SCHOOL

OF

ARCHITECTURE URBAN PLANNING CONSTRUCTION ENGINEERING

(AUIC)

Thesis
in completion of
Master's Degree in Building and Architectural Engineering

Application of Building Performance Simulation and Multi-Criteria Analysis as supporting tools in the choice of building envelope components during early-design stage. Conventional and non-conventional technologies, The case of Tanzania

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Academic year 2018/19

In collaboration with

Constructability Research Institute, The ESTP Paris research department

under
Erasmus+ project

Acknowledgement

This thesis work has been made possible through a genuine support of many actors at institutional and individual capacities. We would, therefore, like to extend our heartfelt gratitude and appreciation to the following:

Our sponsor, the Italian Government under Ministero degli Affari Esteri e della Coorporazione Internazionale (MAECI) (The Ministry of Foreign Affairs and International Cooperation) for granting both of us scholarship without which this two-year Master programme would not have been undertaken.

Our promoters, Ambassador Roberto Mengoni and Miss Elena Galenca for their guidance, and support, before and throughout our studies.

Prof Gabriele Masera and all other professors and staffs at Department of Architecture, Built Environment and Construction Engineering of Politecnico di Milano for being ready to spear their time for consultation and providing materials of great importance in this study.

Our co-supervisors, Francesca Contrada and Andrea Kindinis, Associate Professors at ESTP, Paris, for their valuable time, guidance, consultations and providing materials throughout preparation of this thesis.

Arch Emmanuel Liombo, and Raymond Kasonga for their moral support and intellectual contribution during our thesis work; Mr. Fabian Kigadyc and all members of Energy department of the Ministry of Energy and Natural Resources; Mr. Dawi Mutayoba and Mr. Emmanuel Kijange of Dar es Salaam City Council Town planning department; Mr.Humri, Mr.Kabusinje of Ministry of Land for their time and basic materials for this work.

Our parents and relatives, for their continuous encouragement throughout our studies in Italy, and during our thesis work.

Our friends in Milan and Lecco, for their support and contribution throughout our stay in Italy.

Above all, we thank our almighty Lord for everything. We wouldn't have made this far if it hadn't been for him. It is regrettably impossible to mention all of whom we are indebted. To them, we say thank you.

Asanteni sana

Abstract

The building industry around the globe is facing an increasing demand on energy efficient buildings, with healthy indoor environment and low environmental impact. As a result, sustainability is becoming an important factor in design, construction and operations of buildings. However, sustainable or green goals isn't the only objective to be attained, a building project oftentimes, should respect other factors such as technical feasibility (structural integrity, fire safety etc), project management (time, cost, maintenance etc) and aesthetics. In order to respond to global objectives, a building project should therefore, be developed by applying a holistic approach, which incorporates a global performance on sustainability, technical and project management aspects. This approach should be applied in early stage of design, where decisions could highly influence the final intended performance and related costs.

Nonetheless, early-design stage represents a very volatile phase of a project. There is often, a rapid change of ideas, information is either uncertain or insufficient, requirements are sometimes conflicting, and time is always a scarce resource. As a result, decision-making process on design options becomes complex but crucial task among projects collaborators.

To enhance the decision-making process during early design stage, this thesis presents how two already existing tools: Building Performance Simulations (BPS) and Multi-criteria analysis can be used, in the specific context of Tanzania, to guide design choices. The suggested tools analyse the global performance goals or objectives (including sustainability, technical and project management methods), by providing a capacity to anticipate challenges of proposed solutions ahead in early design stage. The aim of this thesis is therefore, to help designers and other collaborators in the context of Tanzanian building industry, to compare and analyse the output performances of different design solutions and improve the collaboration by smoothen the decision-making process in early design stage.

In BPS, performance criteria chosen is energy demand (*cooling loads*). On the other hand, the multi-criteria analysis relies on seven criteria: *simplicity of solution, verifiability, skills availability, simplicity to manage, compliance with user-centric requirements, sustainability* and *cost efficiency* to evaluate and compare the sustainability and technical performances, as well as project management methods of design solutions in all stages of building life cycle. In this thesis, the two approaches are used to evaluate and compare the performance of building envelope components including *window size (WWR), shading devices,* and *four different climate-based designed opaque wall constructive systems*, for a mid-rise residential block in Dar es Salaam, Tanzania, a warm humid climatic context.

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Acronyms

AQRB	Architects and Quantity Surveyors Registration Board
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AQC	Agence Qualité de la Construction
BREEAM	Building Research Establishment Environmental Assessment Method
BIM	Building Information Modelling
BOT	Bank of Tanzania
CFD	Computational Fluid Dynamics
CRB	Contractors Registration Board
CIRIA	Construction Industry Research and Information Association
CII	Construction lndustry lnstitute
ERB	Engineers Registration Board
EPBD	Energy Performance of Buildings Directive
EPS	Expanded polystyrene
HQE	Haute Qualité Environnementale (High Quality Environmental Standard)
IRC	Institut de Recherche en Constructibilité (Constructibility Research Institute)
IDP	Integrated Design Process
LEED	Leadership in Energy and Environmental Design
NZEB	Nearly Zero Energy Building
NCC	National Construction Council
PCI	Processus de Conception Intégré (Integrated Design Process)
PPRA	Public Procurement Regulatory Authority
RIBA	Royal Institute of British Architects
SHGC	Solar Heat Gain Coefficient
TANESCO	Tanzania Electric Supply Company Limited
UN	United Nations
UHI	Urban Heat Island
UPM	Ultra-Photovoltaic Membrane
WWR	Wall to window ratio
WGR	Wall to ground ratio

Introduction

Building industry is one of the main contributors of greenhouse gas emissions and energy consumption around the globe. For example, according to G. C. Kazoora (2014), buildings account for more than half of the electrical consumption in Sub-Saharan Africa, with big cities consuming more than 75% of total electrical energy produced. In coastal-tropical and warm cities such as Dar es Salaam in Tanzania, the highest energy consumption in buildings is mainly for space cooling and ventilation (Ministry of Energy and Natural Resources, 2016).

According to Lall, Somik Vinay, et al. (2017), the number of people living in urban areas in Africa will double to more than 1 billion by 2042, with cities such as Dar es Salaam expected to have a population of 10 million by 2030. The increasing rate of urbanization, rapid population growth and climate change are some of the challenges which put pressure on the building industry across many cities in Africa. Among other aspects, this means, more energy will be needed to power buildings and more resources to provide for the construction materials. It is, therefore, important now, more than ever for stakeholders in the built environment to take initiatives that will contribute to the efforts in mitigating these challenges.

In other parts of the world, actions have already been taken to make sure that the building industry environmental footprint is reduced, while maintaining healthy indoor spaces for end-users. For example, according to the recast of the Energy Performance of Buildings Directive (EPBD), all new buildings in the European Union should be "nearly zero energy" buildings by 2020 (European Parliament and Council, 2010). Moreover, different certifications such as BREEAM, LEED and HQE have also been integrated in building practice in order to standardise how buildings sustainability performances can be analysed by considering a range of factors. While this practice is already becoming a norm in building industry mainly in other parts of the world, the situation is not the same in many countries across Africa, where the actions are really needed.

In Tanzania for example, despite the establishment of Green Building Council in 2014, which is responsible for putting in place a regulatory framework for buildings sustainability performance evaluation, the conventional building practice is yet to fully integrate the sustainability parameters into the building practice. As a result, architects and engineers, design and build, buildings which consume more energy than they should have, buildings with indoor discomfort for end-users and buildings with unmonitored environmental impacts during their entire life cycle.

Apart from sustainability setbacks, the building industry in Tanzania also faces other challenges associated with technical and managerial aspects of construction projects. To name, a few examples: late design changes and errors, poor project management, improper planning, defective workmanship, information delays, time and cost overrun. One of the approaches that project collaborators can apply to mitigate the risks associated with these challenges is the application of tools to assess the global performances of the proposed design solutions early in the design stage before construction or operation stages of a building.

Early design phase represents one of the most important stages of any construction project. At this stage, the design team has an opportunity to think about a range of parameters such as building form, construction materials, building services, envelope and structural technologies. Iteration of these choices can also be performed in order to allow for solutions that responds to the client's needs and the expected building performance objectives.

By assessing the performances of design solutions, one can understand, either sustainability, technical or managerial challenges that can be encountered later at the construction site or during operation stage of a building. In this way, a decision can be made, to either improve or change the design option early other than later. For example, the design team may opt for a design concept that favours automated control of daylight (e.g. advanced dynamic façade system), but later discovers that, the design solution will consume high amount of energy, and costly maintenance system. If this discovery is made in the early design stage, it will be easy to either improve it or change before moving on to later stages. In this way, challenges anticipated in the early stage of design are avoided in the later stages of a project.

Therefore, understanding and anticipating either the overall building or sub-systems (envelopes, structures, services etc.) performances during early design stage is highly crucial.

For this reason, the main objective of this thesis is to show how already existing tools can be adapted into Tanzanian context and therefore applied by architects and engineers, during early design stage to evaluate buildings and sub-systems sustainability and technical performances, along with project management methods. These tools are Building Performance Simulations (BPS) and Multi-Criteria Analysis.

By evaluating the performances of design solutions, architects and engineers can well understand if what they propose might work or not, and therefore make decisions to improve or change their design solutions during the early phases of building projects. In this thesis, these tools are applied to support choices of building envelope components including *window size (WWR), shading devices,* and *four different climate-based designed opaque wall constructive systems* for a mid-rise residential block in Dar es Salaam, Tanzania, a warm humid climatic context.

The application of these tools in building design is not new. In his 2006 editorial, Spitler stated that "The simulation of building thermal performance using digital computers has been an active area of investigation since the 196Os, with much of the early work focusing on load calculations and energy analysis. Over time, the simulation domain has grown richer and more integrated, with available tools integrating simulation of heat and mass transfer in the building fabric, airflow in and through the building, daylighting, and a vast array of system types and components. At the same time, graphical user interfaces that facilitate use of these complex tools have become more and more powerful and more and more widely used" (Jeffrey D. Spitler, 2006).

The European EPBD, actually mentions dynamic simulations, as one of the approaches that can be used in assessing the energy performance in buildings (European Parliament and Council, 2010). One should note that simulations do not provide the ultimate solution, however, they give an idea on how the real building performance might be. It is, therefore, not a substitute but rather a supporting tool that designers, researchers and engineers can work with in finding solutions for the required projects objectives.

Even though, the application of BPS is already becoming a norm in other building industries such as in France and Italy, the situation is not the same in Tanzanian, where the potentials and challenges are immense. It is therefore the interest of this study to show that, tools already applied in other contexts, can also be adopted and hence improve the overall decision-making process in design stages in Tanzanian building industry.

On the other hand, the multi-criteria analysis methodology is based upon a French concept called constructibility, which originates from two other known concepts called buildability and constructability. In the 80s, CIRIA defined *buildability as the extent to which the design of the building facilitates the ease of construction, subject to the overall requirements for the completed building* (Nielsen, J. et al., 2009) or simply *the practice to be adopted by designers to facilitate the building construction* (F. Contrada et al., 2019). *Buildability is therefore limited to only conception stage*. Later, the Construction lndustry lnstitute (CII) based at the University of Texas, Austin, defined *constructability as the optimum use of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall project objectives* (S. Khan, 2018). *Constructability extends to all phases of project's life cycle.* The constructability concept enhances buildability, extending the practice of sharing knowledge to the whole construction lifecycle (F. Contrada, 2019).

In both approaches, a set of guidelines, help designers, during the design phase of a project to understand issues related to the technicality of their proposed solutions which is important during construction and operation stages. By understanding the technical feasibility of the proposed solutions, a design team may be able to decide a definitive option by evaluating the best outcome performances. Therefore, these two concepts enhance a decision-making process among project collaborators using a performance-based approach.

However, in order to extend the performance-based approach with project management aspects of design solutions, a French Constructibility Research Institute (IRC), proposed in 2010 a new concept of constructibility, which employs a holistic approach in decision making process. By using this approach, project collaborators can anticipate a range of issues related to design solutions based on technical, sustainability and management aspects. It is in this context that; a multi-criteria analysis methodology was developed (F. Contrada, 2019). This methodology relies on seven criteria: *simplicity of solution, verifiability, skills availability, simplicity to manage, compliance with user-centric requirements, sustainability* and *cost efficiency* which can collectively analyse and compare the global performances of multiple design solutions, and therefore support designers and other collaborators in making decision.

However, one should note that, the multi-criteria analysis was not developed by the authors of this thesis, but rather it was developed at the IRC, which is a research department at ESTP, Paris where this thesis was partly conducted. The methodology was developed by Francesca Contrada in her PhD thesis (2019), where she proposed a new method of evaluation of different design alternatives, which also considers adaptability of technological innovation and associated risks on life cycle of building projects in both French and Italian building industries.

In this thesis, the proposed method is used and adapted in order to select the best building envelope design solution and support the decision in early design phase of a new building in the context of Tanzanian building industry.

The structure of the thesis is divided into two main parts:

i. State of the Art and Methodology
ii. Case Study and Application

The State of the Art and Methodology is composed of the following chapters:

1. Chapter 1: Life cycle of a building project and decision-making process in design stage
2. Chapter 2: Building envelope components and systems
3. Chapter 3: The Concept of Building Performance Simulations (BPS)
4. Chapter 4: Multi-Criteria Analysis assessment method
5. Chapter 5: Methodology Application Structure

The Case Study and Application is composed of the following chapters:

6. Chapter 6: Introduction to the case study
7. Chapter 7: Application of Building Performance Simulations to the case study
8. Chapter 8: Application of Multi-Criteria Analysis approach to the case study
9. Chapter 9: Final Architectural Design Solution

The first chapter is related to life cycle of a building project, in Tanzanian and international context. An observation on different stages of a building project, professionals involved, and challenges associated is made. A special emphasis is put on the design stage and associated challenges in decision-making process. A thoroughly investigation of integrated design and conventional design processes, is also performed. And finally, this chapter defines the problem under consideration and objectives of the thesis.

The second chapter investigates thoroughly the building envelope systems, roles performed by building envelope components, and the relationship between building envelopes and other building sub-systems. This chapter enlightens or justify the overall motivation of choosing building envelope design solutions as case study.

The third chapter introduces the concept of BPS. Important ideas related to BPS are unveiled including literature review on the topic.

In fourth chapter, the concept of multi-criteria analysis is introduced. All the seven criteria, sub-criteria development, indicators and the choice of sub-criteria aggregation method are elaborated.

The fifth chapter presents the overall approach on the application of methodology in this study. All the steps performed are introduced in this chapter.

In sixth chapter, a case study is introduced. It is important to keep in mind that the case study used in this thesis, is not an existing building, but rather a new design proposal, which was developed and designed by the authors. Likewise, four different opaque wall constructive systems are also introduced, together with an approach upon which these solutions are proposed and designed.

The seventh chapter explains the overall stages on how BPS is applied on a case study under consideration. Results are presented and compared.

Chapter eight shows how multi-criteria analysis can be used to analyse and compare the performances of four different opaque wall constructive systems under investigation. The results are also compared and explained. The final best performing wall system in comparison to the others is presented.

The last chapter introduces the final architectural design solution of the mixed-use development case study. Since the overall objective of the thesis is to show how BPS and multi- criteria analysis can be used by architects and engineers as supporting tools for design solutions, it is therefore, in the interest of this thesis to present the architectural design solution of the final building envelope components applied in the case study. Moreover, since the case study itself is not an existing building, therefore, the final architectural design solution of the overall case study is also presented in this chapter.

1. Chapter 1: Life cycle of a building project and decision-making process in design stage

This chapter examines the general approaches of building projects in Tanzanian, French and Italian building industries. The observation is made as already examined by F. Contrada in her PhD thesis work (2019), where she observed the life cycle of building projects in French, Italian and British building industries. The emphasis is put on the life cycle of building projects, responsibilities of multiple collaborators, and the overall decision-making process during the design process. Furthermore, since the interest of this thesis lies in design stage, an observation of different phases of design in building practice in each country is done. This allows for understanding the workflow of design process in different contexts.

In the sub-chapter of decision-making process during design stage, a concentration is put on the importance of collaborative approach during this stage and communication challenges associated with decision-making process.

This chapter is critically important, as it shades the light on the need to understand a building project in a global manner. This means, it is important to understand that all decisions made at each stage should be collaborative by involving multiple stakeholders, and by integrating and anticipating a range of parameters. For example, a building material chosen for a particular design solution during early design stage should consider the environmental impact during operation, and end of service life of a project. This can only be achieved, by involving multiple collaborators in early design stage.

And finally, conclusions of this chapter are highlighted, and the general objectives of the thesis are laid out.

1.1 Life cycle of a building project in Tanzanian and international context

1.1.1. Life cycle of a building project in Tanzania

Life cycle of a building represents the overall stages, a building project undergoes, from the very first stages to the end of service life. Each stage involves decisions which critically determine the overall global performance of the project in terms of budget, planning, technical and sustainability aspects. Since the practice in construction industry differ from one context to another, it is therefore important to observe and compare, the overall phases of a building project in Tanzanian and international context.

According to the National Construction Council (NCC, 2016) of Tanzania, under new bylaws, there are three stages, a construction project must undergo:

i. Decision to build
ii. Design phase
iii. Construction phase

In each phase of the project, multiple actors are involved, depending on the type of contract, project objectives and scale. According to NCC (2016), these actors can be grouped into the following categories or teams:

i. Finance and administration, consisting of employer or client of the project (individual, public or private organisation), insurance brokers for the construction site insurance, financial organisations such as banks and mortgage societies for financing the project.

ii. Design team, consisting of architect, quantity surveyor and other consultants.

iii. Construction team, consisting of contractor, sub-contractors, suppliers and clerk of works.

iv. Statutory control bodies, consisting of planning authorities, building control, fire department, environmental and other authoritative bodies such as AQRB, ERB and CRB.

In the first stage, a client starts by establishing the general project's objectives and requirements. In order to create strategies on the project, client may engage with either consultants (architects, quantity surveyors, projects manager, financiers) or contractor. The type and level of engagement between client and stakeholders depends on the type of contract (NCC, 2016).

Likewise, planning and environmental authorities may start to be involved to make sure that, the proposed project is in accordance to the state and local laws and guidelines before moving into design stage.

The design phase involves, the proposition of architectural and technical solutions according to project's specifications and program. Depending on the scale and objectives of a particular project, this stage may involve multiple collaborators such as the design team, construction team and statutory bodies and departments (NCC, 2016). For example, a big and complex project may involve more parties than a small and simple project. Or a high technical design solution may involve architects, engineers and manufacturers from the design and construction teams.

And finally, the construction stage includes all activities and works at the construction site, financial and technical monitoring, quality control till project delivery. The involvement of parties depends on the type of contract and project operation. Normally, the architect's responsibility is to supervise and make sure that, the executed works are in accordance with the intended design solutions (NCC, 2016).

1.1.2. Phases of design stage in Tanzania

As discussed in the paragraphs above, it is also important to understand how the design process work in Tanzanian building practice. The literature review conducted shows that the design stage can further be sub-divided into 3 phases based on 2013 RIBA plan of work. The reason for this is because, as an Anglo-phone country, most building practice regulations in Tanzania are based on British system. Based on 2013 RIBA plan of work, the following are phases of design stage:

i. Concept design
ii. Developed design
iii. Technical design

According to RIBA (2013), the core objectives during concept design stage includes proposals for architectural and structural design, building services systems, and preliminary cost information, all in accordance with initial project brief. At this stage, sustainability strategy or strategies are supposed to be defined, however, in Tanzanian building practice this is not done.

In the developed design stage, the proposed architectural, building services and structural engineering design solutions are further detailed, and project's costs are more elaborated in order to be aligned with project budget. Depending on the scale of the project, this process may involve multiple iterations as the design process evolves (RIBA, 2013).

During the final technical design stage, technical details in architectural solutions, structural technologies and building services are well elaborated, ready for the execution at the construction site. Although this work is done by design team, at this stage the specialist subcontractors' work on design is also developed and concluded (RIBA, 2013).

1.1.3. The feasibility of applying BPS and multi-criteria in design stage in Tanzanian building practice.

As seen in the above paragraphs, sustainability strategies are first defined during the concept design, and further elaborated in later stages. For example, according to RIBA (2013), the following are some of sustainability points that should be checked during the concept design stage:

- Have 'plain English' descriptions of internal environmental conditions and seasonal control strategies and systems been prepared?
- Has the environmental impact of key materials and the Construction Strategy been checked?
- Has resilience to future changes in climate been considered?

Although sustainability is yet to be integrated into Tanzanian building practice, 2013 RIBA plan of work shows that the sustainability strategies are defined in early stages of design.

However, early design stage such as the concept design represents one of the most volatile stages of building projects. The rapid generation of ideas, and possible solutions are sometimes involved with uncertainties while team members can be unfamiliar to each other's style of working. Information is either uncertain or insufficient, requirements are sometimes conflicting, and time is limited. As it is often the case, some team members might disagree on a possible course of action on either design solution, planning or cost related issues, which eventually might cost delays. As a result, the decision-making process in design stage, can sometimes be confusing.

Therefore, it is in the best interests of project collaborators to find an approach that can be used as a guideline on decision of design solutions in order to respond to the defined project objectives in a concise manner.

As previous expressed, in this thesis, two adopted tools: BPS and multi-criteria analysis, are presented to be used as supporting tools by project collaborators on decision-making process by evaluating the technical and sustainability performances, along with project management aspects of design solutions, in the early design stages of building projects. In this way, design teams can anticipate multiple challenges of proposed design solutions, to be encountered at the later stages of construction and operations, ahead before implementing them as final design solutions.

The use of BPS is proposed because it is one of the best ways to evaluate different sustainability parameters, such as building energy demands, and indoor environmental comfort. By performing BPS, especially in early design stage, a design team can make critical decisions on both passive and active strategies to apply in the project. And in this way, a decision on design solution is made based upon BPS and not the other way around. For example, if the objective of the project is to attain a highly natural ventilated building or an envelope solution with acceptable levels of daylight, visual and glare comfort, the best way to attain these objectives is to apply BPS during early stage of design. Based on the results of BPS, eg, form a building, shading devices, WWR, an architect will start to implement design solutions and not vice versa. As the design process continues, the iteration of BPS and implementable design solutions may still be conducted in order to allow for best results based on project objectives.

In Tanzanian building practice, the conventional consulting services such as quantity surveying, structural engineering and service engineering are conducted at the design stage of a project. This means that, under normal circumstances, the building practice in Tanzania allows for different consulting services in design stage, as long as the involved parties have agreed in the contract. However, since the awareness on building sustainability performance is still low, there are no sustainability consulting services. This represent both an opportunity and a challenge at the same time. It is challenging because, in the conventional building practice, consultants and contractors always make decisions based on client's requests, regulations and budget, and not on sustainability performance.

From another perspective, this represent an opportunity especially on regulators and professionals across the building industry. It is time for responsible authorities to put sustainability at the core of the building business, by establishing mandatory laws and regulations. Awareness should be raised across clients and professionals. This will pave a way for designing high performance buildings and conducting the construction business in a sustainable manner, and the use of BPS can be of critical importance in attaining this objective.

On the other hand, sustainability isn't the only performance that needs to be evaluated. The technical feasibility and project management methods of proposed design solutions are equally important. This is where, the multi-criteria analysis methodology comes in. It employs a global analysis of not only sustainability performances but also technical performance and project management methods of proposed design solutions. In this way, a design team can make decisions based on all three equally important parameters: technical, sustainability and project management aspects. The methodology employs seven criteria including: simplicity of solution, verifiability, skills availability, simplicity to manage, compliance with user-centric requirements, sustainability and cost efficiency in evaluating the global performance of different design solutions. The methodology is based on the fact that, one can anticipate both technical and management challenges of proposed design solutions ahead, and therefore decide to continue with highly performing option or improve the available ones.

1.1.4. Life cycle of a building project in France and Italian building industries

After observing the Tanzanian building practice, the next step is an observation of stages of building projects in France and Italian building industries.

F. Contrada (2019) mentions that in France, law n°85-704 of 12 July 1985, defines the principle stages of project's organisation, and mandates the interaction of different actors involved in the project . According to this law, client is the owner of the project, and may entrust a consulting architect with all or part of the design, and assistance on all studies related to project, construction and operation.

The following represents the overall stages of construction project in France:

i. Project feasibility studies
ii. Design
iii. Construction
iv. Operation
v. End of service life

The first phase involves preliminary site studies and definition of project's requisites in order to establish a design program. During this phase, a complex urban project may involve consultants such as architects and urban planners, while a small-scale project may involve fewer actors.

In the design stage, design and technical experts from either consulting firm or contractor proposes different architectural and technical solutions in correspondence to the project's needs.

The construction stage involves all site works until the delivery of the project. It is the responsibility of design consultants to make sure that, the realised works are in accordance to design solutions.

During operations, the building is in use. In this stage, different interventions such as maintenance and/or replacement works are common. These types of interventions may be done by the building owner or operator depending on the type of contract.

The last phase includes all activities related to demolition of the building, waste treatment, recycling and rehabilitation of the construction site if any. It can be done by special contractor or by the owner.

1.1.5. Phases of design stage in France

In France the design process can further be sub-divided into the following phases:

i. Feasibility studies/design program
ii. Detailed design
iii. Planning of construction

In the first phase, different feasibility studies on the project are conducted, early design solutions are proposed, and cost estimations are also done. Likewise, documents which contain information such as architectural and technical descriptions of a project, materials, surface distribution, cost estimation and planning are prepared (F. Contrada, 2019).

In the second phase, architectural plans and technical details are further developed and elaborated.

The planning phase elaborates the administrative, financial and technical operations of the project. During this phase, the general planning of different activities and interventions by contractors are prepared.

1.1.6. Phases of design stage in Italy

In Italy, the emphasis is put on the design stage, whereby according to the law dlgs 50/2017 (*Codice Appalti*) which regulates the public works, the design stage is divided into the following phases:

i. Progetto di fattibilità tecnica ed economica (technical and economic feasibility studies)
ii. Progetto definitivo (definitive design)
iii. Progetto esecutivo (execution design)

In the first phase, different feasibility studies are conducted. Depending on the scale and type of project, these studies are related to architectural, technical, environmental and economic aspects of a project. Moreover, different documents are also prepared containing information such as technological solutions proposed in the project, building services, environmental and site impact assessment, economic feasibility of the project, performance of proposed solutions and estimated energy consumption (F. Contrada, 2019).

In definitive design phase, all the technical and architectural design solutions are further elaborated.

The last stage represents all activities related to documentation of architectural and technical design solutions for execution operations.

1.1.7. Concluding comparison of life cycle of building projects in observed countries

Apart from cultural differences that may slightly influence the construction process, in all three contexts, it can be observed that there is not so much differences in terms of approaches used during building's life cycle. Although there are different names in each context, the phases and goals during the design process are basically the same. As already observed, mainly, there are three steps a project must undergoes during the design stage:

i. Preliminary phase: in which studies are conducted, strategies are defined, and first design ideas are implemented

ii. Second phase: where design solutions are more elaborative

iii. Last phase: where design solutions are definitive and ready for execution

Therefore, as proposed in this thesis, BPS and multi-criteria analysis can be applied in the preliminary phase of design. This is where, the design team clarify among other strategies, the sustainability parameters that can later influence the design solutions in the later stages of design. Moreover, it is in this stage, where the first proposals of structural and other technical solutions are made.

1.2 Design approaches: Integrated Design Process versus Conventional Design Process

As already observed, design process involves a series of steps with defined objectives and tasks to be accomplished by different collaborators in a design team. As the project evolves, these objectives determine the overall building performance. In order to ensure building performance-based approach, inter-disciplinary project collaborators need to be involved through an integrated design process (IDP).

In 2007, B. Perkins et al., defined IDP as "*an approach to building design that seeks to achieve high performance on a wide variety of well-defined environmental and social goals while staying within budgetary and scheduling constraints. It relies upon a multidisciplinary and collaborative team whose members make decisions together based on a shared vision and a holistic understanding of the project. It follows the design through the entire project life, from pre-design through occupancy and into operation*" (B. Perkins et al., 2007).

In a conventional design process, decision making process is linear, as expressed by Pearl in 2004 who stated that "*In conventional design, the architect (or designer) and the client agree on a design concept consisting of a general massing scheme, orientation, fenestration, and the general exterior appearance of the building. Then the mechanical, electrical and structural engineers are asked to implement the design and to suggest appropriate systems. The problem with conventional practice is that this design process is too quick and simple, often resulting in high operating costs, poor comfort performance and very few sustainable gestures that fall within the client's restrained budget*" (B. Perkins et al., 2007).

Based on the scale of a project, conventional design process involves traditional project team members, who oftentimes start to be fully involved in a project during the late stages of design and construction. As mentioned in a second edition of ASHRAE Green Guide (2006), this team may include:

- Owner
- Architect/ Project manager
- Cost estimator
- HVAC engineer
- Plumbing/fire protection engineer
- Electrical engineer
- Lighting designer
- Structural engineer
- Landscaping/site specialist
- Civil engineer
- Code enforcement official

This is well presented in the figure below:

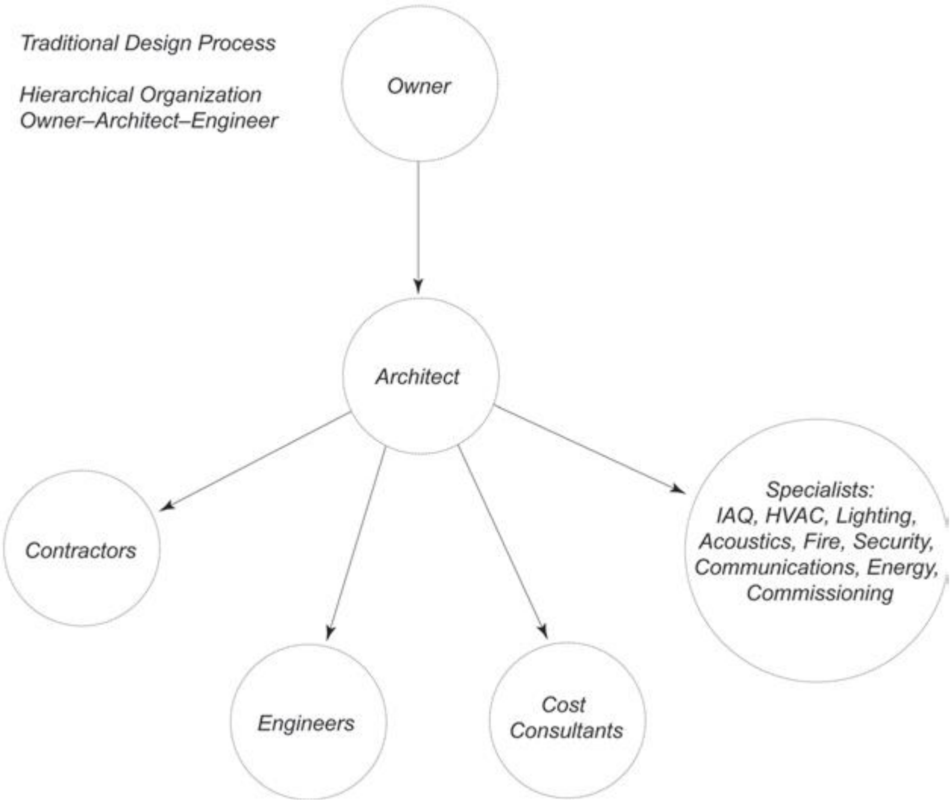


Figure 1 Traditional Project Design Team Adapted from ASHRAE(2009)
Source: ASHRAE Design Guide (2011)

However, IDP is often used to design, build and operate sustainable, and high performance buildings, which require involvement of more stakeholders like *building users or occupants, operators, green buildings commissioning authorities* and specialists such as *Energy analysts* and *Environmental design consultants* who will work closely with other collaborators in order to implement both passive and active sustainable design solutions, early in the design stages of a project. For example, early after an architect proposes the general conceptual design of a building e.g. a form, an *Energy analyst* can use energy and daylighting modelling tools, to analyse energy or daylight optimisation parameters that may influence the final design features such as building form, architectural solutions, mechanical and electrical systems. In this way, an architect may improve the initial design ideas based on the recommendations from an energy analyst.

