.d.), Fan pressurization test (bottom left) (Kim et al., 2012), curtain wall performance mock-up test (bottom right) (Carbary et al., 2014)

2.1.6.2. Computer Simulation

For experimentation, this approach makes use of a model and a computer. A model is created to generate virtual buildings with the right simulation tools. For simplicity, all elements are not fully included in the model. In contrast to actual measurement, computer simulation allows the investigator to specify what we want to happen, select parameters, and repeat the experiment as many times as needed, which is difficult in actual experiments.

While this technique is a practical and widely accessible tool in the industry, it is not without its drawbacks as potential performance gaps with underlying concerns occur, such as basic model uncertainty, tool inadequacies, and training issues. Experts versed in both software and calibration methodologies should perform such simulations.

Some of the simulation tools include

- Acoustical simulation involves simulating noise mapping, sound power determination, and shaping the acoustic profile of part of the building and the whole building.
- Computational fluid dynamics (CFD) simulation aims to investigate the flow and distribution of air within the building.
- Energy consumption modeling is a computer-based analytical procedure that aids in evaluating a building's energy performance and making it more energy-efficient.
- Heat and moisture transfer simulation is used to calculate sensible and latent loads through envelopes of buildings.
- Lighting simulation is utilized to design buildings using artificial and natural lighting.
- Thermal building simulation focuses on the thermal behavior of the building.
- Fire simulation examines interrelationships among fire development, the spread of combustion products, and people movement in residential occupancies.

2.1.6.3. Expert Judgement

This is based on a person's knowledge and skill in a particular field of interest, usually senior academicians or consultants. This is generally done when a simulation isn't an option and there isn't enough data. To consider this method dependable, an independent expert who does not have a vested interest in the subject of performance measurement shall be employed. This method must be carried out with a completely unbiased and transparent process.

This is commonly used to provide judgment and insight on the issues or circumstances of faulty construction or defective system units, whether they have occurred unexpectedly, outside of anyone’s control, or due to sub-par methodology, material, or negligence practice.

2.1.6.4. Stakeholder Evaluation

This approach is made to investigate and quantify the performance of buildings through stakeholder evaluation. Some methods to obtain feedback stated in CIB Publication 64 include a list of surveys, a panel of skilled and uniformed observers, systematic investigation and analysis of specific complaints, measurement of performance in use under conditions that can be accurately measured, and measure the capacity of occupants of any particular building.

This quantification method interacts directly with the building's occupants to obtain feedback about the structure. Surveys, audits, focus groups, and walkthroughs are commonly used. Having a system to collect data on how the development is used and how satisfied users are with it can aid the project's post-construction/commissioning success.

A key parameter in this approach of stakeholder evaluation of building performance is Post Occupancy Evaluation (POE). This method aims to identify the occupant's perceptions and quantify their level of satisfaction. Information and feedback are gathered regarding the facility's performance, identifying gaps that impact operations and highlighting immediate issues that can be addressed and solved.

Building Research Establishment (2019) describes post-occupancy methods that will serve their purpose to the stakeholders of this project, including occupant and client consultation, data quality management assessment, and sustainability and utility audits. This information can help facility operators lower operating expenses and improve user satisfaction. However, there are a variety of procedures that may be utilized to conduct an evaluation. The relevance of the technique depends upon factors such as:

- The level of required detail;
- The level of information available;
- The time and financial resources available;
- The speed with which the research will be completed;
- The skill levels of people who will be conducting the study.

It is essential to involve experienced personnel in the architectural, engineering, and construction industry to work with the facility management team to evaluate how the infrastructure performs post-commissioning and develop a thorough strategy. One should take precautions that stakeholder evaluation is subjective.

2.2. Performance-Based Design

The performance-based design may be generally considered an approach in which building performance becomes the guiding factor in design (Oxman, 2008). Current performance-based terminology uses two widely used terms, user needs and performance requirements.

The key processes in a performance-based design include identifying all relevant user needs and transforming them into performance requirements and quantitative performance criteria using reliable design and evaluation tools to determine whether the suggested solutions meet the stated criteria at a deemed acceptable level.

User needs are mostly quantified in non-engineering terms, transforming them into performance requirements specified qualitatively in physical terms. This is accompanied by performance criteria, the quantitative values of a set of physical factors that serve as the performance indicator (Becker, 2008).

Deru & Torcellini (2004) summarize the approach of a performance-based approach in the following five steps as follows.

- Develop a mission or vision statement - this indicates a declaration of a statement such as “A building designed and constructed with energy efficiency, promoting a healthy and comfortable environment in a cost-effective scheme.”
- Divide statement into topics and subtopics – this includes areas of interest where performance is needed, such as occupant health and environmental loadings, and subtopics such as energy and materials.
- Establish clear and measurable goals – these are established from the objective statement.
- Define performance metrics to measure progress towards reaching the goal.
- Develop and execute a plan for monitoring building performance throughout design and operation.

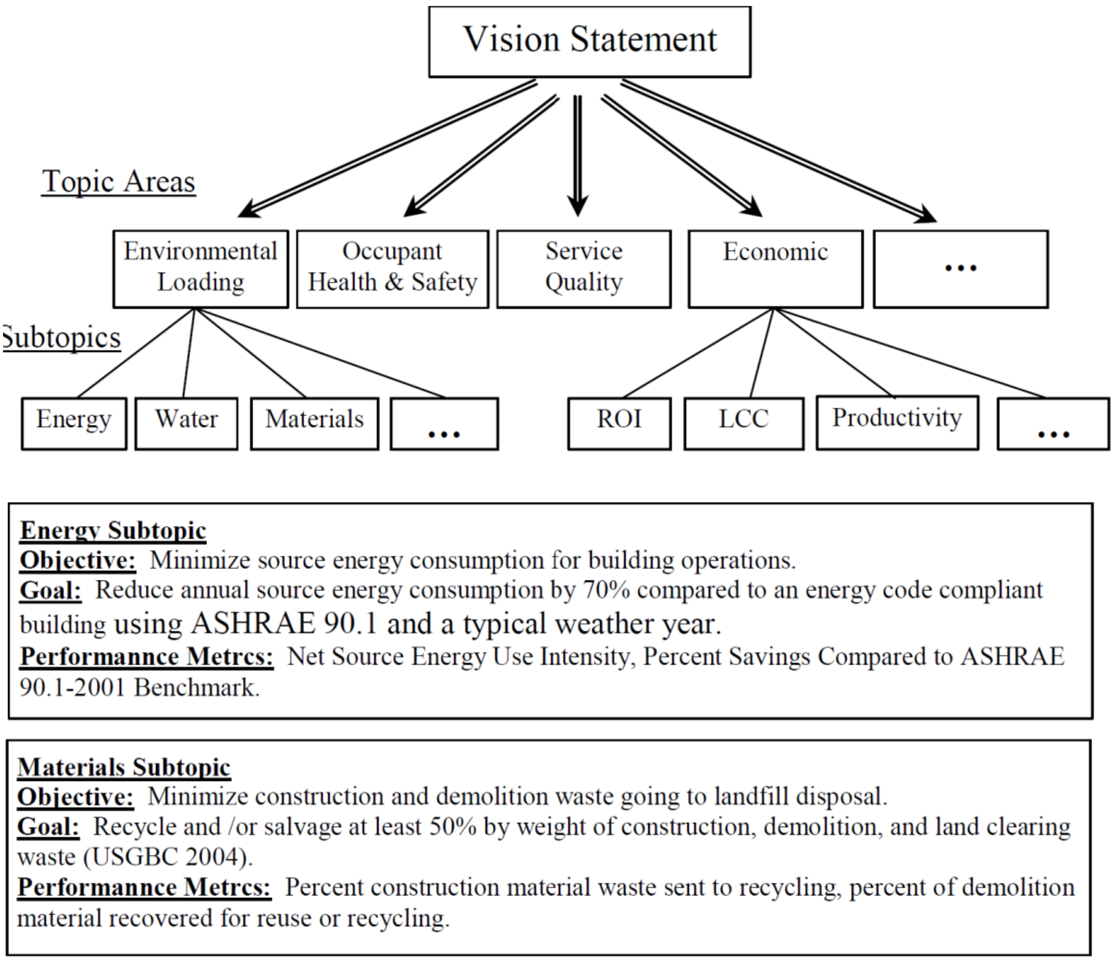

Figure 2.2 – Approaches for performance-based design (Deru & Torcellini, 2004)

2.3. Building Performance Simulation

The terms modeling and simulation are sometimes interchanged, but there is a distinct difference between building modeling and building simulation. A building model is a physical or digital representation, similar to but simpler than a system it represents (Chaib, 2022). Models describe how things work and approximate most of the features of the actual system or building as close as possible.

Simulation is the process of using a model to investigate the behavior and performance of a building system. The whole purpose of simulations is to study the characteristics of a building system by manipulating variables and evaluating a model to optimize the performance (Maria, 1997). Simulation allows users to determine how a system responds to different inputs to understand better how it operates.

Hensen and Lamberts (2019) define building performance simulation as multidisciplinary computational modeling and simulation that provides solutions close to real-world conditions. Quantifying the important aspects of a building or system's required performance is the objective of building performance simulation.

Building simulations are virtual experiments that may be used to compare and evaluate the performance of two or more competing design options. These experiments are mostly done on specialized simulation tools such as whole building, thermal, acoustic, airflow, and ventilation. A computational model is generated on a concept of physical phenomena and objects consisting of input data such as internal gains, building envelope, geometry, and climate to reproduce a real-world situation.

There are hundreds of tools available, both freeware and commercial, with the object of simulating attributes such as energy, thermal, daylight, air quality, and life cycle assessment. Østergård et al. (2016) classify these tools into four categories.

- BPS tools with integrated simulation engine, i.e., tools with their engines such as EnergyPlus, ESP-r, and IES Virtual Environment.
- BPS tools dock to an external engine, such as DesignBuilder, eQuest, and Sefaira.
- Plug-ins for other tools to enable particular performance analysis, such as DIVA for Rhino and Green Building Studio
- Glue scheme, where the tool enables links between building performance simulation and geometrical modeling through graphical programs such as Dynamo and Grasshopper.

2.4. Building Performance Analysis at Design Stages

Throughout the design development stages of a building, i.e., conceptual, preliminary, and detailed/final design, the attributes of building performance analysis and its requirements differ based on the information available at each stage and evolve as much insight is gained. Jin et al. (2019) describe the requirement of building performance analysis and attributes during conceptual design, preliminary design, and the final design, shown in Figure 2.7.

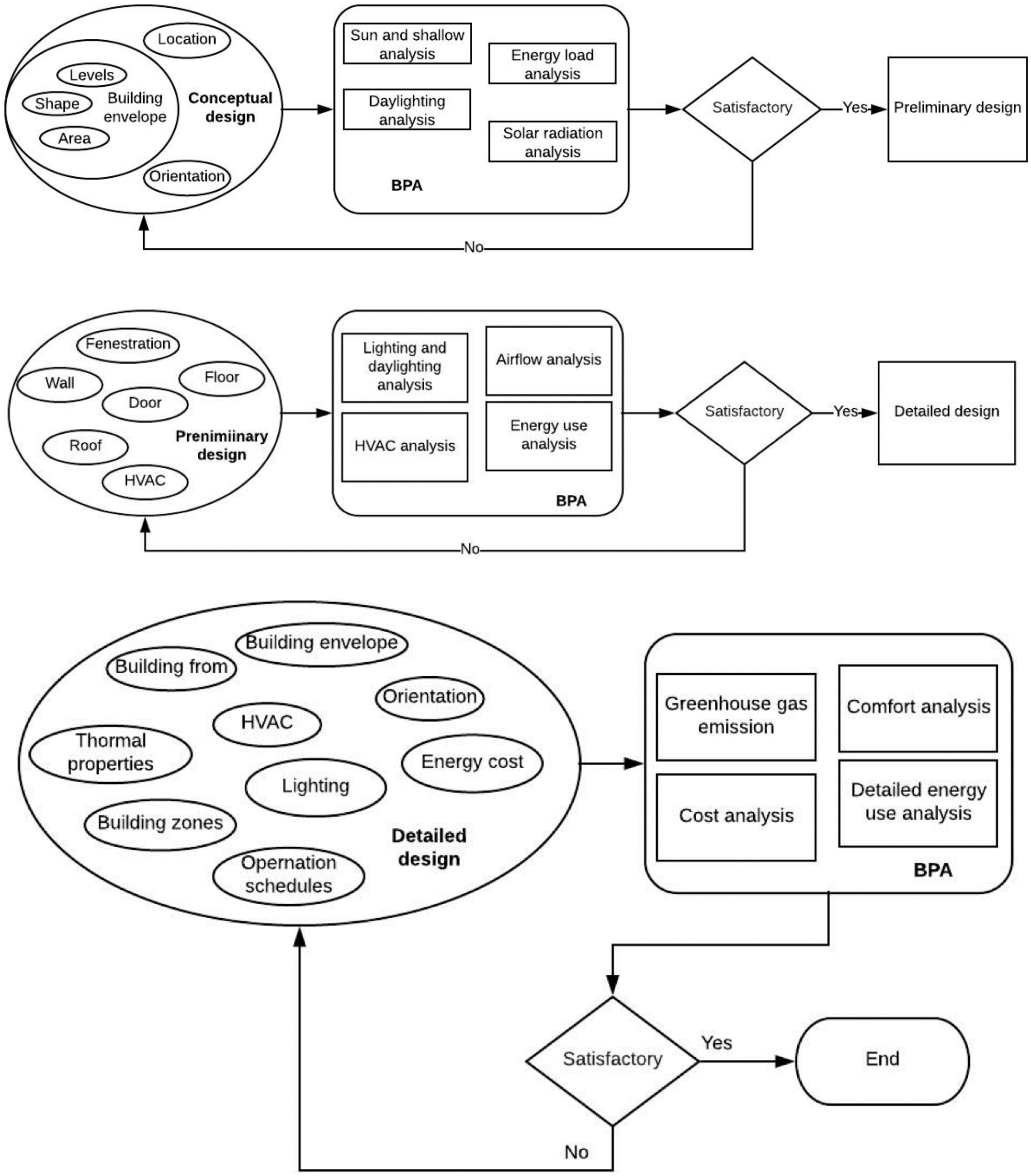

Figure 2.3 – Building performance analysis at the conceptual, preliminary, and detailed final design stage (Jin et al., 2019)

2.5. Building Information Modeling for Building Performance Simulation

BIM is a digital form of construction and asset operations. It combines technology, process improvement, and digital information to improve client and project outcomes and asset operation radically. In her research paper "Design Management using BIM," Tesfaye (2020) further states that BIM is comprehensive information management capable of simulating the design and construction method alternatives beyond a mere

3D graphic representation. Furthermore, the five-level tier of BIM interoperability stated by Grilo & Jardim-Goncalves (2010) is described as follows.

- Communication – better understanding through 3D visualization
- Coordination – Overlap avoidance and clash detection
- Cooperation – supply chain visibility, construction, energy simulation, and cost prediction
- Collaboration – assumes BIM collaborative environment
- Channel – Automatized environment permeated the whole process

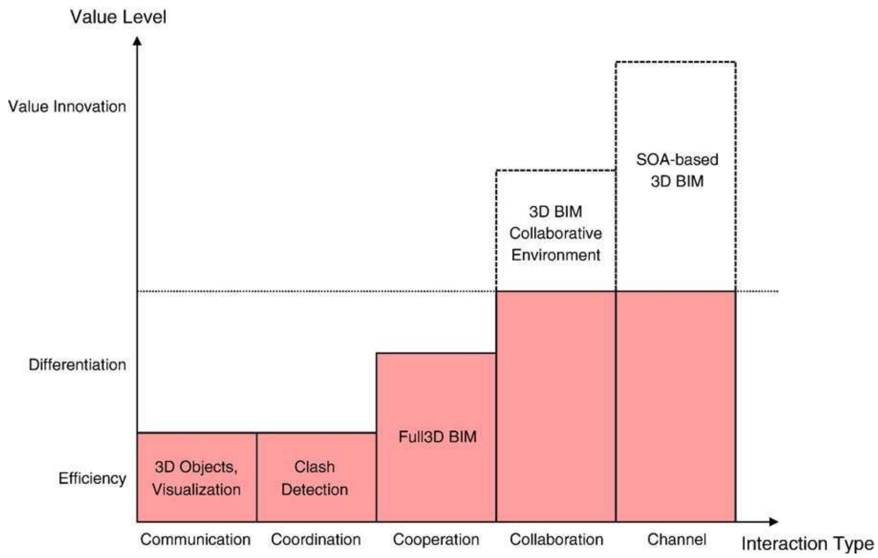

Figure 2.4 – Interoperability of BIM (Grilo & Jardim-Goncalves, 2010)

In practice, the benefit of building performance simulation is that predicting and analyzing building behavior is more efficient and economical than resolving these issues once the building is built. The flow of information needs to be understood to consider BIM as an integral tool for building performance simulation for building design and simulation.

Once data is registered into the building model regarding the physical and functional characteristics of a building, space and information are generated with BIM objects capable of being modified with respect to parameters. (NBIS, 2018) and ISO established Industry Foundation Class (IFC) to facilitate interoperability. The information can be transferred through interoperability to building performance simulation platforms through IFC or gbXML.

Interoperability identifies the need to pass data between applications and for multiple applications to jointly contribute to the work at hand (Eastman et al., 2008). Hemsath et al. (2019) further propose five interoperability methods linking BIM and building performance simulation that architecture, engineering, construction (AEC), owners, and academic researchers use;

i. Intrinsic – often found a limited approach and can only integrate certain aspects of building performance simulation,
ii. Add-on – utilization of customizable plugins to leverage information within BIM for building performance simulation purposes,
iii. Hybrid – platform is linked to an online source for information/simulation/analysis where it flows back and forth between BIM and the online repository. E.g., Sefaira, Green Building Studio
iv. Adscititious – Builds extrinsic information from BIM for building performance simulation. E.g., dRofus
v. Exogenous – This method is outside of BIM and beyond interoperability, where a separate analysis is done for building performance simulation. E.g., eQuest

Different exchange file formats such as IFC and gbXML can be used depending on the analysis objective. For some BIM platforms and tools, direct links to connect them already exist (Carvalho et al., 2019).

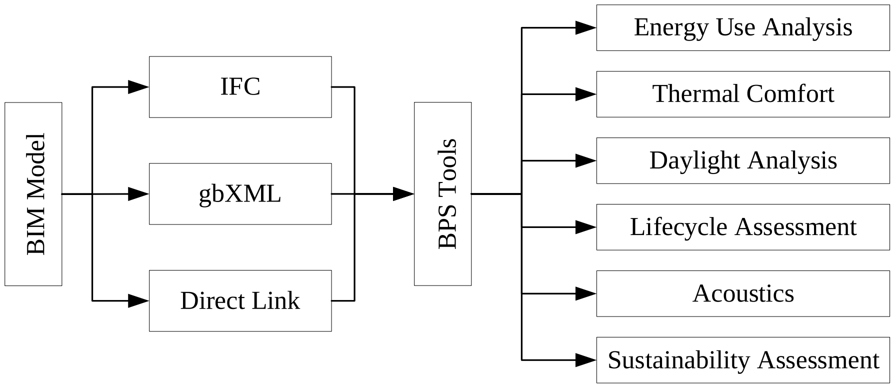

Figure 2.5 – Interoperability of BIM for building performance - Adapted from Bragança et al. (2010) and Azhar & Brown (2009)

Though BIM-enabled BPA is an easy and participatory process that even a non-technical person can use to create results, the quality and depth of the information provided in the model and the needed knowledge base determine the calculation's credibility. Several works done by different researchers (Chen et al.; 2017, Negendahl; 2015, Asl et al.; 2015, Zanni et al.; 2017) indicated in their research that the combination of Building Information Modeling and Building Performance Analysis optimizes building performance in the early design stage.