On the other hand, an *Environmental design consultant* may be involved with implementation of sustainable and green features, such as sustainable site design, water and waste recycling, renewable materials, durability, envelope design, renewable energy and transportation. In this way, he/she can provide recommendations to the design team on how to integrate sustainable solutions in a project, and eventually contributing to the final project performance. It is in fact, through an integrated design approach, the application of BPS and multi-criteria analysis proposed in this thesis could be highly effective.

IDP is therefore, a form of collaborative approach whereby a multi-disciplinary team starts to be involved in a project, early in the design phase, in order to achieve the required functions and objectives through multiple iterations. This concept is well represented in the figure below:

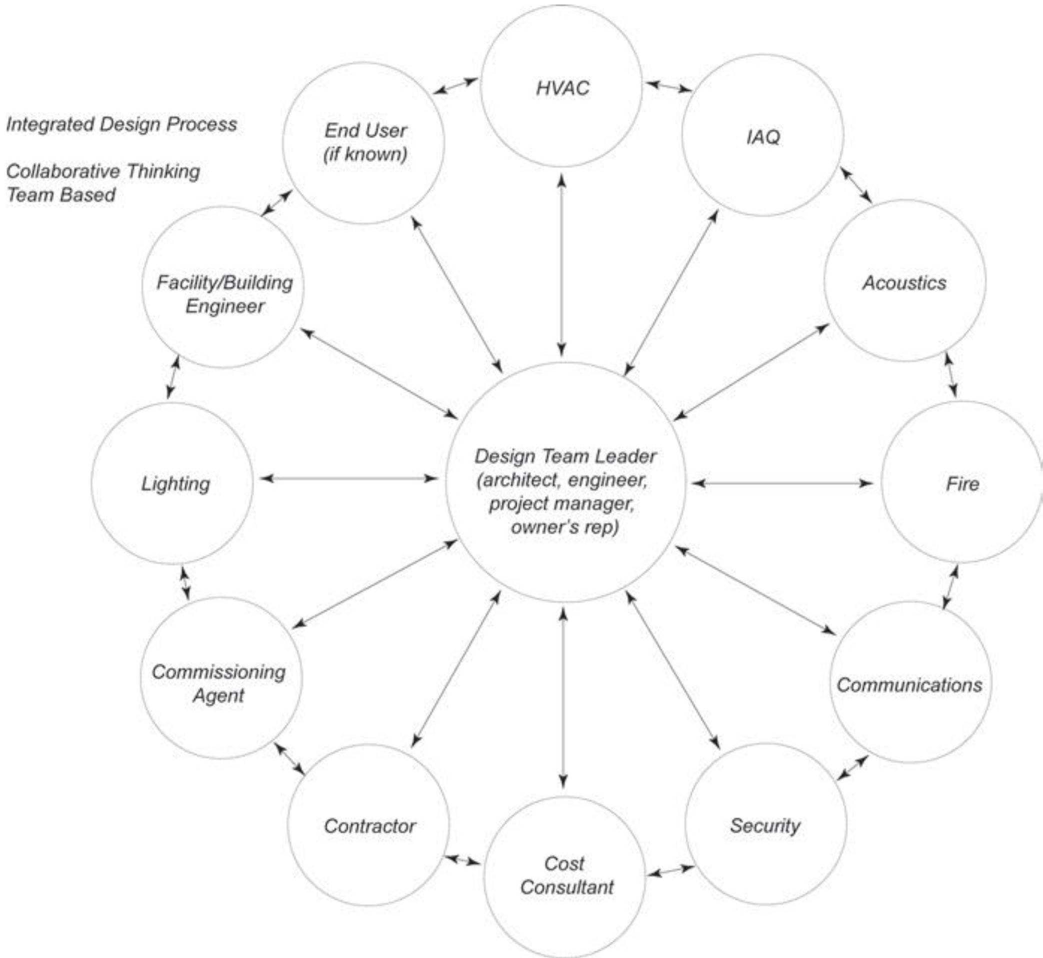


Figure 2 Integrated Project Design Team Adapted from ASHRAE(2009)
Source: ASHRAE Design Guide (2011)

By involving multiple collaborators early in the design process, the possibility of attaining high performance and cost-effective project is elevated. This concept can be illustrated by using a figure below called *MacLeamy curve* which shows the relationship between stages of a building project and either the efforts applied by project collaborators or the overall project variables such as performance, cost, schedules in both conventional and integrated design processes.

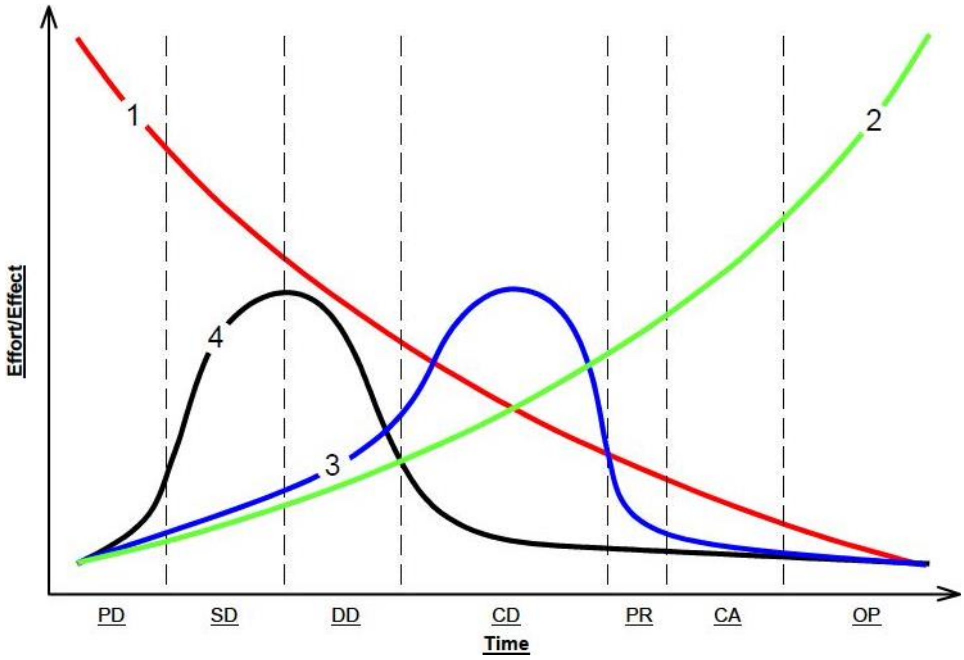


Figure 3 The MacLeamy Curve
Source: Architectural/Engineering Productivity Committee of The Construction Users Roundtable (CURT) (2004)

1	:	Ability to impact cost and functional capabilities	PD	:	Pre-design
2	:	Cost of design changes	SD	:	Schematic design
3	:	Traditional design process	DD	:	Design development
4	:	Preferred design process	CD	:	Construction documentation
			PR	:	Procurement
			CA	:	Construction Administration
			OP	:	Operation

As explained by the Architectural/Engineering Productivity Committee of The Construction Users Roundtable (2004):

- The red line (line 1) represents the team's decreasing ability to affect project variables such as cost, schedule, and functional capability as the project progresses.

- The green line (line 2) shows how the cost of making changes dramatically increases as the project progresses.

- The blue line (line 3) represents the distribution of design effort in a traditional building project, when design information is developed most substantially in the construction document phase.

- The black line (line 4) suggests a new distribution of design effort under a full collaboration model, where substantial information is collected, integrated, and documented earlier in the design process due in part to the input and collaboration of all stakeholders. The red line depicts the critical concept of earliest possible decision making to maximize the ability to effect change and minimize the potential cost of design changes (particularly those caused by mis-integration of design information)

Despite the positive potential of applying IDP, still, many building practices, all around the world prefer to use the conventional design process which they are used to. This may also be attributed by the fact that construction in general is still one of the most traditional industry, which is resistant to technological innovations. Moreover, as shown in the MacLeamy curve, IDP is mostly effective when collaborators start to make decisions in the early design stage, which is really challenging as time is often limited, and requirements are sometimes conflicting.

Nowadays, the application of BIM is increasingly becoming an important tool among project collaborators. By using BIM, information can be shared easily among collaborators, and, hence improving the decision-making process. However, BIM is widely and effectively applied from the second stage of design onwards, where decisions on design are already made, and therefore can be too late (F. Contrada, 2019).

1.3 Conclusion of chapter 1, Problem definition and Thesis Objectives

Life cycle of a building project involves a series of stages that are accompanied by specific tasks in order to attain the final building performance and objectives. Each stage involves multiple collaborators whose responsibilities may vary depending on the scale of the project and the type of contract agreed between involved parties. Decisions taken at each stage are critically important, however, those taken during early design stage have an opportunity to shape the overall project ahead, the reason why early design represents the most critical stage of any project.

At the early design stage, decision-making process can be chaotic or confusing due to involvement of many parties, uncertainties on input information, conflicting project requirements and lack of time. As a result, designers end up proposing solutions without analysing and anticipating the challenges that can be encountered in later stages of construction or operations of the building. This is often the case in traditional design process whereby, only architect and client are involved early in the design process. In contrary to IDP, which involves collaborative approach among multi-disciplinary team members early in the design process. In this way, a project is designed, built and operated using a performance-based approach.

This thesis presents two adopted tools : BPS and multi-criteria analysis, that can be applied in the early design stage in order to help project collaborators in Tanzanian building industry including designers and engineers to make decisions based on performance (technical and sustainability) of proposed design solutions and project management methods. By applying BPS, one can understand the performance of proposed design solutions based on the required output, and therefore decide on either to improve or change before making the final design solution in later stages of design. On the other hand, by applying multi-criteria analysis, one can evaluate and compare the technical performances and project management methods of proposed design solutions.

By using these two approaches, project teams, will be able to answer the following fundamental questions:

- How will the proposed design solution (e.g. building envelope) perform on the required sustainability objective (e. g indoor thermal comfort)?

- What kind of technical challenges will the proposed design solution pose during execution at the construction site?

- What kind of challenges will the proposed design solution pose during project management, for example will it be difficult to maintain? Is a design solution user-friendly to the occupants? Is a design solution cost-effective?

The objective of this thesis is therefore, to help designers and engineers involved with projects in Tanzanian building industry, be able to answer to these kinds of questions, early in the design stage and not later. In this thesis, the focus has been put on applying these tools to support architects on making decision on building envelope components solution, the reason why the next chapter concentrates on understanding the overall concept of building envelope components and systems.

2. Chapter 2: Building envelope components and systems

This chapter examines the general approaches related to building envelope components and systems.

In the first sub-chapter a relationship between building as a system and building envelope as a sub-system is observed. The next sub-chapter enlightens different components of building envelopes and what role they perform in a building in general.

Different typologies of building envelopes are next introduced, followed by an introduction to variable materials that are conventionally applied in building envelope systems.

Apart from just physically separating an indoor and outdoor space, building envelope plays other roles as they're explained in the fifth sub-chapter.

In the final sub-chapter, a critical role that a building envelope can play in contributing to the building energy efficiency is observed by using a case study.

2.1 The concept of building envelope

Building envelope includes the surfaces and components that provide the physical separation between the conditioned, inside space and the unconditioned, outside environment. These components can be floor slab, wall assembly systems, roofing system and glazing.

The function of building envelope is to physically separate the interior of the building from the exterior environment. Therefore, it serves as an external protection to the indoor environment while facilitating as climate control at the same time (Daniel Asinjo, 2018).

According to its design and location, building envelope can perform other functions such as: transmitting building permanent (dead) and variable loads (wind, snow, seismic loads), regulate energy flow between indoor and outdoor environment, control natural lighting and visibility and lastly regulate ventilation of indoor environment.

Different literature has breakdown the relationship between buildings and building envelopes. For example, F. Contrada (2019), considers building as a system, and this system is composed of multiple sub-systems according to functions. These sub-systems may include building structure, building envelope and building services among others. The sub-system is sub-divide into components. For example, components of building envelope include roof, ground floor, opaque and transparent walls. These components are further sub-divided into elements. For example, a multi-layered concrete opaque wall may be composed of various elements such as insulation, concrete block, internal and external finishing. Lastly, these elements can further be sub-divided into materials. For example, insulation can either be made of mineral, synthetic or biodegradable materials. The figure below represents this breakdown relationship.

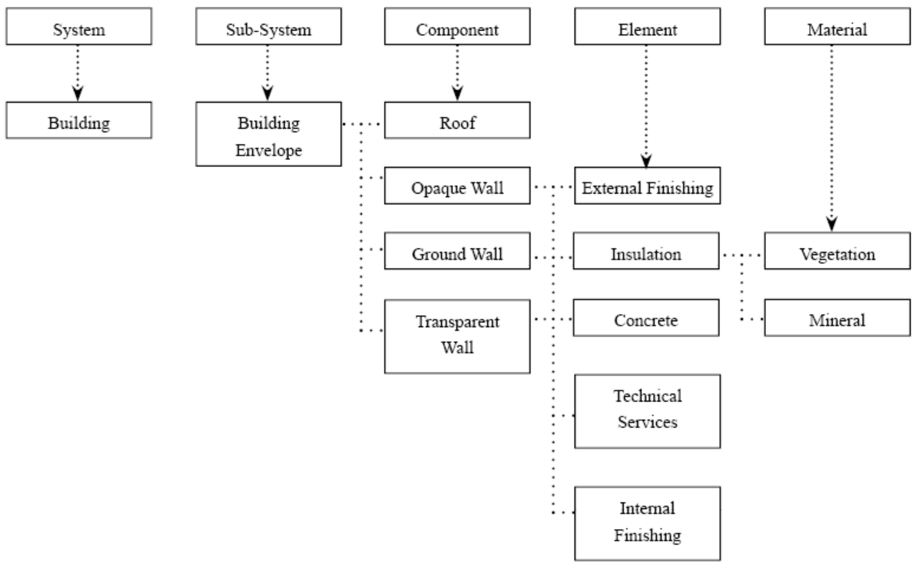


Figure 4 Example of breakdown relationship between building and sub-systems
Source: Modified from F. Contrada (2019)

2.2 Types of building envelope systems

Buildings envelopes can be divided into opaque and transparent categories depending on the materials applied. Transparent envelopes are mainly composed of curtain wall systems and windows, while opaque envelopes include cladding systems, monolayer and multi-layered opaque envelope systems. Moreover, the advancement made in materials and technology in the building industry has allowed designers and engineers to design and build advanced forms of building envelopes such as dynamic façade systems and switchable glazing windows among others.

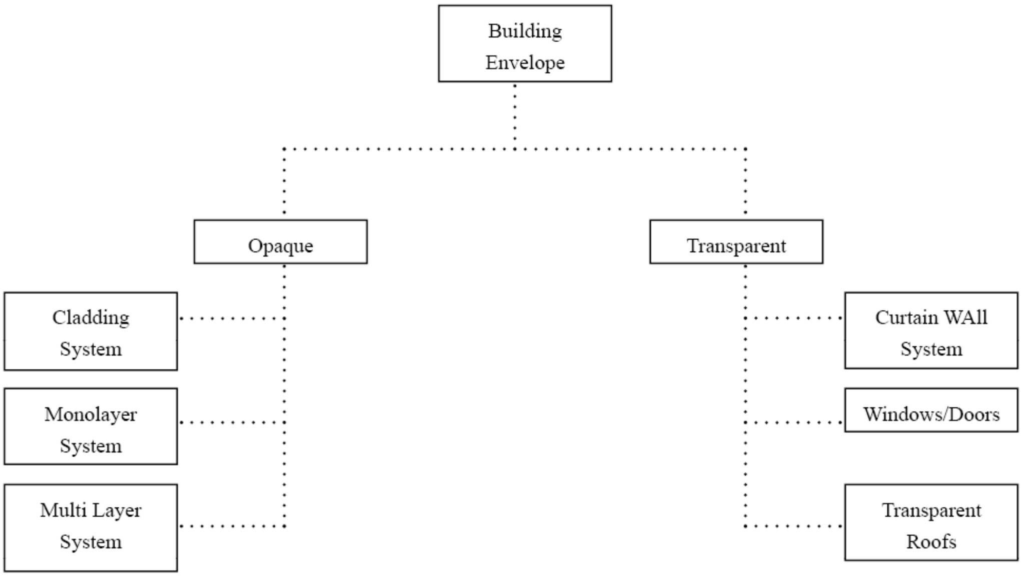


Figure 5 Types of Building Envelope Systems

2.3 Materials for building envelope

Building envelope materials depend on climate, culture, materials and technology availability. Common materials are used to form the building envelope structure and contribute to the structure by having long lasting, insulating, water repellent, sound blocking, and light filtering characteristics. Common roof materials include asphalt, composite, wood, metal, clay, slate, and rubber. Typical wall materials include brick, stone, stucco, glass block, wood, concrete, and vinyl. A floor or ground slab may consist of stone, brick, wood or concrete. Window frames and doors share common materials such as aluminium, composite, fiberglass, vinyl, and wood. Specialty coatings and tints, along with gases, are commonly applied to any glass on both windows and doors.

2.4 The roles performed by building envelope

Apart from just physically separating the interior from exterior, building envelopes can play other roles in the building. According to Cartier-Bresson Henri, building envelope can perform multiple functions such as: control of the flow of matter and energy, which is done with both active and passive means, support of structural loads, and protection against weather patterns elements such as rain.

The building envelope also serves to control air flow and humidity in and out of the building. Windows and skylights that can be opened and closed are perhaps the most obvious examples of envelope components that can be used to control air flow and humidity which is found in the air.

Building envelope also serves as the primary means of controlling the inside temperature. Envelope components that serve this function range from concrete panels and reflective surfaces to thermal breaks and insulation. A figure below summarizes different roles that can be played by building envelope.

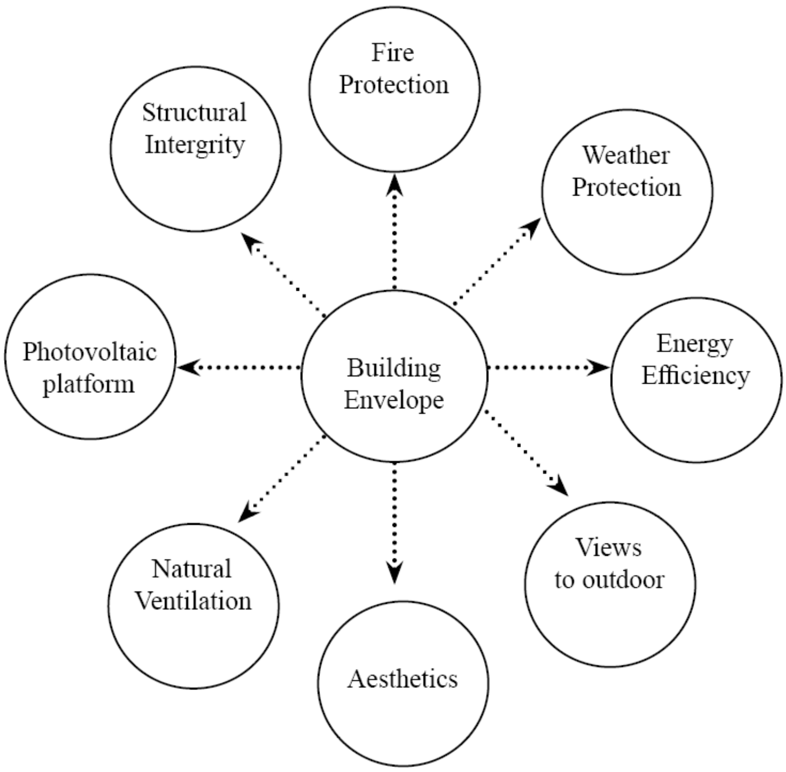
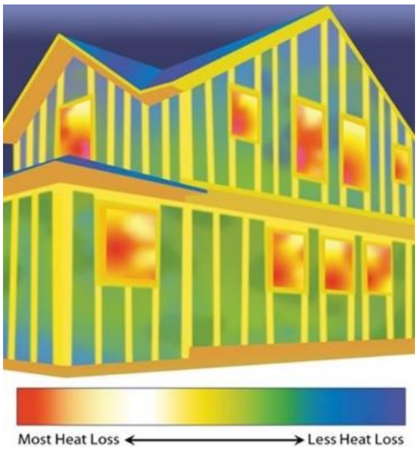


Figure 6 Roles performed by building envelope



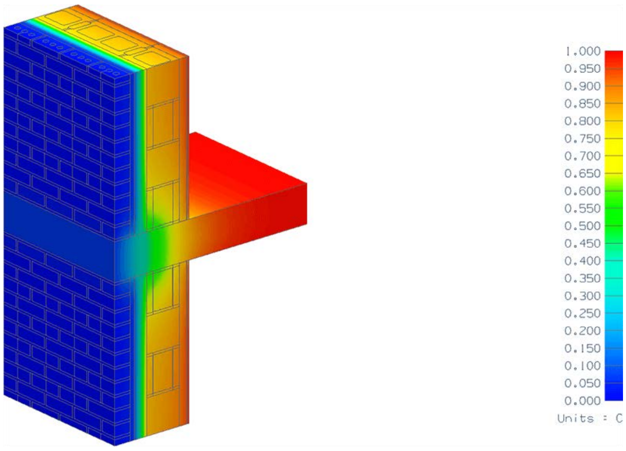


Figure 7 Heat gains and losses across the building envelope components

Figure 8 Temperature gradient across a wall

Source: Cartier-Bresson Henri (2017)

2.5 Building envelope and energy efficiency in buildings

As already seen in the earlier paragraphs, building envelope can control passage of energy, air flow and water vapor in and outside the building. This in turn has paramount effect on the energy performance of the building itself. Therefore, building envelope can be considered to be the main constructive element of a building to meet the requirements of energy efficiency and indoor comfort. The type of system, the design and the right execution of the envelope are critical aspects that determine the final energy consumption of the building. K. Sudhakar et al. (2019), estimated that between 20% and 50% reduction in total energy consumption could be achieved by implementing appropriate building envelope design. However, it is important to note that envelope design depends on aspects such as climate, availability of materials and technology, costs and objectives of a particular project.

In hot climatic regions, such as coastal areas of Tanzania, high level of solar radiation across the building envelope contributes highly to the high cooling energy demands to maintain indoor comfort. Therefore, if well designed building envelope can dramatically improve energy efficiency in the region.

An example is hereby presented on how a building envelope technology was applied to improve energy efficiency of a building. As it is already known that ventilated façades can play a huge role in reducing energy demands of a building, especially in summer, by allowing natural or mechanical forced air flow. The air flow reduces heat and moisture transfer across the building envelope. Today, the conventional ventilated facades are composed of an inner sheet, thermal insulation, ventilation chamber and exterior finish. However, two researchers from the group of Tecnología Edificatoria Medio Ambiente (TEMA) at UPM have developed a new system of ventilated façade whereby a second air chamber is added between the existing one and the facade insulation (Bonanomi, M. 1990). Both chambers are interconnected at the bottom of the facade. Another feature is a new element at the top to regulate the airflow in the chambers, depending on the gradient of the existing temperature between inside and outside the building.

This presents two improvements over conventional systems. Energy gains-losses are reduced through the facades, and consequently, the energy consumption due to air flow. Secondly, the design of the system helps to reduce the vertical temperature gradient along the envelope, homogenizing the air temperature in the chambers throughout the year.

By minimizing the vertical thermal gradients, global consumption due to energy gains-losses through the facade depends less on the height of the building, preventing the upper houses to present higher or lower indoor comfort and degree of energy efficiency than the lower houses. Additionally, this system is a sustainable and efficient solution that can be applied in both rehabilitation works and new buildings due to its simplicity of implementation.

The initial cost can be short-term amortized by accounting for the remarkable energy savings of this design. The authors of this work states that, "This research work highlights the potential energy efficiency of buildings through the redesign of conventional construction systems."

2.6 Building envelope and renewable energy potential - Enhancement of facades for the solar PV potential of high-rise buildings

In an era of growing urbanization when most of energy demand is concentrated in cities, energy sustainability requires that a significant fraction of this energy demand can be fulfilled with local, clean and abundant sources of energy. As it has been highlighted by Hernandez, solar power is an unavoidable piece of the fabric of sustainable cities; solar power is plentiful in most regions of the globe, it is a renewable source of energy and CO_2 emission free.

However solar power has relatively low energy densities, thus requiring considerably larger areas to produce relevant amount of electricity. As modern cities are characterized by high density populations, living in high rise buildings, the available roof area becomes in short supply for solar power to fulfil the local energy demand. As such, building facades offer an attractive and complementary option.

Although vertical solar panels receive less solar radiation than roofs and horizontal surfaces, in particular in the summer months, and are more affected by the compactness of the urban layout ,facades feature high areas (in a building with 4 floors), the area of the facades is about 4 times the area of the roofs. If the whole available area of such building was used for solar panels and shadings from neighbouring buildings are neglected, the total annual electricity production would triple that of the roof. This ratio will obviously increase further for taller buildings.

However, it is important to point out that in this example, the cost of the generated solar electricity (in V/kWh) would also be 4 times higher. Hence, the deployment of PV on less than optimum inclination/orientation must be weighted by economic constraints. Nevertheless, the recent trend of fast decreasing costs of PV, which is expected to proceed in future years, opens a window of opportunity for this type of application

2.7 Conclusion of chapter 2 - appropriate building envelope design is key to an energy efficient building

Appropriate building envelope design is one of the fundamental passive strategies that can be applied in improving building energy efficiency. It is due to this paramount importance of building envelope on energy efficiency that the interest of this thesis lies on the observation of building envelope components on energy demands of a building. Key design concepts and suggestions such as climate resilient envelope design should therefore enhance the adaptability of the building envelope to improving energy efficiency and overall indoor comfort.

However, one should note that an appropriate building envelope design in one climatic context can be inappropriate in another climatic context. Moreover, apart from climatic conditions, one also needs to fully understand the building typology, local code restrictions, and client goals, local traditions and cultural norms of the building occupants.

In the following chapters, this thesis will highlight how multiple factors can be considered in designing building envelope which not only contributes to building energy efficiency but also local culturally and architecturally feasible.

3. Chapter 3: The concept of Building Performance Simulations (BPS)

This chapter examines the general approaches related to BPS. The emphasis is put on understanding the meaning of this tool, literature review, the practice of applying this tool during early design stages among professionals, its objectives and setbacks, and lastly the current trend of using BPS in Tanzanian building industry.

3.1 The meaning of Building Performance Simulation

Hensen, J.L.M. & Lamberts, R. (2011), defines BPS as the science of simulating buildings response to external or internal patterns, including weather parameters variations such as temperature, humidity, and radiation, or building environmental pollutants such as fire propagation and sound distribution, among others. It is the replication of aspects of building performance using a computer-based, mathematical model created based on fundamental physical principles and sound engineering practice. The objective of performing BPS is the quantification of aspects of building performance which are relevant to the design, construction, operation and control of buildings.

Building performance simulation has various sub-domains; most prominent are thermal simulation, lighting simulation, acoustical simulation and air flow simulation. Most building performance simulation are based on the use of bespoke simulation software. Building performance simulation itself is a field within the wider realm of scientific computing.

A figure below illustrate that buildings are not static; they are always in continuous interaction with their indoor and outdoor environmental conditions and sub-systems. It is though BPS, one can understand how this interaction can affect the overall building performance in all stages of life cycle.

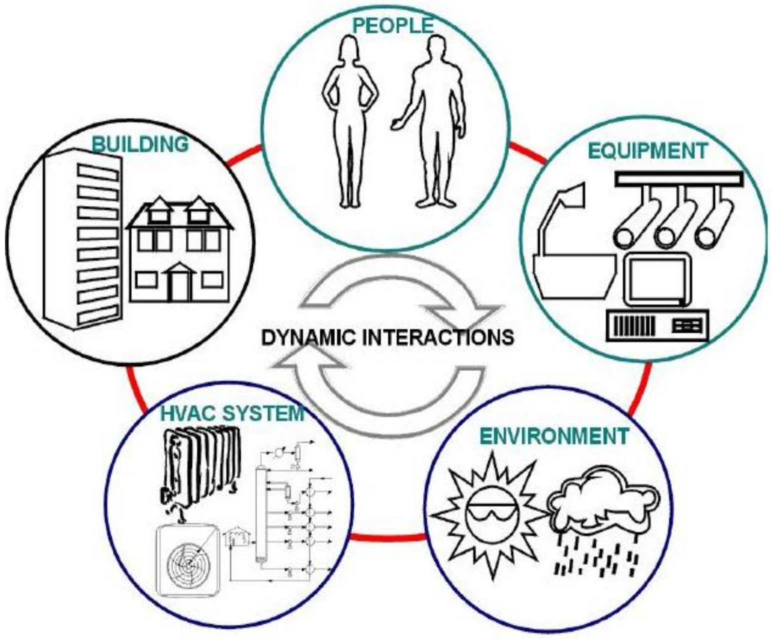


Figure 9 Dynamic interactions of continuously changing sub systems in buildings
Source: Hensen, J.L.M. & Lamberts, R. (2011)

3.2 Literature review on Building Performance Simulation

The science of performing BPS has been applied by many authors in observing different performance parameters including energy demands and indoor comfort in different contexts. I. Imran et al, performed a parametric study by using BPS in order to analyse the impacts of insulation thickness of walls and roofs, heat transfer coefficient and solar heat gain coefficient of windows and lighting density on building energy consumption. H. Buchberg, performed sensitivity analysis by using BPS during investigation of the room thermal response to inside radiation exchange and surface convection.