2.6. Building Performance Gap

A concept one must be careful about is when some buildings do not fully perform as intended, which creates a discrepancy between simulated or predicted performance and measured performance. This is called a performance gap. This is a significant issue and challenge in quantifying building performance through simulation. A few problems that lead to this issue include model uncertainties and training deficiencies. These discrepancies can occur in various areas, including energy usage, thermal comfort, lighting, acoustics, tenant behavior, and actual building use, which may differ from what the design team anticipated. This has a considerable impact on the building's performance.

Sun (2014) states in his dissertation that some discrepancies that may play a significant role in the lack of data regarding

- ✓ Reliable information about input parameters
- ✓ Modeling experience required to conceptualize building specification
- ✓ Validity of model & sub-models in the complicated real world, and
- ✓ Quality assurance of the tool

The viability of modelers' experience plays a role in the building performance gap. Professionals must use extreme caution to prevent 'overselling' the building and its systems, failing to satisfy stakeholders' expectations.

2.6.1. Uncertainty in Building Performance

Uncertainties are circumstances in which unknown knowledge pertains to predictions that have already been made about a system. Walker et al. (2003) define uncertainty as "any deviation from the unachievable ideal of completely deterministic knowledge of the relevant system. These uncertainties can stem from unquantifiable, incomplete, or unobtainable information from partial ignorance (Fenton & Wang, 2006).

There are two sorts of uncertainty in literature: aleatory and epistemic uncertainties. Aleatory uncertainties stem from randomness and are irreducible, whereas epistemic uncertainties stem from a lack of knowledge and are reducible. Uncertainties belonging to the epistemic group arise from many different sources. Hopfe (2009) divides these into three groups caused by physical, design, and scenario uncertainties parameters.

1. Uncertainty in Physical Parameter
    - Physical uncertainties refer to physical properties and characteristics of materials like thickness, density, and thermal conductivity, of a wall, roof, and floor layers. These can be identified with measurement and tests, and considering these uncertainties is related to quality assurance. Here, the designer does not influence the level of uncertainty.
2. Uncertainty in Design Parameter
    - This can be described as design variation that occurs during the planning process. These refer to design variations such as geometry, window size, building massing, and orientation. This is within the control or influence of the designer as the decision-maker determines it. Uncertainties may arise due to a lack of knowledge or anomalies during the planning stage.
3. Uncertainty in Scenario Parameters
    - This differs from physical and design uncertainties in that scenario parameter uncertainties can alter throughout a building's lifetime. These originate from considering a wide range of scenarios in the possible use of a building; usage scenarios such as air infiltration, climate change, and various other unpredictable situations emerging from the building's potential benefits. They are mainly divided into an internal scenario related to building operations or an external scenario caused by weather data/climate change uncertainty.

Including all three uncertainties is essential concerning simulation, performance, and building design. Integration of uncertainties in building performance simulation provides evidence-based decision support in design team meetings.

2.6.2. Uncertainty and Sensitivity Analysis

When conducting a virtual experiment with buildings, the uncertainties of parameters impact the performance outcome significantly. To mitigate this, uncertainty and sensitivity analysis supports the design process by providing additional information on the relevant parameters. It includes information on reliability towards design parameters with respect to the overall design. The primary purpose of uncertainty and sensitivity analysis is to identify the uncertainties of input parameters and the output of the simulation tool.

Uncertainty and sensitivity analysis are closely related activities and have the same purpose of resolving uncertainties but are distinct in scenario assumption.

- Uncertainty analysis is concerned with quantifying the uncertainty in the output or model responses that result from the uncertainty of model input.
- Sensitivity analysis mainly focuses on ranking the importance of parameters relevant to the output uncertainty; how sensitive the outcome variables are to variation of individual input parameters.

Some of the different techniques to perform uncertainty/sensitivity analysis stated by Hopfe (2009), citing Saltelli et al. (2004), include local and global methods, Monte Carlo analysis, screening methods, and variance-based methods.

2.7. Sustainability

As infrastructure development involves the consumption of considerable natural and capital resources and has a long-term impact on the socio-culture of societies, it should be sustainable both in terms of delivery and service. Achieving sustainable infrastructure entails concerted consideration from inception to demolition stages. (Nuramo & Haupt, 2016)

As defined by the UN Brundtland Commission in 1987, sustainability is ‘meeting the needs of the present without compromising the ability of future generations to meet their own needs.’ The triple bottom line model tries to understand how to manage the three components and address how they are connected. As shown in figure 2.8, the triple bottom line depicts the relationship between the three pillars of sustainability and their relationship amongst themselves. Sustainable development requires an equilibrium of all three systems to achieve the optimum outcome. Buildings may only be considered sustainable when all sustainability components are addressed.

Bragança et al. (2010) state three evaluation techniques for sustainability assessment based on the breadth of assistance and assessment systems. These are performance-based design, life-cycle assessment, and sustainable building rating and certification. From the procurement of raw materials through manufacture, consumption, end-of-life treatment, recycling, and final disposal, life cycle assessment examines the environmental elements and potential environmental repercussions throughout a product's life cycle (i.e., cradle-to-grave) (ISO 14040, 2006). A building's life cycle begins before any physical construction activity and concludes when it is no longer functional. The components of a complete building sustainability analysis (BSA) are how a given building is procured and erected, used and operated, maintained and repaired, modernized and rehabilitated, and dismantled and demolished/reused and recycled.

Figure 2.6 – Triple Bottom Line for Sustainability (Chainpoint, 2020)

Sustainable building ratings and certifications are aimed to encourage more environmentally friendly building design, construction, and operation by facilitating greater integration of environmental, societal, functional, and cost issues with other traditional choice criteria. Some examples include the Building Research Establishment's Environmental Assessment Method (BREEAM) in the United Kingdom, Leadership in Energy and Environmental Design (LEED) by the USGBC in the 1990s, and other systems that provided a technique for assessing sustainability. Table 2.1 summarizes the rating certification systems as follows.

Table 2.1 – Summary of rating certification and systems

Certification Tool	BREEAM	HQE	LEED	CASBEE
Year	1990	1996	1998	2001
Country	UK	France	USA	Japan
Developer	Building Research Establishment	Cerway	United States Green Building Council	Japan Green Build Council
Assessment Categories	Management	Energy	Indoor Environment Quality	Quality: Indoor Environment
	Health and Well Being	Environment	Energy and Atmosphere,	Quality: Quality of Service
	Energy	Health	Water Efficiency	Quality: Environment on Site
	Transport	Comfort	Materials & Resources	Load: Energy Features and Innovation
	Water		Sustainable Sites	Load: Resources and Material
	Material		Location and Transportation	Load: Off-Site Environment
	Land Use and Ecology		Innovation in Design	
	Waste		Regional Priority	
	Pollution			
Localized in	Sweden, Norway, Germany, Netherlands	Brazil, Lebanon	Canada, India, Cuba, Italy	
Rating	30 - Pass	Pass	40 - 49 - Certified	BEE - 0.5 ★ Poor
	45 - Good	Good	50 - 59 - Silver	BEE - 0.5 - 1.0 ★★ Fairly Poor
	55 - Very Good	Very Good	60 - 79 - Gold	BEE - 1.0 - 1.5 ★★★ Good
	70 - Excellent	Excellent	80 - Platinum	BEE - 1.5 - 3.0 ★★★★ Very Good
	85 - Outstanding	Exceptional		BEE - 3.0+ ★★★★★ Excellent
Reference to Standards	DIN EN ISO 14040, DIN EN ISO 14044, ISO 21930		ASHRAE 90.1	

Table 2.2 – Summary of rating certification and rating systems (continued)

Certification Tool	Green Star	DGNB	IGBC
Year	2002	2009	2001
Country	Australia	Germany	India
Developer	Green Building Council of Australia	German Sustainable Building Council	Confederation of Indian Industry
Assessment Categories	Management	Ecological Quality	Indoor Environmental Quality
	Indoor Environment Quality	Economical Quality	Energy and Atmosphere
	Energy	Sociocultural and Functional Quality	Water Efficiency
	Transport	Technical Quality	Materials and Resources
	Water	Process Quality	Sustainable Sites
	Materials	Location Quality	Innovation in Design
	Land Use and Ecology		Regional Priority
	Emission		
	Innovation		
Localized in	New Zealand, South Africa	Denmark, Switzerland, Austria, Bulgaria, Thailand	
Rating	10-19p - ★ Minimum Practice	50% - Bronze	0 - 39 - Not Certified
	20-29p - ★★ Average Practice	65% - Silver	40 - 49 - Certified
	30-44p - ★★★ Good Practice	80% - Gold	50 - 59 - Silver
	45-59p - ★★★★ Best Practice		60 - 79 - Gold
	60-74p - ★★★★★ Australian Excellence		80 - 110 - Platinum
	75+ p - ★★★★★★ World Leadership		
Reference to Standards		DIN EN ISO 14025, DIN EN ISO 14040, DIN EN ISO 14044	

Table sources: (Hradil, 2014), (Hamedani & Huber, 2012), (Said & Berger, 2014) (Haute Qualité Environnementale, 2016), (Al-Bakry & Abbas, 2019) (Green Buildings International, n.d.), (Abdullah et al., 2015), (Schuetze et al., 2015), (Indian Green Building Council, 2015)

Preservation of cultural heritage, natural conservation, eco-friendly materials, energy-saving, and quality indoor conditions are the main objectives in the building industry (Tsimplokoukou et al., 2014). Applying sustainable building design principles leads to simpler solutions like smaller mass and energy flows.

Integrating BIM workflow reduces the time needed to do the assessment. A platform that allows for the overlaying and grouping of multidisciplinary designs and information will result in a viable plan for incorporating sustainable measures. This will encourage the development of buildings with higher performance rather than the traditional approach, resulting in a more sustainable environment.

The central aspect of BIM to improve the sustainability level of a project presented by Krygiel & Nies (2008) are

- Building Orientation
- Building Massing
- Daylight Analysis
- Water Harvesting
- Renewable Energy
- Energy Modeling
- Sustainable Materials

A few studies claim the significant benefits of building sustainability assessment in the early stages of the design process. Azhar et al. (2009) state that pre-construction phases, when projects can most benefit from building information modeling, are critical ones. Wong & Zhou (2015) state-building sustainability assessment in preliminary design stages will bring about an efficient, sustainable design.

Despite its potential, some scholars and authors argue the lack of data obtained from BIM platforms and tools for sustainability assessment. They suggest that future platforms be further developed to cover more parameters and aspects of sustainable issues. BIM can become an essential tool for creating more sustainable designs with existing proposals and capacities mentioned (Carvalho et al., 2019).

2.8. Experiences with Building Performance Analysis and Simulation

2.8.1. Sustainability Assessment of DPR Construction Inc.; Sacramento, CA – United States of America (Azhar et al., 2009)

In this research, a feasibility study of BIM's feasibility for sustainability was done on DPR Construction Inc Headquarters in Sacramento, California, USA. Data collection was done through a case study for the construction firm. Building performance analysis was done as the construction firm was seeking LEED® certification and compliance with California's Energy Efficiency Standard for Residential and Non-Residential Buildings, also known as Title 24. The building performance analysis for this project was done in two phases.

I. Phase 1

The tool utilized in this phase was EnergyPro™, a non-BIM software compatible with Title 24. The findings stated that the facility had been estimated with a 20% improvement over Title 24 based on original energy code compliance calculations

II. Phase 2

The goal in phase 2 was to evaluate DPR Construction Inc headquarters LEED® rated facility's performance over time and conduct actual performance vs. designed performance. The tool used was IES Virtual Environment™ for energy analysis, solar analysis, and cost/benefit analysis considering data inputs such as building orientation, HVAC system, and building envelope.

The energy and sonar analysis showed that sun shading devices reduce 19% of building facility surface area, which could further reduce energy costs. Regarding cost-benefit analysis, an amount of $28,000 per year was calculated for energy saving.

They concluded in their findings that there was an annual energy saving of DPR's facilities as a result of building performance analysis. This was realized by the initiation from the client (DPR Construction Inc.) to evaluate the performance over time. It was noted in this research that the BIM-based method saved the company and other stakeholders time and money.

2.8.2. BIM-Based Building Performance Assessment of Emory University; Atlanta, GA – United States of America (Azhar et al., 2009)

The authors have conducted a case study on the Emory Psychology Building with BIM-based performance analysis. They reasoned that BIM was able to reduce the cost associated with traditional analysis while also realizing the benefits associated with energy analysis. Data was gathered through literature review, review of software manuals, and semi-structured interviews with professionals.

The authors' objective was to explore the suitability of BIM for sustainability analysis with specific goals decomposed to the evaluation of three building performance analysis software tools; i.e.

- ✓ Ecotect ™ - This program was capable of analyzing energy, thermal, shading, and acoustics. (This is now a discontinued service from Autodesk.)
- ✓ Green Building Studio - This cloud-based energy analysis service can also do energy/thermal analysis, lighting, shading, and value cost. LEED daylight credit 8.1 is featured here.
- ✓ Virtual Environment - this tool has the same capabilities as Green Building Studio.

Building Information Modeling was used in the early design phase to

- ✓ Determine the best building orientation
- ✓ Evaluate various skin types (curtain wall/masonry)
- ✓ Energy and daylight analysis
- ✓ Create LEED® daylighting credit qualification

The process included a model with BIM applications such as Revit/ArchiCAD, which was transformed into a green building XML file suitable for importation by the simulation tools stated above.

After performing simulations for various types of sustainability analysis and selecting the best suitable tool, analytical analysis was performed. After weighing factors were integrated by BIM and LEED experts, Virtual Environment had a maximum score based on its significance to LEED integration tools, value and cost, and thermal and energy analysis. While the results were not validated against DOE EnergyPlus software, the authors were confident it was within range.

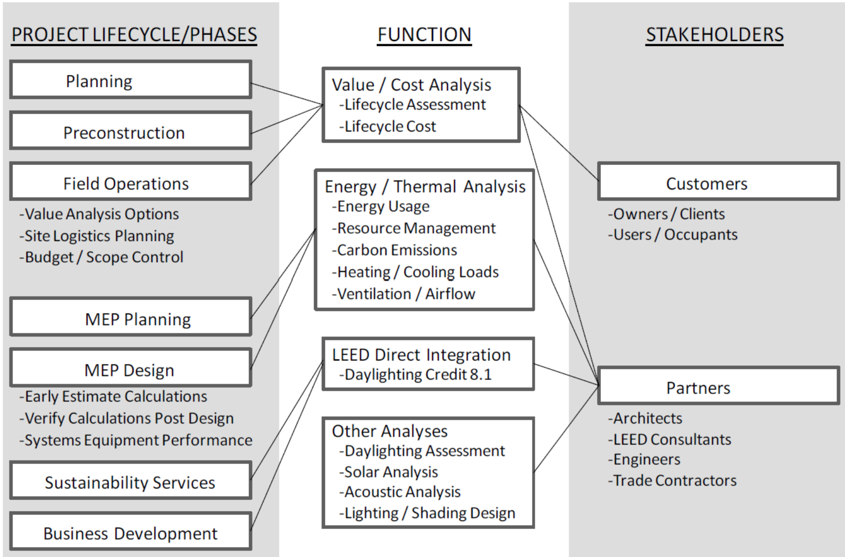

Figure 2.7 – Conceptual framework for BIM-based sustainability analysis (Azhar & Brown, 2009)

2.8.3. <u>Assessment of User Comfort on Commercial Buildings; Addis Ababa, Ethiopia (Melaku, 2016)</u>

This research was done in the effective shading device experiment and the impact of glass façades on user comfort on three distinct buildings; Awash Insurance Company Building, Chelelek Alsam Building, and Debrework Tower, located in Addis Ababa. It was carried out to investigate the effects of radiation on glazed office buildings and the influence of glass façades and shading options on occupants' thermal and visual comfort.

The methodology for this research is briefly described as follows.

- Ecotect and Relux were used in the study by the author as building performance simulation tools to determine the daylight illuminance distributions and daylight factors across the open plane of the spaces within the building.
- The thermal simulation was conducted in internal design conditions and occupancy and operation.

Quantitative data was collected using a lux meter to measure the illuminance of the space within the building and dry-bulb temperature to measure indoor air temperature, respectively.

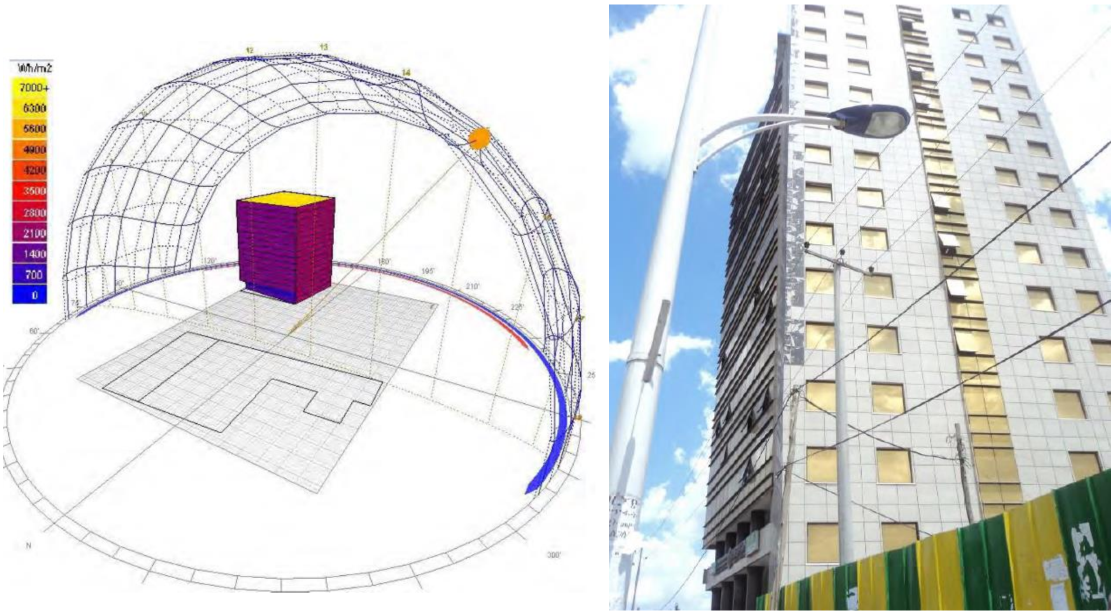

Figure 2.8 – Sun path analysis(left) and existing building (right) of Debrework Tower (Melaku, 2016)

The results of this research showed that

- Out of the three buildings studied, the Awash Insurance Bank building showed a high risk of prolonged discomfort; the Debrework tower came in second.
- Chelelek building resulted in situations on both extremities that were too hot or cold.
- 78.33% of the participants in the subjective evaluation were dissatisfied with the thermal environment.
- 44% of the participants were dissatisfied with the illuminance level.
- The illuminance of the working plane at the central space was 50% lower than what was expected for the Debrework tower.

This research provided an insight into assessing building performance attributes regarding thermal and visual comfort of occupants in the buildings examined in the study. Improving the building performance through a holistic study of the environment, the appropriate geometrical configuration of façades, and investigation of glass material in the local context was suggested in the conclusion of this research.

Figure 2.9 – Proposed façade design for Debrework Tower (Melaku, 2016)

2.8.4. Energy Conserving Design for Commercial Buildings; Addis Ababa, Ethiopia (Teshome, 2013)

In this research, a case study was done on two-sample buildings in Addis Ababa (Beer Garden Hotel building and Yirga Haile Shopping Mall) on the energy-conserving system. The author cited the Ethio Resource Group (ERG) report's forecast that by 2030 the commercial sector will be the most important electricity consumer taking 42% of the estimated total sales, and claimed despite these forecasted data, none of the commercial buildings in Ethiopia have a design that considered any energy efficiency mechanism.

This research intended to introduce an energy-conserving design process and produce commercial buildings that use substantially less energy without compromising occupants' comfort and the building's functionality.

Case studies were conducted on two buildings to demonstrate the prevailing electrical design practice. Data was collected from historical and design data to create the base case profile of the sampled buildings. A spreadsheet was used to organize and calculate required input into the software RETScreen, a tool used for energy management and decision making.

This research showed that a proposed energy-efficient system paired with a Photovoltaic (PV) system resulted in a possible annual energy consumption savings of 30.78% for the hotel and 45.8% for the shopping mall. It was also possible to reduce energy consumption by 25-30% through conservative applications. These numbers could rise by considering optimized energy-efficient design strategies and on-site power generation through PV systems. Building energy-efficient structures are the first step to establishing a sustainable world. Sustainable environments are created by maximizing efficiency and employing renewable energy sources to address issues with energy security, supply, and the environment (Teshome, 2013).

2.9. Challenges with Building Performance Simulation

The dynamic interaction between systems, environment, building, equipment, and people can bring about a high level of health, comfort, and productivity through building performance simulation (Hensen et al., 2004). The authors disclose a few challenges and solutions to each of the corresponding points despite its challenges.

I. Quality assurance – the study mentions the importance of sufficient domain knowledge of buildings and systems paired with verified and validated software. Furthermore, it is essential to use a correct simulation methodology and solve the right equation as accurately as possible. The parameter values registered in the model and which model to use are vital.

II. Sharing developments – This is regarding limitations of a single simulation environment that can cover a whole range of problems at hand. They suggest an open simulation environment to share software development as the best way forward. Four strategies to enable sharing of development cited in their research include,

- Data and process model integration
- Data model interoperability
- Process model interoperation
- Data model and process model co-operation

III. Scope expansion – the researchers disclosed the limitations to building performance simulation in building design projects and the seldom use of building performance simulation for supporting early design phases and alternative design generation. They mentioned that solving this issue would utilize building simulation for conceptual design and design optimization.

The development of computing and technology and the significant contribution by developers have provided several platforms that have solved the barriers of building performance simulation. However, having sufficient domain knowledge of building systems and appropriate utilization of verified software is prevalent.

In summary, some of the challenges faced with building performance are that buildings are one-off products compared to other industries with many stakeholders, necessitating a great deal of effort to achieve common performance goals and objectives. Furthermore, due to the various categories of buildings, such as residential buildings, commercial buildings, hotels, hospitals, and so on, developing a universally applicable list of performance attributes all buildings are expected to fulfill is very difficult. Relevant characteristics of performance for a given building are case-specific. A one-size-fits-all strategy will not be a suitable approach to ensuring building performance. The study of building performance analysis varies and is a complex subject due to these aspects.

2.10. Summary and Gap Identification

The concept of building performance and its practice in the Ethiopian context is a non-existential practice. Despite the potential boom in the development of large-scale construction projects and the possible proven benefits of building performance assessment, its potential is left unsatisfied as a thorough and systematic approach in carrying out performance assessment and sustainability of buildings design stages is far off as it is beset with a vague understanding of the concept and potential unfulfilled use of bootlegged simulation tools.

The practices in the developing world are characterized by diligent efforts and approaches to improve buildings' performance and assure sustainable building development. Legislative frameworks such as the Energy Performance of Buildings Directive by the European Commission and the Environmental Protection Agency (EPA) Building Performance Standards Policy Toolkit in the United States are enforced to improve energy performance and benchmark and reduce energy use and greenhouse effect gas emissions. A myriad of research and development on the concept has helped the AEC industry in their respective countries better understand building performance analysis. Buildings are assessed for sustainability through performance-based design, lifecycle assessment, rating systems, and certification schemes. According to the detailed literature review stated in this chapter, one can realize the potential unexploited benefits in consideration of building performance analysis in building design stages. Building performance analysis and simulation practices are very important to address the environmental, economic, and well-being challenges the built environment faces.

In contrast, these practices have not been adopted into mainstream local practices except for a few academic studies conducted to improve the performance aspects of the building with regards to thermal and user comfort and energy-efficient design. Other than these studies, there has not been comprehensive research on building performance analysis and simulation practices in the country. An underlying cause is linked to education and training, as there has not been developed to ensure the industry access professionals to integrate different aspects and analysis methods. Taking up the task to advance the practice of building performance analysis should not be the sole responsibility of consultants as academic and government institutes should join efforts. Professionals have not fully familiarized themselves with these concepts to fully benefit from them. Therefore, the local consulting firms have a long way to go in exercising and incorporating building performance analysis and simulation tools in their design to bring reliable and applicable results.

This research aims to examine local consultants' current practice regarding building performance analysis and the extent of use in simulation tools. Then with the conceptual gaps identified in this section between research and practice, possible solutions are proposed.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Introduction

The techniques and strategies by which the study's objectives were attained are explained and justified in this research portion. The steps taken to collect all relevant data are described in full. It also details the study's research instruments and strategy. Finally, it discusses sample size, data gathering methods, and the data analysis procedure.

This study's approach consisted primarily of a desk study supplemented with a questionnaire. Various relevant kinds of literature, books, and case studies on the research issue were included in the qualitative research.

The questionnaire was designed and distributed through respective respondents, and Microsoft Excel and Power BI were used to analyze and statistically visualize the response data. A questionnaire was used to obtain information to substantiate the research questions. In addition to the literature review, the questionnaire was used to meet the goals of the planned research. The research findings were used to develop conclusions and recommend the local building sector. The research technique is described in greater detail below.

3.2. Research Approach

3.2.1. Desk Study

The literature review was conducted as a means to provide a foundation of knowledge on the concept of building performance, assessing the practices and trends with building performance and its measurement with virtual experimentation, identify the gaps, pinpoint the area of prior scholarship from research, designing and structuring the research questionnaire and focus points, formulating a conceptual framework, defining the scope of the study, analyzing data for summary and presenting research findings for conclusion and recommendation.

3.2.2. Design and Distribution of Questionnaire and Collection of Data

The questionnaire was created to extract data from the study population and obtain statistically meaningful findings concerning the research subject. The questionnaire can be found attached in Annex 1 of this thesis. The questions were designed on a condition-based scheme where subsequent questions were presented based on the respondent's answers. This was done to improve the accuracy of the primary data. The questionnaire incorporated open-ended and closed-ended questions with nominal and ordinal variables with multiple choices, multiple-choice grids, check box grids, and Likert scale questions.

The population size was a group of consultants in Addis Ababa registered and licensed under the City Administration's Construction Permit and Regulatory Authority of 819 consultants. Those engaged in the building category have been filtered, sizing it down to 732 consultants. Considering the requirements of the Construction Certification Registration Directive No. 648/2021 regarding the capacity of consultants participating in building project's cost, type of project, and professional requirements, Consultants of Grade 1 and Grade 2, are considered in this thesis. The sample size was calculated based on Cochran's formula of sampling a finite population.

The questionnaire generated were distributed through direct messaging and office visits. Discretion of the data provided by responders was communicated and assured before filling out the questionnaire.

The responses to the questionnaire and other primary data collected were evaluated, discussed, and summarized. Following that, conclusions and recommendations were put forward with the support of case studies.

Figure 3.1 – Flowchart for research methodology

3.3. Data Sources

Data for this research included both primary and secondary resources. Primary data resources included;

- ✓ Semi-structured discussions and interviews with architecture, engineering, and construction (AEC) professionals about the current trends in the design process, and awareness of building performance,
- ✓ Information was actively gathered through questionnaire filled out by respondents.

Secondary data sources were publications, literature, journals, books, and case study research in building performance evaluation and analysis.

3.4. <u>Research Instrument</u>

The research used a questionnaire to gather primary data resources.

3.4.1. <u>Structure of Questionnaire</u>

A pilot questionnaire was prepared and tested out on a few industry professionals, specifically two architects, holders of bachelor’s degree and Ph.D. candidate with more than 15 years of experience in building design and three engineers with an average of 12 years’ experience, all three whom have finished graduate school in Masters of Science and Master of Engineering. This was done for clarity, effectiveness, and applicability to the study activity. After the test pilot questionnaire, the final questionnaire was developed using a literature review and observations.

The questionnaire was arranged in five parts, with conditional questioning used to formulate subsequent questions based on the respondents’ answers. The first part was used to categorize entries based on the background and experience of respondents. The second part covered the bases of a design approach for performance. Information for design and extent of awareness of building information modeling and sustainable approaches in building design were covered in the third part. Part four included concepts related to building performance analysis and simulation. The last part aimed to get an overview of buildings' performance gaps and manage the risks of uncertainties of building models.

3.4.2. <u>Study Design and Location</u>

This study falls under the applied descriptive category of research as it aims to solve practical problems. An analytical observational study was chosen based on the problem statement to achieve this study's objectives. The data was then examined using descriptive statistics and frequency distribution, with the results shown in graphs, charts, and statements. The study was conducted in Addis Ababa, Ethiopia.

3.5. Sampling Technique

The sampling method was based on non-probabilistic sampling methods; quota sampling- a tailored sample in proportion to the category and grade of consultants. Data was gathered through convenience and snowball sampling, where participants were selected based on convenience and requested to recruit others for the study who fit the quota. The study population of interest is the collection of registered architecture, architectural and engineering, general and specialized engineering firms subcategorized under building category firms in Addis Ababa, Ethiopia. Figure 3.2 shows a flowchart of the sampling technique.

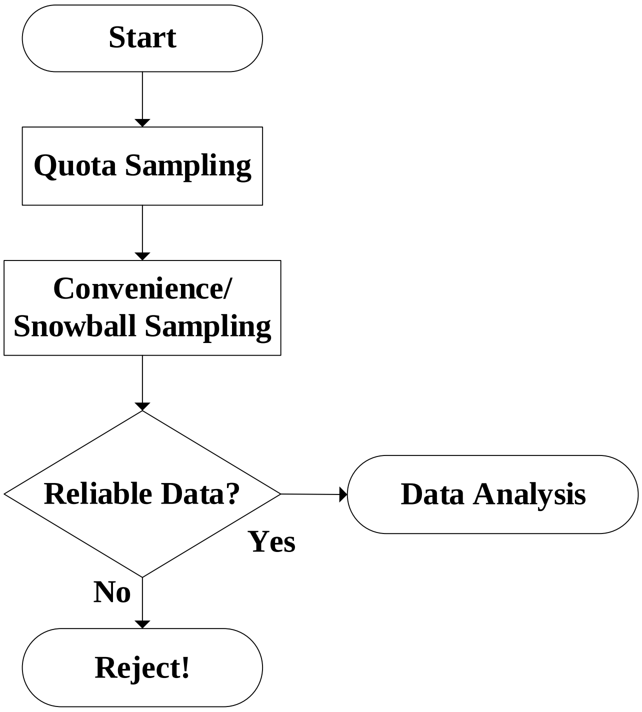

Figure 3.2 – Sampling flowchart

3.6. Sample Population

The research population is consultants based in Addis Ababa as determined from the 2021/22 G.C. registries obtained from Addis Ababa City Administration Construction Permit and Control Authority. The population data is shown in Table 3.1 below.

Table 3.1 – Total registered consultants operating solely in Addis Ababa (From Addis Ababa City Administration Construction Permit and Regulatory Authority)

Category	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Grade 6	**Total**
Building	162	89	155	6	280	40	**732**
Construction Management	8	17	6	3	1	5	**40**
Highway and Bridge	38	1	2	-	2	-	**43**
Water and Sewerage	-	-	-	1	4	-	**5**

The consulting firms in the building category from the total sample population are filtered out. The sample is reduced to four sub-categories based on the scope of the industry. Furthermore, considering the capacity of the consultants with requirements of project cost, type, and experience of professionals, the study focuses on Grade 1 and Grade 2 consultants. The filtered and study population is shown in Tables 3.2 and 3.3.

Table 3.2 – Filtered population for consultants operating under building subcategory

Sub-category: Buildings	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Grade 6
Architectural	10	1	4	1	5	3
Architecture and Engineering	140	82	138	2	256	34
Engineering (General)	12	4	13	3	16	1
Engineering (Specialized)	-	2	-	-	3	2
Total	**162**	**89**	**155**	**6**	**280**	**40**

Table 3.3 – Population of the study

Sub-category: Buildings	Grade 1	Grade 2
Architectural	10	1
Architecture and Engineering	140	82
Engineering (General)	12	4
Engineering (Specialized)	-	2
Total	**162**	**89**

3.7. <u>Sample Size Determination</u>

A quota sample strives to represent a significant characteristic of the wider proportion. According to Iliyasu & Etikan (2021), the population is divided into categories, and elements from each category are chosen. Then sorting the categories or elements according to their percentage of the total population is done to ensure characteristic percentage representation.

The sample size determination for this research is as follows.

<u>Step 1</u>: Divide and categorize the population into groups or strata

- Total number of registered consultants under Grade 1 and Grade 2 as of 2021/22

  G.C. – 251

  G1 – 162

  G2 – 89

<u>Step 2</u>: Identify the proportion of subgroups to the wider population; *pp – population portion*

- $pp_{G1} = \frac{162}{251} = 64.54\%$
- $pp_{G2} = \frac{89}{251} = 34.56\%$

Then, we introduce Cochran's (1977) formula to calculate sample sizes in finite population cases.

$$n = \frac{n_o}{1 + \frac{n_o}{N}}, \qquad n_o = \frac{z^2 p(1-p)}{e^2}$$

Where:	n:	sample size
	z:	confidence interval corresponding to a level of confidence
	p:	population portion
	N:	population size
	e:	precision or error limit

For this sampling technique, we use the following parameters

- ✓ The margin of error (confidence interval) is taken as ±10%
- ✓ The confidence level is set at 90%
- ✓ Standard deviation is set as 0.5 (50%) (population portion)
- ✓ The confidence level of 90% Z-score is calculated from the positive z-table.

  $$AL = \frac{1 + CL}{2}$$

  Where: AL = Area to the Left of the positive z-table

  CL = Confidence Level

$$AL = \frac{1 + 0.90}{2}$$

$$AL = 0.950$$

Identifying the z-score given of an area of 0.950 from the positive z-score table gives a value of 1.65,

Inserting all the figures into Cochran's formula (1977) for finite population becomes,

$$n_o = \frac{z^2 p(1-p)}{e^2}$$

$$n_o = \frac{1.65^2 * 0.5 * (1 - 0.5)}{0.1^2}$$

$$n_o = 68.0625$$

Then n is obtained as,

$$n = \frac{n_o}{1 + \frac{n_o}{N}}$$

$$n = \frac{68.0625}{1 + \frac{68.0625}{251}}$$

$$n = 53.54 \approx 54 \text{ respondents}$$

Step 3: Percentage distribution

- G1 = $54 * {}^{64.54}/_{100}$ = 34.85 ≈ 35
- G2 = $54 * {}^{35.46}/_{100}$ = 19.14 ≈ 19

The quota sample distribution for the sample population is calculated as above. The respondents were chosen in adhering to the subgroup characteristics.

3.8. Analysis Strategy

The data retrieved was collected, compiled, and analyzed using Microsoft Excel and Power BI as this research follows a descriptive statistics method. The frequency distribution method was employed in the descriptive statistics method.

CHAPTER FOUR

ANALYSIS AND DISCUSSION

This chapter analyzes and presents the analysis collected through primary and secondary methods. It entails using analytical reasoning and logic to find patterns, correlations, or trends to analyze acquired data. The results analysis section objectively summarizes what was discovered with the distributed questionnaire. The results of this study were presented using frequency distributions in tables, different types of bar charts, cards, and tree maps. Once the data analysis has been thoroughly done, the discussion part of this chapter analyzes the findings, places them in perspective, and explains their significance.

4.1. Analysis

4.1.1. Response Rate of Questionnaire

The questionnaire was distributed to 54 respondents corresponding to each consultant registered in the respective grades. The turnout of the questionnaire has resulted in 45 accepted responses, four rejected responses, and five unanswered, recording a mean 83.34% overall response rate. Therefore, the following data analysis used the 45 respondent’s responses.

Table 4.1 – Consultants with the respective grade, sample size, and response rate

		Population		Response			Response Percentage Per Quota
No	Consultants	Population Size	Quota Sample Size	A*	R**	U***	
1	Grade 1	162	35	29	2	4	82.86%
2	Grade 2	89	19	16	2	1	84.21%
Sum		**251**	**54**	**45**	**4**	**5**	**83.34%**

A – Accepted, R** - Rejected, U*** - Unanswered*

The results of the assessment of the 45 respondents are presented here onwards, and the population distribution with respect to the category and their response rate is shown in table 4.1. The response rate between Grade 1 and Grade 2 category consultants is relatively tied to each other.

4.1.2. Respondent's Profile

Figures 4.1 and 4.2 show the respondents' profession and years of experience. The profession of the respondents included architects, civil engineers, mechanical engineers, sanitary engineers, and electrical engineers with roles of project directors, project coordinators, supervisors, designers, and engineers. Most respondents had acquired a Master's degree in their respective fields.

The range of experience years of the respondents is presented in figure 4.3. Professionals with 9-12 years of experience are a slight majority, followed by professionals with 6-9 years of experience. Entry-professionals share approximately the same ratio as professionals with 3-6 years of experience.

The involvement in the Architecture, Engineering, and Construction (AEC) of the respondents consulting services, with a quarter of the respondents also providing freelance services and academics, is shown in Figure 4.4.