In their study Liqiang Hou et al. (2017), performed BPS in order to investigate thermal and energy performance of office buildings and to identify major energy efficient strategies in different climate zones in China.

X. Chen et al. (2018), applied simulation-based approach to optimize passively designed buildings in different hot humid climatic cities in China. They investigated the effects of changing envelope u-values, SHGC, WGR, infiltration and air tightness rates on cooling, lighting and total energy consumptions.

M. Rossi, and V.M. Rocco (2014), performed thermodynamic simulations to investigate the role of periodic thermal transmittance and internal areal heat capacity in heating and cooling energy consumptions in two different cities in Italy.

Even though, literature review shows that BPS is widely applicable in different contexts, the use of BPS is not popular if not non-existing among different collaborators in Tanzania. In fact, this is why, this thesis is focusing on how the application of BPS can also be of paramount importance in Tanzanian building industry.

3.3 Building Performance Simulation during early design stages among professionals

The employment of simulation into the design process brings different advantages to building design. The advantages become even more apparent when simulations are performed in early design stages. At this stage, simulations can help in identifying passive strategies that can be used to improve the overall building performance as per project objectives. However, in conventional building practices, usually designers do not apply BPS as a guiding design tool especially in early design stages. Different reasons may account for this situation.

Usually the available software to perform BPS require professional knowledge which most designers do not possess. Moreover, early design stages are distinguished by unstructured and insufficient information which is required as inputs to perform BPS. As a result, most software tools are targeted to be used by building services engineers at detailed stages of design and does not suit the purposes of design community.

One should however note that, the situation is not the same in all contexts. For example, in countries where design process was observed in earlier chapters, BPS is increasing becoming a norm in building practice. It is, therefore, the interests of this thesis to outline, the design opportunities of performing BPS that designers and engineers can exploit in early design stages in Tanzanian building practice where BPS is not popular.

3.4 Objectives of Building Performance Simulation

The following paragraphs outline the potential that BPS can have in overall stages of building life cycle, from the early stages of design to the end of service life.

3.4.1. To predict various building performances and outdoor conditions

i) Indoor thermal comfort: indoor temperature

By performing BPS, one can understand the indoor thermal environmental conditions that will exist in a building. By comparing with the specified values of different standards such as ASHRAE and Eurocodes, one can understand if occupants will explain comfort or not. From here important design decisions can be made by implementing both passive and active strategies.

ii) Indoor visual comfort

BPS can be used to assess the level of daylight, visual and glare comfort inside a space. This is important especially for office spaces where visual comfort is of paramount importance.

iii) Outdoor environmental conditions: solar gain

Solar gain is the main source of indoor thermal discomfort in hot climatic regions. Therefore, by performing solar gain simulations, designers can understand which strategies to apply in order to reduce solar gains and eventually reducing energy demands. For example, among other strategies, a designer may opt for a glazing material with low SHGC, lower WWR or shading devices in order to reduce solar gains.

The following figure presents results of performing BPS in order to understand solar gains.

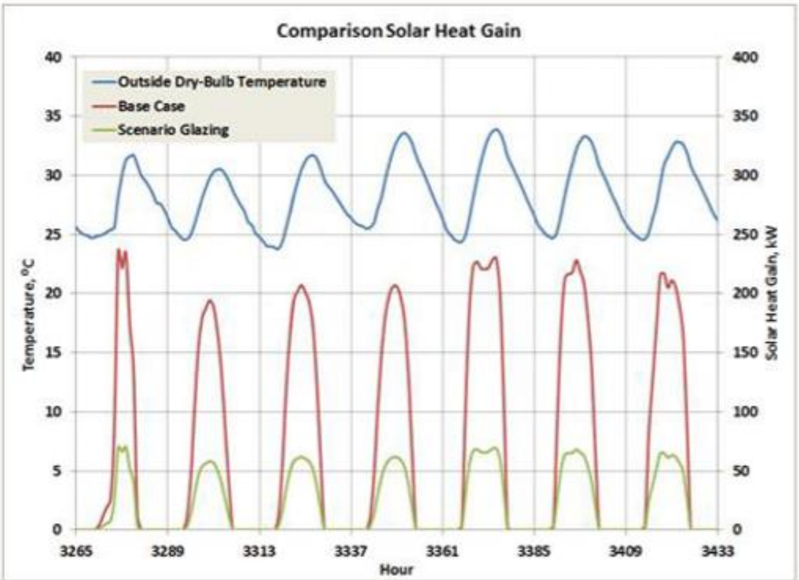


Figure 10 Comparison of Solar Heat Gain
Source: Suzuki-Zadeh-Kokil (2017)

iv) Energy demands

By applying BPS, one can predict the energy demands of a building, and hence size the type of HVAC system to be used. In fact, one can also decide on the passive and active measures that can be applied in order to reduce energy demands. A figure below shows how much electrical energy is going to be used by chiller all over the year after performing BPS.

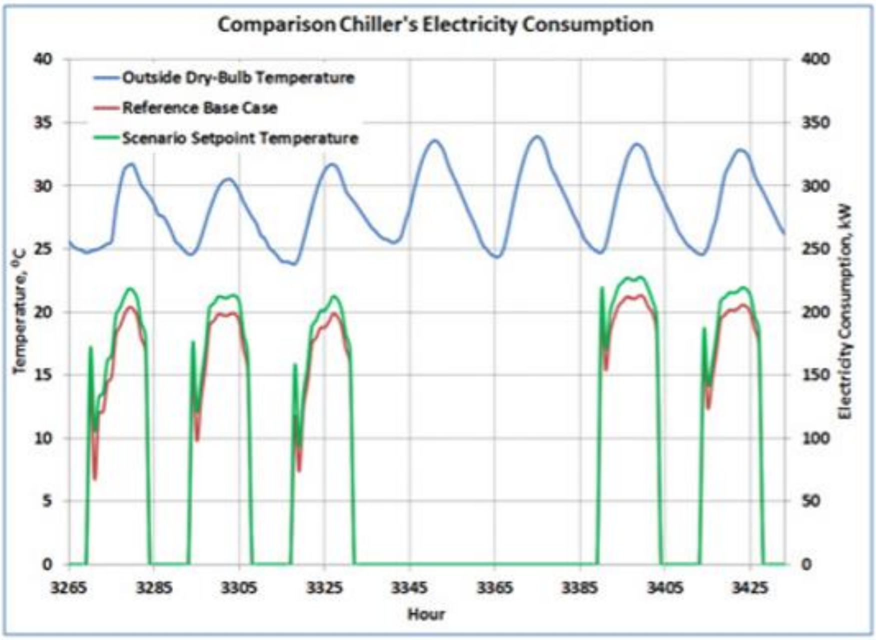


Figure 11 Chillers electical consumption
Source: Suzuki-Zadeh-Kokil (2017)

3.4.2. Make important decisions on passive and active strategies in order to ensure that buildings perform to the standards and guidelines put in place

i) Building Form/ Geometry (passive strategy)

Development in algorithms has allowed for various optimization even in BPS. Designers now have an opportunity to design an optimized form of a building based on let's say solar radiation minimization. This means by applying BPS, architects can come up with designs that best minimize solar gains or maximize the use of natural ventilation.

ii) Building envelope systems (passive strategy)

Like illustrated in this thesis, BPS can be used to determine the components of building envelope that can be used to either improve building energy efficiency or indoor environmental comfort. In this thesis for example, BPS was used to compare how the WWR, shading devices and insulation thickness can affect the energy demands of a building. Likewise, through the use of BPS, one can understand how building envelope components can affect daylighting, glare and visual comfort in a space.

iii) Building HVAC system (active strategy)

BPS can be used to size the HVAC system of a building based on energy demands. Different HVAC systems can also be compared by using BPS in order to understand which one is performing better based on climatic context, building's use and available technology.

3.5 Building Performance Simulation towards high performing buildings

Designing sustainable buildings that also fulfil all operational requirements of the users is an unprecedented challenge for our times. Researchers, practitioners and other stakeholders are faced with enormous challenges of taking into account various dynamic processes such as: global climate change; depletion of fossil fuel stocks; increasing flexibility of organizations; growing occupant needs and comfort expectations; increasing awareness of the relation between indoor environment and the health and wellbeing of the occupants, and consequently their productivity. Managing all these aspects in order to achieve robust building and system solutions which will be able to withstand future demands requires an integrated approach of the subsystems.

Legislation such as European Performance of Buildings Directives and ASHRAE Standard mandate the BPS approach in order to bring about high-performance buildings through a holistic approach to design. In this way, buildings will be able to comply with international and local standards for building performances such as LEED, BREEAM, HQE (European Parliament and Council, 2010 and ASHRAE, 2006).

When used appropriately, building performance simulation has the potential to reduce the environmental impact of the built environment, to improve indoor quality and productivity, as well as to facilitate future innovation and technological progress in construction. Since publication of the first edition of Building Performance Simulation for Design and Operation, the discussion has shifted from a focus on software features to a new agenda, which centers on the effectiveness of building performance simulation in building life cycle processes.

3.6 The Setbacks of Building Performance Simulation

There are different challenges associated with application of BPS. Some of these challenges are expressed in the following paragraphs.

i) Volatility in design ideas

Early design stages for example represents one of the most volatile phase of building project, ideas come and go so fast. Design changes are sometimes rapidly implemented. Sometimes there is a mismatch of workflow among project collaborators. All of these challenges make it difficult to perform BPS in a systematic manner.

ii) High number of tools available in the marketplace

The International Building Performance Simulation Association (IBPSA), states that there are more than 140 competing building simulation tools with overlapping functionalities available in the market today. As a result, non-simulation experts struggle in identifying the best-suited tools to use (Hensen, J.L.M. & Lamberts, R.,2011).

iii) Inaccuracy of input information

Inaccuracy of input information such as weather file data, thermal properties of materials, unpredicted behaviour of occupants (oversimplifications and uncertainties) can lead to inaccurate results during BPS. For example, when performing BPS for urban context, phenomenon such as UHI (whose effects is normally ignored), can lead to inaccurate output

3.7 The current trend of BPS in Tanzania

As already noted earlier, the application of BPS is practically non-existing in Tanzanian building practice. Design decisions are not performance-based but rather they hugely depend on client's objectives and budget. As a result, stakeholders do not see the necessity of applying BPS as a tool towards decision making during building design process. In fact, designers, normally depend on their experiences in making decisions on design solutions.

In fact, lack of regulatory framework that could provide a roadmap towards designing high performance buildings contributes to the low motivation for applying BPS. Furthermore, there is a major technical barrier, as many professionals in the current practice do not have skills and knowledge on BPS.

However, as we're currently facing challenges such as high levels of urbanization and climatic changes, the conventional building practice cannot resist the need for designing sustainable and high-performance buildings. This in turn is possible only by integrating BPS into the practice.

Therefore, one can urge that, the overall situation presents both challenges and opportunities at the same time.

3.8 Conclusion of chapter 3: BPS as the tool towards designing high performance buildings

One cannot deny the potential that BPS poses towards designing and operating high performance buildings around the world. When used appropriately BPS has the potential to improve competitiveness, productivity, quality and efficiency in buildings and in the construction industry as well as facilitating future innovation and technological progress.

4. Chapter 4: Multi-Criteria Analysis assessment method

This chapter presents the Multi-criteria analysis methodology that can be used as supporting tool in decision-making process on design solutions during early design stage. As already expressed, the methodology was not developed by the authors of this thesis, but rather it was developed by Francesca Contrada in her PhD thesis (2019), where she proposed a new method of evaluation of different design alternatives, which also considers adaptability of technological innovation and associated risks on the life cycle of building projects in both French and Italian building industries. For the sake of completeness, the framework and the main ideas already developed are summarized in this chapter.

This assessment method employs seven criteria that analyse the performance of design solutions under investigation in both qualitative and quantitative manner. By applying this methodology, different stakeholders can evaluate and verify different design solutions by comparing their global performances.

The first sub-chapter demonstrates the problem under investigation, which justify the application of the proposed methodology. Also, the concept of constructibility upon which multi-criteria analysis is based, is also discussed.

In the second sub-chapter, all seven criteria, sub-criteria and indicators are introduced.

The third sub-chapter illustrates, a process upon which all sub-criteria are aggregated. In this way, all sub-criteria with different measurement units are compared by assigning a value to each one of them. This is achieved by using a research methodology called Analytical Hierarchy Process (AHP).

The chapter ends with a conclusion, which highlights important remarks on the multi-criteria analysis methodology.

4.1 Problem definition and justification of proposed methodology

In the past chapters, different challenges associated with decision-making process in early design stage have been elaborated. Among others, during early design stage, time is always a limited resource, design ideas are rapidly changing, and sometimes project requirements are conflicting. In fact, there is lack of standardised way that projects collaborators can apply in evaluating global performance of design solutions in early design stage.

The current performance-based approaches such as guidelines, simulation tools and rating systems (e.g. BREEAM, LEED, HQE) (*as classified by Gowri, 2005*), do not include the assessment of technical performance and project management methods of design solutions. As a result, even if, these tools are applied in design process, project teams, may end up facing technical challenges associated with design solutions in later stages of building life cycle mainly during construction, operations and end of service life.

According to Contrada (2019), this new methodology applies a holistic approach towards assessing the global performance of design solutions including technical performance, project management methods and sustainability parameters obtained from simulation results and rating systems. It, therefore, includes the comprehensive performance of design solutions in all life cycle of a building project.

As already expressed in introduction section, the multi-criteria analysis methodology is based upon a French concept called constructibility, which originates from two other known concepts called buildability and constructability. In the 80s, CIRIA defined *buildability as the extent to which the design of the building facilitates the ease of construction, subject to the overall requirements for the completed building* (Nielsen, J. et al., 2009) or simply *the practice to be adopted by designers to facilitate the building construction* (F. Contrada et al., 2019). *Buildability is therefore limited to only conception stage*. Later, the Construction lndustry lnstitute (CII) based at the University of Texas, Austin, defined *constructability as the optimum use of construction knowledge and experience in planning, engineering, procurement and field operations to achieve overall project objectives* (S. Khan, 2018). *Constructability extends to all phases of project's life cycle.* The constructability concept enhances buildability, extending the practice of sharing knowledge to the whole construction lifecycle (F. Contrada, 2019).

In both approaches, a set of guidelines, help designers, during the design phase of a project to understand issues related to technicality of their proposed solutions which is important during construction and operation stages. By understanding the technical feasibility of proposed design solutions, a design team is able to decide a definitive option by evaluating the best outcome performances. Therefore, these two concepts enhance a decision-making process among project collaborators using a performance-based approach.

However, in order to extend the performance-based approach with project management aspects of design solutions, a French Constructibility Research Institute (IRC), proposed in 2010 a new concept of constructibility, which employs a holistic approach in decision making process (F. Contrada, 2019). By using this approach, project collaborators can anticipate a range of issues related to design solutions based on technical, sustainability and management aspects. It is in this context that, a multi-criteria analysis methodology was developed. This methodology relies on seven criteria: *simplicity of solution, verifiability, skills availability, simplicity to manage, compliance with user-centric requirements, sustainability* and *cost efficiency* which can collectively analyse and compare the global performances of multiple design solutions, and therefore support designers and other collaborators in making decisions.

4.2 Criteria definition

As already expressed, multi-criteria analysis consists of seven criteria which are applied in the assessment of performance of design solutions. These criteria are:

i. CC1 - Simplicity of solution
ii. CC2 - Verifiability
iii. CC3 - Skills availability
iv. CC4 - Simplicity to manage
v. CC5 - Compliance with user-centric requirements
vi. CC6 - Sustainability
vii. CC7 - Cost efficiency

From these criteria, two groups can be observed: criterion CC1, CC2, CC3 and CC4, relate to *technical performance evaluation*. Criterion CC5, CC6 and CC7 relate to *indoor comfort, environmental strategies* and *economic performance evaluation* respectively (F. Contrada, 2019).

For further details about each criterion see Annex A.

4.3 Evaluation system

4.3.1. Rating system - CC1, CC2, CC3, CC4

Each criterion consists of several sub-criteria, corresponding to different phases of building life cycle. For each sub-criterion, there is a set of indicators, which quantitatively and qualitatively assess the performance of design solutions.

As a result, the first group of criteria (CC1, CC2, CC3, CC4) applies a *rating system*, while the second group of criteria (CC5, CC6, CC7) uses a *numerical indicator* to evaluate the performance of design solutions as indicated in a Table below.

The rating system consists of a scale ranging from 1 to 6, in which each number is related to a certain indicator of performance. Number 1 represents the least score, while number 6 represents the highest score. As highlighted by F. Contrada (2019), these indicators are based upon concepts related to constructibility and the best practices in design. For example, a complete introduction of the best practice in early design is rated “six”, while the lack of constructibility concept is rated “one” (F Contrada et al., 2019).

The following table shows all criteria, sub-criteria and system of evaluation for each criterion.

Criterion	Sub-criterion	Type of evaluation
CC1 - Simplicity of solution	CC1.1 Level of standardization of vertical structure	Rating system
	CC1.2 Level of standardization of horizontal structure	
	CC1.3 Level of standardization of facades	
	CC1.4 Level of standardization of openings	
	CC1.5 Organization of technical equipment	
	CC1.6 Type of production technology	
	CC1.7 Construction type	
	CC1.8 Types of technical interfaces	
CC2 - Verifiability	CC2.1 Tools and measures to support the design	Rating system
	CC2.2 Risk consideration and implementation of register of problem	
	CC2.3 Need for testing	
	CC2.4 Ease of access to verification (during operational phase)	
CC3 - Skills availability	CC3.1 Development of technical details	Rating system
	CC3.2 Modeling of elements	
	CC3.3 Use of a specialized workforce and special equipment (site)	
	CC3.4 Instruction planned for end-users	
CC4 - Simplicity to manage	CC4.1 Systems durability	Rating system
	CC4.2 Transport	
	CC4.3 Assembly sequence	
	CC4.4 Regulation and control technic	
	CC4.5 Interaction with end-users	
	CC4.6 Maintenance	
	CC4.7 End of service life	
CC5 - Compliance with user-centric requirements	CC5.1 Indoor thermal comfort	Numerical indicators
CC6 - Sustainability	CC6.1 Soil resource consumption	Numerical indicators
CC7 - Cost efficiency		Numerical indicators

Table 1 Criteria, sub-criteria and system of evaluation
Source: Modified from F. Contrada, 2019

The following table shows all sub-criteria, indicators and a rating system for the first criterion CC1, as defined by Contrada (2019).

CC1 - Simplicity of solution								
Objective: Promote simple technical solutions in geometry, composition and technical interfaces. Reward the effort on design of the functioning of facade and flexibility of construction in terms of detachable interfaces.								
Effort: The designer must provide, with the plans, the specification of the technical solutions and their production processes.								
	Desing (Juaristi, et al., 2018) (Zhang, et al., 2016)					Production and installation (Durmisevic, 2006) (Juaristi et al., 2018)		
Score	Structure sub-system		Envelope sub-system		Equipment sub-system			
	CC1.1 Level of standardization Vertical structure	CC1.2 Level of standardization Horizontal structure	CC1.3 Level of standardization of facades	CC1.4 Level of standardization of openings (form and materials)	CC1.5 Organisation of equipment	CC1.6 Types de production	CC1.7 Construction type	CC1.8 Types of technical interfaces
6	$\Sigma S_{sv, pref}/S_{sv, tot} = 100\%$ and grid regular vertical structure	$\Sigma S_{sh, pref}/S_{sh, tot} = 100\%$ and grid regular horizontal structure	$(\Sigma S_f * ci/S_{tot}) * 100 = 100\%$	$\Sigma Nb_s/Nb_{tot} = 100\%$	Technical equipment are minimized through optimization of facades and structures, vertical continuity of ducts is ensured	Production anticipates the use of industrialization systems on site (Lean, 3D printing etc.)	Vertical & horizontal structure are prefabricated and continuous	Construction is completely detachable. Elements are easily connected
5	$\Sigma S_{sv, pref}/S_{sv, tot} = 100\%$ and grid non-regular vertical structure	$\Sigma S_{sh, pref}/S_{sh, tot} = 100\%$ and grid non-regular horizontal structure	$80\% \leq (\Sigma S_f * ci/S_{tot}) * 100 < 100\%$	$80\% \leq \Sigma Nb_s/Nb_{tot} < 100\%$	Classic equipment are minimized, but the use of technology requires other requirements, vertical continuity of ducts is ensured	Production foresees the use of factory prefabrication processes	Prefabricated beam post structure, facade in prefabricated modules	Construction is partly prefabricated &limit assemblies. Connections by third party elements are limited
4	$60\% < \Sigma S_{sv, pref}/S_{sv, tot} \leq 100\%$ and grid regular vertical structure	$60\% < \Sigma S_{sh, pref}/S_{sh, tot} \leq 100\%$ and grid regular horizontal structure	$60\% \leq (\Sigma S_f * ci/S_{tot}) * 100 < 80\%$	$60\% \leq \Sigma Nb_s/Nb_{tot} < 80\%$	Equipment are necessary, & they're not integrated into the construction elements, vertical continuity of ducts is ensured	Production anticipates the use of unit prefabrication processes in factory	Structure realised on site by automation, facade in prefabricated modules	Several assembly options by adhesion, non-detachable welds, metal connections, screws or fasteners
3	$60\% < \Sigma S_{sv, pref}/S_{sv, tot} \leq 100\%$ and grid non-regular vertical structure	$60\% < \Sigma S_{sh, pref}/S_{sh, tot} \leq 100\%$ and grid non-regular horizontal structure	$40\% \leq (\Sigma S_f * ci/S_{tot}) * 100 < 60\%$	$40\% \leq \Sigma Nb_s/Nb_{tot} < 60\%$	Equipment are necessary, but they're integrated into the construction elements, and the vertical continuity of ducts is ensured	Production anticipates the use of mass prefabrication processes	Prefabricated beam post structure, façade realised on site	Connections are mainly metallic through screws or fasteners
2	$30\% < \Sigma S_{sv, pref}/S_{sv, tot} \leq 60\%$	$30\% < \Sigma S_{sh, pref}/S_{sh, tot} \leq 60\%$	$20\% \leq (\Sigma S_f * ci/S_{tot}) * 100 < 40\%$	$20\% \leq \Sigma Nb_s/Nb_{tot} < 40\%$	Equipment are necessary, and they're not integrated into the construction elements, the vertical continuity of ducts is not ensured	Production anticipates the use of unitary prefabrication processes	Structure completely realised on site, facade integrates standardized elements	Construction completely realized on site; some elements are detachable
1	$\Sigma S_{sv, pref}/S_{sv, tot} < 30\%$	$\Sigma S_{sh, pref}/S_{sh, tot} < 30\%$	$(\Sigma S_f * ci/S_{tot}) * 100 < 20\%$	$\Sigma Nb_s/Nb_{tot} < 20\%$	Equipment are necessary, but they're integrated into the construction elements, and vertical continuity of ducts is not ensured	Prefabrication processes are minimized	Structure and facade completely realised on site	Construction completely realized on site, nondetachable elements
Vertical structure: $\Sigma_{Ssv, pref}$ = Sum of planar surfaces of prefabricated elements of vertical structure; Ssv, tot = Total surface in plan of elements of vertical structure								
Horizontal structure: $\Sigma_{Ssh, pref}$ = Sum of surfaces of floors constituted by prefabricated elements; $S_{sh, tot}$ = Total surface area of floors								
Facade: ΣS_f = Sum of facade surfaces of the same typology; $S_{f, tot}$ = total surface of facades; ci = coefficient linked to type of facade (Table 23)								
Openings: Σ_{Nbs} = sum of standard openings; Nbtot = total number of openings								

Table 2 Rating system for criteria CC1, Simplicity of Solution

Source: F. Contrada, 2019

Value of coefficient of facade typology ci						
Trench	Light façade of frame type	Light façade of grid type	Light elements attached to the trench (ventilated facades type)	Heavy elements attached to the trench	Non-load-bearing facade by filling	Masonry facade
1	1	0.99	0.99	0.8	0.6	0.5

Table 3 Values of facade typology coefficients
Source: F. Contrada, 2019

*For criteria CC1; in order to consider the levels of standardization of building sub-systems, including structure and building envelope, a range is established relative to the ratio between surfaces with certain characteristics and all surfaces. For structure, a ratio is established between the plan surface of prefabricated structures and all surfaces related to the structures; for facades, coefficients are established relative to the typology of facades based on execution strategies (Table 3). As highlighted by F. Contrada (2019), this strategy has been taken based on a reference method used for calculation of buildability in the framework of the B-Score provided by (BCA, 2017).

The following table shows all sub-criteria, indicators and a rating system for the second criterion CC2, as defined by Contrada (2019).

CC2 - Verifiability				
Objective: Promote the use of tools and methods, provide for tests on building envelope components and ergonomics for future maintenance actions				
Effort: Demonstrate the implementation of good practices regarding control, consideration of façade type, planning of maintenance strategies				
	Design		Construction	Operation
Score	CC2.1 Tools and measures to support design	CC2.2 Risk consideration and implementation of register of problem	CC2.3 Need for testing (AQC, 2017)	CC2.4 Ease of access of verification (BCA, 2017b)
6	Design - **is subject** to third party review (peer-review) or PCI - is developed using **BIM** tools associated with energy, environmental **simulation tools** - anticipates a **4D planning**, allowing optimization of process	The **risks** concerning the subsystems **have been considered** and, a **commissioning plan** and a **register of problems have been established** which will be the basis of verifications to be made and which will be updated	- Facade systems are **known** - Real scale physical models **are prepared** in order to determine the assembly sequence and the aesthetic effect - Laboratory and on-site tests **are prepared**	**All technical equipment** and **all elements of facade** (including coatings, solar protection, lighting elements, etc.) are easily accessible, requirements relating to verification, cleaning and maintenance **have been considered**
5	Design - **is not subject** to third party review (peer-review) or PCI - is developed using **BIM** tools associated with energy, environmental **simulation tools** - anticipates a **4D planning**, allowing optimization of process	The **risks** concerning the subsystems **have been considered** and a **register of problems have been established** which will be the basis of the verifications to be made and which will be updated	- Facade systems are **not known** - Real scale physical models **are prepared** in order to determine the assembly sequence and the aesthetic effect - Laboratory and on-site tests **are prepared**	**All technical equipment** and **all elements of facade** (including coatings, solar protection, lighting elements, etc.) are easily accessible, requirements relating to verification, cleaning and maintenance **have not been considered**
4	Design - **is subject** to third party review (peer-review) or PCI - is developed using **BIM** tools associated with energy, environmental **simulation tools,** allowing optimization of process	The **risks** concerning the subsystems **have been considered** and, a **commissioning plan have been established**	- Facade systems are **known** - Real scale physical models **are not prepared** - Laboratory and on-site tests **are prepared**	**All technical equipment** and **some elements of facade** (including coatings, solar protection, lighting elements, etc.) are **easily accessible**
3	Design - **is not subject** to third party review (peer-review) or PCI - is developed using **BIM** tools associated with energy, environmental **simulation tools** in order to verify the level of performance	The **risks** concerning the subsystems **have been considered** and, a **commissioning plan** and a **register of problems have not been established**	- Facade systems are **not known** - Real scale physical models **are not prepared** - Laboratory and on-site tests **are prepared**	**All elements of facade** (including coatings, solar protection, lighting elements, etc.) and **some technical equipment** are **easily accessible**
2	Design - **is not subject** to third party review (peer-review) or PCI - is developed using numerical models associated with energy, environmental **simulation tools** in order to verify the level of performance	The **risks** concerning the subsystems **have partly been considered** and, a **commissioning plan** and a **register of problems have not been established**	- Real scale physical models **are not prepared** - Laboratory or on-site tests **are prepared**	**Some elements of facade** (including coatings, solar protection, lighting elements, etc.) and **some technical equipment** are **easily accessible**
1	Design - **is not subject** to third party review (peer-review) or PCI - is developed using numerical models **not associated** with any **simulation tools**	The **risks** concerning the subsystems **have not been considered** and, a **commissioning plan** and a **register of problems have not been established**	No test are prepared	Technical equipment and elements of facade are not easily accessible

Table 4 Rating system for criteria CC2, Verifiability
Source: F. Contrada, 2019

The following table shows all sub-criteria, indicators and a rating system for the third criterion CC3, as defined by Contrada (2019).

CC3 - Skills availability				
Objective: To reward the effort made on upstream communication and evaluation, to anticipate the availability of skills on site and training tools for end-users				
Effort: Develop technical details and understand the feasibility of systems				
	Design		Execution	Operation
Score	CC3.1 Development of technical details	CC3.2 Modelling	CC3.3 Specialized workforce and special equipment	CC3.4 Instruction for end-users
6	**All** technical details concerning technical interfaces have been developed, they're **clear** and **exhaustive**	The subsystems can easily be implemented in various simulation models; product, characteristics and operation are known, and they're all integrated by libraries, **no need for high levels of expertise**	No specialized team is necessary for execution, the use of special equipment is not required	Instruction to the end-users is provided through user booklet, training session or brochures or / and educational posters or / and the establishment of advisers who seek to educate users on good practices and gamification devices capable of empowering the user
5	**Some** technical details concerning technical interfaces have been developed, they're **clear** and **exhaustive**	The subsystems can easily be implemented in various simulation models; product, characteristics and operation are known, and they're all integrated by libraries, but **some aspects** need **high levels of expertise**	Special training is required for internal teams for execution, the use of special equipment is not necessary	Instruction to the end-users is provided through user booklet, training session or brochures or / and educational posters or / and the establishment of advisers who seek to educate users on good practices
4	**All** technical details concerning technical interfaces have been developed, they're **clear, but not exhaustive**	The subsystems can be implemented in various simulation models through simplifications; product, characteristics and operation are known, and they're all integrated by libraries, but some aspects **need high levels of expertise**	Special training is required for internal teams for execution, the use of special equipment is necessary and have been considered	Instruction to the end-users is provided through user booklet and training session or educational brochures or posters
3	**All** technical details concerning technical interfaces have been developed, they're **not clear, but exhaustive**	Some subsystems require creation of model concerning operation and characteristics, and certain data are available from producers or from literature, **no need for expertise**	No special training is required for execution, the use of special equipment is necessary and have been considered	Instruction to the end-users is provided through user booklet and training session
2	**All** technical details concerning technical interfaces have been developed, they're **neither clear nor exhaustive**	Some subsystems require creation of model concerning operation and characteristics, **a high level of expertise is required**, but some data are available from producers or from literature.	One or more specialized teams is needed for execution, the use of special equipment is not necessary	Instruction to the end-users is provided through user booklet
1	All technical details concerning technical interfaces **haven't been developed**	Some subsystems require creation of model concerning operation and characteristics, **a high level of expertise is required**, no data related to subsystems is available	One or more specialized teams is needed for execution, the use of special equipment is necessary	No instruction to the end-users is considered

Table 5 Rating system for criteria CC3, Skills availability

Source: F. Contrada, 2019

The following table shows all sub-criteria, indicators and a rating system for the fourth criterion CC4, as defined by Contrada (2019).