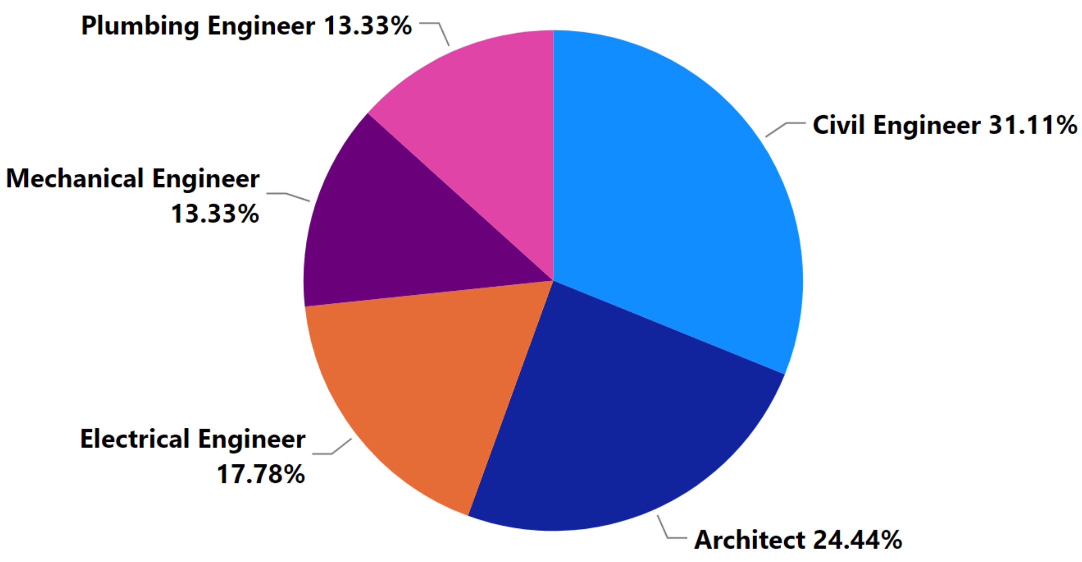

Figure 4.1 – Profession of respondents

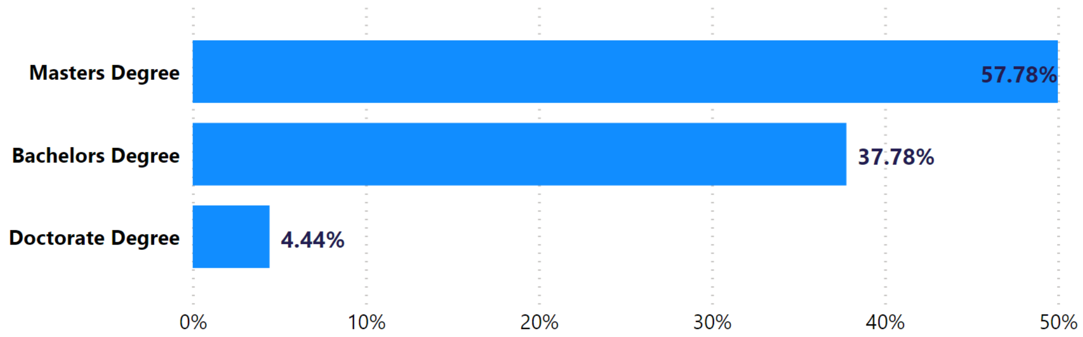

Figure 4.2 – Educational background of respondents

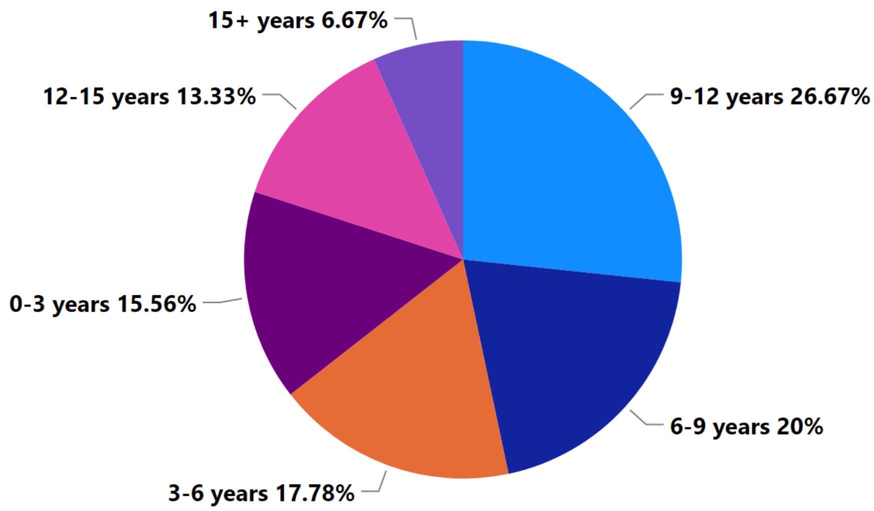

Figure 4.3 – Experience of respondents

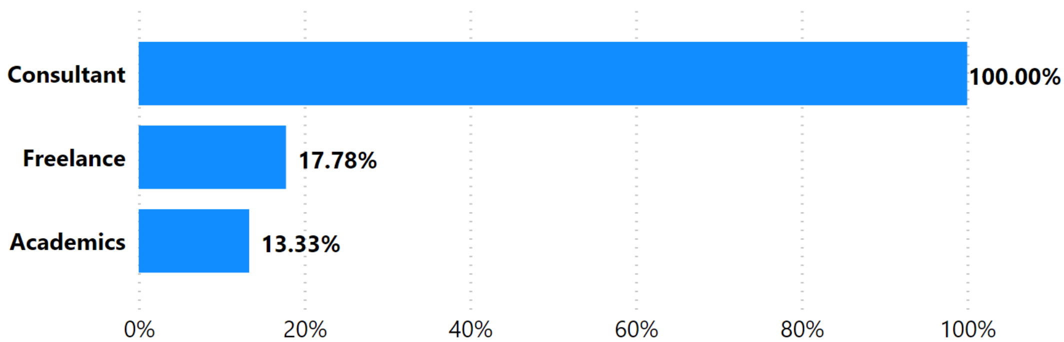

Figure 4.4 – Involvement in the selective AEC sector of Addis Ababa

4.2. Results

The findings of this research are categorized into six sections dealing with the design approach, background on the extent of the practice of Building Information Modeling (BIM) authoring tools, sustainability, Building Performance Analysis and Simulation, current practices and prospects, and closes with gaps with building performance.

The respondents were inquired set of condition-based closed-ended questions, multiple-choice and grid questions, and Likert scale questions shown in Annex I. The descriptive statistical analysis results are presented in tables and charts in the following sections.

4.2.1. Design Approach

All but one respondent stated the involvement of design teams of different engineering disciplines, architects, and designers in the design stage of building projects. A majority of the respondents said establishing a list of User Needs (UN) and the approach they mainly used for expressing the UN in the design stages stems from a target-oriented scheme, which focuses more on the request for specified performance or achievement rather than a fault preventive approach aimed at decreasing the emergence of faults that adversely affect the building from serving its intended function. These needs often stem from discussions with the consulting firm where the firm creates a list of the user needs or the user brings a specified list of needs. This is designated in Figure 4.5 as follows.

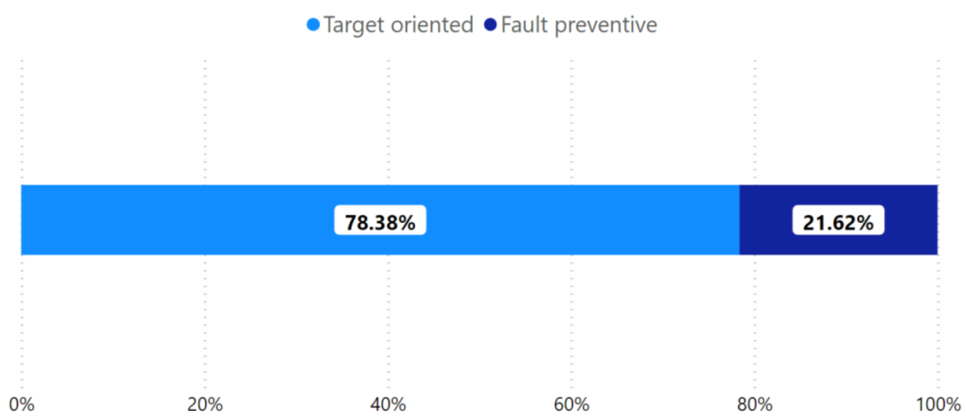

Figure 4.5 – Approach for expressing user needs

The design process considers a prescriptive-based approach. All respondents stated they do not pursue a performance-based design approach, i.e., setting performance requirements, criteria, indicators, and validation are not done.

4.2.2. Practices with Building Information Modeling (BIM) Tools

Figures 4.6 and 4.7 represent findings of using and practicing Building Information Modeling (BIM) authoring tools. 46.67% of the consultants stated to use BIM authoring tools. The remaining consultants who did not utilize these tools exercised design decisions and forwarded information in conventional computer-aided design solutions.

Almost all the consultants acquired a bootlegged copy of the software through unofficial distributors. One consultant acquires these tools through an official license from an authorized vendor through its office in the United States.

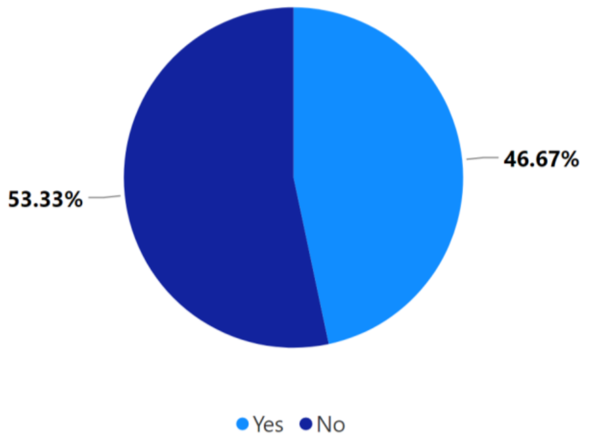

Figure 4.6 – Use of BIM authoring tools

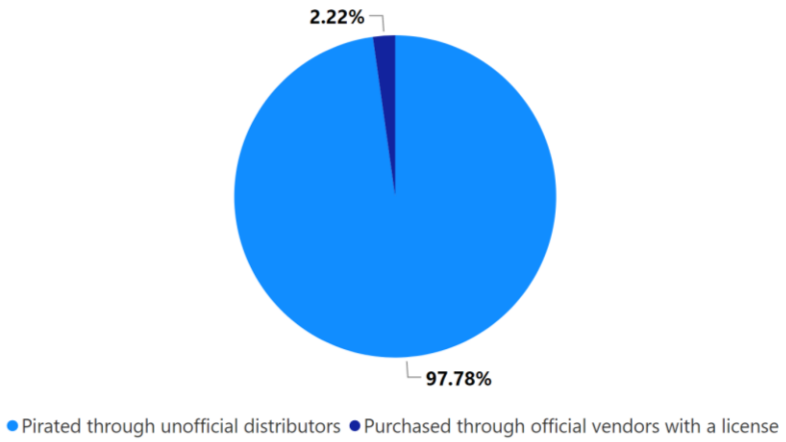

Figure 4.7 – Acquisition of BIM authoring tools

The use of BIM dimensions by the consultants is shown in figure 4.8 below. The consultants mainly used the dimensions in processing the data associated with modeling, predominantly used for 3D Geometry. One consulting firm utilizes 4D BIM and 5D BIM for project timeline scheduling and cost estimation in its particular projects.

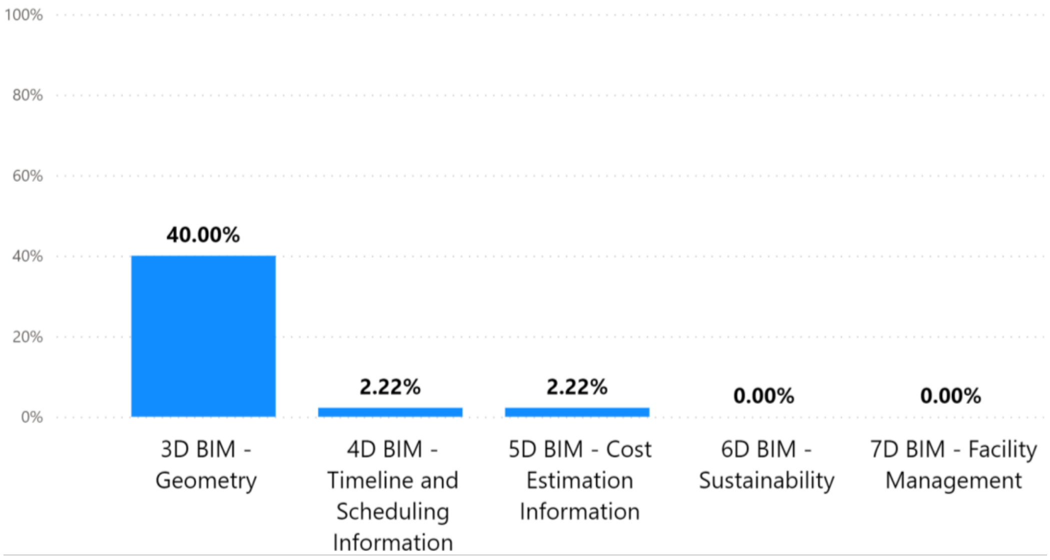

Figure 4.8 – BIM Dimensions used by consultants

Figure 4.9 shows this frequency distribution of BIM authoring tools used by consultants. The BIM authoring tools used by most of the consultants in a hierarchy are Autodesk Revit®, ArchiCAD®, and Sketchup®. The predominant tool, Autodesk Revit, was used by professionals in each discipline but dominated mainly by architects and engineers.

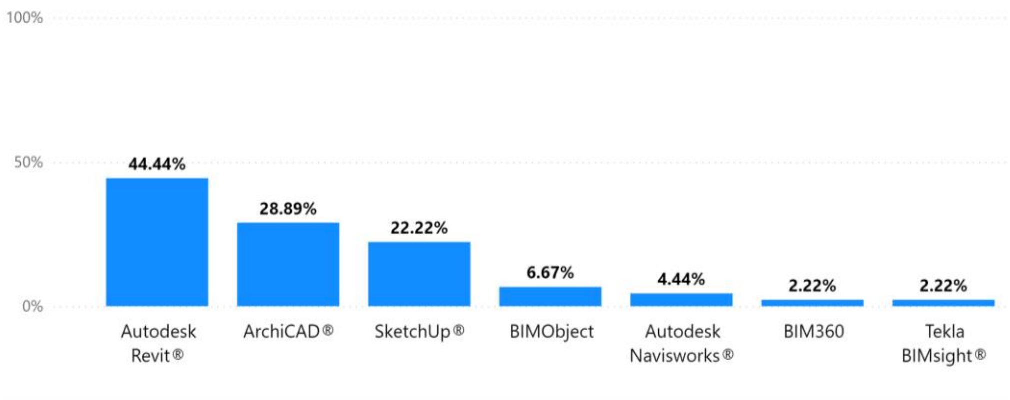

Figure 4.9 – BIM authoring tools used by consultants

4.2.3. Sustainability

The consultants in this study were inquired about their practice of considering of sustainability aspect of building projects concerning the parameters of the triple bottom line. Figure 4.11 shows the sustainability attributes that the consultants considered in the research. Some of the aspects of sustainability considered by the consultants primarily focused on building orientation (86.67%), building massing (73.33%), and daylight analysis (62.22%). These aspects were considered with design philosophies and principles based on the stakeholders' inputs with intrinsic features of computer-aided design and BIM authoring tools. Material conservation and water harvesting were less considered, with more than 50% of the population study stating they do not incorporate this in their design decisions. Aspects that are least considered is energy use modeling which consultants said they have not had experience with or need to consider building projects' design stages.

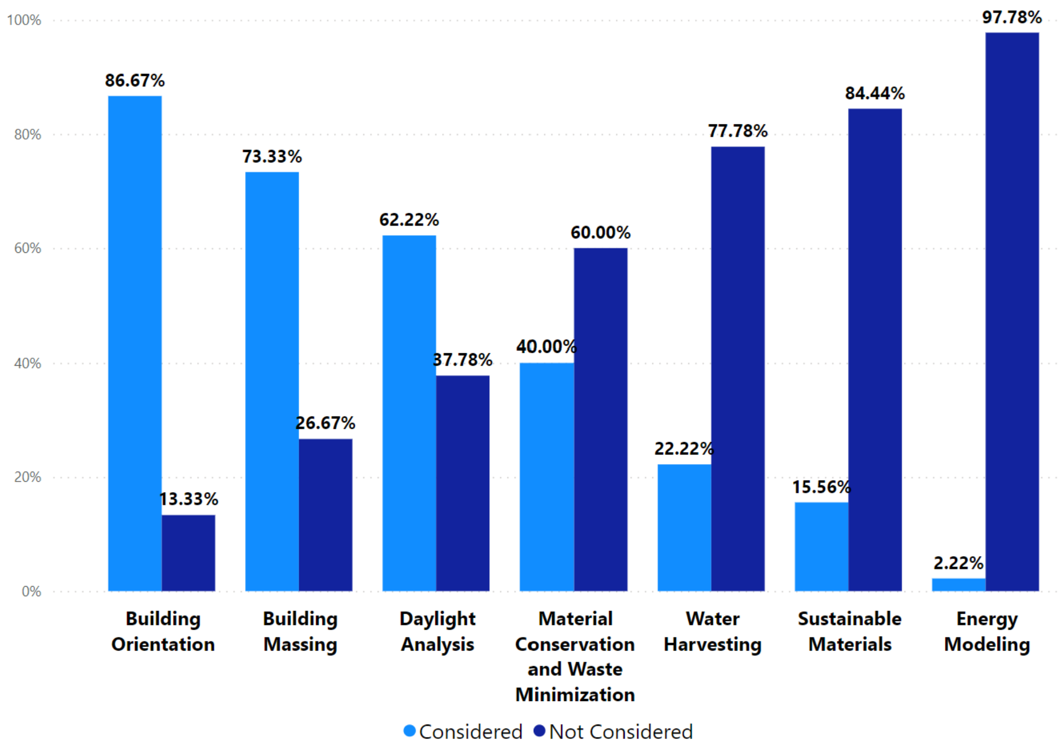

Figure 4.10 – Sustainability aspects considered by consultants

The results above show that some consultants have a particular disparity in the practice of sustainability or a lack of unequivocal methods with sustainability-based design approaches. The data shows that a thorough consideration of buildings' environmental impact on the ecosystem is not considered in tandem with building construction's economic and social aspects. It is difficult to state a holistic approach in the design phase of a building according to the triple bottom line.

4.2.4. Building Performance Analysis – Current Practice

The consultants of the research study were inquired about their familiarity and background knowledge regarding building performance analysis. Figure 4.12 shows the descriptive graphical representation regarding familiarity and practice of building performance analysis and utilization of simulation tools. 24% of the respondents stated that they were familiar with the concept of Building Performance Analysis, while less than 10% of the respondents have had background knowledge. All the respondents who have had prior background knowledge stated that this concept was brought to them during their graduate programs through conferences and workshops while studying abroad; none of the respondents have had exposure to the subject in Addis Ababa.

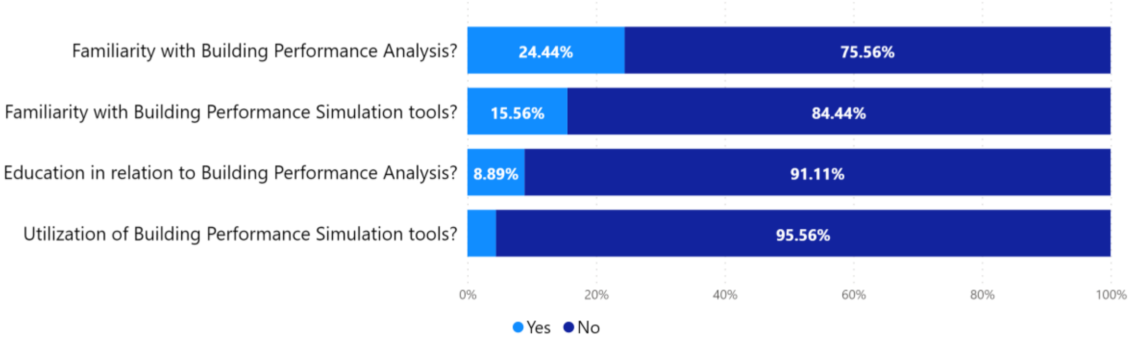

Figure 4.11 – Concept of Building Performance Analysis and Simulation Practices

Similar to Building Information Modeling (BIM) tools, the consultants were also asked about their familiarity with building performance analysis and practice of building performance simulation tools. 15% of respondents stated they are aware of these tools, and their use goes down by two-thirds. Approximately 5% of the consultants said using Building Performance Simulation tools to assess the performance requirements of buildings. These results are shown in Figure 4.11. Figure 4.12 shows some of the simulated attributes done by the very few consultants during the design stage.

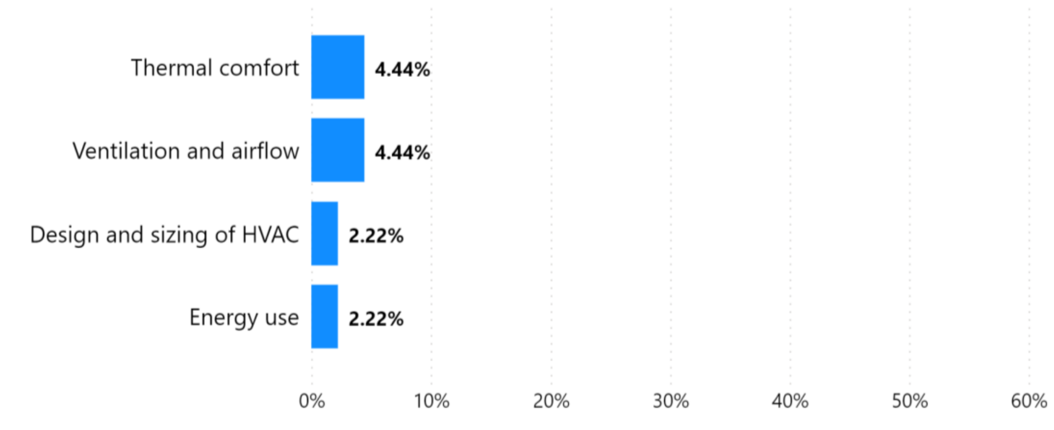

Figure 4.12 – Simulated attributes during the design stage

Figure 4.13 shows the simulation tools used by consultants such as Autodesk CFD®, DesignBuilder®, Green Building Studio®, and eQuest®. These tools range from open-source programs to commercial software to cloud-based services.

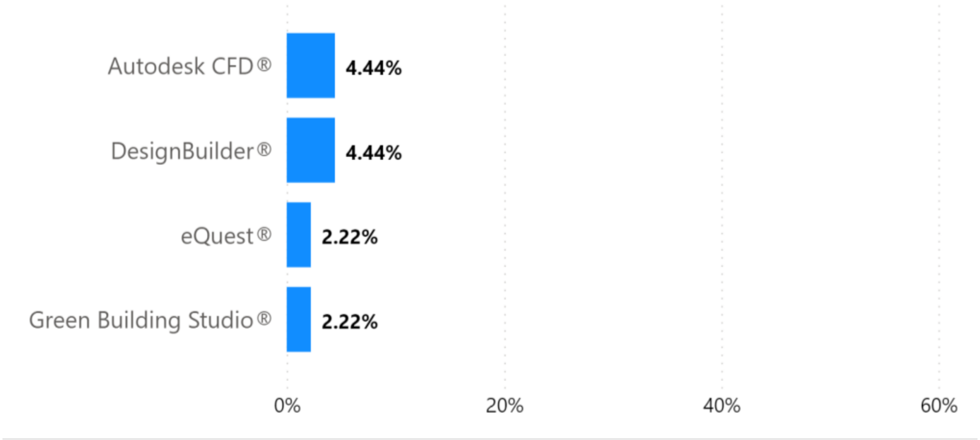

Figure 4.13 – Utilization of Building Performance Simulation tools of the overall survey population

These results show that the concept of building performance analysis and simulation tools is not widely practiced with consultants in Addis Ababa. While few consultants are aware of the concept and tools, the practice is more limited to a further few.

Summarizing the consultants' involvement with regards to design participation, BIM utilization, and building performance analysis, a Likert scale question was presented to the study population where a response set of was given as; 1 for "Never," 2 for "Rarely," 3 for "Sometimes," 4 for "Often," and 5 for "Always." This is done to get a definitive answer to the question presented. The range is calculated by 5-1=4, divided by 5 since it is the largest value. The division's output is then used to define the minimum and maximum length of the 5-point Likert type scale. Finally, the minimum value on the scale is added to determine the cell's maximum value as follows.

Table 4.2 – Likert scale range – frequency and importance

No	Response - frequency	Response - importance	Scale
1	*Never*	*Not at all important*	1.00 - 1.80
2	*Rarely*	*Slightly important*	1.81 - 2.60
3	*Sometimes*	*Moderately important*	2.61 - 3.40
4	*Often*	*Very important*	3.41 - 4.20
5	*Always*	*Extremely important*	4.21 - 5.00

Table 4.3 – Likert scale question and results

Participation in design team meetings?	R	F	Use of BIM software tools?	R	F	Use of BPS software tools	R	F
Never	1	1	*Never*	1	25	*Never*	1	43
Rarely	2	5	*Rarely*	2	1	*Rarely*	2	-
Sometimes	3	15	*Sometimes*	3	4	*Sometimes*	3	1
Often	4	9	*Often*	4	7	*Often*	4	1
Always	5	7	*Always*	5	8	*Always*	5	-
Total Sum		37	Total Sum		45	Total Sum		45
Mean		3.43	Mean		2.38	Mean		1.11
SD		3.07	SD		2.45	SD		0.63

R – Response Set; F – Frequency; SD – Standard Deviation

Interpretation of the result of respondents' responses is as follows.

i. The mean score based on the frequency of respondents regarding participation in the design stage is 3.43, which falls within the fourth Likert scale description, indicating that the respondents in this study **often** participated in design meetings with professionals of different engineering backgrounds.

ii. Regarding the practice of BIM authoring software tools, the mean score is 2.38, implying that the respondents **rarely** use BIM tools.

iii. Lastly, the highest frequency of the respondents using BPS tools is 90%, with a mean score of 1.20. The result shows that the respondents **never** used BPS tools in the design stage of buildings.

4.2.5. Building Performance Analysis – Prospect

In continuation with the study about the current practices of building performance based on condition-based inquiry, the consultants were asked if they would be interested in using these tools in future projects. The results showed that almost all consultants are interested in utilizing these tools with a range of attributes stated in figure 4.15. These attributes include energy use performance simulation, ventilation and indoor air quality, lighting simulation, and sustainability assessment.

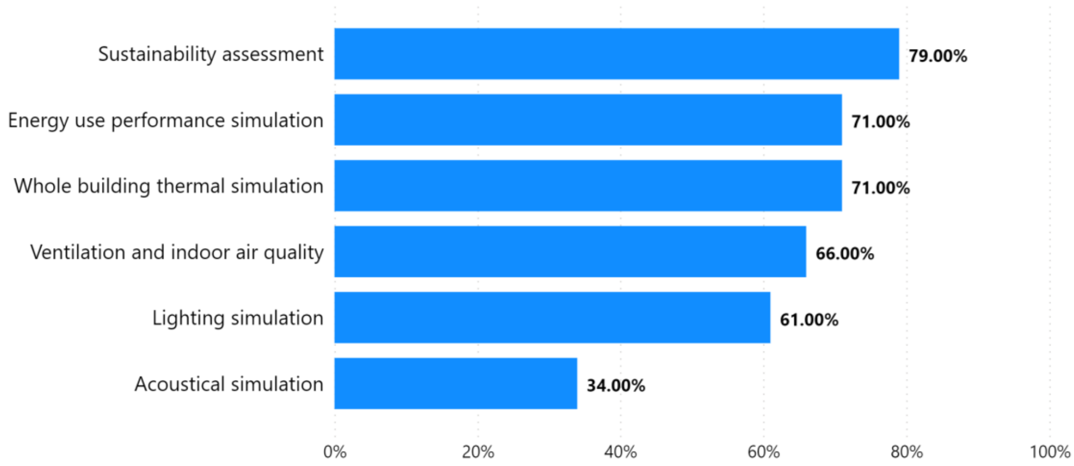

Figure 4.14 – Attributes of interest in simulating building performance

A descriptive statistical chart presenting uncertainties in design stages is shown in figure 4.16. Picking a suitable point during the key design stages (conceptual. preliminary, and final design stages) to consider building performance simulation is essential. The consultants were further inquired to consider this with physical, scenario, and design uncertainties in conjunction with different design phases, with the results shown as follows. Physical uncertainty is opted to be dealt with in the final stages and scenario uncertainty in the preliminary stages of the design. Design uncertainty is slightly more opted for in the conceptual design stage by the consultants in the study.

Despite their interest in the practice of these concepts, there are challenges currently present in the industry, as stated in Figure 4.17. The top three challenges expressed by the consultants in implementing the practice of building performance simulation are lack of training, lack of skilled professionals, and lack of awareness about the concept.

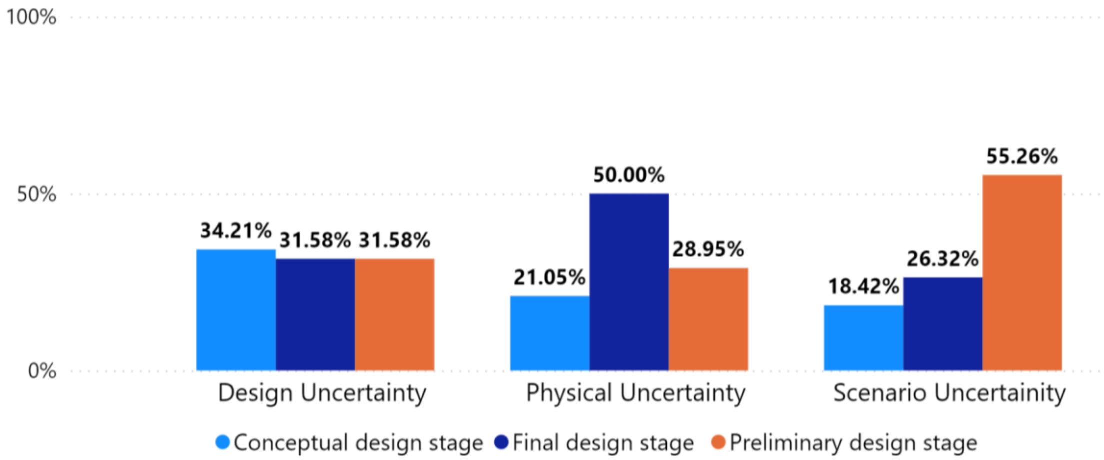

Figure 4.15 – Uncertainties in design stages

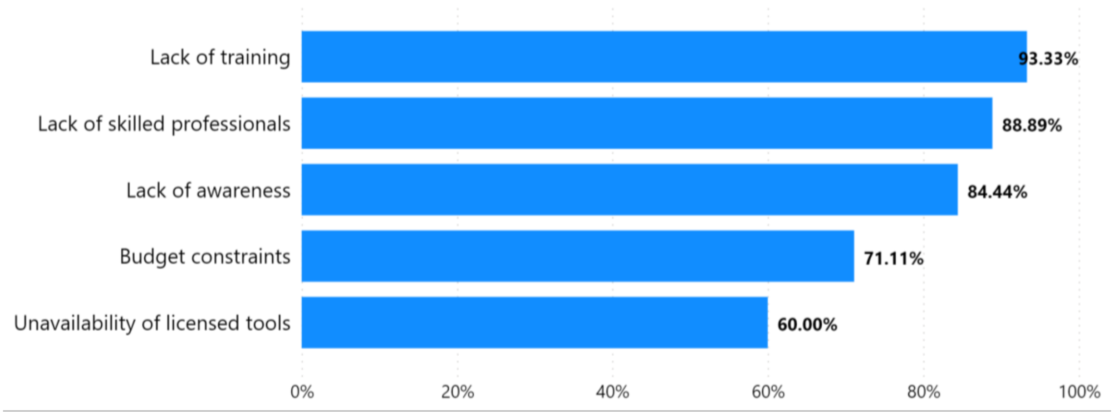

Figure 4.16 – Challenges in the AEC with BPS implementation

4.2.6. Bridging the Performance Gap

This section presents the results of consultants' views with respect to performance gaps in building projects in Addis Ababa. Figure 4.18 states the possible underlying causes of building performance gaps. The reason that stands out with most consultants is the limited understanding of the impact an early design decision will have on the overall project lifecycle of the building. This notion is shared by 91% of the study population. Some consultants believe that alterations made after the design can also contribute to the performance gap, with a few crediting uncertainties in building modeling and on-site workmanship.

The consultants' use of uncertainty analysis or sensitivity analysis is shown in Figure 4.19. The results showed only 22% of them practiced such an approach to alleviate unknown scenarios. In this case, local methods were primarily used to determine partial derivation of output related to input, with global methods coming second.

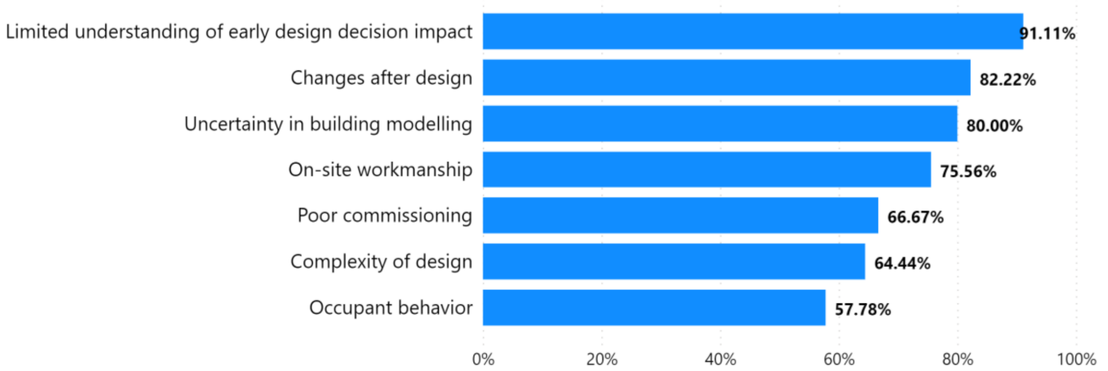

Figure 4.17 – Possible underlying causes of building performance gaps

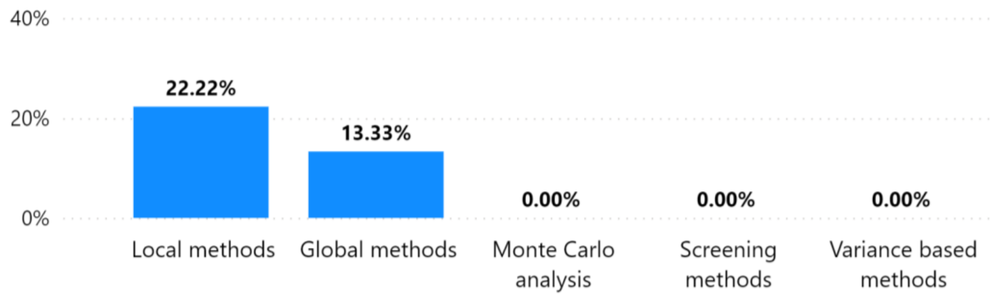

Figure 4.18 – Uncertainty/sensitivity analyses techniques

Results inquiring about the consultants' perception of the need to implement uncertainty or sensitivity analysis are analyzed using a Likert scale for importance. The response response set for this case was given as; 1 for "Not at all important," 2 for "Slightly important," 3 for "Moderately important," 4 for "Very important," and 5 for "Extremely important."

Table 4.4 – Likert scale questions and results – uncertainty/sensitivity analysis

Importance of Uncertainty/Sensitivity Analysis	**Frequency**
Not at all important	3
Slightly important	4
Moderately important	6
Very important	22
Extremely important	10
Total	45
Mean	3.71
Standard Deviation	3.36

According to the results, the highest frequency is 22 consultants representing 48% of the sample population. The mean score based on the frequency is 3.71, which falls within the fourth Likert scale, indicating that consultants believe it is **very important** to consider the uncertainty analysis during the design stages.

Regarding the suitable methods to mitigate building performance gaps, the top three methods stated by consultants included training and education, directives and frameworks from regulatory authorities, and design improvement shown in Figure 4.20.

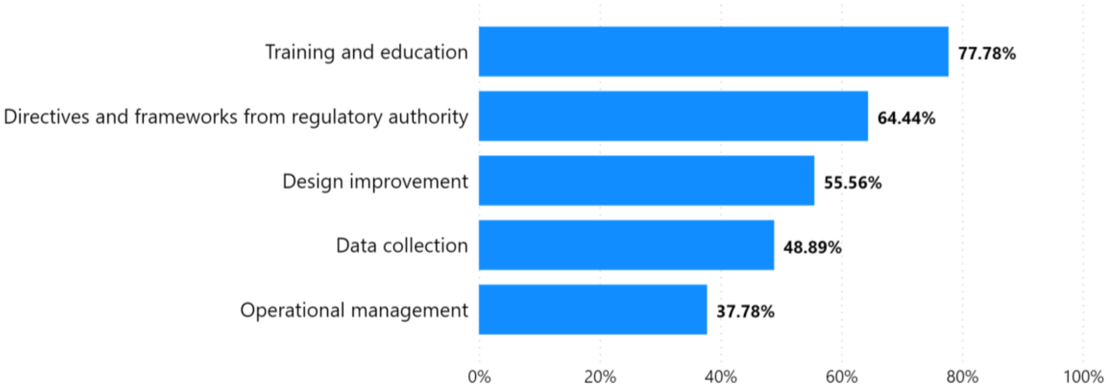

Figure 4.19 – Ways to mitigate building performance gap

4.3. Case Studies

4.3.1. Hidassie Telecom S.C. Headquarters Commercial Building

A. Introduction

This building is designed to provide services for the future headquarters of Hidassie Telecom S.C, a private national distributor of telecom products. This building is designed by a Grade-1 private consulting firm comprised of architects and engineers of different fields, currently being constructed in Bole sub-city, Addis Ababa.

B. Design Approach

The building's front side is more open and has a complete visual connection to the outside, thanks to the curtain wall and glass material. Sun orientation and visual connectivity are considered in designing the façade of the building. The façade detailing incorporates aluminum louvers to provide shading to the interior space.

Figure 4.20 – Hidassie Telecom HQ building (from Hidassie Telecom HQ project archives)

The design of the building is done through conventional methods with AutoCAD, where the 3D model for geometry representation and visualization is done for massing and orientation throughout from the conceptual design stage to the final design stage with Revit Architecture and Sketchup. After the architectural and structural design is complete, the electrical and plumbing design is generated accordingly. The design decisions are made primarily through face-to-face meetings and discussions.

No other dimensions of BIM besides the 3D BIM dimension were utilized for this project solely for 3D space visualization. Based on the user requirements, the design was developed with an emphasis on the function of the building through a prescriptive approach.

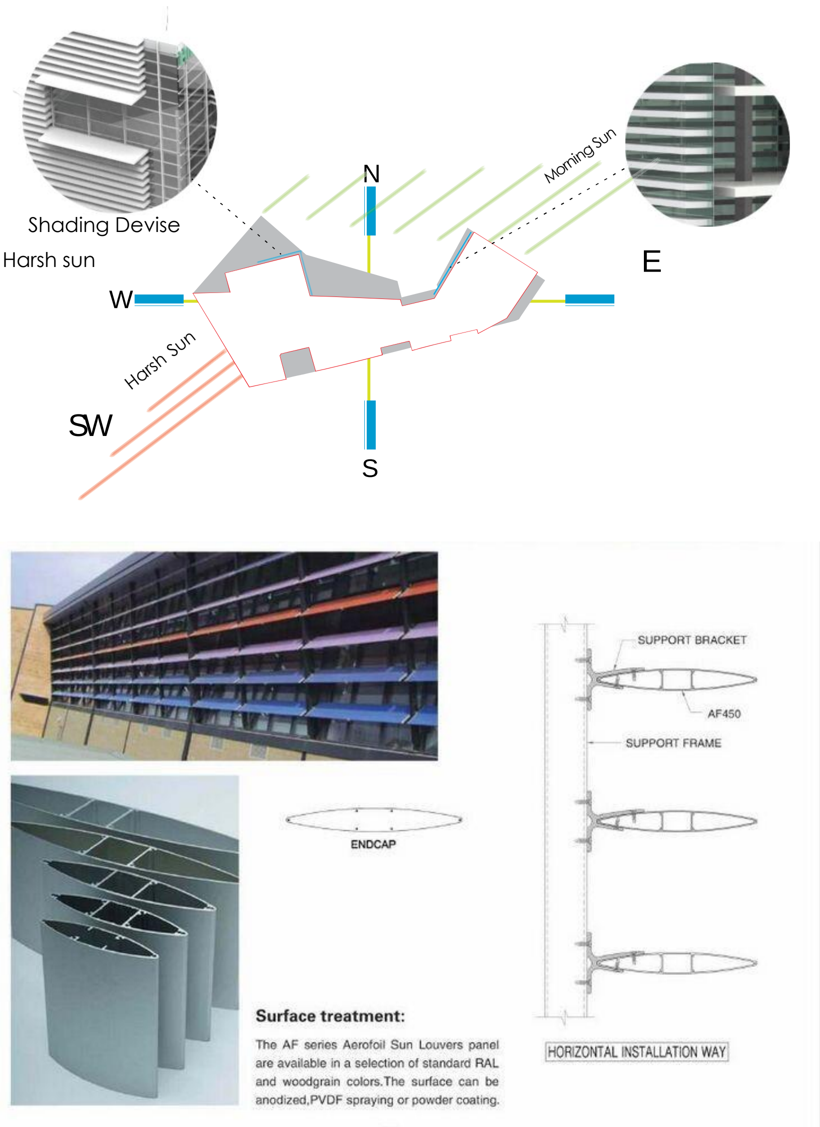

Figure 4.21 – Façade material for the building envelope (from Hidassie Telecom HQ project archives)

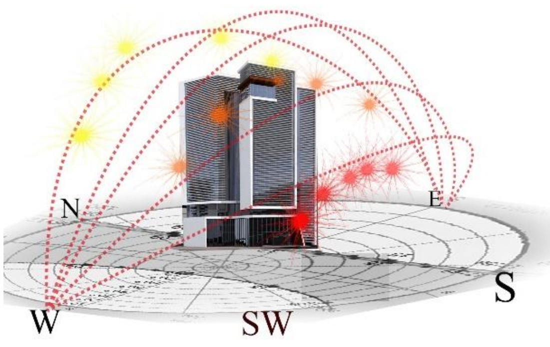

Figure 4.22 – Sun path analysis and positioning of the building (from Hidassie Telecom HQ project archives)

C. <u>Sustainability</u>

The consultant has taken specific approaches to improve the sustainability of the building by considering aspects such as passive design, building orientation, energy efficiency, water harvesting, and daylighting. The building project did not require rating system certification, such as LEED certification. The sustainability aspects of the measures used are summarized in Table 4.6 below.