CC4 - Simplicity to manage							
Objective: To facilitate the implementation process and reward easily maintainable solutions, consideration of end-user and recyclability of components							
Effort: Consideration of challenges coming from later stages of design and information for end-users							
	Design	Production and installation		Operation			
Score	CC4.1 Systems durability	CC4.2 Transport	CC4.3 Assembly sequence	CC4.4 Regulation and control technic	CC4.5 Interaction with end-users	CC4.6 Maintenance	CC4.7 End of service life
	(Juaristi, et al., 2018)	(Juaristi, et al., 2018)	(Zhang, et., 2016)	(Juaristi, et al., 2018)	(Juaristi, et al., 2018)	(Juaristi, et al., 2018)	(Juaristi, et al., 2018)
6	The chosen materials **are not degradable** by aggressive environment or by climatic conditions, they're **not incompatible with each other**	Construction is realised with **light** elements, of dimensions which **do not require exceptional transport,** and for the most part, transportable by one or two workers	A first analysis of assembly sequence of the building system was carried out and it **provides** for site optimization systems	Centralized management and control for all subsystems, the control is designed for local variations and impacts	The user can intervene on automation systems and the reactions of the adaptive subsystems are immediate	To ensure performance, construction requires **infrequent** (year) and **light maintenance (cleaning)** done by **users** or **non-specialized** third party.	Construction elements are easily separable and completely recyclable and biodegradable
5	The chosen materials **are degradable** by aggressive environment, but **not** by climatic conditions, and they're **not incompatible with each other**	Construction is realised with **light** elements, of dimensions which **do not require exceptional transport**, and partly, transportable by one or two workers	A first analysis of assembly sequence of the building system was carried out and it **does not provide** for optimization systems	Centralized management and control for all sub-systems, the control is designed for variations concerning parts of the building	The user can intervene on automation systems and the reactions of the adaptive subsystems are not immediate	To ensure performance, construction requires **infrequent** (year) and **light maintenance (cleaning)** done by **users** or **specialized** third party.	Construction elements are easily separable and completely recyclable and/or reusable, but not biodegradable
4	The chosen materials **are not degradable** by aggressive environment, **but they're degradable** by climatic conditions, however, they're **not incompatible with each other**	Construction is realised with **light** elements, of dimensions which **do not require exceptional transport, cannot be transported** by one or two workers	A first analysis of assembly sequence was carried out on one or more subsystems by providing optimization systems	Centralized management and control for all sub-systems, the control is designed for variations concerning the whole building	The user can intervene on automation systems but not directly	To ensure performance, construction requires **more or less frequent** (year / month) and **heavy maintenance (repair or replacement)**, done by **users** or a **non-specialized** third party.	Construction elements are partly recyclable and/or reusable, and easily separable
3	The chosen materials **are not degradable** by aggressive environment or by climatic conditions, but they're **incompatible with each other**	Construction is realised with **heavy** elements, of dimensions which **do not require exceptional transport,** and **partly can be transported** by one or two workers	A first analysis of assembly sequence was carried out on one or more subsystems without providing optimization systems	Centralized management and control for some local response subsystems	The user cannot intervene on adaptive systems because the adaptability of the subsystems is established during the production phase of the components	To ensure performance, construction requires **frequent and light maintenance (months) (cleaning)** done by **users** or a **specialized** third party or not.	Construction elements are partly recyclable and/or reusable, but difficult to separate
2	The chosen materials **are degradable** by aggressive environment and by climatic conditions, however, they're **not incompatible with each other**	Construction is realised with **heavy** elements, of dimensions which **do not require exceptional transport,** and **cannot be transported** by one or two workers	A first analysis of assembly sequence was carried out on a single subsystem	Centralized management and control for some global response subsystems	Integrated solutions are self-reactive and do not allow external intervention	To ensure performance, construction requires **frequent (monthly) and heavy maintenance (repair or replacement)** done by **users** or a **non-specialized** third party.	Non-recyclable, but easily separable
1	The chosen materials **are degradable** by aggressive environment and by climatic conditions, and they're **incompatible with each other**	Construction is realised with **heavy** elements, of dimensions which **require exceptional transport,** and **cannot be transported** by one or two workers	No analysis of assembly sequence	No centralized management and control	The integrated solutions are unadaptable	To ensure performance, construction requires **frequent (monthly) and heavy maintenance (repair or replacement)** done by **professionals.**	Non-recyclable and difficult to separate

Table 6 Rating system for criteria CC4, Simplicity to manage
Source: F. Contrada, 2019

4.3.2. Numerical indicator - CC5, CC6, CC7

For criterion CC5 and CC6, the numerical indicators are obtained after calculating a ratio between calculated and reference values of performance indicators. The original author and developer of the methodology (F. Contrada) applied several indicators in each of these two criteria during evaluation of performance of proposed design solutions. For a complete list of those indicators, see Annex A.

However, for these two criteria, the authors of this thesis have modified the indicators and chose one for each criterion as indicated in the paragraphs below.

Since CC5 evaluates the capacity of design solutions to meet the required performance objectives that will ensure acceptable levels of indoor environmental comfort for occupants, in this thesis the concentration is put on *indoor thermal comfort* as a sole indicator of performance evaluation.

Simulations are therefore performed in order to understand *degree-hours above indoor comfort temperature* for each of the four opaque wall constructive systems under investigation. The ratio of this value to the total number of occupancy hours in a year, is then compared for all four opaque wall constructive systems.

The simulations are performed to check the number of hours of occupation, in which the indoor operative temperature is within respected values in a year. Since the climatic condition is warm humid, the temperature values to be observed are those below 26°C as recommended by EN 15251 (*see Annex D*). The observation is done on a thermal zone defined in chapter 7. A numerical evaluation is done by calculating a ratio between the number of hours in which the temperature is below 26 (comfort hours), and total number of hours of occupation during a year as shown below:

$$\mathrm{CC5} = \mathrm{n°hconf/n°hoccupation}$$

where:
n°hconf = number of hours of occupation below 26°C (*indoor comfort operative temperature limit*)
n°hoccupation = total number of hours of occupation in a year

CC6 evaluates the environmental sustainability performance of design solutions. The assessment is done by comparing the calculated values of environmental parameters of design solutions to limit values defined by authorities or project's environmental performance objectives. In this thesis, the concentration is put on only one indicator: *soil resource consumption* [m^2].

The observation is done by calculating a ratio between a built surface area and the available site surface as shown below:

$$\mathrm{CC6} = \mathrm{Sused}\ /\mathrm{Savailable}$$

where:
S$u$sed = built surface area [m^2]
Savailable = available site surface [m^2]

*For further elaboration on how to assess the indoor environmental comfort performance, and environmental sustainability performance for CC5 and CC6 respectively by using the rest of the indicators, refer to *Francesca Contrada. (2019). L'apport de la constructibilité au pré-design. Evaluation et support au choix des solutions techniques. PhD Thesis in Science de l'Ingénieur Université Paris Est.*

For criterion CC7, a ratio between *investment cost* and *global cost* of proposed design solutions is calculated as shown below:

$$\mathrm{CC7} = \mathrm{CO}inv\ /\mathrm{CG}$$

where:

$\mathrm{CO}inv$ = investment cost

CG = global cost

For the reasons of simplicity, only cost due to energy consumption (*only cooling, lighting are neglected*), are considered as a contribution of operation cost. All other costs are neglected. Therefore, the global cost is calculated as:

$$CG = CO_{inv} + \left[\sum_{i}^{t_{TC}} CO_{a(i)}(j) * (1 + RAT_{xx(i)}(j)\right]$$

where:

CG = global cost

$COinv$ = investment cost

$COa(i)(j)$ = operation cost in a year i for a component or service j (in *this case, only cooling energy costs are considered*)

$RATxx(i)(j)$ = inflation rate in a year i for a component or service j, (this can be related to cost of energy consumption, products, building systems, services, installations, maintenance etc.)

*For further elaboration on the calculation procedure for CC7, cost components of investment and global costs, refer to Annex A.

4.4 Analysis and aggregation of sub-criteria and indicators

The important question that can be asked is how a final rating value for a certain criterion is assigned, considering that in a criterion, there are several sub-criteria with different notes that have been assigned to them? The easiest way would be, to take an average of all notes from each sub-criterion. However, one challenge of using this method is that, based on building practice, not all sub-criteria of a certain criterion, carry the same weight (*meaning they're not equally important*). Therefore, it will be wrong to represent the average, as the average weigh all sub-criteria as the same.

This is why, the methodology provides an aggregation method. Referring to Contrada (2019) the Analytical Hierarchy Process (AHP) is applied for the aggregation process. This method provides the required weight for each sub-criterion according to the importance of each one of them. A method called Analytical Hierarchy Process (AHP) is applied for the aggregation process.

According to Saaty (1987) four steps characterise AHP:

i. Ranking of sub-criteria in order of importance, from highly to less important
ii. Creation of matrix from two by two comparison of the sub-criteria
iii. Determination of the weights associated with each criterion thanks to an approximate method of calculation of the eigen vectors
iv. Verification of the consistency of the results

In order to show how above steps work, refer to Annex B where an example is presented.

4.5 Assigning the intensity of importance for sub-criteria

A relationship between one sub-criteria and another is established by assigning an intensity of importance to each one of them. By assigning an intensity of importance to each sub-criterion, a matrix of intensity is therefore generated. The question is, how is one sub-criteria either equally, less or more important than the other? In other words, it is important to understand, how can one sub-criterion affect the performance, in comparison to other.

F. Contrada (2019), applied two ways in order to understand the intensity of importance among sub-criteria:

- By performing literature review on the dysfunctions of the process
- By performing survey among building professionals in the context of French and Italian building industries

In this thesis, however, the authors have contextualised, the above approaches used by F Contrada, according to Tanzanian building industry. In order to reflect the practicality of Tanzanian building industry, only the order of importance for sub-criteria CC2.1 is assigned slightly different compared to the way assigned by F. Contrada (2019). As shown in Annex A, only a moderate level of importance (3) is assigned for sub-criteria CC2.1, and not essential or strong importance (5) as done by F. Contrada (2019) because, in Tanzanian building industry the use of tools such as BIM, and simulation to support design process is not as strong as in French or Italian building industries.

For the rest of the criteria, the order of importance in this thesis is assigned the same as done by F. Contrada (2019).

A table below elaborates how intensity of importance of one sub-criteria in comparison to the other can be assigned as suggested by Saaty, R.W (1987).

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment strongly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored, and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Table 7 The fundamental scale
Source: Saaty, R.W (1987)

In order to understand how the intensity of importance is assigned to sub-criteria of criterion CC1, CC2, CC3 and CC4 refer to Annex C. An explanation on how to assign the intensity of importance to sub-criteria of criterion CC5, CC6 and CC7 is not presented because the order of importance in these criteria is just 1 as only one sub-criterion is observed for each one of them.

4.6 Conclusion of chapter 4

As it has been observed in this chapter, multi-criteria analysis provides not only an assessment approach to designers but also a set of tools that can be included during early designs stage in order to arrive at a proper design solution. It is a flexible methodology that can be adopted to different building industries/contexts, building types and sub-systems.

This methodology relies on a set of criteria, sub-criteria and indicators in assessing design solutions in all life cycle stages. The first four criteria *CC1- simplicity of solution, CC2 - verifiability, CC3 - skills availability, CC4 - simplicity to manage* relate to *technical performance evaluation*. And the other criteria CC5 - *Compliance with user-centric requirements*, CC6 - *Sustainability* and CC7 - *Cost efficiency* relate to *indoor comfort, environmental strategies* and *economic performance evaluation*

In order to obtain a final rating assessment score, an aggregation of sub-criteria is done through AHP. This method is applied because it weights different sub-criteria according to their order of importance in impacting a performance of a certain criterion.

5. Chapter 5: Methodology Application Structure

This chapter presents the overall approach on the application of methodology in this study. All the steps performed are introduced in this chapter.

5.1 First step: Application of stages in BPS

As already stated, this thesis first applies BPS in comparing the performance of building envelope components under investigation. For the purpose of this study, four opaque wall constructive systems are therefore used as case studies.

During BPS, six stages of simulations are performed. The first step of simulation helps to understand the type of energy demands in this particular context. During this step, important questions are therefore answered; Do we need to cool or to heat buildings in this climate? If either of the two is yes, to what extent do we need to do that? Also, is climatic analysis consistency with the results of simulations or not?

The second step of simulations demonstrates the potential of natural ventilation in reducing energy demands in this particular climatic context. This step is important in understanding one of the most important passive design strategies that can be applied in bringing indoor comfort in hot climatic regions.

The third step is performed in order to understand different ways heat can transfer in buildings. Since, the investigation is on building envelope components, it is therefore important to see to what extent can these components contribute to heat gains or losses in the case study.

The next three steps of simulations compare the performances of different building envelope components (*WWR, shading devices and insulation thicknesses*) on energy demands in the case study.

The final result after performing BPS: is the four opaque wall systems, each with the best performing WWR, shading device and insulation thickness, which are then analysed using multi-criteria analysis approach.

5.2 Second step: Application of multi-criteria analysis

In multi-criteria assessment, the technical performances, along with project management methods of all four opaque wall systems are analysed and compared by using a set of criteria as later demonstrated. The final result: is the best performing opaque wall system with the same WWR, shading device and insulation thickness obtained after performing BPS.

5.3 Third step: Application of architectural design solution on case study

Since the overall objective of this study is to show how BPS and multi-criteria analysis can be used by architects and engineers in Tanzanian building industry, as supporting tools for design solutions, it is therefore, in the interest of this thesis to present architectural presentation of the final opaque wall system with WWR, shading device and insulation thickness obtained after performing BPS and multi-criteria analysis. Moreover, since the case study itself is not an existing building, therefore, the final architectural design solution of the overall case study is also presented.

A figure below summarizes the overall steps performed in the application of proposed tools in case study.

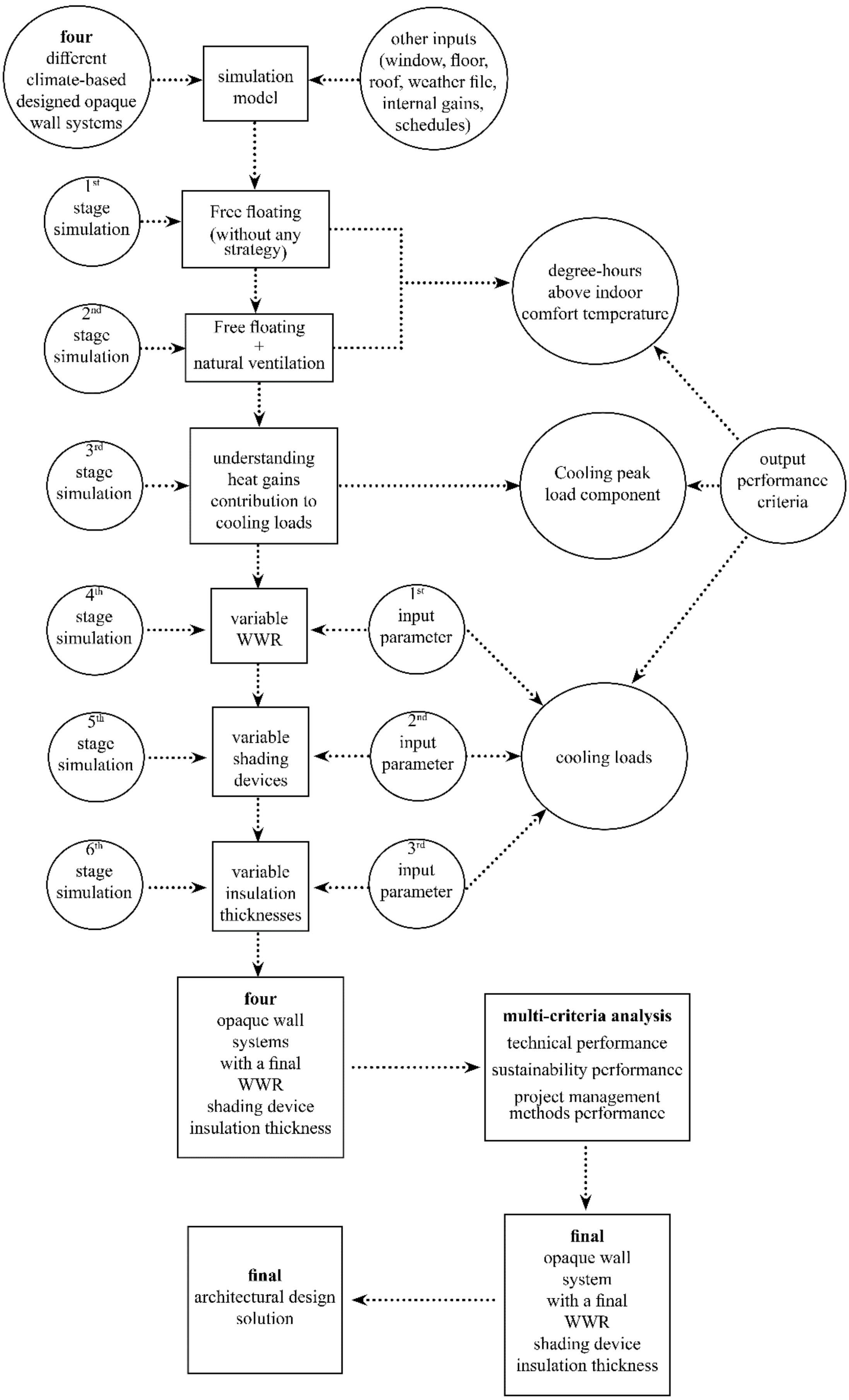


Figure 12 Summary of the steps performed in this study

6. Chapter 6: Introduction to the case study

This chapter presents the overall steps that have been followed in order to present the case study used in this thesis. As already explained in the abstract and introduction, the case study used is not an existing building, but rather a design proposal, which was developed and designed by the authors of this thesis. The interest of doing this lies in the fact that, since the proposed methodologies are applied to support choices of building envelope design solution, it will be interesting to show the final architectural design solution of the overall project.

At this particular chapter, we are assuming that, the project has already passed the preliminary stage and it is now at the early design stage. Therefore, all the important information from the design brief, and those developed by the authors will be presented, in order to understand the context, and scope of the project itself. This includes Tanzania and Dar es Salaam cultural, socio-economical and climatic contexts, site information, project requirements and design objectives, early architectural form, study of local architecture and sustainability aspects in the built environment.

On top of that, since the proposed methodologies are applied on building envelope solutions, the authors of this thesis also developed and designed four different envelope solutions, which were designed based on aspects such as local availability of materials, climatic conditions and local sustainability agenda. These applied methodologies will also be presented in this chapter.

6.1. Contextual situation of Tanzania

6.1.1. Geographical location

The United Republic of Tanzania is an independent and sovereign state located in East Africa. It is positioned at latitudes 1° 00’ and 11° 45’ south of the Equator and Longitudes 29° 15’ and 41° 00’ East of the Greenwich meridian.

Tanzania is bordered by the Republics of Kenya and Uganda to the north, Rwanda and Burundi to the northwest, Democratic Republic of Congo to the west, Republic of Zambia to southwest, Republic of Malawi and Republic of Mozambique to the south. In the Eastern side, it is bordered with Indian ocean, forming 1400 kilometres of coastline.

It is the largest country in the eastern Africa region with an extension of 945,000 km^2, including mainland and the Zanzibar islands. This includes forest and game reserves, and 60,000 km^2 of large water bodies including Lake Victoria, Lake Tanganyika and Lake Nyasa.

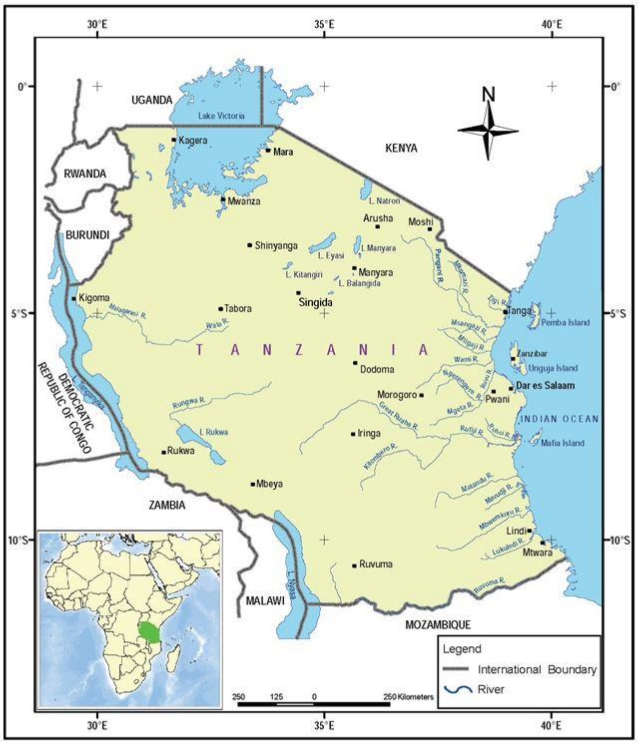


Figure 13 Map of the United of Tanzania
Source: Evelyen I. Mbede, et al. (2012)

6.1.2. Political context

Tanzania has been independent since 1961 (Tanganyika since 1961 and Zanzibar since 1963), and in 1964 the two countries merged to form the United Republic of Tanzania. The country is organized in 30 administrative regions. Tanzania had a mono-party political system of socialist inspiration from independence until the 1980s. It allowed other parties to become active in 1992 and held its first multiparty elections in 1995. The president and the National Assembly are elected for five years.

6.1.3. Socio-economic context

According to 2017 UNDP report, in the last 35 years, Tanzania's population has almost tripled to 50.1 million (2016 estimate). At 2.7 percent per annum, the national average population growth rate is one of the fastest in the world and translates to a net addition of 1.2 million people each year. At the present rate, Tanzania's population is projected to reach 67 million in 2025 and 89.2 million by 2035. This rapid growth increases a huge demand for public infrastructure and facilities, housing, employment and social services, particularly in the areas of education, health and water supplies (UNDP, 2017).

As highlighted in the 2017 report by Deloitte on Tanzania Economic Outlook, the country's economic growth is expected to average 6.2% between 2017 and 2026. The growth is underpinned by infrastructure development and a growing consumer base. The report also stated that heavy infrastructure investment into rail, port and road is expected to be one of the main drivers of Gross Domestic Product (GDP) growth between 2017 and 2026

6.1.4. Climatic context

Tanzania's mainland is divided into a central plateau, highlands along the north and south, and coastal plains. The climate of Tanzania is different from place to place due to its geographical location, altitude, relief and vegetation cover. In fact, region climate is mainly influenced by its location close to the equator, the impact of the Indian Ocean and the physiography in general.

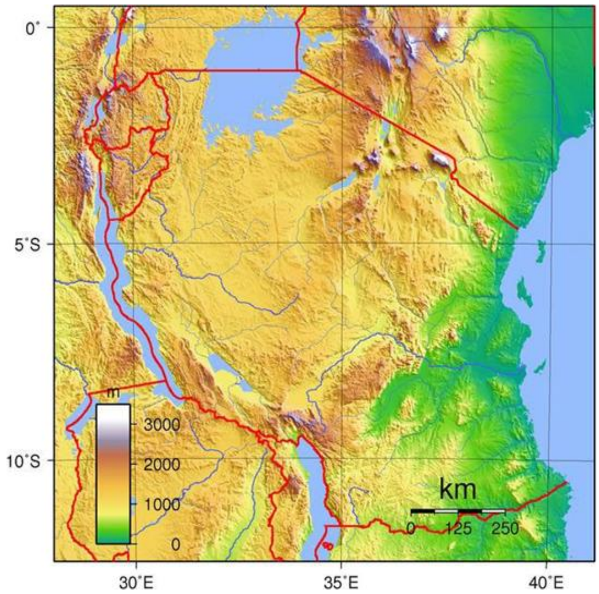


Figure 14 Topographic map of Tanzania
Source: www.emapsworld.com

As a result, Tanzania experiences a variety of climatic conditions. The coastal area and all of the islands in the Indian Ocean experience a *tropical climate,* and most of the country is *sub-tropical* except for the areas at *higher altitudes*. Tanzania is mountainous in Northeast where Kilimanjaro and Meru mountains are situated, the climate is *cool* in *high mountainous regions*.

The following map shows different regional climate over the country based on Koppen climate classification.

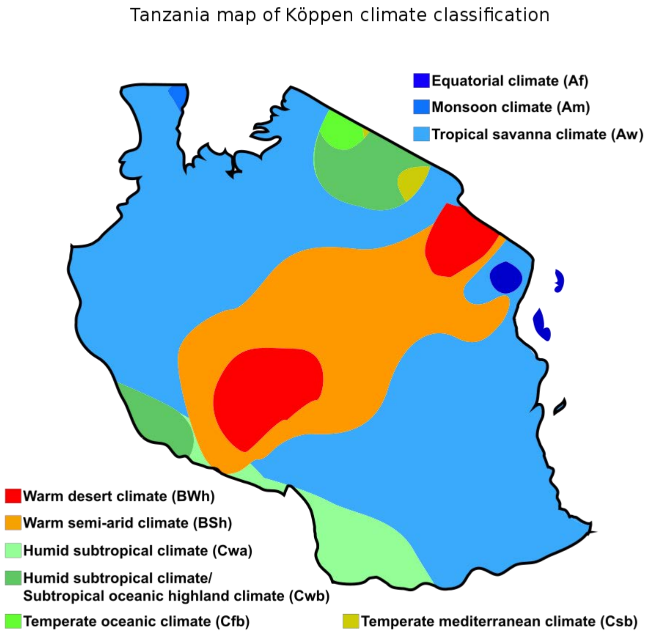


Figure 15 Different regional climate of Tanzania based on climate classification
Source: Koppen Climatic Classification

Main Climates	Precipitation	Temperature
A: equatorial	W: desert	h: hot arid
B: arid	S: steppe	k: cold arid
C: warm temperature	f: fully humid	a: hot summer
D: snow	s: summer dry	b: warm summer
E: polar	w: winter dry	d: extremely continental
	m: monsoonal	c: cool summer
		F: polar frost
		T: polar tundra

As seen from the figure above, there are different climatic conditions with different levels of rainfall and temperature. The main reason for this type of differences, is due to topographical levels as for example, northern and southern regions have higher mountains and therefore high amount of rainfall compared to other regions.

6.1.5. Current and future climatic trends, and the impacts on building industry

Like other countries in the world, Tanzania is no exception when it comes to vulnerability to climate change and extreme weather events. The impacts of both climate change and extreme weather events have significant consequences on the livelihoods of the people and different sectors including building industry.

Up to date, Tanzania's main source of electrical energy is still hydroelectric power. However, according to Irish Aid (2018), the annual rainfall in Tanzania has decreased at an average rate of 2.8mm per month (3.3%) per decade. The greatest annual decreases have occurred in the southern most parts of Tanzania where the largest hydroelectric power station is located. This makes, the electrical power production very vulnerable. In fact, during extreme droughts, the capacity of hydroelectric power stations to produce energy is significantly reduced. This results in power shortage especially in urban areas where energy is needed to power buildings. On top of that, during drought, water shortage increases the cost of construction especially in urban areas, where water becomes a scarce resource.

According to the same group, the average annual temperature in Tanzania has increased by 1.0ºC since 1960 and the mean annual temperature is projected to increase by 1.0 to 2.7°C by the 2060s, and 1.5 to 4.5°C b y the 2090s. In warm humid coastal towns such as Dar es Salaam, the temperature rise is significantly high. This means, more energy demands to cool and ventilate homes and workspaces. In recent years, floods have been hitting Tanzania regions so often. Homes and public infrastructure have been significantly destroyed.

Different studies are projecting significant threats posed by climatic change in Tanzania. This means, it is time for different stakeholders in the building industry to no longer ignore the significance of putting in place a regulatory framework that will guide the process of designing and building climate resilient buildings and social infrastructures.

It is in fact, the interest of this thesis to highlight the significance of designing buildings based on performance approach, which in turn would help designers to apply passive strategies in reducing energy demands early on, during the project. The shift should also be moving towards applying innovative technologies such as renewable energies, automatic lighting systems, high performing HVAC systems, in order to reduce energy demands.

6.2 Climatic analysis of Dar es salaam (city of case study)

6.2.1. Location

The case study is located in Dar es Salaam, a coastal city located at *6°51'S, 3918'E* along the south-western coast of the Indian Ocean (Jonsson et al. 2004). As a region, Dar es Salaam covers an area of *1,393 km²* of land mass including eight offshore islands (DCC, 2999) (E. L. Ndetto et al., 2013). It is the leading economic powerhouse of Tanzania, however, in terms of land size, it is the smallest region. According to UN (2018), Dar es Salaam's current population is six million, and it is expected to grow to 10 million inhabitants by 2029, making it the third fastest growing city in Africa and ninth in the world.

Figure 16. Map of Tanzania showing adminstrative regions

Figure 17. Map of Dar es Salaam

Source : www.tanzania.go.tz/census/regions.htm-4/5/2008

Source: www.clintonctfire.com/

6.2.2. Climatic analysis

Based on Koppen climate classification above, the coastal areas of Tanzania are classified as *warm humid*, experiencing warm temperatures and high humidity throughout the year, and rainfall sometimes during a year.

Climatic analysis was conducted using a plugin called Ladybug of the software called Grasshopper, which is integrated with Rhinoceros 3D. Ladybug allows an importation of a weather file of the location or city under consideration in the form of epw, and hence analyse standard weather data in Grasshopper. With ladybug one can analyse different weather patterns and present the results in graphical ways by customizing diagrams such as Sun-path, wind-rose, radiation-rose, etc.

The following diagram shows schematic representation of the overall workflow of the plugins and software described above.