Table 4.5 – Sustainability aspects for Hidassie Telecom HQ

Sustainability aspects	**Measures used**
Passive design	The building is designed to block the harsh southwest sun while disregarding any possible significant openings. See Figure 4.22.
Building orientation	Minimizing the demand for air conditioning
Energy efficiency	On-site power generation through Building Integrated Photovoltaic Installations (BIPV) systems, i.e., solar panels, is proposed on the roof and sides of the building capable of providing energy for the building for night illuminance. See Figure 4.23.

Water harvesting	Storm water design considered rain water to be utilized for restroom
Daylighting	A high transparent façade with glazing is used to provide natural day lighting in the space

Figure 4.23 – Proposed location for the BIPV system (from Hidassie Telecom HQ project archives)

D. Building Performance Analysis

Besides the conventional and prescriptive design approach taken for this building project, there were no performance simulation tools for predicting performance attributes.

E. Uncertainties in the Design Stages

In an interview with one of the firm members, uncertainties in the design stages of the building were limited to physical and scenario parameter uncertainties in the structural design. These uncertainties were in relation to material characteristics for the concrete structures and the occupants' loadings per space which multipliers factored specific parameters in the loading as a safety factor.

4.3.2. Addis Ababa City Library

A. Introduction

The Addis Ababa City Library, also known as Abrehot Library, was designed and constructed over a 19,000m plot of land with the government's initiation. A local consultant carried out the design for the library, reportedly the largest library in Ethiopia.

B. Design Approach

The design-build contractor hired the design consultant to carry out all the design works for the Addis Ababa City Library. The government initiated the project to be designed and completed in 18 months. Since there were financial constraints set for this project, there had not been much room for the designer to exercise in further improving the design parameters and the material selection for the building. Much focus was given to the project's function and purpose, leading to an understanding that the building was considered under prescriptive-based design. The designer was provided with a fixed project total cost and had to design and value engineer to reach the project's target cost.

Figure 4.24 – Abrehot library (3D rendering) (from Addis Ababa City Library project archives)

The design firm utilized Autodesk Revit for the multidisciplinary designs of the building. The design firm had acquired these tools from Autodesk with an official license. As depicted in figure 4.28, the dimension used for this project was 3D BIM geometry for model aggregation and visualization. The coordination layout designated 3D space visualization of the floor and model aggregation of ventilation, firefighting, and electrical systems.

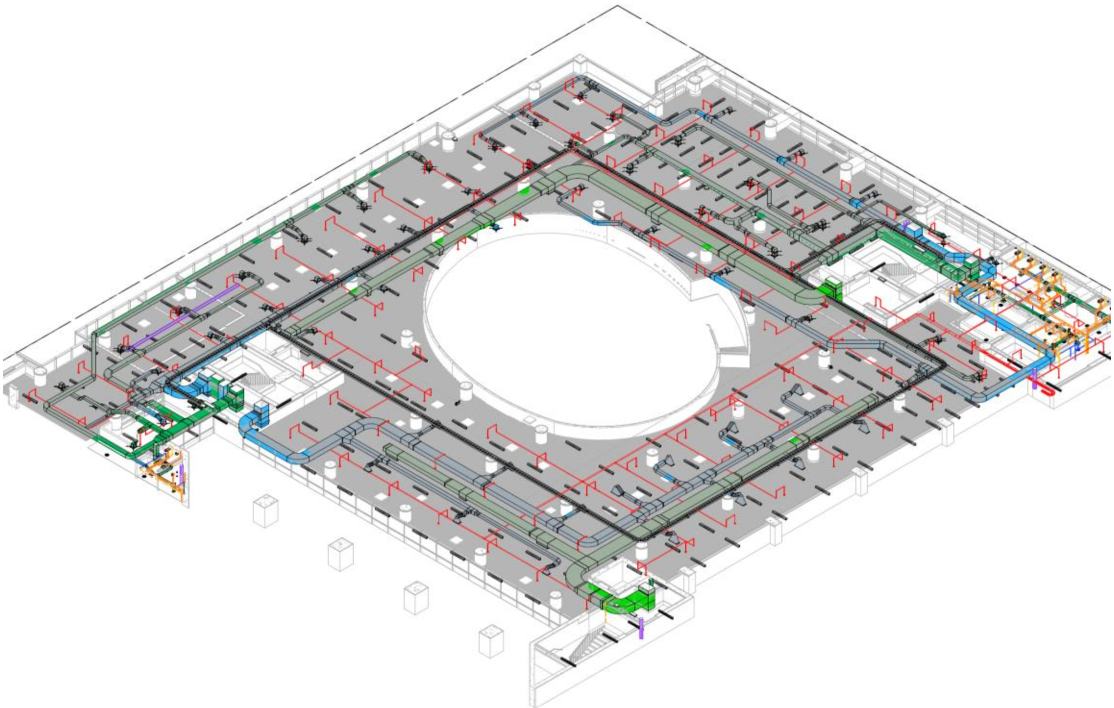

Figure 4.25 – 3D coordination layout (from Addis Ababa City Library project archives)

C. <u>Sustainability</u>

Regarding the sustainability of the building, LEED certification for the building was not a requirement, but the company pursued improving the building’s sustainability. Different approaches were used to attain this, such as specifying energy-saving items, local product uses, and social community inputs. The building was designed and constructed to benefit social variables dealing with community, education, and social resources from the social perspective.

D. <u>Building Performance Simulation</u>

Based on the information gathered from the design firm, performance attributes regarding building performance simulation were not done for the Addis Ababa City Library.

E. Uncertainties in the Design Stages

Regarding uncertainty, the design team had considered the design parameter uncertainty with respect to the room height. The stakeholder proposed the initial clearance of room height to be 2.5 m. The design consultant had considered a much higher consideration of 4 m to consider auxiliary facilities, ducts, and other systems that may and could be included in the building. This had implications for the quantity and cost of the material.

4.3.3. Meskel Square/Palace Heritage Underground Parking Buildings

A. Introduction

The government had initiated the construction of two city-funded parking structures, one for the palace heritage parking and one for Meskel Square. Both projects have been constructed by foreign construction companies based on a design-build project where the design-build designer was a local Grade 1 consultant for both parking structures. The palace heritage parking is a 4-level underground parking structure with a recreational complex constructed on 10,000 square meters. The Meskel Square basement parking is a 2-level underground basement with a refurbished public plaza built over 22,500 square meters.

Based on the agreement between the government and the DB contractor, the design for the basement parking structures was based on the prescribed list of requirements and technical specification of works which followed a more prescriptive-based approach. The user needs were listed out by the employer and forwarded to the DB contractor and local DB consultant, in which the design was generated as such.

B. Design

The 2D design was developed with AutoCAD, and a 3D geometry representation was done with Revit Architecture. The design used a prescriptive method based on the user's needs, emphasizing the building's purpose.

After generating architectural and structural designs, MEP designs were done in tandem using 2D computer-aided design. The 3D model for the interior parking was solely used to represent the space and visualization with generic model families in Revit

Architecture. Since the delivery of this design was immediate, most design workshop decisions are done through face-to-face meetings and much more frequently.

Figure 4.26 – Meskel Square parking (left), Palace heritage parking (right) (from Meskel Square and Palace Heritage project archives)

C. <u>Sustainability</u>

LEED or any rating certification was not required for this project. Provisions for a green roof on top of the recreation building and a dedicated water well are made for the Palace heritage parking. These projects were designed and built with the motivation and desire for economic contribution and employment. Still, the true impact with a holistic consideration of the triple-bottom cannot be said that it is considered.

D. <u>Building Performance Analysis</u>

i. <u>Computation Fluid Dynamics (CFD) Analysis</u>

Since both the parking structures are underground boxed and exposed to vehicular exhaust, a need to verify the design of the ventilation systems was required. The specific aim was to find the optimal locations, number, and configuration of necessary fans for the structure. Furthermore, the provision of a pedestrian tunnel at Palace Heritage parking and the CFD simulation had to be done for the tunnel.

The CFD analysis was done with Fire Dynamics Simulator (FDS), an open-source software developed by the National Institute of Standards and Technology (NIST) of the United States Department of Commerce, in cooperation with VTT Technical Research Centre of Finland. Although the local consultant did the mechanical design, the CFD analysis simulation for both projects was outsourced to a firm abroad. The manufacturer simulated the analysis based on its equipment rating and configuration.

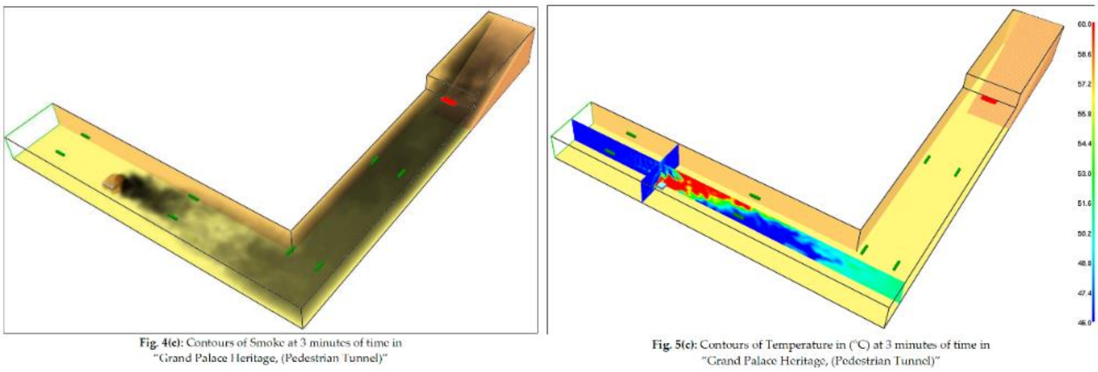

Figure 4.27 – CFD simulation for palace heritage tunnel (from Palace Heritage project archives)

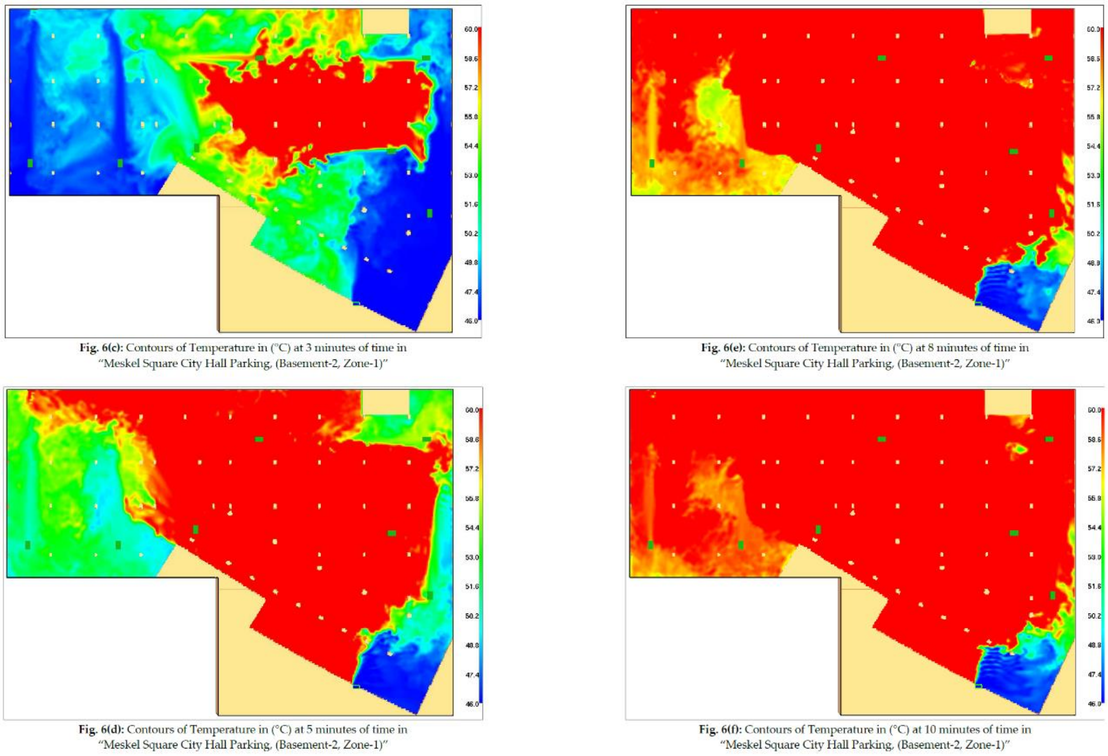

Figure 4.28 – CFD simulation for Meskel Square parking (from Meskel Square project archives)

ii. Lighting Simulation

Lighting simulation was also done for these projects, but the local design consultant did not do the simulation. The design-build contractor requested the manufacturer to conduct light simulations based on the project's context.

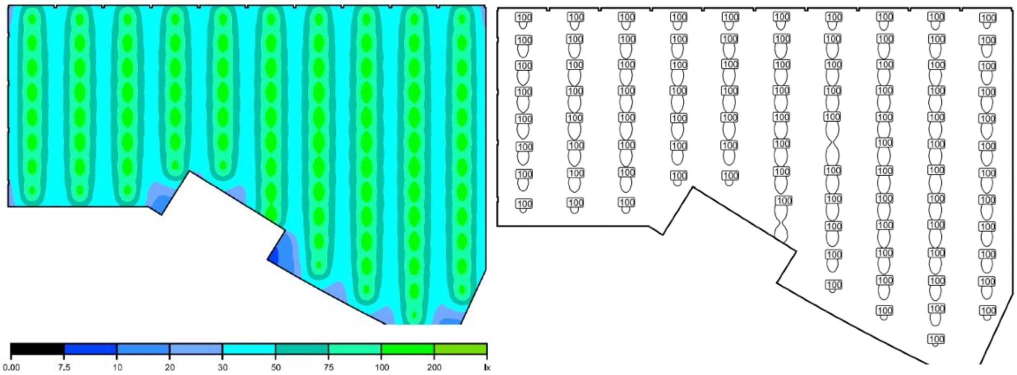

Figure 4.29 – Lighting simulation for Meskel Square basement parking (from Meskel Square project archives)

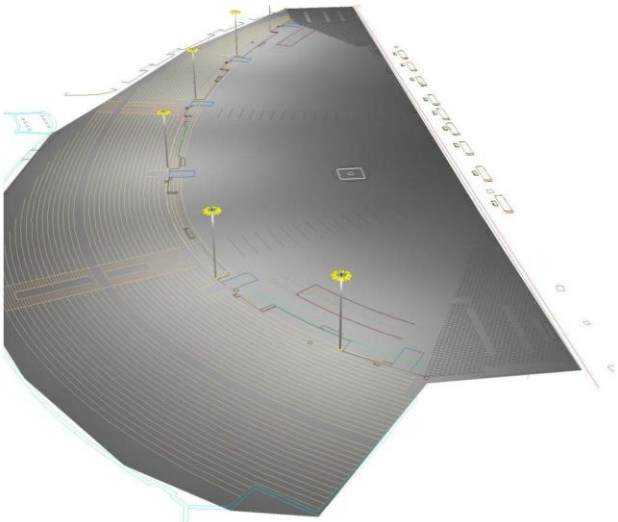

Figure 4.30 – Lighting simulation for Meskel Square Plaza (from Meskel Square project archives)

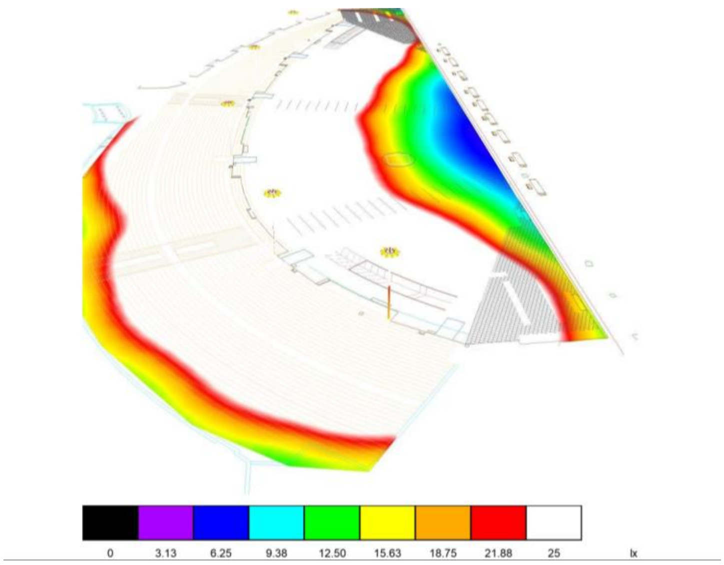

Figure 4.31 – 3D illumination graph of Meskel Square Plaza (from Meskel Square project archives)

E. Uncertainties in the Design Stages

During the design stages, the consultant considered uncertainties in the design input in connection to significant surcharge load from an adjacent building, MEP equipment loads on generators, transformers and ventilation equipment, and variation in raw material characteristics for designing the concrete structure.

4.3.4. Center of Excellence for Sustainable Construction Engineering and Management (CoESCEM)

A. Introduction

In the GTP II initiative of the country, the Ethiopian Construction Project Management Institute (ECPMI) was given the assignment to establish two entities

i. An institute to study and research the country's mega projects design, construction, and operation systems and exploit the local capacity capable enough to construct these projects beyond research and study, and
ii. A national construction quality assessment laboratory that is responsible for carrying out tests, experiments, and simulations.

The stratagem was to bring the management scope and incorporate the engineering aspect of the industry. The "Center of Excellence for Sustainable Construction Engineering and Management (CoESCEM) was conceived based on this initiative. This center's objective includes three main concepts: sustainability, construction engineering, and construction management. In addition to getting support from the government, a feasibility study was done with the expected employment of nearly a thousand people in the center once complete. Based on the inputs from a senior project representative, it has required a large amount of land to show its aimed visionary features of the project.

B. Design Approach

The owner of this project is the Ethiopian Construction Project Management Institute (EPCMI) under the Ministry of Urban Development and Construction sectorial domain. It is conceptualized to be constructed and operated by the institute, where 30% of the design concept emanated from them. The consultant for this project is a governmentowned consulting firm that took on a set of 'visionary statements' from the institute to design the facility. Some of these statements include requirements such as.

- The demand for green spaces
- Zero displacements of the local population
- Resource harvesting for water and electricity for an optimized project aimed at experience development
- Protection of seeded areas.

Considering these points, the consultant has aimed to design this project to "maximize opportunities for integrated, cost-effective adoption of green design and construction strategies, emphasizing human health as a fundamental evaluative criterion for building design, construction, and operational strategies," showing traits of a performance-based design approach.

The purpose of this facility is to enforce policy on a national level. The aim is to create a centralized and organized scheme that is the competitive and productive construction industry. The CoESCEM is focused on experience development which involves collecting people with experience & enrich the construction industry.

C. <u>BIM Utilization</u>

EPCMI was established with the initiation to adopt the BIM technology by the construction industry, certifying professionals with accreditation of BIM tools. CoESCEM is being used as a pilot project from the early stages of the project up to operation and management to produce motivation to accept BIM as a project practice. It is set out to be an exemplary project. All information generated in the design stage will be transferred to the construction phase of the building. After it has been constructed, this information will be transferred to support the lifetime operation system. The institute has stated this in the Terms of Reference (TOR), where the consulting team is working with its dedicated in-house BIM team, where the institute has supported the team with official training. Therefore, it is aimed that this facility will use up to 7D dimensions of BIM.

Specifications must be linked with the material used in the model with the BIM authoring tools such as Revit or ArchiCAD. On a national scale, these specification lists have to be standardized and contextualized in the Ethiopian construction industry. In collaboration with the Ethiopian Standard Agency (ESA), the EPCMI is working to establish such standards, and after attaining these standards, mandating can be done like in the United Kingdom.

D. Sustainability

In the CoESCEM project, LEED certification is made a requirement. The entire project's tier of certification is aimed for silver-level certification. The consultant was assigned to study the criteria for LEED certification. The consultant was made to adopt USGBC's methods in its entirety. The consultant has taken LEED for New Construction, considering sustainable sites, water efficiency, energy and atmosphere, materials and resources, indoor environmental quality, innovation, and design process. The consultant has stated in each design stage a corresponding LEED compliance shown below.