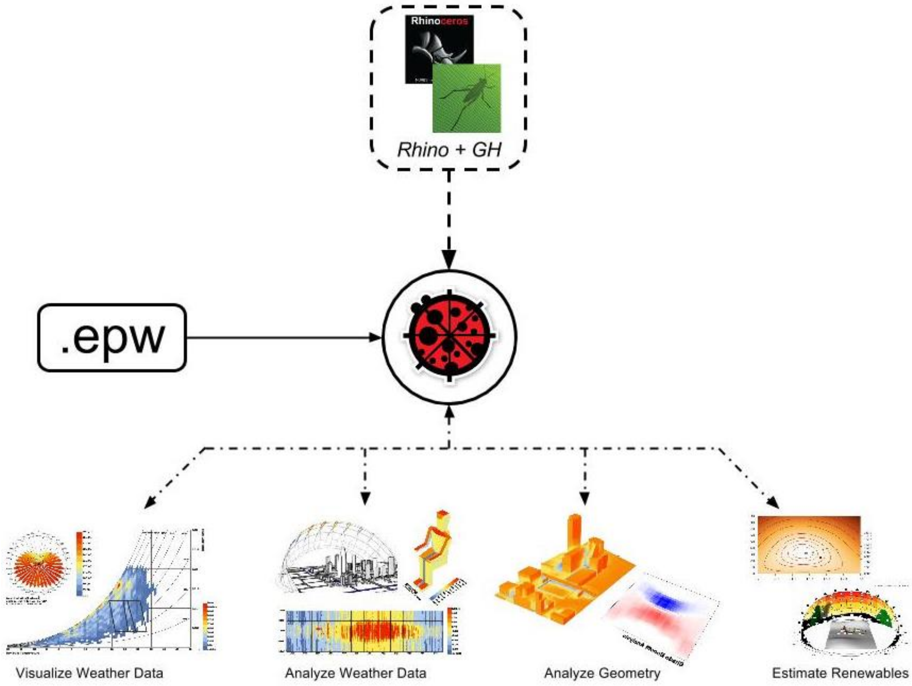


Figure 18 Different plugins of Rhinoceros Grasshopper
Source: http// www.food4rhino.com

The following were climatic parameters were analysed:

6.2.2.1. Dry bulb temperature

a) Average monthly high, mean and low dry bulb temperature

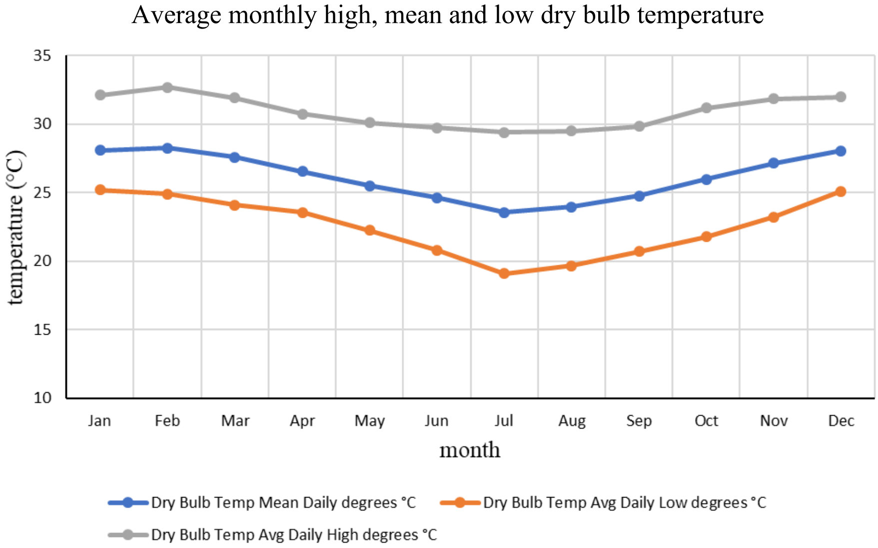


Figure 19 Average monthly high,mean and low dry bulb temperature

The graph is important to understand on average, the scale at which the hotness is experienced, monthly in Dar es Salaam. Two sets of periods are observed. The first is from January to April, and from September to December where the outdoor dry bulb temperature is high, on average at 27◦C. The second period is from May to August where the outdoor dry bulb temperature is low, on average at 24◦C.

However, the temperature can reach as high as 33◦C in February and as low as 17◦C in July. These can therefore be considered as the warmest and coldest months in Dar es Salaam.

b) Annual hourly dry bulb temperature

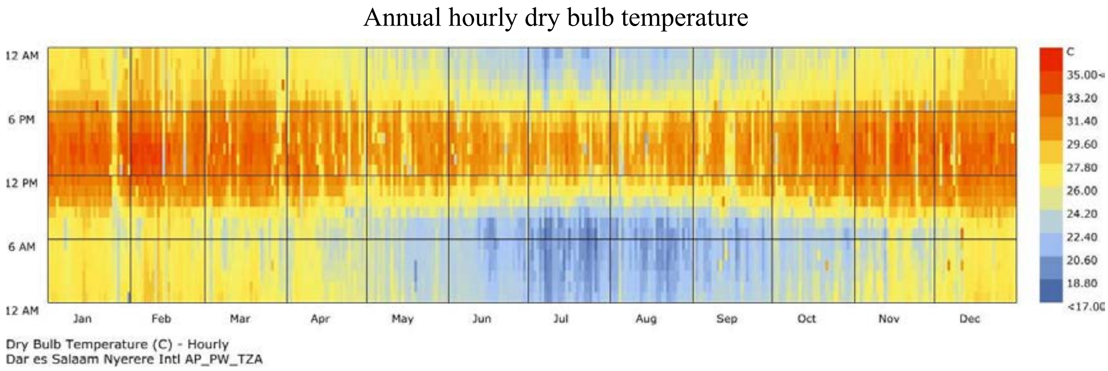


Figure 20 Annual hourly dry bulb temperature

The graphs represent the changes of dry bulb temperature that take place hourly in each day of the year. This shows that the outdoor temperature is not entirely constant in 24 hours. The differences can reach as much as 10◦C between maximum and minimum temperatures at different hours in a single day.

c) Hourly dry bulb temperature in each day of the hottest month, February and coldest month, July

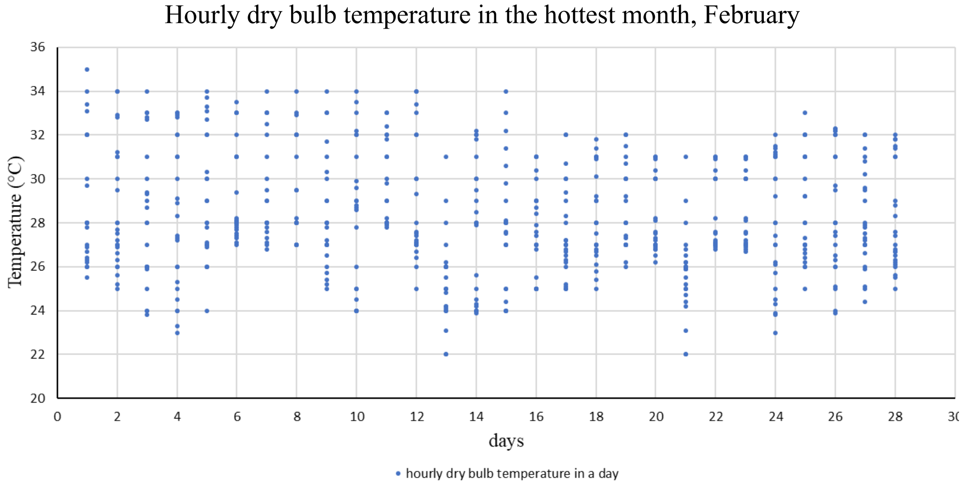


Figure 21 Hourly dry bulb temperature in a day

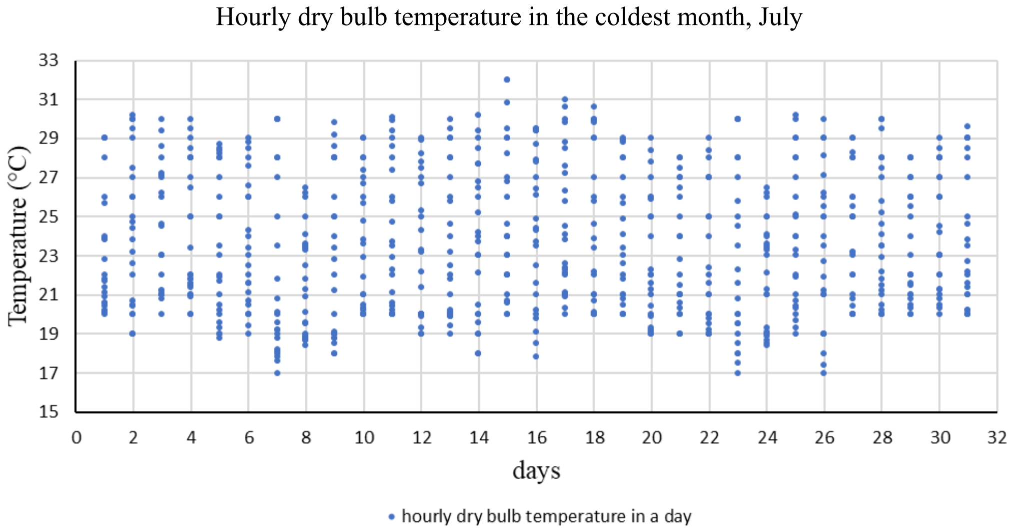


Figure 22 Hourly dry bulb temperature in a day

The two graphs are another proof that, the outdoor dry bulb temperature changes in each day of the month. Even for the hottest month of February where the average temperature is 28 ◦C, in some time during the same day, the temperature can reach as low as 22 ◦C and as high as 31◦C.

The same is observed for the coldest month of July with an average temperature of 24◦C, where in some time during the same day the temperature can reach as low as 17 ◦C, and as high as 30◦C.

Moreover, the trend of the two graphs also show that, during the hottest month, the outdoor temperature difference during the day and night is not as significant as during the coldest month where the temperature difference can reach 13◦C.

d) Hourly dry bulb temperature on the hottest day, 1st of February and on coldest days: 7th, 23rd and 26th of July

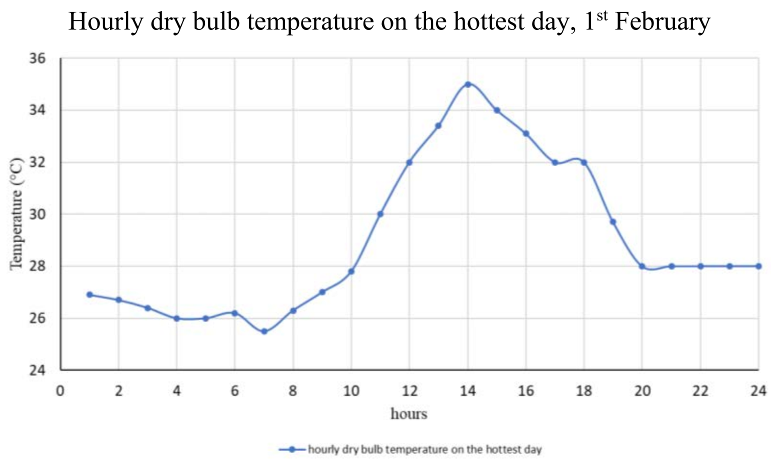


Figure 23 Hourly dry bulb temperature on the hottest day, 1 February

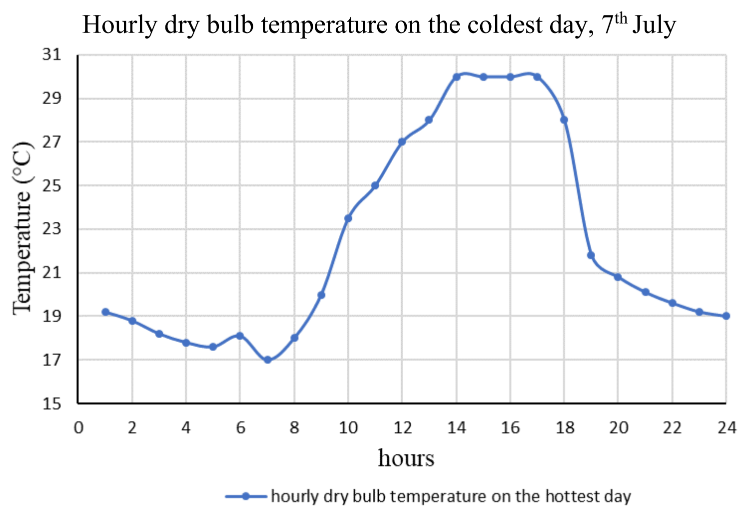


Figure 24 Hourly dry bulb temperature on the coldest day, 7 July

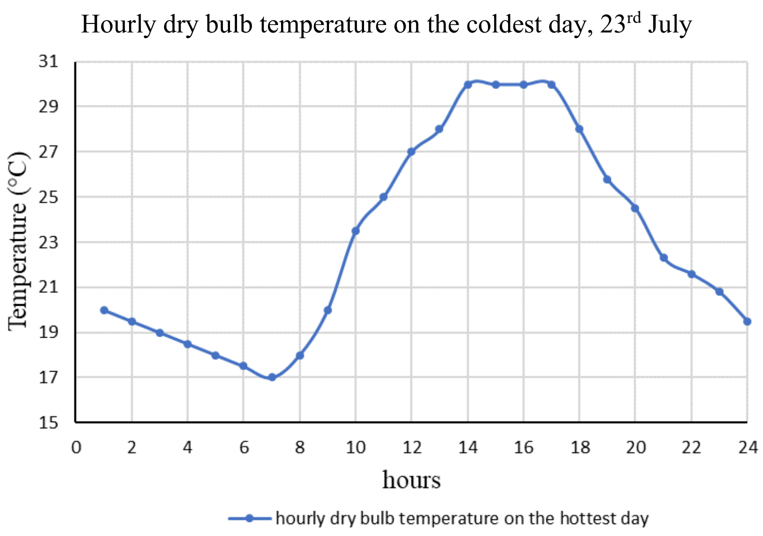


Figure 25 Hourly dry bulb temperature on the coldest day, 23 July

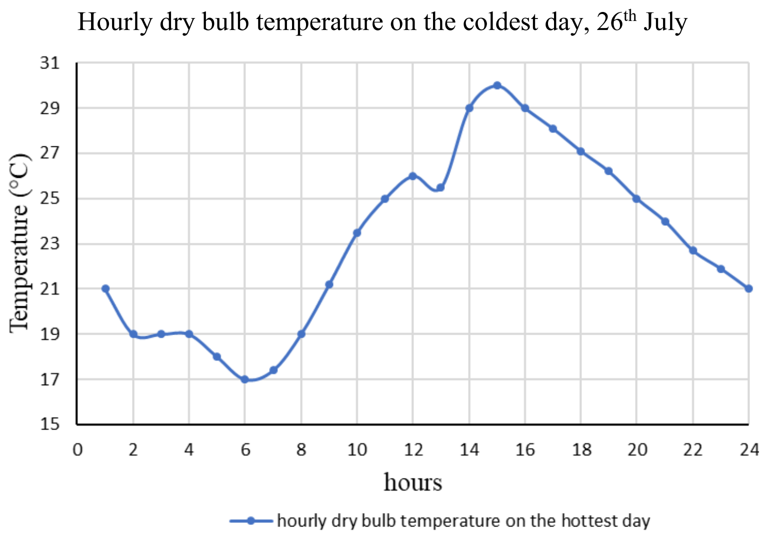


Figure 26 Hourly dry bulb temperature on the coldest day, 26 July

The graphs demonstrate that, in Dar es Salaam, the low outdoor temperature is experienced during the night up to early morning, while the high outdoor temperature is experience during the day up to early evening.

For this reason, one can merely experience the difference of temperature during the warm and cold months as the outdoor temperatures are almost the same during the day. The real difference happens during the night and early morning and evening hours.

For example, during the warmest day the outdoor temperature is around 34° C from 1400-1600 hours, while during the coldest day the outdoor temperature is around 30°C during the same hours. Therefore, the difference of temperature is around 4 °C.

However, during the warmest day the outdoor temperature is around 27 °C from 0000-0600 hours, while for the coldest day the outdoor temperature is around 18°C during the same hours, therefore, the difference of temperature is around 9°C.

6.2.2.2. Relative humidity

a) Average monthly high, mean and low relative humidity

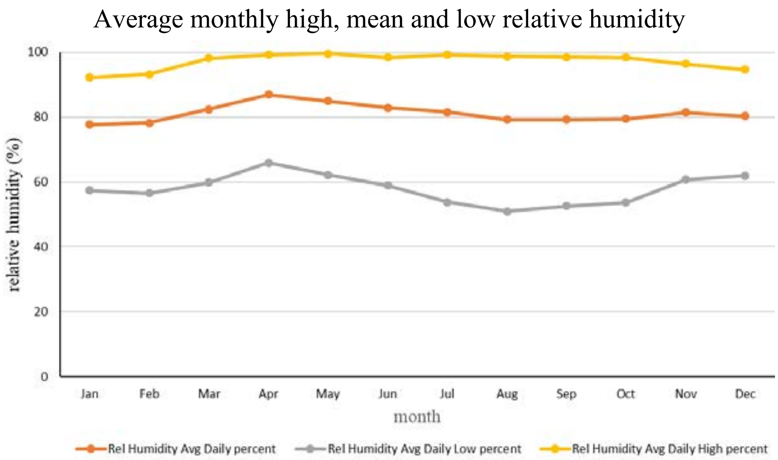


Figure 27 Average monthly high,mean and low relative humidity

The high humidity condition of Dar es Salaam as revealed in this graph characterizes the warm humid climatic condition of the city. On average the humidity level is around 80% during the year.

b) Annual hourly relative humidity

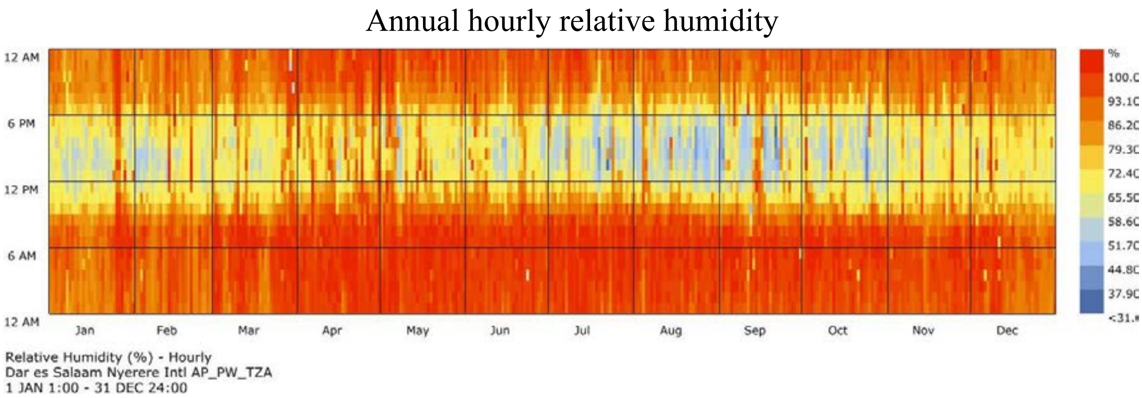


Figure 28 Annual hourly relative humidity

The two graphs above show that, the relative humidity is not constant during the day. On the contrary to temperature trend, relative humidity is high during the night hours and low during the day (from noon to early evening).

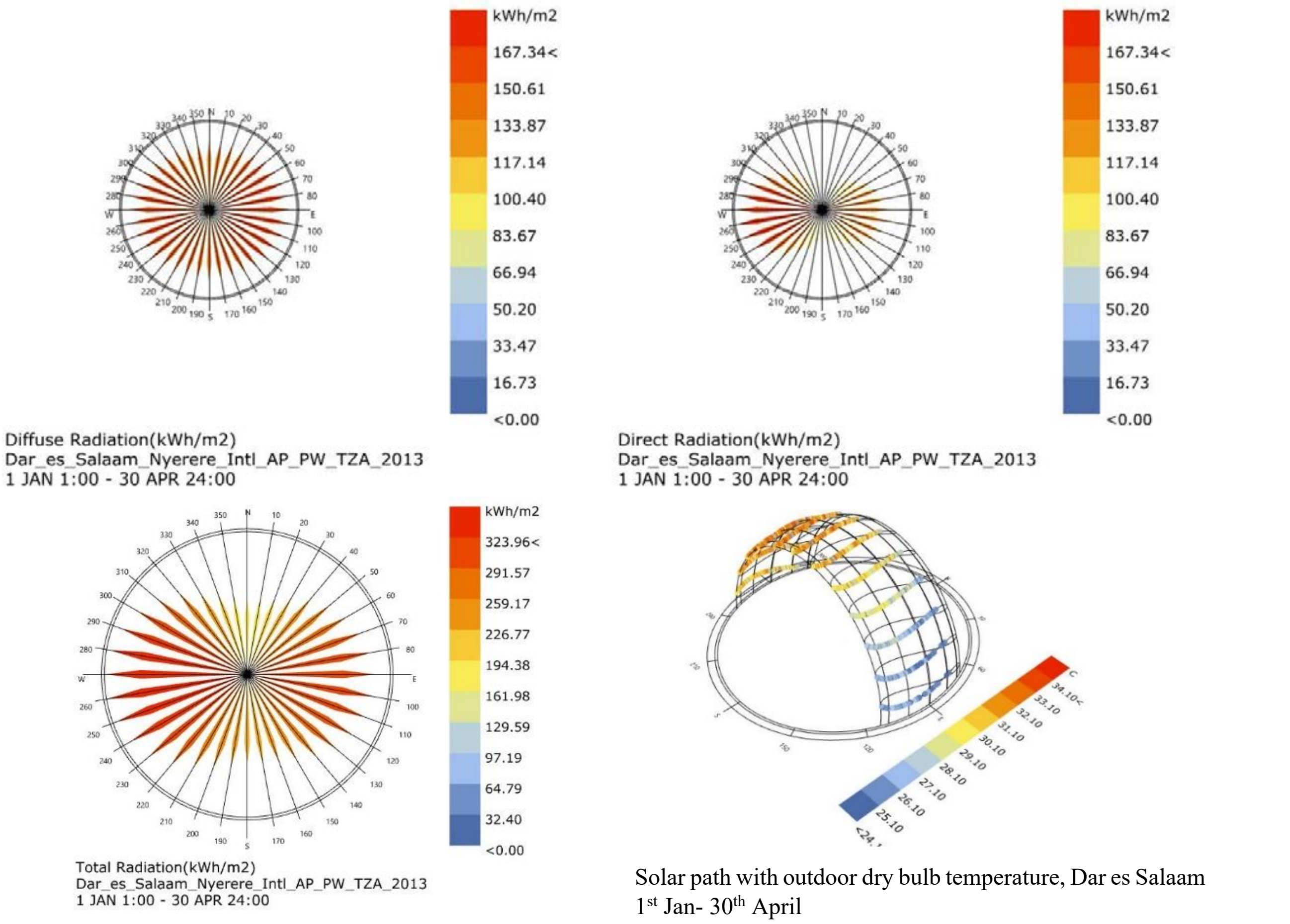
6.2.2.3. Solar radiation and Solar path

Direct normal radiation, Diffuse horizontal radiation and Global horizontal radiation

The distribution of solar radiation is represented in the following radiation roses as analysed with grasshopper plug in of rhinoceros software. The period of analysis is divided into:

a) 1st Jan to 30th April and 1st September to 31st December, high temperature months
b) 1st May to 31st August, low temperature months
c) 1st January to 31st December, annual

1st Jan- 30th April



Solar path with outdoor dry bulb temperature, Dar es Salaam 1st Jan- 30th April

Figure 29 Diffuse, Direct, Total Radiation and Solar path from 1Jan-30April

It can be observed that from January to April, Dar es Salaam receives more diffuse horizontal radiation than direct normal radiation. Moreover, the west direction receives the most direct radiation. This can also be observed from the solar path where highest temperatures are observed when the sun is heading towards the west side.

1st May to 31st August

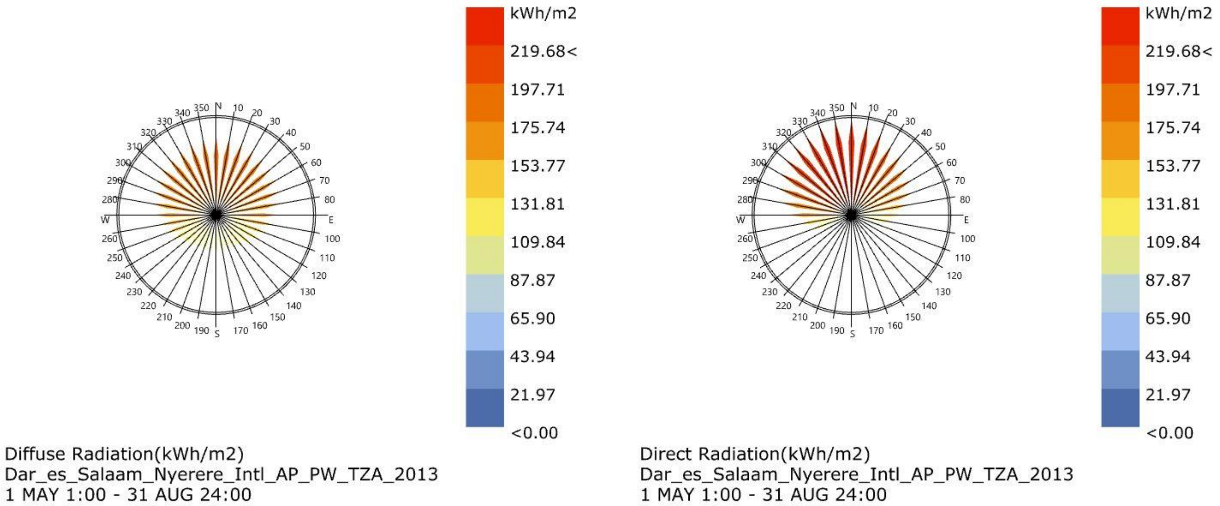


Figure 30 Diffuse and Direct from 1Jan-30April

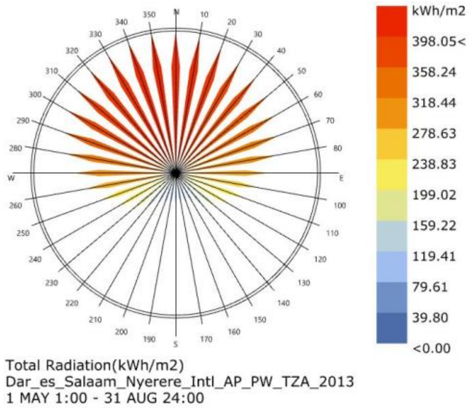


Figure 31 Total Radiation

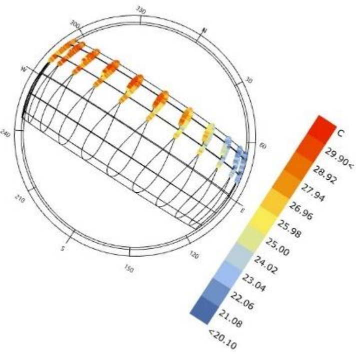


Figure 32 Solar path with outdoor dry temperature, Dar es Salaam from 1May to 31 August

From May to August, Dar es Salaam receives more direct normal radiation than diffuse horizontal radiation. Moreover, the North direction receives the most direct radiation. This can also be observed from the solar path where the sun's position is mostly in the Northern side. This information is of paramount importance in controlling solar radiation by the use of shading devices in the North façade of the building.

1st September to 31st December

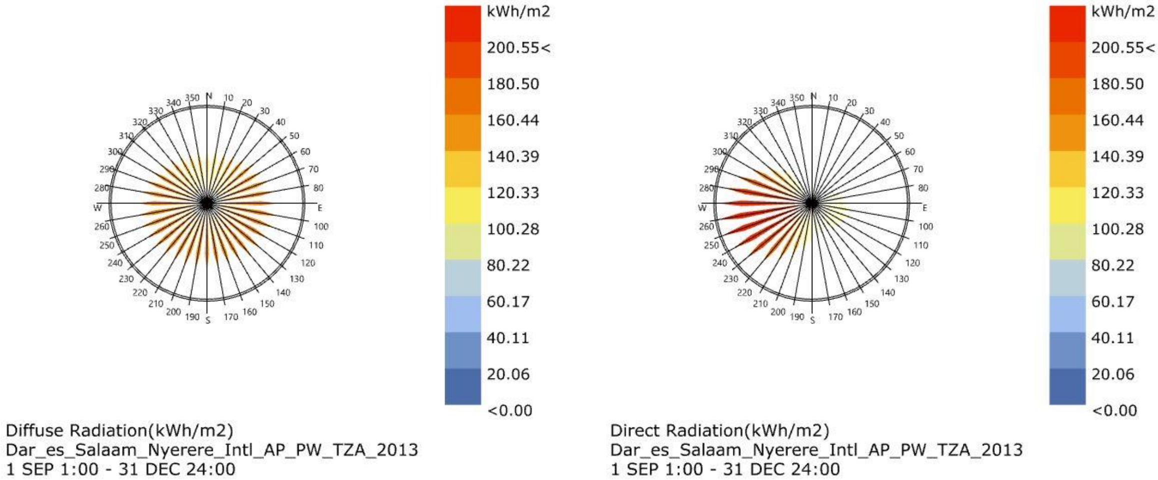


Figure 33 Diffuse and Direct Radiation from 1Sep to 31Dec

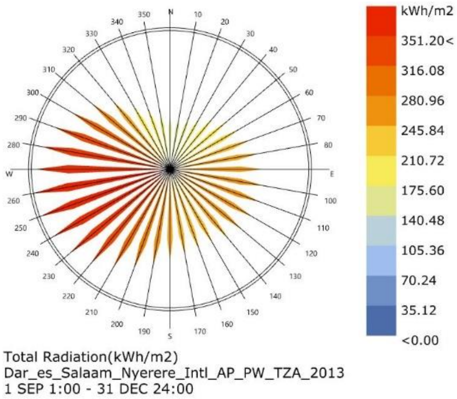


Figure 34 Total Radiation

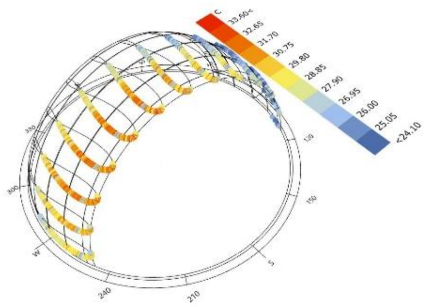


Figure 35 Solar path with outdoor dry temperature, Dar es Salaam from 1Sep to 31Dec

It can be observed that from September to December, Dar es Salaam receives more diffuse horizontal radiation than direct normal radiation. Moreover, the west direction receives the most direct radiation. This can also be observed from the solar path where highest temperatures are observed when the sun is heading towards the west side. The trend is similar to that of the period of 1st Jan to 30th April. Therefore, one can urge that dominantly, Dar es Salaam receives more diffuse horizontal radiation than direct normal radiation in a year (as shown in the annual radiation roses below). Moreover, shading strategies should be implemented both on the North and West façades as these are the direction which receives direct radiation the most.

1st Jan-31st Dec

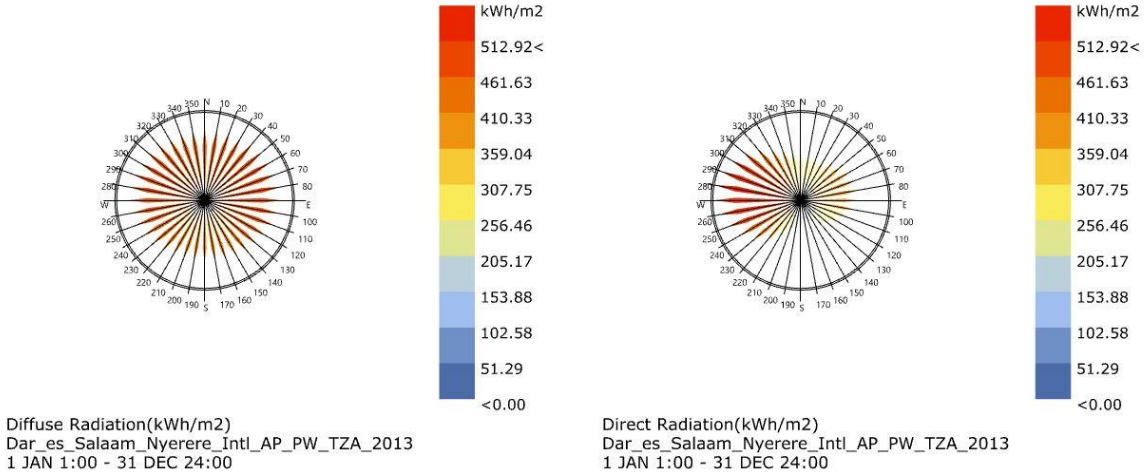


Figure 36 Diffuse and Direct Radiation from 1Jan to 31Dec

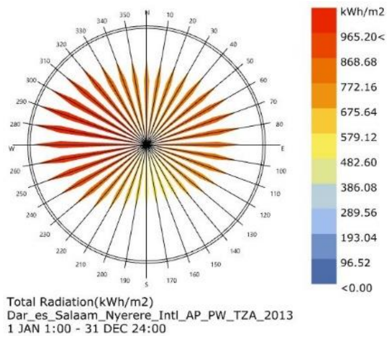


Figure 37 Total Radiation, Dar es Salaam from 1Jan to 31Dec

6.2.2.4. Wind speed and Direction

The wind speed and direction are represented in the following wind roses as analysed with grasshopper plug in of rhinoceros software. The period of analysis is divided into:

a) 1st Jan to 30th April and 1st September to 31st December, high temperature months
b) 1st May to 31st August, low temperature months

1st Jan- 30th April

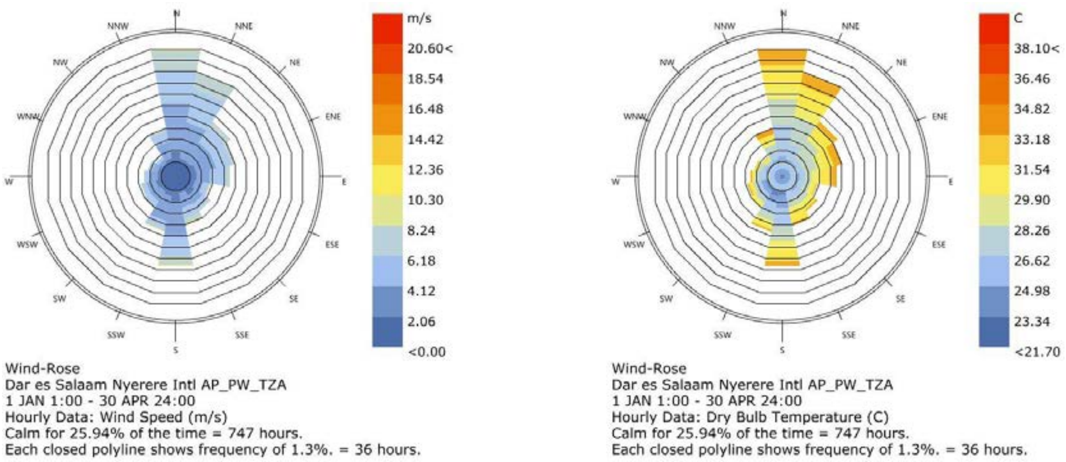


Figure 38 Wind Rose -Wind Speed and Dry Bulb Temperature from 1Jan to 30April

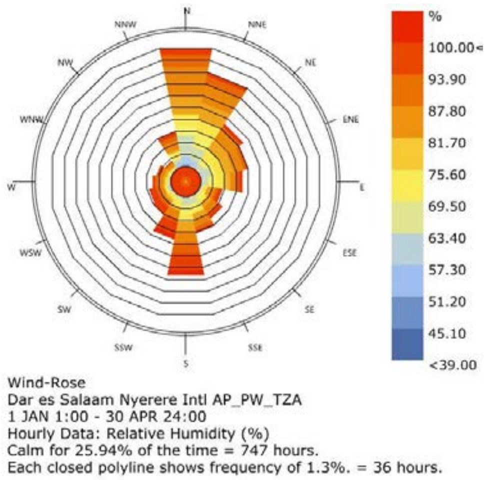


Figure 39 Wind Rose - Relative Humidity from 1Jan to 30 April

As observed, the wind average speed is about 5 m/s coming from North and North East directions, with an average temperature of 28°C and relative humidity at 80%. Moreover, as seen in the previous graphs, the outdoor air temperature is not constant during the entire day. Therefore, even if the average out door temperature of the air coming with the incoming wind is 28°C, which might be uncomfortable temperature for natural ventilation, still users of the building can adapt a natural ventilation strategy at some hours during the day and night as well when the outdoor temperature coming with the wind is comfortable enough.

1st May to 31st August

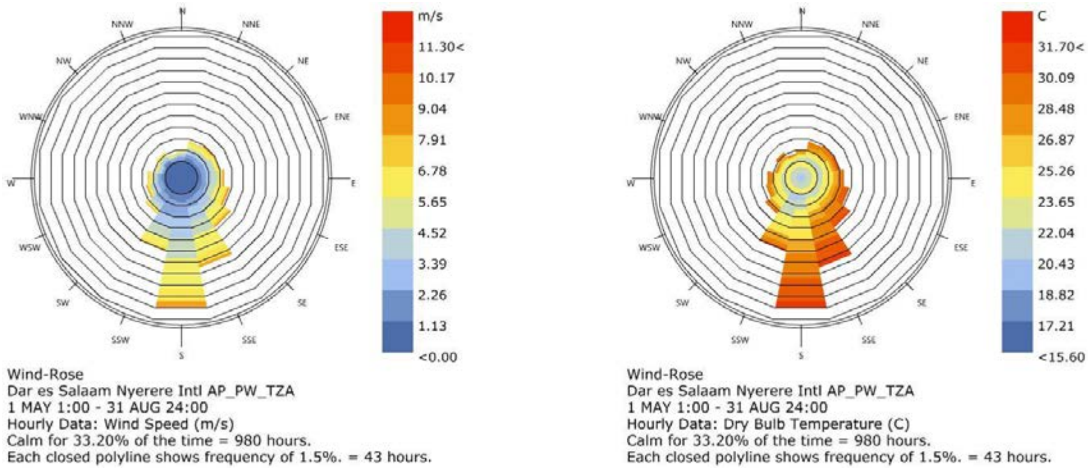


Figure 40 Wind Rose -Wind Speed from 1May to 31Aug

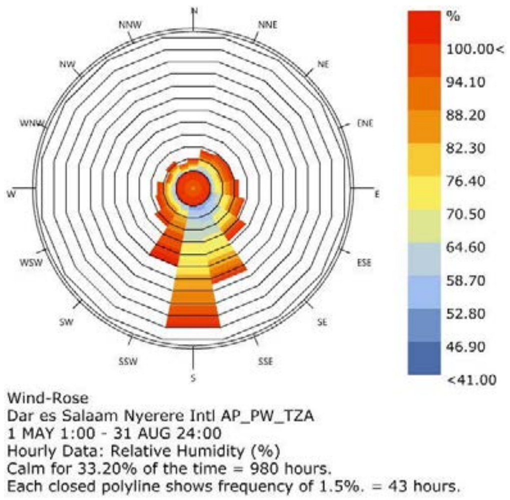


Figure 41 Wind Rose - Relative Humidity from 1May to 31Aug

At this period of the year, the wind changes direction, where it comes from South and South West direction. The wind speed and relative humidity of the outdoor air do not change that much. However, the outdoor temperature is now reduced. As explained above the users can still adapt the natural ventilation strategy as the temperature of the outdoor air is not constant during the entire 24 hours in a day.

1st September to 31st December

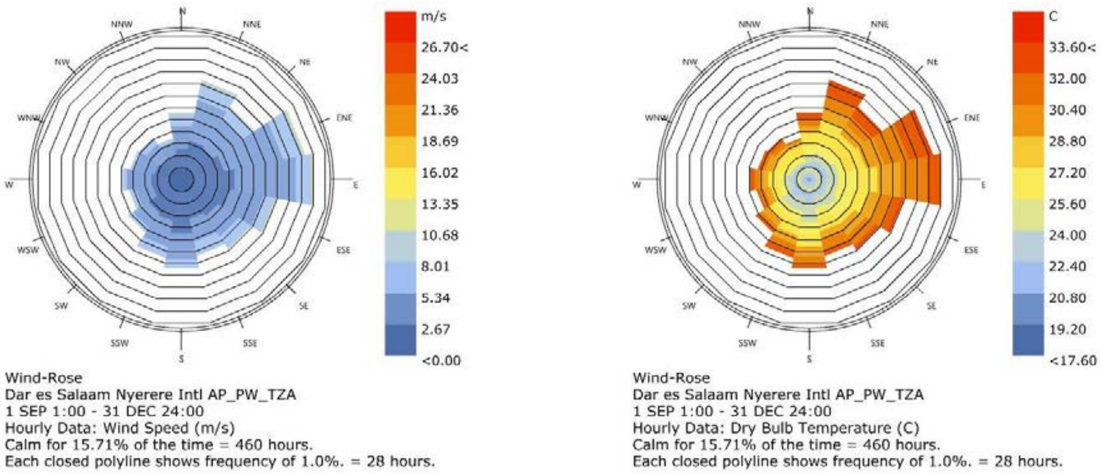


Figure 42 Wind Rose -Wind Speed and Dry Bulb Temperature from 1Sep to 31Dec

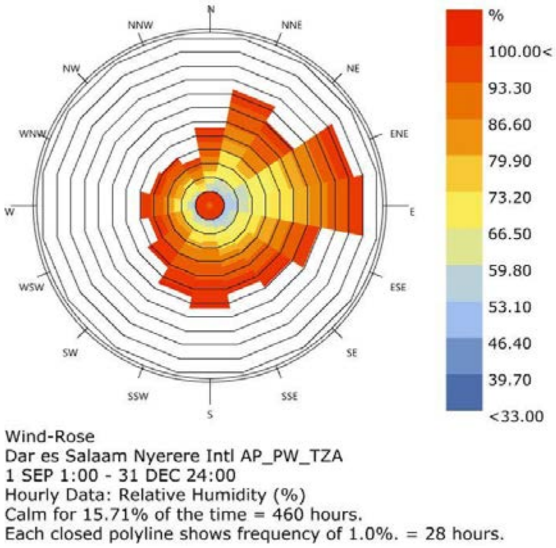


Figure 43 Wind Rose - Relative Humidity from 1Sep to 31Dec

As the end of the year is approaching, the wind speed increases a bit more up to on average 8m/s, with higher relative humidity than in other periods of the year. Moreover, the direction also changes as the wind comes from East and East North East directions.

6.3 Site information

6.3.1. Location

The case study is located in central business district of Dar es Salaam called Kariakoo. Therefore, the site is densely populated and surrounded with buildings of high and medium rise heights. Specifically, the proposed case study is located within block 8 along the Kongo street in Kariakoo as shown in the figure below:

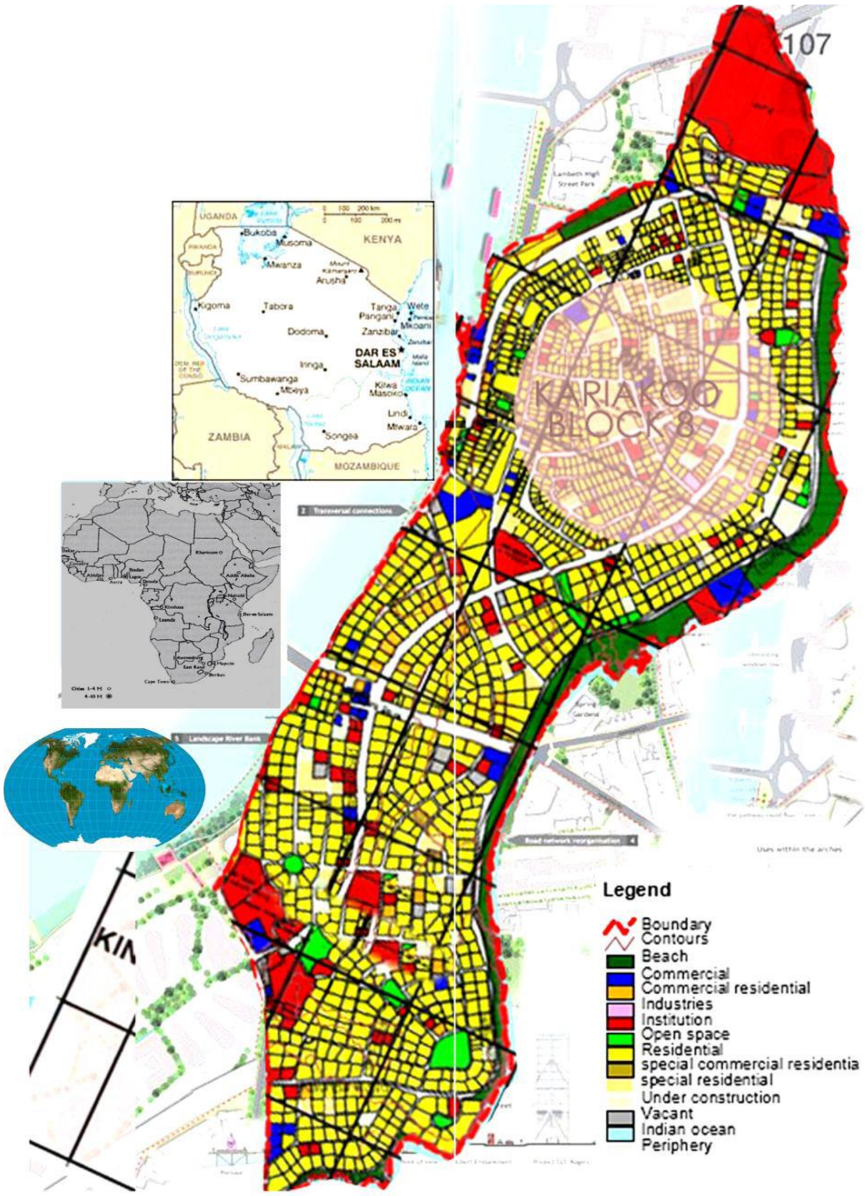


Figure 44 Kariakoo Typomophological analysis plan
Source: Project brief, Ilala Municipal Council (2019)

6.3.2. Site infrastructures and Accessibility

The area is easily accessible for all significant modes of transport. The main road between Ubungo (central bus station) and Posta (city centre) runs through the area and provides easy accessibility for cars and trucks. Streets within the designated area can constitute an important economic activity as wells as provide a visual connectivity. Finally, the distance to the airport of Dar es Salaam is fairly short, about 10km.

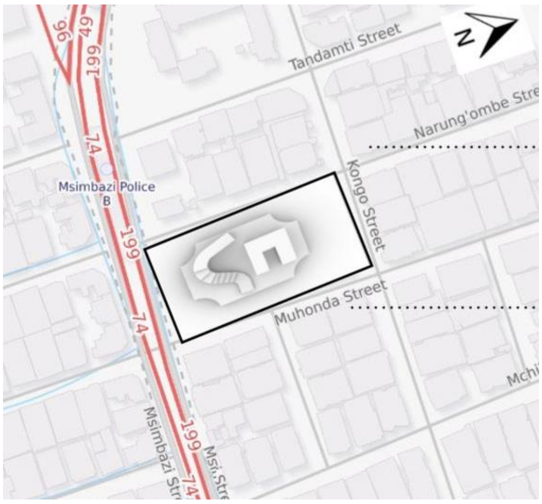


Figure 45 Site Plan
Source: Author and Open street maps

6.4 Building design proposal

Since at this point, we are considering that the project is still in early design stage, therefore, this sub-chapter will present design information that is useful for performing simulations and for applying multi-criteria analysis in the next stages. More elaborative design details will be introduced in chapter 8. The proposed design solution consists of mixed-use development project to be constructed in an urban area. However, for the objective of this thesis, only a residential block is considered during BPS, as shown in figure below:

6.4.1. Residential block design program

Storey	Function	Floor area (m^2)
Eighth to Sixteenth (last floor)	Apartments	6400

Table 8 Number of Storeys, Functions and Floor Area

Typical apartment	
Space	Floor area (m^2)
Bedroom 1	13
Bedroom 2	13
Bedroom 3	13
Lounge	25
Kitchen	9
Bath with toilet	5.5
Toilet	1.5
Storage	4
Lobby	6

Table 9 Typical apartment, space and Floor area

6.4.2. Building form

For the objectives of simulations only a residential block is considered during BPS.

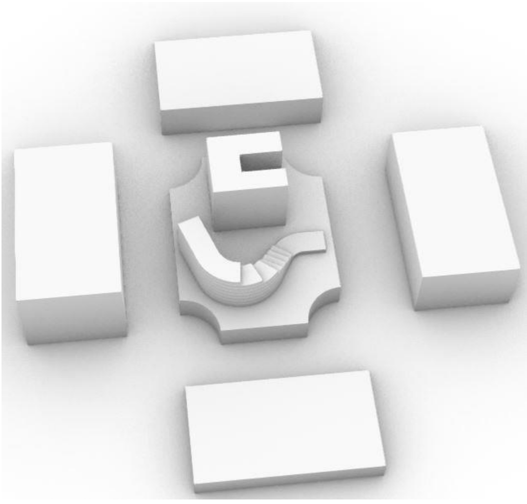


Figure 46 Mixed-use development design proposal (residential, office, and commercial block)

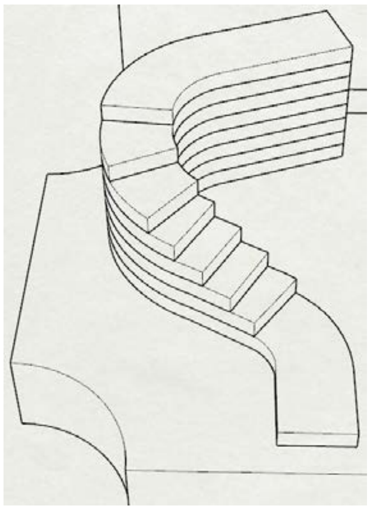


Figure 47 Residential block

6.4.3. Typical apartment plan/partly floor plan

As it is shown in the later chapters, during simulations a bedroom is considered as a thermal zone. For this reason, it is important to observe a typical apartment floor plan at this stage.

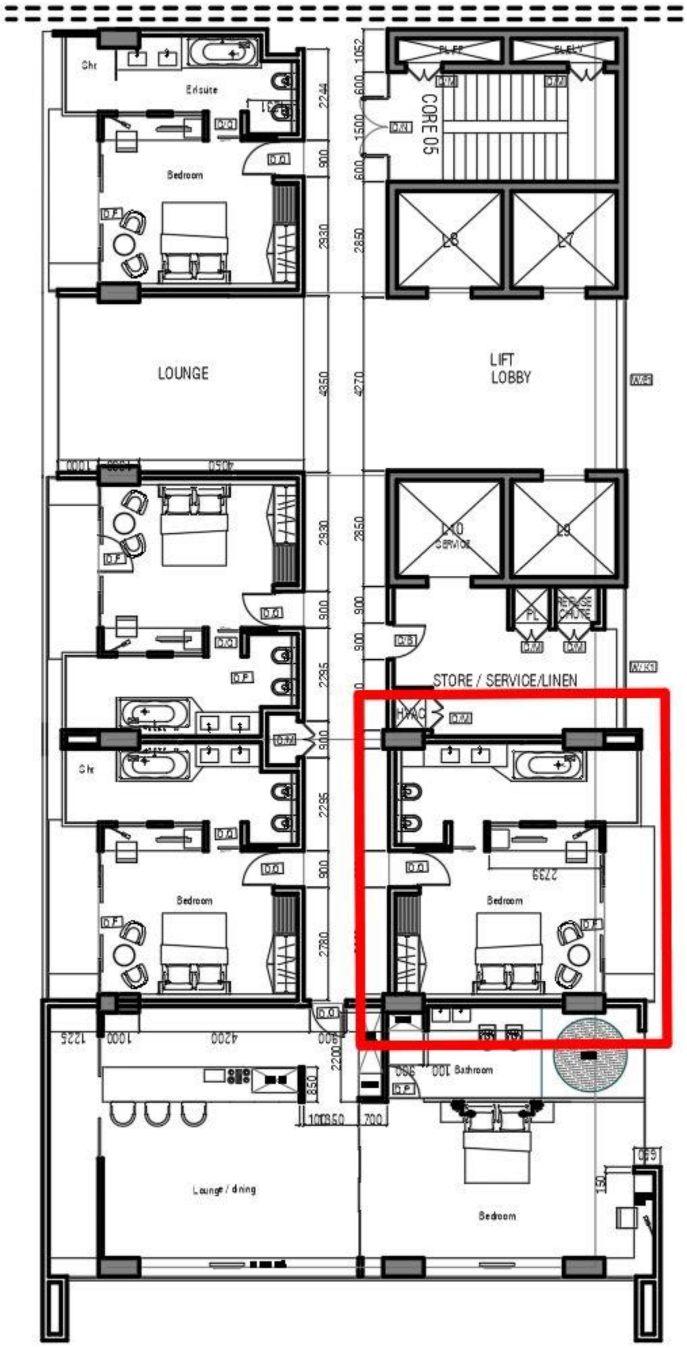


Figure 48 Typical appartment plan/partly floor plan and a studied bedroom

6.5 Building envelope design proposals

In order to design building envelope systems, a thoroughly investigation of local architecture and sustainability in built environment in Tanzania was first done.

6.5.1. Study of local architecture for building envelope systems

6.5.1.1 Construction materials

Construction materials refer to any substance, natural or man-made which is used for construction purposes to create structures and buildings.

The choice of building materials to use in a construction is determined by factors such as availability, cost, tenacity and durability. For this reason, it is important to understand the locally available construction materials.

6.5.1.2 Traditional materials

Stone - This is the one of the most common construction materials in the country. There are two types of stones in the market; manually cut stones and machine cut stones. The manually cut stones are strong and are preferred for foundations and load bearing walls.

Fired brick - These are made using clay which is compressed to form blocks then air-dried. After drying, the bricks are burnt or fired in a kiln to permanently harden them. Fired bricks are commonly used for construction of walls and arches as a substitute to stone. Bricks can have hollow cavities to lighten them and hasten the drying process. The products are popular due to their fire resistance abilities.

Wood (Timber) - Due to its abundant availability, wood has been used as the main traditional material in many rural parts of Tanzania for a very long time. Used mainly for traditional houses, wood is used as structure for walls and roofs. In urban areas, wood is mainly used as sub-structure in the construction of roofs and ceiling. Also, wood is used for doors and windows frames as well as for floor finishing.

Adobe brick - adobe is widely used to make bricks especially in rural and sub-urban areas. Locally made, adobe brick is made by mixing earth with grass to increase its stiffness. Later, the brick is left to dry for a couple of days and then used to make walls.

6.5.1.3 Modern Materials

Cement - Introduction of cement in Tanzania construction market completely shifted the traditional ways of construction methods. For building envelopes, it is mainly used to make bricks by mixing with sand and water and left to dry. Also used as adhesive to hold stones and bricks in place as well as in plastering.

Aluminium - The use of aluminium is becoming one of the most used construction materials especially for doors and windows frames in both residential and high rising buildings. Aluminium is also becoming useful in the construction of cladding especially for high rising commercial buildings.

Glass - Glass is quickly becoming an essential material in modern architecture. The material is important on buildings since it provides the ability to let in light into the interiors while simultaneously locking out undesirable weather elements. Though glass is very brittle, modern technologies have enabled it to be used for covering entire walls of a building with the support of some form of frame. The use of decorative glass is now a trend as more designers seek innovative ways to decorate the exteriors of buildings.

Glazed ceramic tiles - These have quickly become one of the most popular building materials in modern buildings. They are formed from a mixture of clay, sand and natural additives molded into desired shape then permanently hardened by heat in a kiln at very high temperatures of up to 1500 degrees. They are commonly used to cover floors, walls and surfaces such as counter tops. The tiles come in a wide variety of designs ranging from simple squares to complex mosaics. They are durable, resistant to tread wear, have color permanence and are easy to clean.

Concrete - This is a composite building substance made by combining cement, gravel, sand and water in recommended proportions. It is mainly used in floor and roof slab construction mainly for commercial and high rising residential buildings.

EPS panels - The use of prefabricated building materials (prefabs) is fast gaining currency in the country. The technology involves the frames of houses being manufactured in a factory before being shipped to a construction site for assembly. There are different types of prefabs available in the market with the most popular ones in the country being the pre-engineered steel structures. Prefab structures are easier, cheaper and faster to construct than the normal brick and mortar buildings.

6.5.1.4 The integration of new technologies in construction

In recent years, the Tanzanian construction market has witnessed the integration of new technologies especially in high rising commercial buildings. In building envelope for example, new glazing technologies are allowing new ways designing and building. For example, an envelope system for a high rising commercial building in Dar es Salaam was built using glass and composite. A composite material was used to make composite profiles that are loadbearing and transparent allowing for natural daylighting while reducing the intensity of solar radiation.

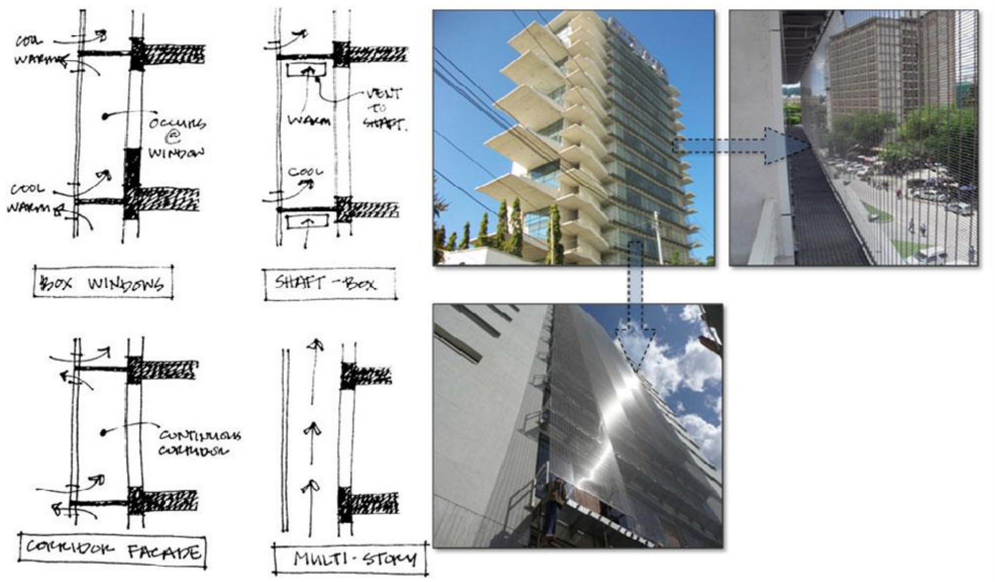


Figure 49 The use of glazing and composite materials in high rising commercial building in Dar es Salaam
Source : https://drift.eur.nl/

6.5.2. The study of sustainability in built environment in Tanzania

As mentioned earlier, challenges such as high rate of urbanization and climate change are increasingly putting pressure on building industry across many parts of the globe. As a result, the demand is shifting towards designing environmentally friendly, energy efficient and high-performance buildings. Although, the scale of awareness on this is still low in Tanzania, there are ongoing measures that have been undertaken to establish a framework that will provide a road map towards sustainable and high-performance building design.

Three organizations: AQRB, NCC and Tanzania Green Building Council have already established a regulatory framework that specify all parameters that need to be met in order to design, build and operate sustainable buildings. These parameters include specific levels of indoor visual and thermal comfort, indoor air quality, building energy demands, environmental impacts, freshwater consumption and sustainable construction.

However, one should note that the integration of these parameters into building practice is still an ongoing process. As future building practice professionals in Tanzania, we’re therefore contributing towards sustainable building design by proposing the methodologies in this thesis, which aims at helping building industry professionals in the country to apply a performance-based design approach, a step closer towards sustainable building practice.

6.5.3. Background and literature review - how to design building envelope in warm-humid climate

The proposed building envelope components are climate-based designed. This means they're designed based on climatic conditions of the area in question. Since the case study is in warm-humid climatic context, a thorough literature review on how to design building envelope solutions on this climate was done.

6.5.3.1. On insulation

K. Sudhakar et al. (2019), stated that in hot and humid climate, the u-value has to be kept low by installing insulation layers. The same authors urged that, by applying an exterior insulation, the walls are protected from solar heat gains, while thermal bridges are averted. Moreover, they pointed out the necessity of finding the most effective ratio between energy savings and insulation costs which linearly rise with insulation thickness. A study by J.C. Lam et al. (2010), found out that in hot and humid climate in Cameroon, the optimum thickness for an extruded polystyrene insulation layer was from 0.092 to 0.102m.

A study by A. Torres-Rivas et al. (2018), showed that bio-based insulation materials such as cotton, cork, corn, hemp and straw offer not only better results compared to conventional insulation materials such as polyurethane, but also, they're less costly and environmentally friendly. For example, F Pittau et al. (2019), outlined that hemp and straw have a potential of capturing and storing carbon when used as thermal insulation, while conventional materials such as EPS cannot remove CO_2 from the air.

The results obtained by A. Torres-Rivas et al. (2018), also showed that the use of bio-based insulation materials in hot temperatures and high relative humidity, must be preceded by a detailed analysis of construction solution in order to prevent interstitial condensation. The same authors also urged that the use of ventilated cavity walls and water vapor barrier can also help in reducing the risks of condensation.

6.5.3.2. On shading devices

S. Mirrahimi et al. (2016), emphasized on the importance of considering shading devices as they provide positive impact towards energy efficiency in buildings. The authors also highlighted a study in warm humid climate in Singapore whereby energy savings in cooling between 2.62–3.24% occurred as a result of applying a simple 30 cm-deep horizontal shading device to the window.