Table 4.6 – Design phases and corresponding LEED compliances (From CoESCEM project archives)

Schematic Design	Determine LEED certification level to pursue
	Select the LEED credits to meet the targeted certification level
	Identifies the responsible parties to ensure the LEED requirements for each prerequisite and selected credit are met
	Preliminary energy modeling to test initial default assumptions
	Preliminary schedule of accommodation for building
Preliminary Design	Site conditions, assess shading, exterior lighting, hardscape, landscaping, and adjacent site conditions
	Massing and orientation, assess massing and orientation that affect HVAC sizing, energy consumption, lighting, and renewable energy opportunities
	Basic envelope attributes assess insulation values, window-to-wall ratios, glazing characteristics, shading, and window operability.

	Lighting levels and indoor programmatic layout, Assess interior surface reflectance values and lighting levels in occupied spaces.
	Thermal comfort ranges, assess thermal comfort range options
	Plug and process load needs, assess reducing plug and process loads through programmatic solutions and layout options
	Programmatic and operational parameters, Assess multi-functioning spaces, operating schedules, space allotment per person, teleworking, reduction of building area, and anticipated operations and maintenance.
Final Design	Provide analytical-qualitative and quantitative building performance data set to meet the targeted certification level

E. Uncertainties in the Design Phase

The following schemes are put forward for the CoESCEM project to alleviate uncertainties.

- In collaboration with a team at the institute and CoESCEM and establishing a dedicated team to scrutinize and evaluate the process,
- Involvement of many stakeholders in different disciplines where a series network of interconnected fields feed off of each other's input and outputs,
- Management of data loss – implementation of BIM on full scale
- Manuals of construction inputs such as material components, manufacturer, and product specifications are used to minimize epistemic uncertainties.

4.4. Discussions

This part connects the findings of this study to the conclusions presented in the following chapter, which explains the scheme used to report the findings. The data has been reorganized to suit better the analysis technique, with specific components being arranged slightly differently from the questionnaire format. The results presented in the previous section of this chapter are discussed below in correlation with the case studies described above.

i. Design Approach

A simple scheme for a performance-based design approach involves a set of user needs to be translated to a performance requirement. A group of factors is established to serve as a performance indicator for a recognized performance criterion. The process involves describing building performance requirements, choosing methods of delivering the required performance, and proving the fulfillment performance. Most consultants' understanding and practice of building performance are inadequate to contemplate that a performance-based approach for buildings during the design stage is considered in Addis Ababa. Despite exercising certain practices to improve the performance of the building for a given set of user needs, most consultants fail to establish performance criteria.

ii. BIM Tools And Dimensions

The concept of BIM goes beyond the mere practice of BIM authoring software tools, and the practice of BIM in the country has not developed enough to have become the trend in the AEC industry. ZIAS Design International and the Ethiopian Construction Management Institute (ECPMI), an authorized Autodesk training center for BIM training and support in Ethiopia, are instances of licensed establishments to practice BIM in the private and public sectors, respectively. In consultations with the Director of Structural Engineering, ZIAS Design International executes designs using BIM but conventional ways without full guidelines and BIM protocols. 3D BIM Dimensions are mainly used to design and represent architectural, structural, and MEP design, whereas they have practiced 4D and 5D dimensions of BIM on a few projects.

From the public sector, the ECPMI works closely with different associations of architecture and engineering in the country and the government sector to provide ways to implement BIM as a design process and equip trainees with sufficient knowledge of the tools. The institute has created a roadmap for implementing BIM as industry practice and is studying standards to adapt to the local context. Designs are mostly done with 2D computer-aided design programs, and bootlegged BIM tools are used for visualization purposes, primarily by architects.

Despite professionals going to great lengths to be certified and local consultants and associations' efforts, The institute is wary that mandating without pilot projects and enhancing motivation will push perspective stakeholders in the AEC of the country.

In the BIM implementation and adoption study, the ECPMI stated that the industry is exposed to inadequate interoperability. Reasons for this include inconsistent technology adoption and stated for this challenge being the entrenched current 2D/3D practice. The report on the uptake of BIM through a VDC scorecard (a methodical framework focusing on qualitative planning as well as quantitative performance metrics and other areas to track and control Virtual Design and Construction (VDC) and BIM use) stated Ethiopia's implementation of BIM was a conventional practice (without BIM).

Tesfaye (2020) also stated in her research that design management practice has limitations for coordination since 2D CAD design is used for clash detection. This practice is still persistent, and most entrenched 3D practices are solely utilized by architects who use the 3D BIM dimension for only 3D space visualization with the sole knowledge of operating the software. Knowledge of BIM authoring tools does not deduce BIM practice, which involves guidelines, standards, proper education, and training. Design information is still done through a paper-based approach, and a collaborative design with different engineering disciplines is not practiced thoroughly.

iii. <u>Sustainability</u>

As briefly stated in the previous section, the results show a lack of unambiguous practices with sustainability-based design concepts. It is difficult to declare a comprehensive strategy in the design phase of a building that considers the triple bottom line. Some consultants made efforts to improve the sustainability level of buildings. Selection of sustainable materials by the consultants is limited to proposals in the selection of energy-efficient fixtures, sourcing local materials and inputs from the society for the building input, and if materials are imported from outside the country, suggesting materials that have energy ratings by their manufacturers such as EnergyStar rated equipment. Nonetheless, interests wane as this sometimes has price implications and most private stakeholders are not interested in partaking in the approach. Investment in infrastructure is still increasing, and much emphasis is given to the economic parameter. At the same time, pre- and post-value analyses are done, but a significant impact on the social and environmental effects is made, mostly neglected factors.

To guarantee that a sustainable infrastructure is created, policymakers must build long-term visions for sustainable national infrastructure systems guided by the Sustainable Development Goals (SDG) and adaptive plans that can demonstrate that their vision is being realized. Implementing a building rating system such as LEED is a way to go.

iv. Building Performance Analysis – Present and Future

Most consultants are not familiar with building performance analysis and practicing building performance simulation tools. Although very few consultants stated simulating a building's performance, the information placed into the model and the expertise of the modeler is worth considering when discussing the accuracy of the model and the result of the simulation. Furthermore, these exercises are not incorporated with the practical design process as developing the software skills is more personal practice. From the case studies described in the previous sections, building projects that have practiced performance simulation are limited to a few performance aspects and done by an outsourced company outside Ethiopia. In summary, the results from the study showed that building performance simulation is not practiced by consultants in Addis Ababa.

The prospect of incorporating building performance analysis by consultants in the design stage is of high interest with energy use simulation, sustainability assessment, lighting simulation, and whole building thermal simulation.

v. Uncertainty In Design Parameters

The need to address physical and design uncertainties issues are preferred mainly in the conceptual design phases of the project, whereas scenario uncertainties are selected in the preliminary stages. Consultants will have a chance to identify the design objectives, desired space, and relationship of the building with the project site. However, based on the information processed and gathered during the design stages, there will be a preference at which stage the type of uncertainty will put forward a meaningful outcome. For example, considering the physical uncertainty regarding the physical properties of materials in the designed building may be difficult at the conceptual design stage as a sufficient amount of material/physical information may not be present.

Considering the uncertainty in design parameters may better suit the designer at either the conceptual or final design phase, depending on the project's context, to evaluate any design variations due to epistemic conditions in the planning phase.

vi. Mitigating Uncertainty

Local methods were primarily used for the few consultants who used uncertainty analysis during the design stages. These methods are used to investigate the quantitative effect of different sources of variation (physical parameters, models, and measured data) on the variation of the model output. These are applied for linear correlation between inputs and outputs, where the input parameters are sampled individually. Most of the consultants in the study saw the need to incorporate uncertainty analysis as being very important for the reliability of results.

vii. A Way Forward

The results showed that there is little to no practice in building performance analysis and simulation tools to prove the fulfillment of requirements and uncertainty analysis for performance by consultants in Addis Ababa. To close performance gaps, consultants believed the main focus on training and education should be given in the AEC industry, along with improvement of design and sufficient data collection. However, directives and frameworks from regulatory authorities may require a comprehensive study as this necessitates the active participation of knowledgeable professionals and qualified government, academic, and construction personnel.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

The general conclusions and recommendations are presented in this chapter based on the study findings, analysis, and discussions of data obtained from primary and secondary sources.

5.1. <u>Conclusion</u>

The research findings show that the understanding of building performance analysis and practice of performance simulation tools by consultants in Addis Ababa leaves much to be desired. The results suggest that the consideration of building performance during the design stage is not widely practiced. Therefore, it is concluded that;

1. Consultants do not exercise a comprehensive performance-based design approach to building projects. The main steps of identifying the user needs, transforming relevant information into performance requirements and quantitative performance criteria, and finally proving fulfilling the performance requirements are not done. One of the main reasons is that most of the projects in Addis Ababa have a prescriptive-based approach. It is commonly accepted to follow deemed-to-satisfy solutions to building design rather than a goal-oriented design strategy that focuses on performance-related factors like energy consumption, running costs, and occupant comfort, among other things. Consultants take a more straightforward prescriptive approach because of the demanding and complex process of the performance-based approach. Most consultants are engaged in designing conventional buildings and prefer a prescriptive approach since it is faster and less expensive.
2. Consultants use BIM authoring tools for 3D space visualization. The interoperability methods linking BIM and building performance simulation are at an intrinsic level. This restricted technique can only incorporate a few areas of building performance modelings, such as structural analysis, solar path analysis, and building orientation. Furthermore, BIM-based performance simulation is not a mainstream practice in the industry due to the infancy of BIM in Ethiopia.
3. Despite selective approaches to improve the sustainability aspect of a specific building, sustainability assessment of the building during the design stage is not

done to its full depth by consultants. Sustainability rating and certification systems are not made a requirement in building designs. There is a scarcity of precise methods involving sustainability-based design principles concerning the triple bottom line.

4. There is limited familiarity and little depth of understanding of building performance analysis by most consultants in Addis Ababa. Furthermore, consultants do not utilize building performance simulation tools for alternate design generation and optimal solutions in building design projects. Few consultants practice these tools to have software knowledge. Still, the information included in the model and the modeler's competence, understanding the theory of fundamental expertise in building performance should be considered when analyzing model correctness and simulation results. Unthorough consideration runs the risk of poor-quality input producing flawed output, i.e., garbage in, garbage out.
5. Consultants' consideration of addressing physical, scenario, and design uncertainties in the conceptual design phase may not be suitable. The information processed and obtained during the design phases may present a relevant consequence for which stage these uncertainties will be well suited for consideration.

5.2. <u>Recommendation</u>

Based on the research findings, the following recommendations are put forward.

1. The consultants and other participants of the country's AEC sector shall shift toward a performance-based approach to selective building projects in the city. Since the city is witnessing large-scale and mega-projects with a significant footprint and purpose to last several decades, a scheme on how these buildings will perform in the long run shall be considered. Many research showed a significant impact building has on the overall energy consumption, greenhouse gas emissions worldwide, and impact on land use and ecology. Though it might be a complex and demanding process, more optimal solutions shall be sought to improve the performance of buildings and evaluate how they will fulfill their function during the design stage and in construction and operation.
2. The Ethiopian Construction Management Institute (ECPMI) is the official Autodesk Training Center for BIM training and support in Ethiopia for tools

such as Revit, Navisworks, and Robotic Structural Analysis. The ECPMI should capitalize on the existing network with Autodesk to train in building performance simulation tools such as Autodesk CFD and Green Building Studio in total capacity and establish networks with other official companies that provide such tools. Several studies indicate that the combination of Building Information Modeling and building performance analysis optimizes building performance in the early design stage. Equipping professionals with the knowledge to utilize these tools will improve their performance to a greater extent.

3. The rating and certification systems used for sustainability assessment and the success achieved in developed countries shall be adapted to the culture, social and economic aspects related to production, operation, and modification of the built environment for the construction industry in Addis Ababa rather than a mere importation of existing methods. This involves a collaboration in research and development between the Ethiopian Green Building Council (EGBC) and the Ethiopian Standard Agency to evaluate respective LEED rating systems and contextualize them in the Ethiopian context. The government shall also support the Ethiopian Green Building Council to build its capacity as an institution.

5.3. Call for Further Research

Despite its capabilities in improving the performance of buildings, building performance analysis remains a relatively untouched subject in Addis Ababa or the Ethiopian construction industry context. The following potential calls for research are made to the academia and AEC industry.

- Assessment of building performance in other phases of a building lifecycle; such as construction and operation, for a different perspective,
- A study of building rating systems (such as LEED or BREEAM) in the context of the Ethiopian construction industry.

BIBLIOGRAPHY

Abdullah, L., Jumadi, N., Sabu, R., Arshad, H., & Fawzy, F. (2015). Assessment criteria on sustainable rating tools used in Asian countries. *Jurnal Teknologi 1(1),* 1-11.

Alani, Y., Dawood, N., Rodriguez, S., & Dawood, H. (2020). Whole Life Cycle Construction Information Flow Using Semantic Web Technologies: A Case for Infrastructure Projects. *In Proceedings 37th CIB W78 Information Technology for Construction Conference (CIB W78)*, (pp. 141-155). São Paulo, Brazil.

Al-Bakry, H., & Abbas, S. (2019). Towards a more relevance university campus with its biosphere based on LEED-Case study. *In IOP Conference Series: Materials Science and Engineering (Vol. 518, No. 2,)* (pp. 22-30). Baghdad: IOP Publishing.

Almeida, N., Sousa, V., L., A., & Branco, F. (2010). A framework for combining risk-management and performance-based building approaches. *Building Research & Information, 38(2)*, 157-174.

Anderson, B. (2006). *Energy performance of buildings directives.* Building Research Environment.

Asl, M. R., Zarrinmehr, S., Bergin, M., & Yan, W. (2015). BPOpt: A framework for BIM-based performance optimization. *Energy and Buildings, 108,* 401-412.

Augengroe, G. (2019). The Role of Simulation in Performance Based Building. In J. &. Hensen, *Building Performance Simulation for Design and Operation* (pp. 343-373). London and New York: Routledge.

Azhar, S., & Brown, J. (2009). BIM for sustainability analyses. *International Journal of Construction Educationand Research 5 (4)*, 276-292.

Azhar, S., Brown, J., & Rizwan, F. (2009). BIM-based sustainability analysis: An evaluation of building performance analysis software. *Proceedings of the 45th ASC annual conference.* Gainesville, Florida: Associated Schools of Construction.

Azhar, S., Brown, J., & Sattineni, A. (2010). A case study of building performance analyses using building information modeling. *In Proceedings of the 27th international symposium on automation and robotics in construction (ISARC-27),* (pp. 25-27). Bratislava, Slovakia.

Becker, R. (2008). Fundamentals of performance based building design. *Building Simulation (Vol. 1, No. 4),* 356-371.

Blyth, A., & Worthington, J. (2010). *Managing the Brief for Better Design.* Abingdon: Routledge.

Bragança, L., Mateus, R., & Koukkari, H. (2010). Building sustainability assessment. *Sustainability, 2(7).*

BS EN 15221-7:2012. (2012). *Facility management. Part 7: guidelines for performance benchmarking.* London: British Standards Institute.

Building acoustics measurement set. (n.d.). Retrieved May 08, 2022, from InnoRenew CoE: https://innorenew.eu/equipment/room-and-building-acoustic-measurement-set/

Building Research Establishment. (2019). *Post-Occupancy Evaluation*. Retrieved December 4, 2021, from Building Research Establishment: https://www.bre.co.uk/page.jsp?id=1793

California Commissioning Collaborative. (2011). *The Building Performance Tracking Handbook.* Sacramento, California: California Energy Commission.

Carbary, L., Stanley, Y., & Nick, B. (2014). Architectural insulation modules: Thermal and structural performance for use in curtainwall construction. *In Proceedings of the International Conference on Building Envelope Systems and Technologies* (pp. 9-12). Aachen, Germany: ICBEST.

Carvalho, J., Bragança, L., & Mateus, R. (2019). Optimising building sustainability assessment using BIM. *Automation in Construction*, 170-182.

Chaib, M. (2022). *What is the difference between simulation and modeling?* Retrieved May 18, 2022, from ResearchGate: https://www.researchgate.net/post/What_is_the_difference_between_simulation_and_modeling/62b7b0d291c04340d54366a6/citation/download.

Chainpoint. (2020, October 21). *Triple Bottom Line: measuring social and environmental KPIs*. Retrieved September 09, 2021, from Chainpoint: https://blog.chainpoint.com/blog/triple-bottom-line-measuring-social-and-environmental-kpis#:~:text=The%20so%2Dcalled%20triple%20bottom,perspective%20than%20financial%20results%20alone.utm_source=twitter

Chen, C.-J., Chen, S.-y., Li, S.-h., & Chiu, H.-t. (2017). Green BIM-based building energy performance analysis. *Computer-Aided Design and Applications, 14(5),* 650-660.

CIB. (1982). Working with the performance approach to building. *Report of Working Commission W60, Publication 64* (p. 30). Rotterdam, The Netherlands: CIB.

CIB, International Council for Research and Innovation in Building and Construction. (1982). *Working with the performance approach to building. Report of Working Commission W60, Publication 64.* Rotterdam, The Netherlands: CIB.

Clarke, J. (2015). A Vision for Building Performance Simulation: A Position Paper Prepared on Behalf of the IBPSA Board. *Journal of Building Performance Simulation*, 39-43.

Cochran, W. (1977). *Sampling techniques.* New York: John Wiley & Sons.

De Wilde, P. (2018). *Building Performance Analysis.* John Wiley & Suns.

Deru, M., & Torcellini, P. (2004). *Improving sustainability of buildings through a performance-based design approach (No. NREL/CP-550-36276).* Golden, Colorado: National Renewable Energy Lab.

Deru, M., & Torcellini, P. (2005). *Performance metrics research project - final report.* Golden, Colorado: National Renewable Energy Laboratory.

Efficiency Valuation Organization. (2012). *International Performance Measurement and Verification Protocol: Concepts and options for determining energy and water savings, Volume 1.* Washington, DC: Efficiency Valuation Organization.

Ethiopian Construction Project Management Institute. (2019). *Roadmap for adoption and implementation of BIM technology in the Ethiopian architectural, engineering and construction (AEC) industry.* Addis Ababa: FDRE Minstry of Urban Development and Construction: Ethiopian Construction Project Management Institute.

European Commission. (n.d.). *Energy performance of buildings directive*. Retrieved May 22, 2022, from European commission, official website: https://energy.ec.europa.eu/topics/energy-efficiency/energy-efficient-buildings/energy-performance-buildings-directive_en

Fahy, R. F. (1985). Building fire simulation model. An overview. *Fire safety journal 9(2)*, 189-203.

Fenton, N., & Wang, W. (2006). Risk and confidence analysis for fuzzy multicriteria decision making. *Knowledge-Based Systems, 19(6)*, 430-437.

Foliente, G. (2000). Developments in performance based building codes and standards. *Forest Products Journal*, 12.

Foliente, G. C., Leicester, R. H., & Pham, L. (1998). Development of the CIB proactive program on performance based building codes and standards. *BCE Doc, 98*, 232.

Getachew, B. (2016). *Role Of Building Information Modeling In Improving Building Design Process In Ethiopia.* (Master's Thesis, Addis Ababa Institute of Technology).

Getachew, N. (2018). *Performance of Construction Consultants in Addis Ababa: A Study of Current Practices.* (Master's Thesis, Addis Ababa Institute of Technology).

Gilb, T. (2005). *Competitive engineering: a handbook for systems engineering, requirements engineering, and software engineering using planguage.* Oxford: Butterworth-Heinemann.

Gillespie, K. L., Haves, P., Hitchcock, R. J., Deringer, J. J., & Kinney, K. (2007). *A specifications guide for performance monitoring systems.* Berkeley, California: Lawrence Berkeley National Laboratory.