A study by E. Halawa et al. (2018), stated that in hot climates, pairing shading devices with suitably composed and oriented openings can be considered as an effective approach towards preventing excessive solar heat gain, resulting in significantly reduced building cooling loads.

W. Feng et al. (2019), also highlighted existing studies that found shading windows can reduce about 25% of the summer cooling load, and a total energy use reduction of approximately 20%.

6.5.3.3. On window technologies

S. Mirrahimi et al. (2016), also highlighted that the thermal performance of window improves when the U-value becomes lower, and this can be achieved in different climate conditions through different means such as adding more glazing layers, applying special coatings to control solar radiation, and avoiding gaps between two layers with low thermal conductive gases such as argon or krypton. The same authors showed that there is much better improvement of cooling loads when double coated reflective glass is used instead of the single clear glass.

They also explained different studies that investigated the relationship between WWR and either energy consumption or indoor thermal comfort in buildings. One study found that energy requirement at four climates in Turkey became higher when the glazed area increased. Another study applied building simulation and indoor CFD to predict the indoor thermal environment for naturally ventilated buildings in the hot-humid climate of Singapore whereby a WWR of 10% to 40% was applied for all orientations. From the results, it was recommended that the optimum window to wall ratio in Singapore to be 24%, based on the improvement achieved in the indoor thermal comfort.

6.5.3.4. On external wall materials

S. Mirrahimi et al. (2016), further mentioned several studies that investigated the use of low and thermal mass construction in warm and humid climate. They highlighted that, in high humid climates, high mass construction is not recommended because of their limited diurnal range. However, low mass buildings are preferred due to their effectiveness in passive cooling.

6.5.3.5. On façade technics

W. Feng et al. (2019), pointed out that one of the ways to improve NZEB envelope performance is by setting up a ventilation layer between the outer envelope and indoors, by means of an attic roof, double roof, or double-skin wall. This can contribute to the reduction of thermal gain. The same authors elaborated the application of green roofs and walls in reducing the heat across building envelope by cooling the ambient air through transpiration and photosynthesis. The authors also highlighted a study which found out that in the summer, green roofs can reduce heat through building roofs by about 80%, and also green roofs can reduce energy consumption by 2.2%–16.7% in summer, compared to traditional roofs.

6.5.4. Applied approach in proposed design of building envelope components

Although the building envelope components are climate-based designed, other aspects such as local architecture and materials and sustainability objectives of Tanzania built environment are also considered. This approach can be summarized in the figure below:

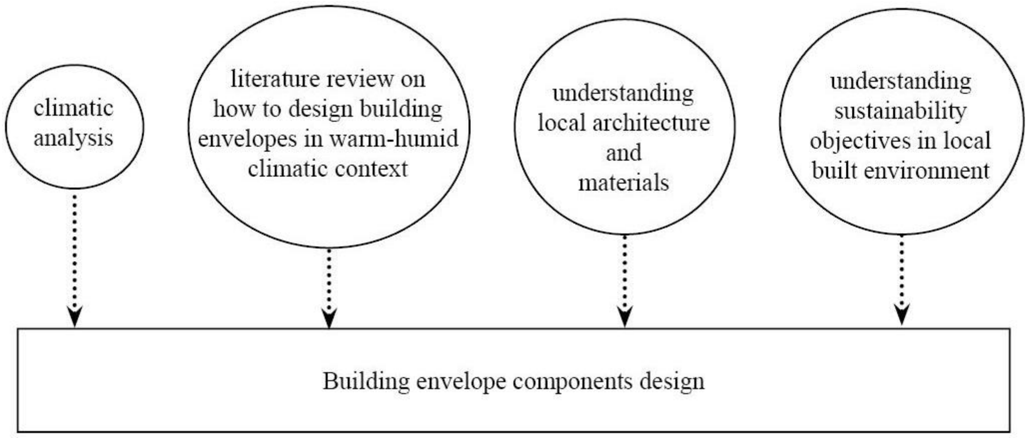


Figure 50 Approaches applied in designing building envelope components

In the design of building envelope components, the following important points were therefore, redefined:

a) Understanding and take into consideration the use of convectional construction materials

In Tanzania, the use of bricks made of cement and sand mixture, is the most conventional construction technic especially in urban areas. Moreover, the use of bricks made of adobe/earth is the most conventional technic especially in rural and sub-urban areas. Therefore, building envelope configurations made out of these materials are proposed in order to understand the indoor comfort conditions and cooling energy demands when conventional building materials are used.

b) Turning unpopular materials into new construction materials

Based on literature review, it is advisable to apply an outside insulation on envelopes in hot climatic regions. This is due to the fact that, since almost all over the year it is normally hotter outside than inside during the day, an outside insulation will therefore reduce the rate of heat passage across the envelope during the day.

Apart from insulation position, insulation materials as well as insulation optimum thickness are other important factors to consider when applying insulation in a particular weather context. However, the exact thickness should be determined based on the desired results in terms of thermal performance, manufacture standards and climate context.

Normally, in Tanzania the use of insulation is practically non-existing. However, there are various available local materials which could be used as insulation materials. These materials are bio-based materials with thermal properties close or even better than conventional insulation materials. Moreover, the use of bio- based materials offer less environmental impact. Therefore, another building envelope solution is the application of bio-based insulation materials (specifically corn insulation), as corn is practically available across all regions of Tanzania.

However, since the climate of the region is warm humid, it is important to control humidity in order to reduce the risks of both superficial and interstitial condensation on the layers of the building envelope, especially when using bio-based insulation. One of the ways to do that, is by applying vapor barrier layers or by using moisture resistance treatment. In the proposed solutions water vapor barriers is therefore applied.

Another unpopular material in Tanzania construction industry is bamboo. Locally abundantly, bamboo is one of the untapped potentials that could offer environmentally friendly solutions in the building industry.

Bamboo can be used in its natural form or can be processed to produce different products that can be used in façade construction. In this thesis, the use of bamboo cladding has been proposed in one of the building envelope solutions. Moreover, in the proposed building envelope solution, bamboo is treated with coating such as polish so as to avoid condensation of rainwater on its surface and increase reflective properties for solar radiation.

Last but not least, coconut fiber is another locally abundant material that is yet untapped and that could be turned into useful construction material. For example, coconut fiber can be used to make bricks. Dar es Salaam is a coastal city, and therefore coconut trees are easily available. In one of building envelope solutions, it is therefore proposed to use coconut fiber brick in order to understand the thermal performance of a building envelope made out of this material.

However, one should note that currently, the technology to make bio-based insulation products, coconut fiber and bamboo-based products does not exist, or at least there is no one doing it in Tanzania. This doesn’t mean, it is impossible to make this happen, as the technology can be easily adapted from other countries.

c) Application of an entirely new technic

Here, the introduction of an entirely new way of building envelope in Tanzania is proposed. In a sense, these construction technics are not entirely new, however, they are just not popular in Tanzania. Basically, the climate of Dar es Salaam is characterized mainly by high humidity, and one of the ways to control humidity is by allowing air circulation across the building envelope. Micro-ventilated façade seems to offer such a solution.

This construction technic is not popular in Tanzania. However, global manufactures of construction materials and building envelope solutions such as Knauf, have already entered the Tanzanian market, and therefore, it is a matter of time before these technics becomes popular. For this reason, one of the proposed building envelope solution is a micro-ventilated façade made of OSB panels.

Moreover, the use of green roofs is almost non-existing in Tanzanian building industry. However, the advantages of applying green roofs as a sustainable strategy, especially in urban and warm humid areas are immense. As explained in the literature review section, among other benefits, green roofs provide natural insulation, offer good solution for phenomenon such as UHI in urban areas. Therefore, the use of green roof is also proposed as one of the building envelope solutions.

6.5.5. Opaque building envelope solutions proposed

Based on the paragraphs of the above section, the final proposed opaque building envelope solutions consists of:

i. traditional construction materials (cement, sand, concrete)
ii. bio-based (corn) insulation, and locally available materials (coconut fiber, bamboo)
iii. micro-ventilation and prefabricated façade technic

In this thesis, only properties of external and internal walls are changed during simulations. For this reason, four different types of external and internal walls are proposed as follows:

i. Cement and sand mixture brick wall
ii. Coconut fiber brick wall
iii. Adobe/earth brick wall
iv. Micro-ventilated OSB panel wall system

Floor slab is made of multi-layered concrete, while roof is made of multi-layered green roof materials.

6.5.6. Physical and thermal properties of building envelope solutions for the energy model

An extensive literature review was performed in order to obtain the numerical values of physical and thermal properties of different materials on each of the building envelope technologies defined, which are required as inputs for the simulation model. For example, a user guide provided by IES Virtual Environment (2014) has a range of physical and thermal properties of different materials. EnergyPlus input output reference (2019) contains standard values of thermal and physical properties of different envelope systems such as green roofs. F. Pittau, et al. (2019) presented various physical and thermal properties of bio-based insulation materials. T.R Alba, et al. (2018) outlined physical and thermal properties of different building materials.

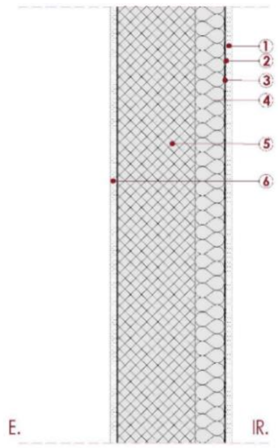
These properties are the required inputs for the energy simulation model. The input physical and thermal properties defined for each building envelope material are thickness [m], density [Kg/m3], thermal conductivity [W/mK], and specific heat capacity [J/kgK]. The following tables display the physical and thermal properties of different building envelope components which are needed as inputs for the energy model:

6.5.6.1. Cement and sand mixture brick

The use of cement and sand mixture brick, and mortar with outside insulation

Exterior wall (cement/sand brick + outside insulation)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	outside					
1	render/plaster	10	0.5	1300	1000	0.020
2	plastering soft woven wire mesh	2	75	8777	377	0.000
3	aluminium vapor barrier	3	160	2800	895	0.000
4	corn insulation board	25	0.038	1800	100	0.658
5	cement/sand brick	200	0.721	1922	837	0.277
6	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 10 Properties of exterior wall (cement/sand brick + outside insulation)



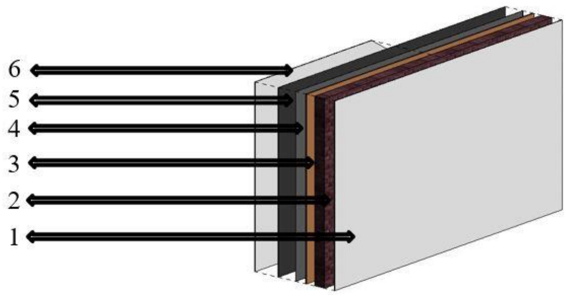
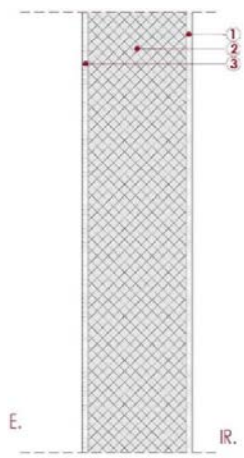


Figure 52 3D Perspective Cement and sand mixture brick

Figure 51 Section-Exterior Cement and sand mixture brick

Internal wall (cement/sand brick)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	inside					
1	render/plaster	10	0.5	1300	1000	0.020
2	cement/sand brick	110	0.721	1922	837	0.0
3	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 11 Properties of Interior wall (cement/sand brick + outside insulation)



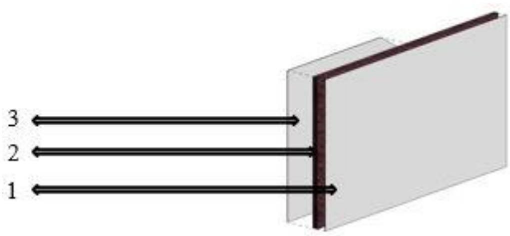


Figure 54 3D Perspective- Interior Cement and sand mixture brick

Figure 53 Section- Interior Cement and sand mixture brick

6.5.6.2. Coconut fiber brick

The use of coconut fiber brick with outside insulation

Exterior wall (coconut fiber brick + outside insulation)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	outside					
1	render/plaster	10	0.5	1300	1000	0.020
2	plastering soft woven wire mesh	2	75	8777	377	0.000
3	aluminium vapor barrier	3	160	2800	895	0.000
4	corn insulation board	25	0.038	1800	100	0.658
5	coconut fiber brick	200	0.048	1180	2600	4.167
6	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 12 Exterior wall (coconut fiber brick + outside insulation)

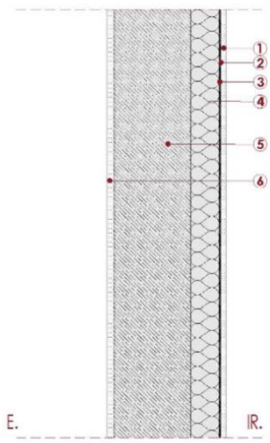


Figure 55 Section - Exterior wall coconut fiber brick with outside insulation

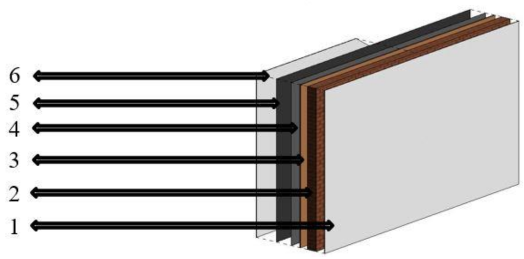


Figure 56 3D Perspective - Exterior coconut fiber brick with outside insulation

Internal wall (coconut fiber brick)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	inside					
1	render/plaster	10	0.5	1300	1000	0.020
2	coconut fiber brick	110	0.048	1180	2600	2.292
3	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 13 Internal wall (coconut fiber brick)

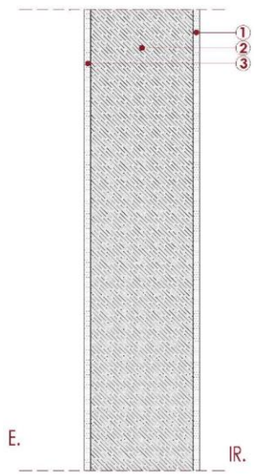


Figure 57 Section - Interior wall coconut fiber brick with outside insulation

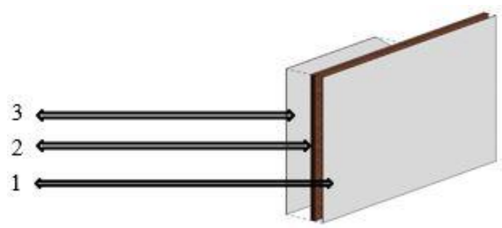


Figure 58 3D Perspective - Interior wall coconut fiber brick with outside insulation

6.5.6.3. Adobe/earth brick

The use of adobe/earth brick and mortar with outside insulation

Exterior wall (adobe/earth brick + outside insulation)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	outside					
1	render/plaster	10	0.5	1300	1000	0.020
2	plastering soft woven wire mesh	2	75	8777	377	0.000
3	aluminium vapor barrier	3	160	2800	895	0.000
4	corn insulation board	25	0.038	1800	100	0.658
5	adobe/earth brick	200	0.83	1040	1887	0.241
6	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 14 Exterior wall (adobe/earth brick + outside insulation)

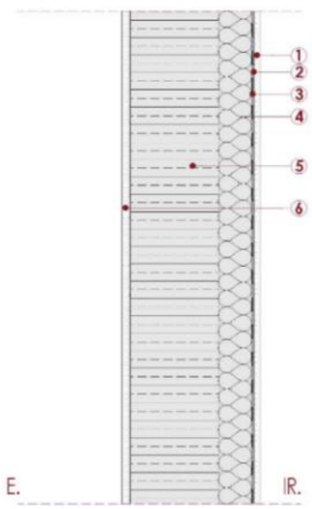


Figure 59 Section - Exterior wall adobe/earth brick and mortar with outside insulation

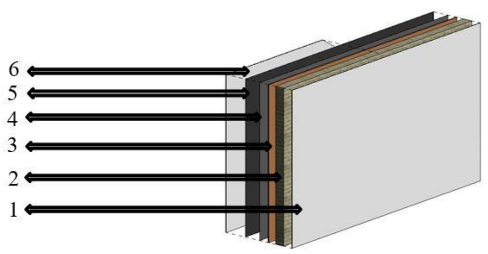


Figure 60 3D Perspective - adobe/earth brick and mortar with outside insulation

Internal wall (adobe/earth brick)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	inside					
1	render/plaster	10	0.5	1300	1000	0.020
2	adobe/earth brick	110	0.048	1180	2600	0.133
3	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 15 Internal wall (adobe/earth brick)

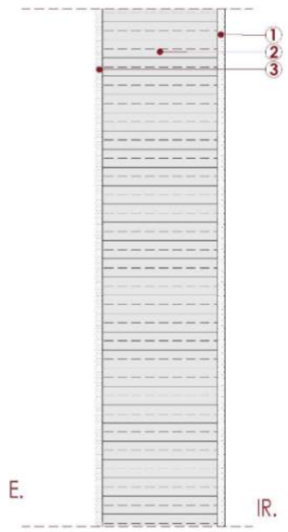


Figure 61 Section- Internal wall adobe/earth brick and mortar with outside insulation

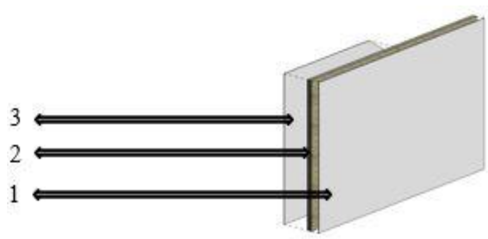


Figure 62 3D Perspective- adobe/earth brick and mortar with outside insulation

6.5.6.4. Micro-ventilated OSB panel wall system

Exterior wall (OSB panel wall system + outside insulation + air gap + outside cladding)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	outside					
1	bamboo cladding	15	0.21	900	840	0.071
2	air gap	76.5	0.024	1.275	1006	3.188
3	aluminium vapor barrier	3	160	2800	895	0.000
4	corn insulation board	25	0.038	1800	100	0.658
5	OSB panel	40	0.15	650	1600	0.267
6	gypsum plasterboard	12.5	0.16	950	840	0.078
7	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 16 External wall OSB panel

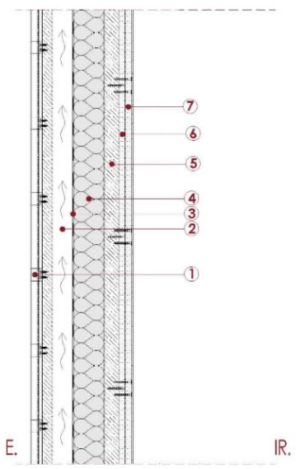


Figure 63 Section - Exterior wall micro-ventilated OSB panel wall system

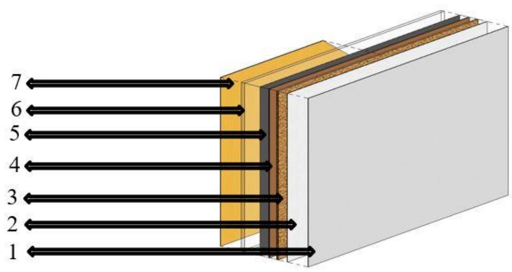


Figure 64 3D Perspective – micro-ventilated OSB panel wall system

Internal wall (OSB panel wall system)						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	inside					
1	render/plaster	10	0.5	1300	1000	0.020
2	gypsum plasterboard	12.5	0.16	950	840	0.078
3	OSB panel	0.020	0.150	1600	650	0.133
4	corn insulation board	25	0.038	1800	100	0.658
5	OSB panel	0.020	0.150	1600	650	0.133
6	gypsum plasterboard	12.5	0.16	950	840	0.078
7	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 17 Internal wall (OSB panel wall system)

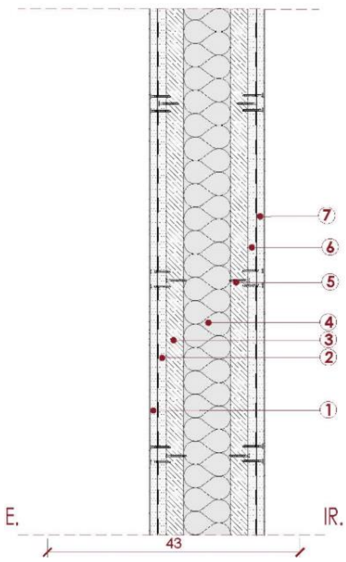


Figure 65 Section - Exterior wall micro-ventilated OSB panel wall system

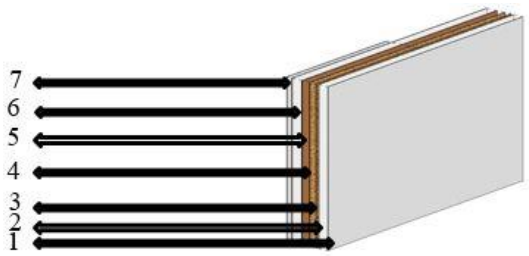


Figure 66 3D Perspective - micro-ventilated OSB panel wall system

6.5.6.5. Roof

Roof						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	outside					
1	roof vegetation	180	0.4	641	1100	0.450
2	corn insulation	25	0.038	1800	100	0.658
3	lightweight concrete screed	50	0.38	1200	1000	0.132
4	cast concrete	200	1.4	2100	840	0.143
5	ceiling gypsum plasterboard	12.5	0.16	950	840	0.078
6	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 18 Roof

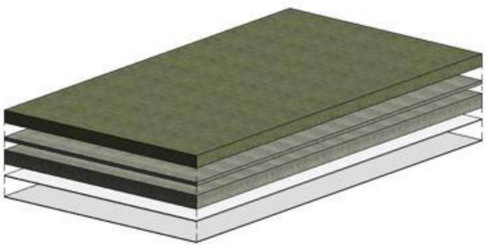


Figure 67 3D-Green Roof

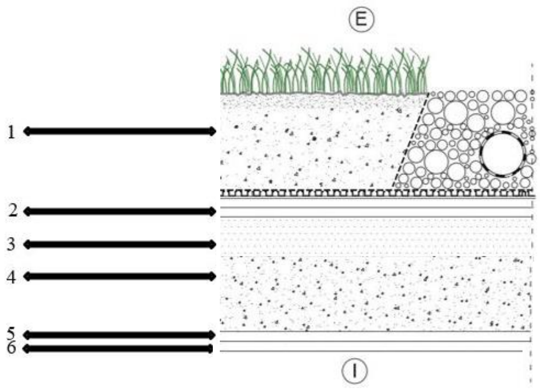


Figure 68 Section-Green Roof

6.5.6.6. Floor

Floor						
	Layer	Thickness [mm]	Conductivity [W/mK]	Density [Kg/m3]	Specific heat capacity [J/kgK]	Thermal resistance [m2k/W]
	inside					
1	wood finishing	5	0.21	500	840	0.024
2	lightweight concrete screed	50	0.38	1200	1000	0.132
3	cast concrete	200	1.4	2100	840	0.143
4	ceiling gypsum plasterboard	12.5	0.16	950	840	0.078
5	render/plaster	10	0.5	1300	1000	0.020
	inside					

Table 19 Floor

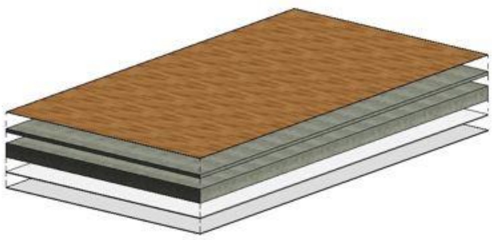


Figure 69 3D-Ground Floor slab

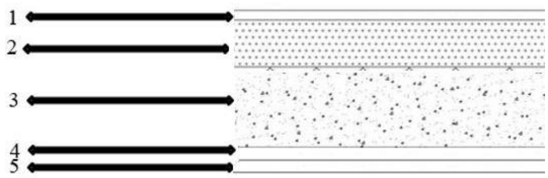


Figure 70 Section-Floor Slab

6.5.7. Window technology

Window configuration is defined using a software called LBNL window, which has a data base of window glazing, frame and shading materials together with their optical properties. After choosing the window glazing and frame configuration, the software calculates separately the thermal and optical properties of the total glazing configuration and the overall window configuration (glazing and frame) total u value, solar gain heat coefficient (SHGC) and visible transmittance.

A double-paned, low-e coating window is selected. As noted by K. Sudhakar et al. (2019), a low-e glass has a metal or metallic oxide coating which increase reflectance thus decreasing the absorbance and lowering u-value. However, the same authors urged that low-e coatings can reduce visual transmittance. Therefore, to solve this problem, spectrally selective coatings can be applied, which only transmit visible light and still work as insulation. They also, pointed out that double-paned windows have a gap which can either be vacuumed or filled with either air or inert gases such as argon, krypton and xenon. The inert gases are denser than air thus reducing air movement and convectional heat gains, and also the higher R-values reduces the heat transfer by conduction.

The following figure shows the glazing technologies proposed as screenshotted from LBNL window software user interface:

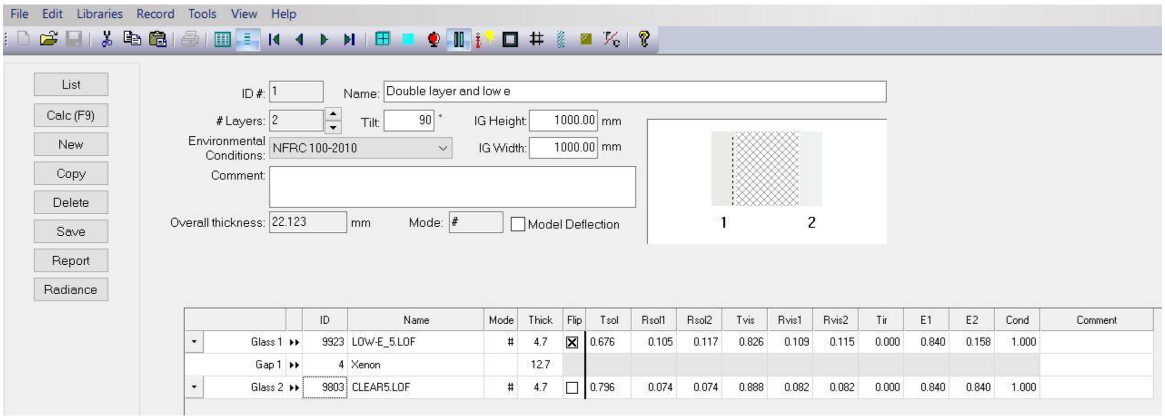


Figure 71 LBNL glazing assembly user interface

whereby:
Glass 1 is low-e coating glass pane
Glass 2 is clear internal glass pane
The air gap is filled with xenon gas

Optical and thermal properties of glazing defined as:

Tsol	Solar transmittance of the glazing layer
Rsol1	Solar reflectance of the glazing layer, exterior-facing side
Rsol2	Solar reflectance of the glazing layer, interior-facing side
Tvis	Visible transmittance of the glazing layer
Rvis1	Visible reflectance of the glazing layer, exterior-facing side
Rvis2	Visible reflectance of the glazing layer, interior-facing side
Tir	Thermal infrared (longwave) transmittance of the glazing layer
E1	Infrared (longwave) emittance of the glazing layer, exterior-facing side
E2	Infrared (longwave) emittance of the glazing layer, interior-facing side
Cond	Conductance of glass, Units: W/m-K

Table 20 Optical and thermal properties definition of glazing

Overall, the defined window is a horizontal sliding type with aluminium frame, with the following thermal and optical properties which are need as inputs for the simulation model:

U factor	2.022 W/m^2-K
Solar Heat Gain Coefficient (SHGC)	0.591
Visible Transmittance (VT)	0.664

Table 21 Thermal and Optical properties which are need as inputs for the energy model

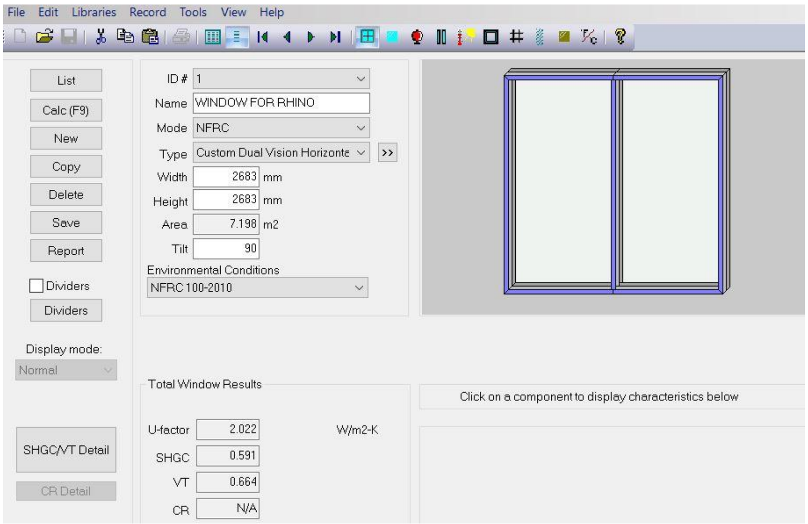


Figure 72 LBNL final window assembly user interface

7. Chapter 7: Application of Building Performance Simulations to the case study

This chapter explain the overall steps followed during simulations performed. The necessary inputs and outputs for the simulation are also defined. The simulation is performed for each of the four building envelope design solutions and results are analysed and compared.

7.1 Thermal zone input definitions for the energy model

7.1.1. Internal gains

In order to run energy simulations, a hypothesis on the internal heat gains needs to be put into consideration. Here, we assume that, apart from outside source of heat e.g. solar radiation, there are other sources of heat inside of a thermal zone which will contribute to the rise of indoor temperature and hence affect the thermal comfort of end users.

The ability of these sources of heat gains to produce heat may differ from one thermal zone to another. For example, heat gains from an office thermal zone may differ from those of a residential thermal zone. In the office, there are more electrical equipment such as computers and lights than in a residential room. Or in a gym there are higher level of metabolic activities and hence higher heat gains from people compared to an office.

Since the thermal zone defined is assumed to be a residential bedroom, the following are the hypothesis of heat gains considered:

No. of People	Metabolic (W/person)	Lighting (W/m2)	Equipment (Laptop, TV) (W/m2)
2	46	5	5

7.1.2. Internal gains schedule

In order for the energy simulations to consider properly the internal gains, a schedule should be assigned to each source of internal gain defined. For example, inside a thermal zone energy simulation software needs to understand if the electrical lighting will be turned on in all 24 hours during a day or just during a certain period of time. Or at what time will occupants be in a thermal zone and what kind of specific activities will they be performing as each activity leads to specific heat gain value.