Green Buildings International. (n.d.). *HQE | Sustainable Construction*. Retrieved April 30, 2022, from Green Buildings International: https://www.greenbuilding.saint-gobain.com/hqe-international

Grilo, A., & Jardim-Goncalves, R. (2010). Value proposition on interoperability of BIM and collaborative working environments. *Automation in construction, 19(5)*, 522-530.

Hamedani, A., & Huber, F. (2012). A comparative study of DGNB, LEED and BREEAM certificate systems in urban sustainability. *The sustainable city VII: Urban regeneration and sustainability, 1121*, 121-132.

Haute Qualité Environnementale. (2016). *HQE certification*. Retrieved May 2, 2022, from Haute Qualité Environnementale: http://www.behqe.com/

Hemsath, T., Goldsberry, M., & Yow, J. (2019). BIM and BPS: A case study of integration cost metrics and design options. In J. &. Hensen, *Building Performance Simulation for Design and Operation* (pp. 374-383). London & New York: Routledge.

Hensen, J., & Lamberts, R. (2019). *Building Performance Simulation for Design and Operation (2nd ed.).* London and New York: Routledge.

Hensen, J., Djunaedy, E., Radošević, M., & Yahiaoui, A. (2004). Building performance simulation for better design: some issues and solutions. *In Proceedings of the 21st Conference on Passive and Low Energy Architecture (PLEA)*, (pp. 1185-1190).

Hitchcock, R. J. (2003). *Standardized Building Performance Metrics Final Report.* Berkeley, California: Lawrence Berkeley National Laboratory.

Hopfe, C. J. (2009). *Uncertainty and sensitivity analysis in building performance simulation for decision support and design optimization.* Eindehoven, the Netherlands: PhD diss., Eindhoven University.

Hradil, P. (2014). *Barriers and opportunities of structural elements re-use. Research raport.* Espoo: VTT Technical Research Centre of Finland.

Hussein, J. (2011). *Assessment of Building Performance Measurement in Tanzania.* Stockholm: (Master's Thesis, KTH Architecture and the Built Environment).

Iliyasu, R., & Etikan, I. (2021). Comparison of quota sampling and stratified random sampling. *Biom. Biostat. Int. J. Rev, 10*, 24-27.

Imam, S., Coley, D., & Walker, I. (2017). The building performance gap: Are modellers literate? *Building Services Engineering Research and Technology, 38(3)*, 351-375.

Indian Green Building Council. (2015). *Green Building and Sustainable Architecture in India*. Retrieved May 2, 2022, from Indian Green Building Council: https://igbc.in/igbc/redirectHtml.htm?redVal=showAboutusnosign&id=about-content

International Council on Systems Engineering (INCOSE). (2015). *Systems Engineering Handbook: a guide for system lifecycle processes and activities.* San Diego, California: Wiley.

ISO 14031:2021. (2021). *ISO 14031:2021. Environmental management – environmental performance – guidelines.* Geneva: International Organisation for Standardization.

ISO 14040:2006. (2006). *ISO 14040: Environmental Management – Life Cycle Assessment – Principles and Framework.* Geneva: International Organization for Standardization.

ISO 6241:1984. (1984). *Performance standards in building – principles for their preparation and factors to be considered.* Geneva: International Organisation for Standardization.

Jin, R., Zhong, B., Ma, L., Hashemi, A., & Ding, L. (2019). Integrating BIM with building performance analysis in project life-cycle. *Automation in Construction*.

Keeney, R. L., & Gregory, R. S. (2005). Selecting attributes to measure the achievement of objectives. *Operations Research, 53(1)*, 11.

Kim, H. B., Kim, S., Oh, J., Park, J., & Lee, J. (2012). Influence of air-tightness on heat energy performance in post and beam building with exposed wood frame. *Journal of The Korean Wood Science and Technology, 40(5)*, 319-326.

Krygiel, E., & Nies, B. (2008). *Green BIM: successful sustainable design with building information modeling.* John Wiley & Sons.

Labate, L. (2016). *Metrics, Measures and Indicators*. Retrieved February 23, 2022, from Carebot: https://thecarebot.github.io/metrics-measures-and-indicators/

Lee Hansen, K., & Vanegas, J. (2003). Improving design quality through brief automation. *Building Research & Information*, 379-386.

Louis, C., Keith, M., & Manion, L. (2000). *Research methods in education.* London and New York: Routledge.

Lovas, G. G. (1994). Performance Measurements of Evacuation Systems. *In Fire safety science-Proceedings of the fourth international symposium*, (pp. 589-600). Oslo.

Mahdavi, A., Feurer, S., Redlein, A., & Suter, G. (2003). An inquiry into the building performance simulation tools usage by architects in Austria. 777-784.

Maria, A. (1997). Introduction to modeling and simulation. *In Proceedings of the 29th conference on Winter Simulation*, (pp. 7-13). Binghamton, New York.

Melaku, D. (2016). *The impact of glass facade on users comfort: the case of radiation vulnerable offices in Addis Ababa.* (Master's Thesis, Ethiopian Institute of Architecture, Building Construction and City Development).

Negendahl, K. (2015). Building performance simulation in the early design stage: An introduction to integrated dynamic models. *Automation in Construction, 54*, 39-53.

Nuramo, D., & Haupt, T. (2016). BIM for infrastructure sustainability in developing countries. *In Proceedings of the 20th CIB World Building Congress.* Addis Ababa.

Oliviera, L., Mitchell, V., & Badni, K. (2010). Using social network games to reduce energy consumption. *In 5th International Conference on Persuasive Technology Design for Change'. 7th-9th June* (pp. 1-8). Copenhagen, Denmark: IVA (Royal School of Library and Information Science).

Østergård, T., Jensen, R., & Maagaard, S. (2016). Building simulations supporting decision making in early design–A review. *Renewable and Sustainable Energy Reviews, 61,*, 187-201.

Oxman, R. (2006). Theory and design in the first digital age. *Design Studies, 27(3),* 229-265.

Oxman, R. (2008). Performance-Based Design: Current Practices and Research Issues. *International Journal of Architectural Computing, 6(1),* 1-17.

Said, H., & Berger, L. (2014). Future trends of sustainability design and analysis in construction industry and academia. *Practice Periodical on Structural Design and Construction, 19(1),* 77-88.

Saltelli, A., Tarantola, S., Campolongo, F., & Ratto, M. (2004). *Sensitivity analysis in practice: a guide to assessing scientific models. Vol. 1.* New York: Wiley.

Schuetze, T., Willkomm, W., & Roos, M. (2015). Development of a holistic evaluation system for BIPV façades. *Energies, 8(6),*, 6135-6152.

SEBoK. (2014). *The Guide to the Systems Engineering Body of Knowledge.* Hoboken, New Jersey: Body of Knowledge and Curriculum to Advance Systems Engineering/Trustees of the Stevens Institute of Technology.

Shi, X., Si, B., Zhao, J., Tian, Z., Wang, C., Jin, X., & Zhou, X. (2019). Magnitude, causes, and solutions of the performance gap of buildings: A review. *Sustainability, 11(3), 937*, 937.

Spekkink, D. (2005). *Final report on performance based design of buildings (Domain 3).* PeBBu Network. Rotterdam, the Netherlands: International Council for Research and Innovation in Building and Construction.

Sun, Y. (2014). *Closing the building energy performance gap by improving our predictions.* (Doctorial dissertation, Georgia Institute of Technology).

Tesfaye, B. (2020). *Design Management Using Building Information Modeling: In Case of Projects in Addis Ababa.* (Master's Thesis, Addis Ababa Institute of Technology).

Teshome, B. (2013). *Energy Conserving Electrical System Design and Performance Analysis for Commercial Buildings in Addis Ababa.* (Master's Thesis, Addis Ababa Institute of Technology).

TSI Energy Solutions. (n.d.). *Masonry Building Infrared Thermography*. Retrieved May 11, 2022, from TSI Energy Solutions: https://tsienergysolutions.com/infrared-electrical-inspection/masonry-building-infrared-thermography/

Tsimplokoukou, K., Lamperti, M., & Negro, P. (2014). *Building design for safety and sustainability, Number EUR, 27116.* Luxembourg: Institute for the Protection and Security of the Citizen, Joint Research Center, European Commission.

Tsimplokoukou, K., Lamperti, M., & Negro, P. (2014). *Building design for safety and sustainbility. Number EUR, 27116.* Luxembourg: Publications Office of the European Union.

Ugwu, O. O., & Haupt, T. C. (2007). Key performance indicators and assessment methods for infrastructure sustainability – a South African construction industry perspective. *Building and environment*, 665-680.

Van Dronkelaar, C., Dowson, M., Burman, E., Spataru, C., & Mumovic, D. (2016). Review of the Energy Performance Gap and Its Underlying Causes in Non-Domestic Buildings. *Frontiers in Mechanical Engineering*, 17.

Vanier, D. J., Lacasse, M. A., & Parsons, A. (1996). Modeling of user requirements using product modeling. *International Symposium on Applications of the Performance Concept in Building* (pp. 73-82). Ottowa, Ontario, Canada: National Research Council Canada.

VillarinhoRosa, L., & Haddad, A. (2013). Building Sustainability assessment throughout multicriteria decision making. *environment, 7(9),*, 11.

Walker, W. E., Harremoës, P., Rotmans, J., Van Der Sluijs, J. P., Van Asselt, M. B., Janssen, P., & Krayer von Krauss, M. P. (2003). Defining uncertainty: a conceptual basis for uncertainty management in model-based decision support. *Integrated assessment, 4(1)*, 5-17.

Wong, J., & Zhou, J. (2015). Enhancing environmental sustainability over building life cycles through green BIM: A review. *Automation in Construction*, 156-165.

Zanni, M., Soetanto, R., & Ruikar, K. (2017). Towards a BIM-enabled sustainable building design process: roles, responsibilities, and requirements. *Architectural engineering and design management. 13(2)*, 101-129.

Zimring, C., & Reizenstein, J. (1980). Post-Occupancy Evaluation: An Overview. *Environment and Behavior, 12(4)*, 429-450.

APPENDIX 1

Questionnaire Cover

Dear respondents,

Thank you in advance for taking the time to fill out this questionnaire. I am presently researching the practice of building performance and performance simulation tools in the Architecture, Engineering, and Construction (AEC) industry in Addis Ababa. This is brought to you seeking your earnest response, and your contribution will significantly help. This questionnaire comprises five (5) parts; Background Information, Design Approach, Building Information Modeling, Building Performance Analysis, and Bridging Performance Gap.

This research aims to study the current practices and extent of building simulation tools for the performance and sustainability of building projects. Ultimately the goal is to improve the local industry and benefit all partaking and non-partaking stakeholders.

DISCLAIMER:

I solemnly assure the information you provide here will remain confidential, and the information you provide will only be used for academic purposes. I kindly ask you to complete the questionnaire within seven days of receipt. If you have any questions, please do not hesitate to contact me.

Thank you for your time and cooperation.

Kind regards,

Michael Teshome Tekleyohannes

Graduate Student | Addis Ababa Institute of Technology

School of Civil and Environmental Engineering

+251-91-317-3131 | michaelttekleyohannes@gmail.com

Building Performance & Simulation Tools: A Survey

* Required

Part I: Background Information

The following questions will categorize entries based on your background and experience.

1. Name (Optional)

   ____

2. E-mail address/contact information for possible follow-up communication (Optional)

   ____

3. What is your profession? *

   Mark only one oval.

- ◯ Architect
- ◯ Civil Engineer
- ◯ Electrical Engineer
- ◯ Mechanical Engineer
- ◯ Plumbing Engineer
- ◯ Other: ________________________

4. How many years of experience do you have? *

   Mark only one oval.

- ◯ 0-3 years
- ◯ 3-6 years
- ◯ 6-9 years
- ◯ 9-12 years
- ◯ 15+ years
- ◯ Other: ________________________

5. What is the highest level of education you have received? *

   Mark only one oval.

- ◯ Bachelor’s Degree
- ◯ Master’s Degree
- ◯ Doctorate Degree

6. Please choose your involvement in the following selective AEC industry sector? *

Check all that apply.

- [ ] Consultants
- [ ] Academics
- [ ] Freelance
- [ ] Other: ________________________

7. Please specify the category in consulting services (as per Ethiopian Construction Authority) *

Mark only one oval.

- ( ) Grade 1
- ( ) Grade 2

Part II: Design Approach

This section covers the approaches during the design stage of building projects.

---

8. Do you/does your company create an exhausting list of user needs for building projects during the design stage? *

Mark only one oval.

- ( ) Yes
- ( ) No

9. Which of the following approaches do you use to express users' needs? *

Mark only one oval.

- ( ) Target oriented: express the request for specified achievement
- ( ) Fault preventive: express requests to decrease the risk of occurrence of faults that interfere with the building's purpose

10. Do you/does your company transform these user needs into performance requirements expressed qualitatively in physical terms? *

Mark only one oval.

- ( ) Yes
- ( ) No

11. Do you/does your company set performance criteria in a quantitative value of a set of physical factors to serve as a performance indicator? *

Mark only one oval.

- Yes
- No

12. Do you use simulation tools to prove the fulfillment of performance requirements explicitly? *

Mark only one oval.

- Yes
- No

13. Do you discuss and evaluate these findings with the stakeholders and decision-makers of the building projects? *

Mark only one oval.

- Yes
- No

14. Do you discuss and evaluate these findings with the stakeholders and decision-makers of the building projects? *

Mark only one oval.

- Yes
- No

Part III: Building Information Modeling (BIM)

This section covers information regarding Building Information Modeling (BIM) tools

15. Does your company organize and hold discussions between design teams (architects, designers, and engineers of different disciplines)? *

Mark only one oval.

- Yes
- No

16. Do you use BIM software tools in your field of work? (Some BIM software tools include Autodesk Revit, Autodesk Civil 3D, ArchiCAD, and so on) *

Mark only one oval.

- Yes
- No

17. Does your company organize and hold discussions between design teams (architects, designers, and engineers of different disciplines)? *

Check all that apply.

- ☐ 3D BIM - Geometry
- ☐ 4D BIM – Timeline and Scheduling Information
- ☐ 5D BIM – Cost Estimation Information
- ☐ 6D BIM – Sustainability
- ☐ 7D BIM – Facility Management

18. Which of the following BIM authoring software tools do you use? *

Check all that apply.

- ☐ ArchiCAD®
- ☐ Autodesk Revit®
- ☐ Autodesk Navisworks®
- ☐ BIMObject®
- ☐ BIMsight®
- ☐ Civil 3D®
- ☐ dRofus®
- ☐ Sketchup®
- ☐ Tekla BIMsight®

19. How do you acquire these software tools? *

Mark only one oval.

- ◯ Purchased through official vendors with a license
- ◯ Pirated through distributors

20. Does your office execute feasibility studies during the project design phase? *

Mark only one oval.

- ◯ Yes
- ◯ No

21. Do your office study the social, economic, and environmental implications of the projects you participate in? *

Mark only one oval.

- ◯ Yes
- ◯ No

22. Does your office prepare an Environmental Impact Assessment Report? *

Mark only one oval.

- Yes
- No

23. Does your office execute a sustainability design approach for projects in the design phase? *

Mark only one oval.

- Yes
- No

24. Have you participated in a project that took a sustainability-based approach? *

Mark only one oval.

- Yes
- No

25. If so, which aspects of improving the sustainability level of the projects were considered? *

Mark only one oval per row.

	Considered	Not Considered
Building Orientation		
Building Massing		
Daylight Analysis		
Water Harvesting		
Energy Modeling		
Sustainable Materials		
Material Conservation and Minimizing Waste		

Part IV: Building Performance Analysis

This section is concerned with information regarding building performance analysis/simulation

---

26. Is Building Performance Analysis a familiar concept in your field of work? *

Mark only one oval.

- Yes
- No

27. Have you taken any education related to Building Performance Analysis? *

Mark only one oval.

- ◯ Yes
- ◯ No

28. Are you familiar with Building Performance Simulation (BPS) tools? *

Mark only one oval.

- ◯ Yes
- ◯ No

29. Select your level of experience in *

Check only one box per row.

	Always	Often	Sometimes	Rarely	Never
Participation in design team meetings	☐	☐	☐	☐	☐
Use of BIM software tools	☐	☐	☐	☐	☐
Use of BPS software tools	☐	☐	☐	☐	☐

30. Do you use Building Performance Simulation (BPS) software tools in your line of work? *

Mark only one oval.

- ◯ Yes | Continue to question 31
- ◯ No | Skip to question 34

31. Are Building Performance Simulation tools employed in your office? *

Mark only one oval.

- ◯ Yes | Continue to question 32
- ◯ No | Skip to question 34

32. Which of the following BIM authoring software tools do you use? *

Check all that apply.

- ☐ Autodesk CFD®
- ☐ DesignBuilder®
- ☐ eQuest®
- ☐ Green Building Studio®
- ☐ IES™ Virtual Environment™
- ☐ OpenStudio®
- ☐ Sefaira Architecture®

33. Which of the following attributes do you simulate during the design phase? *

Check all that apply.

- [ ] Daylight assessment/sun path analysis
- [ ] Lighting simulation
- [ ] Thermal analysis
- [ ] Energy use
- [ ] Ventilation, airflow, and indoor air quality
- [ ] Design and sizing of HVAC simulations
- [ ] Sustainability assessment

34. Would you be interested in using Building Performance tools in the future? *

Mark only one oval.

- ( ) Yes | Continue to question 35
- ( ) No | Skip to question 36

35. Which of the following selective domains would you be interested in? *

Check all that apply.

- [ ] Energy use performance simulation
- [ ] Acoustical simulation
- [ ] Whole building thermal simulation
- [ ] Ventilation and indoor air quality
- [ ] Lighting simulation
- [ ] Sustainability assessment

36. What would you say is the most pressing challenge in the industry regarding implementing building performance tools? *

Check all that apply.

- [ ] Lack of teaching/Lack of awareness
- [ ] Budget constraints
- [ ] Unavailability of a licensed commercial software
- [ ] Lack of skilled professionals
- [ ] Other: ______________________________

Part V: Bridging Performance Gap

This section is concerned with issues related to uncertainties in building design and gaps in building performance.

---

37. Have you observed a significant difference in performance (predicted performance vs. actual/possibly measured performance) in any of the projects you have participated in? *

Mark only one oval.

- ⬭ Yes | Continue to question 36
- ⬭ No | Skip to question 39

38. What do you believe could be the underlying causes of the building performance gaps? *

Check all that apply.

- ☐ Limited understanding of early design decision impact
- ☐ Complexity of design
- ☐ Uncertainty in building modeling
- ☐ On-site workmanship
- ☐ Changes after design
- ☐ Poor commissioning
- ☐ Occupant behavior

39. At which design stage (DS) do you believe is appropriate in considering physical, scenario and design uncertainties? *

Check only one box per row.

	Conceptual DS	Preliminary DS	Final DS
Physical uncertainties	☐	☐	☐
Scenario uncertainties	☐	☐	☐
Design uncertainties	☐	☐	☐

40. Do you use uncertainty or sensitivity analysis techniques to alleviate possible performance gaps during design stages? *

Mark only one oval.

- ⬭ Yes | Continue to question 41
- ⬭ No | Skip to question 42

41. Which of the following uncertainty/sensitivity analysis do you utilize during the design stages? *

Check all that apply.

- ☐ Local methods: aimed at determining partial derivation of output related to input)
- ☐ Global methods: aimed at determining the uncertainty of specific input to overall output)
- ☐ Monte Carlo analysis
- ☐ Screening methods
- ☐ Variance-based methods

42. Do you see a need to integrate uncertainty/sensitivity analysis in the design stages of buildings? *

Mark only one oval.

- ◯ Yes
- ◯ No

43. Please rate the importance of uncertainty analysis during the design stage? *

Mark only one oval.

- ◯ Not at all important
- ◯ Slightly important
- ◯ Moderately important
- ◯ Very important
- ◯ Extremely important

44. Which of the following uncertainty/sensitivity analysis do you utilize during the design stages? *

Check all that apply.

- ☐ Data collection
- ☐ Directives and frameworks from the regulatory authority
- ☐ Design improvement
- ☐ Training and education
- ☐ Operational management

You have completed this questionnaire. Thank you for your time and input.