In the defined thermal zone, schedules for all internal gains were defined based on default values defined by ASHRAE standards for a midrise apartment type of building program (*as defined by Honeybee component of Grasshopper software*).

7.1.3. Thermal zone

Different literatures define thermal zone in different ways. For example, Mridul Sarkar (2018) defines thermal zone as a single space or a group of spaces that have similar thermal load characteristics, such that a HVAC system may control and maintain approximate levels of prescribed conditions inside. EnergyPlus Version 9.1.0 documentation (2019) define thermal zone as an air volume at a uniform temperature plus all the heat transfer and heat storage surfaces bounding or inside of that air volume.

This means, that thermal zone is not an architectural or geometrical space but rather as an air volume with defined and uniform thermal characteristics, and which can exchange heat with its surrounding environment.

In this thesis, a bedroom located on the 12th story (last floor) of a multi-story residential building is chosen as the thermal zone. The location of the thermal zone has been chosen based on the fact, after climatic analysis of the region, the *West facade* is found to experience the *highest level of both normal* and *direct solar radiation*. Therefore, it will be interesting to observe building envelopes facing this facade during simulations. The thermal zone has dimensions 5.00 x 4.50 m, height 4.00m. In the simulation software the roof and west wall are exposed to outdoor conditions, while the internal walls and floor slab are defined as adiabatic.

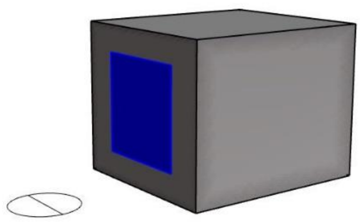


Figure 73 Thermal zone

7.2 Simulation software

In this thesis, dynamic simulations were performed using a simulation engine software called *EnergyPlus*. EnergyPlus 9.1.0 documentation (2019) describe EnergyPlus as an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical makeup, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control set points, conditions throughout an secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would.

During simulations, EnergyPlus was not used directly but rather, it was used as a plugin of a parametric modelling software called *Grasshopper* which is also integrated with *Rhinoceros* 3D modelling software. In Grasshopper another plugin tool called *Honeybee* was used as it connects Grasshopper 3D with simulation engines such as EnergyPlus.

A figure below represents different plugins that are integrated with Rhinoceros 3D modelling and Grasshopper 3D.

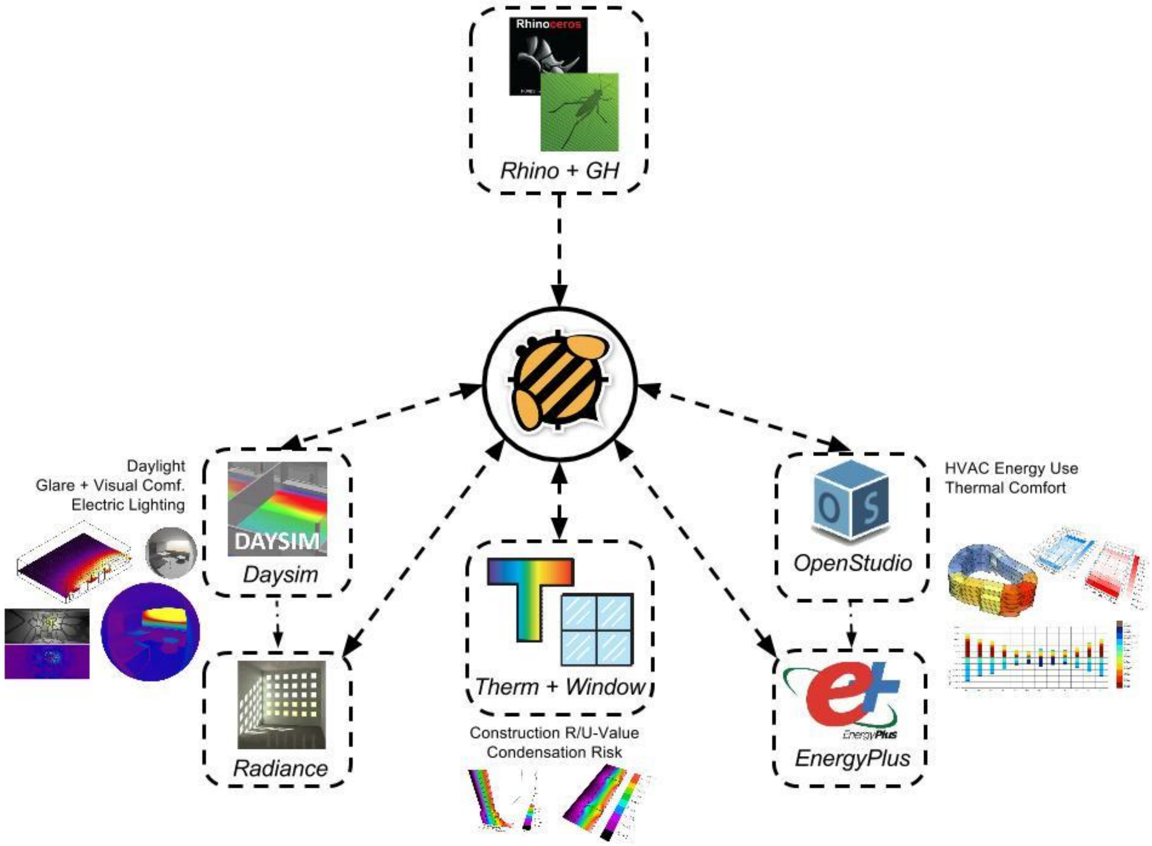


Figure 74 Different plugins of Rhinoceros Grasshopper
Source: http// www.food4rhino.com

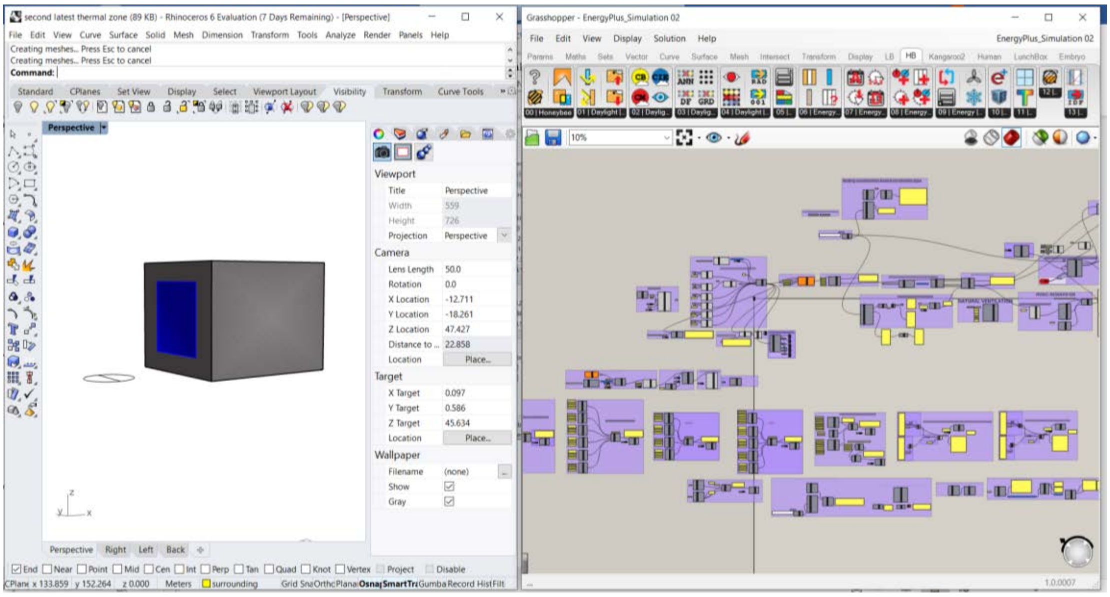


Figure 75 Rhinoceros and Grasshopper user interface

Below is a representation of EnergyPlus interface which can sometimes be used without integration of a third-party interface. However, one must understand that EnergyPlus itself is not a user interface. It is intended to be the simulation engine around which a third-party interface can be wrapped.

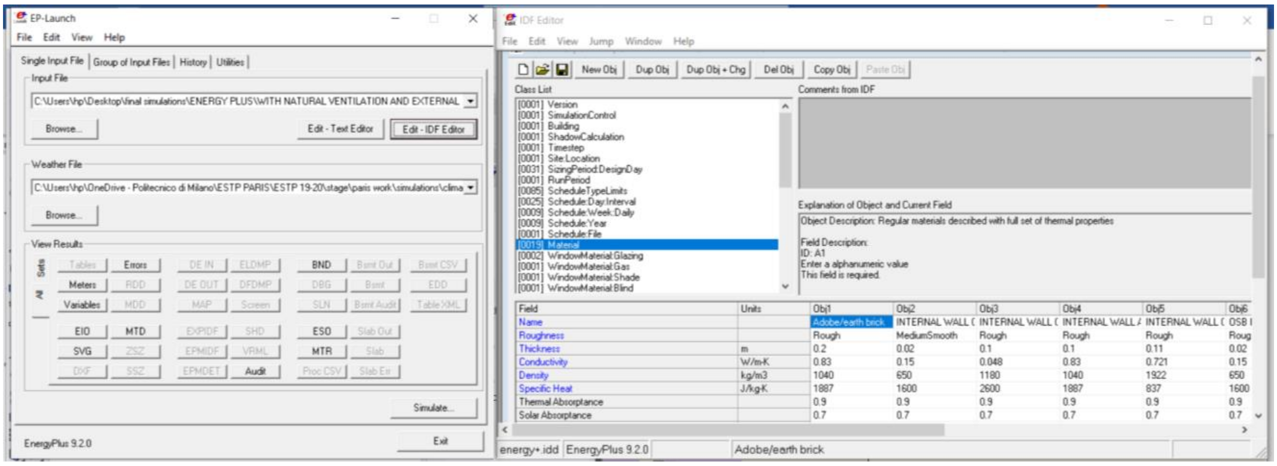


Figure 76 EnergyPlus interface

7.3 Steps performed during BPS

Simulations are performed for each of the four building envelope design solutions under investigation. Only external, internal walls and windows parameters are changed, while floor and roof parameters are kept constant. The outputs performance criteria during simulations are *degree-hours above indoor comfort temperature* and *cooling loads*. The overall steps are summarized in a figure below.

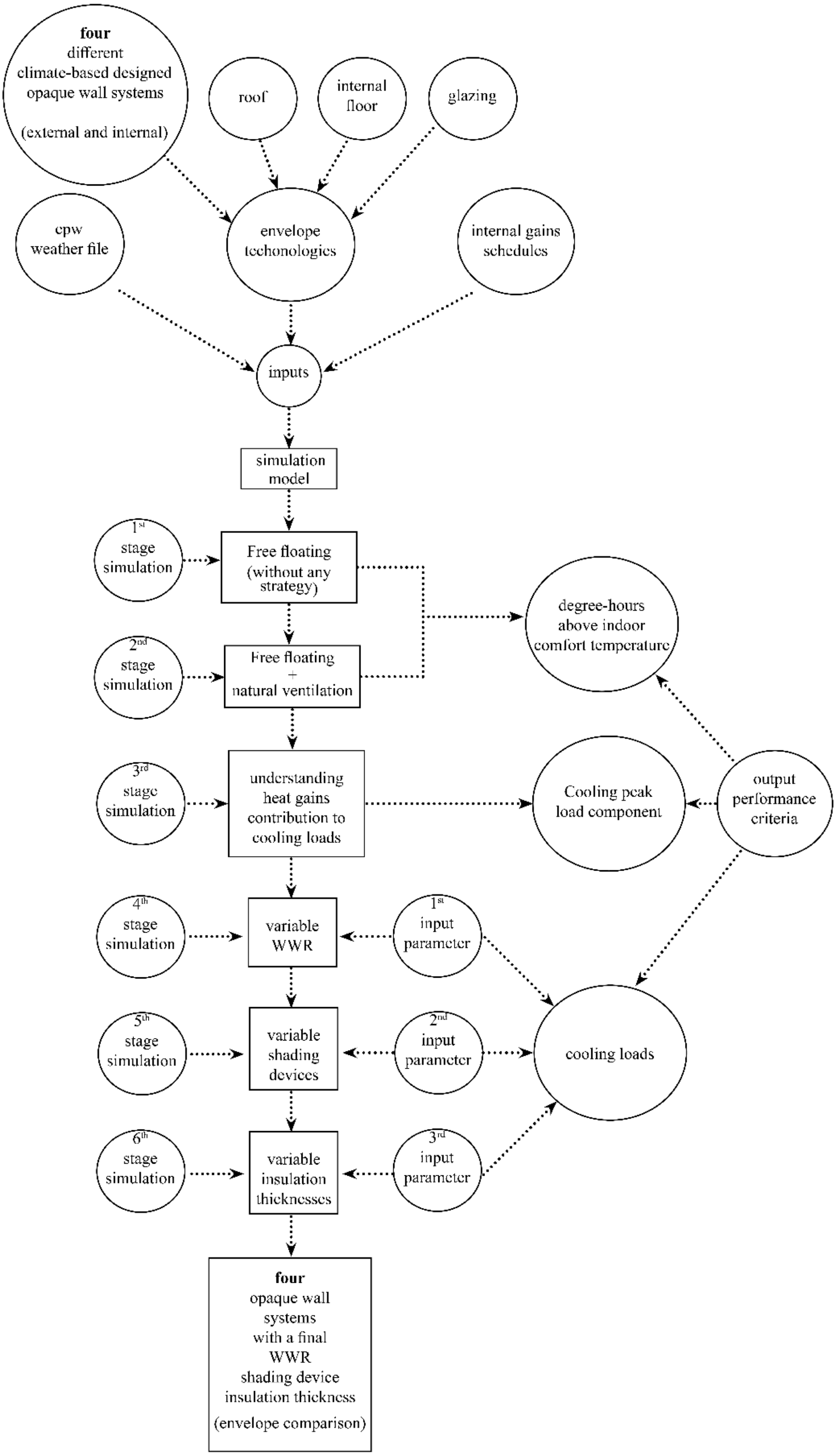


Figure 77 Summary of the steps during BPS

7.3.1. The first step: free floating simulation (without any strategy) - showing consistency with climatic analysis

Although, climatic analysis has already shown that, the context experiences hot climatic condition, meaning there is a need to cool down buildings, free floating simulation provides an opportunity to visualise the exact scale at which the building needs to be cooled. In free floating simulation, a cooling plant is not turned on. Moreover, at this step of simulation, there are no other applied strategies to provide for indoor thermal comfort. In this way, this step of simulation acts as a baseline for the overall next stages of simulations performed in this study.

As it is shown in the resulting figures below, consistently with climatic analysis, it is clear that in this particular climate, regardless of envelope technologies applied, one needs to cool down buildings rather than heating. Simulations are performed using an Adaptive comfort model as recommended by EN 15251 (*see appendix A*).

The following table summarises the input and output variables applied during this step of simulation.

Inputs		
Envelope technologies	**Internal gains**	**Schedules**
four opaque wall constructive systems as defined above without insulation	people, lighting and equipment as defined above	default schedules by ASHRAE for apartment building program
floor as defined above roof as defined above without insulation	infiltration rate: $0.0001 m^3/s$ per m^2 of exposed façade as recommended by ASHRAE for tight buildings	always on
window technology as defined above without shading device WWR: 40%		
Output		
Annual degree hours outside the upper (26°C) or lower (20°C) boundary for indoor temperature as suggested by EN 15251		

Table 22 Input and output parameters in first step of simulation

Figure below shows that, if no strategies (either passive or active) are applied in bringing indoor thermal comfort, the occupants will experience thermal discomfort all over the year. This is due to the fact that, the indoor temperature is always out of upper and lower boundaries as recommended by EN 15251.

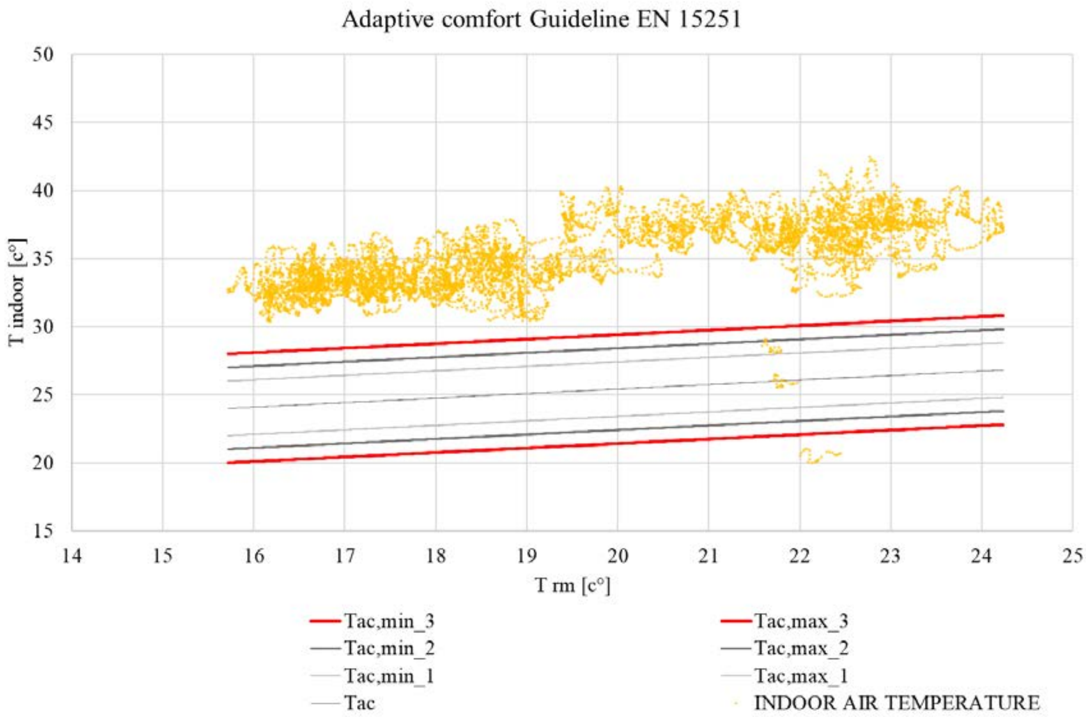


Figure 78 Adaptive comfort model, without any strategy

As a result, both figures below show that all over the year, for all four opaque wall systems under investigation, there is a need for cooling. This observation is consistency with the already observed climatic analysis, which showed that the context experiences hot climatic condition all over the year, implying the need for cooling.

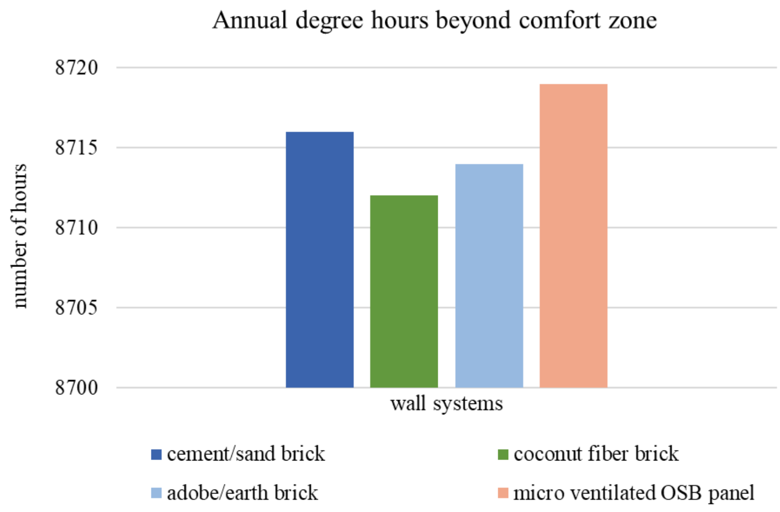


Figure 79 Annual degree hours beyond comfort zone, without any strategy

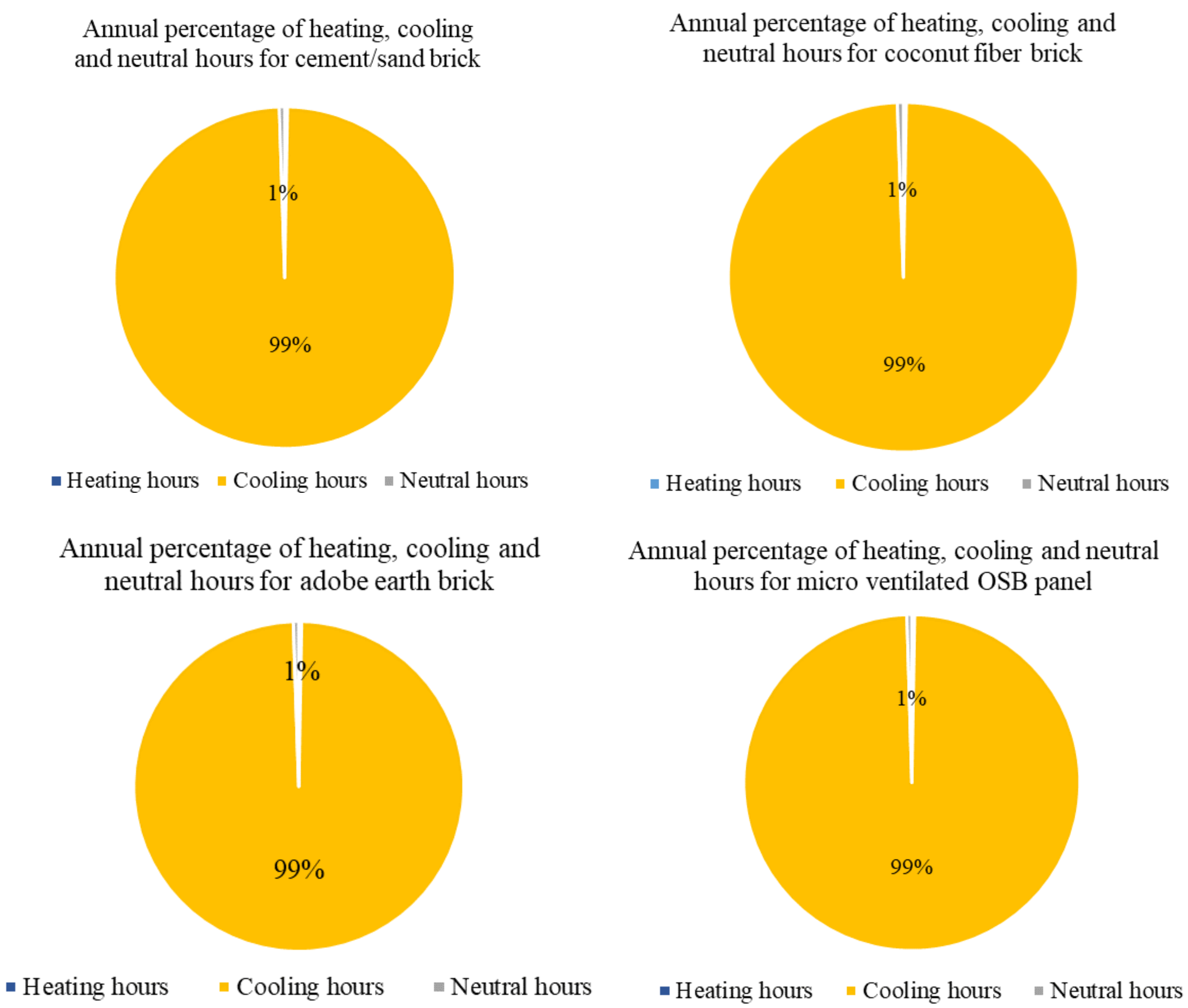


Figure 80 Annual percentage of heating, cooling,and neutral hours for all four opaque wall constructive systems, without any strategy

*where:

heating hours is number of hours when T_i <20
cooling hours is number of hours when T_i > 26
neutral hours is number of hours when 20<T_i<26
T_i is indoor temperature

7.3.2. The second step: free floating simulation with natural ventilation – understanding the role of natural ventilation strategy in warm humid climatic context

Natural ventilation can be considered as one of the most applicable passive design strategy in reducing cooling energy demands by lowering indoor temperature especially in hot climatic regions. In fact, I. Oropeza-Perez, et al. (2014), highlighted that in hot humid climatic conditions, natural ventilation has an energy saving potential, whereby a combination of night ventilation and low heat capacity present the best results. In order to show the potential of natural ventilation in bringing indoor comfort and reducing energy demands, simulations are hereby performed, and the results demonstrate that, natural ventilation can critically reduce cooling energy demands by lowering indoor temperature to comfort levels.

The following table summarises the input and output variables applied during this step of simulation.

Inputs		
Envelope technologies	**Internal gains**	**Schedules**
four opaque wall constructive systems as defined above without insulation	people, lighting and equipment as defined above	default schedules by ASHRAE for apartment building program
floor as defined above roof as defined above without insulation	infiltration rate: 0.0001m^3/s per m^2 of exposed façade as recommended by ASHRAE for tight buildings	always on
window technology as defined above without shading device WWR: 40%		

<table>
<tr><td>Natural ventilation defined with the following parameters:</td><td>always on</td></tr>
<tr><td colspan="2">Operable area of the window to allow for natural ventilation: 3.6m^2 (half the size of the whole window as the window is sliding type)
Minimum indoor temperature to allow for natural ventilation: 15°C
Maximum indoor temperature to allow for natural ventilation: 35°C
Minimum outdoor temperature to allow for natural ventilation: 20°C
Maximum outdoor temperature to allow for natural ventilation: 30°C

EnergyPlus simulation engine calculates the effect of natural ventilation by considering the size of the operable window, the speed of the local wind and the schedule of the operable size of the window.

Moreover, the limits of the temperature defined above means that, for indoor temperature range, natural ventilation will be allowed into the building when the indoor temperature is between 15°C and 35°C, this is quite a large range, as in most of the case the indoor temperature is out of thermal comfort as seen in the first case of simulations above.

For outdoor temperature, the range between 20°C and 30°C means, the simulation engine will simulate that occupants will only open the window when the outdoor temperature is within these temperatures. This means, occupants won't allow too cold or too hot air into indoor spaces.</td></tr>
<tr><td colspan="2" align="center">Output</td></tr>
<tr><td colspan="2" align="center">Annual degree hours outside the upper (26°C) or lower (20°C) boundary for indoor temperature as suggested by EN 15251</td></tr>
</table>

Table 23 Input and output parameters in second step of simulation

The adaptive comfort chart below shows that, after application of natural ventilation, roughly half of the indoor temperature values are now within the comfort limits. This means, cooling energy demands are significantly reduced by applying natural ventilation strategy.

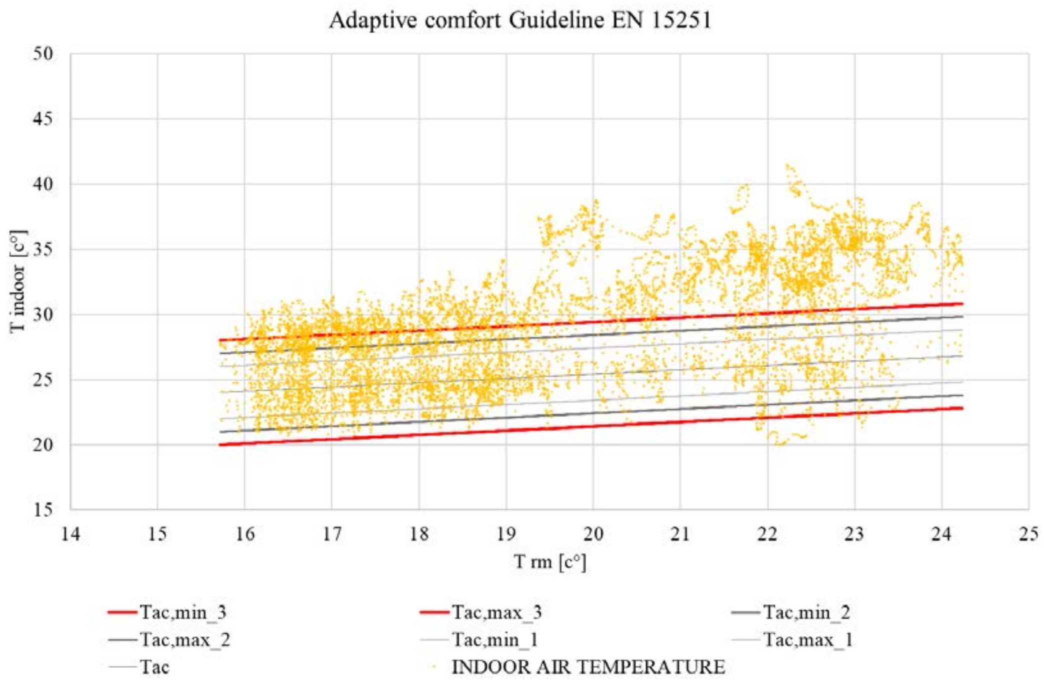


Figure 81 Adaptive comfort with natural ventilation

A graph below shows that after applying natural ventilation, for all four opaque wall systems, annual total number of hours beyond comfort zone are reduced by almost a half in comparison with the first step of simulation. Moreover, adobe/earth brick wall system seems to perform better than the rest by having the least number of annual degree hours beyond comfort zone.

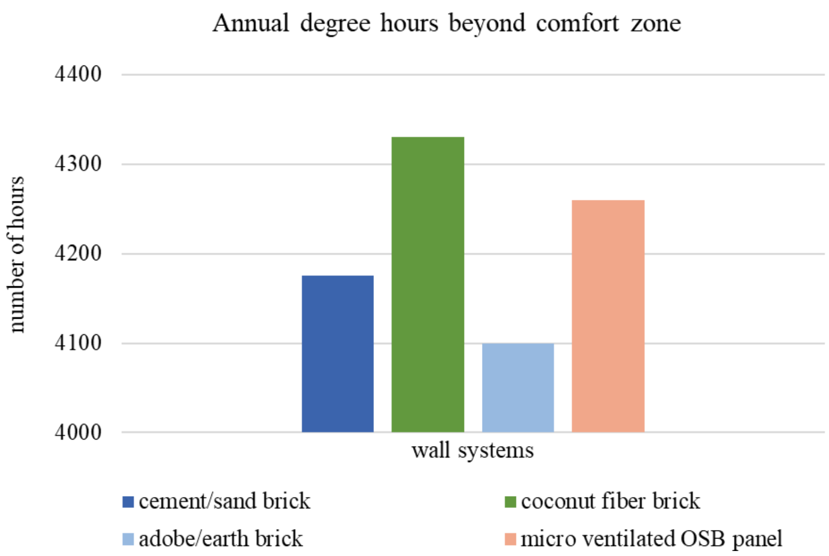


Figure 82 Annual degree hours beyond comfort zone, with natural ventilation

The resulting graphs below, show that for all wall systems, indoor temperatures can be brought to comfort limits by almost a half.

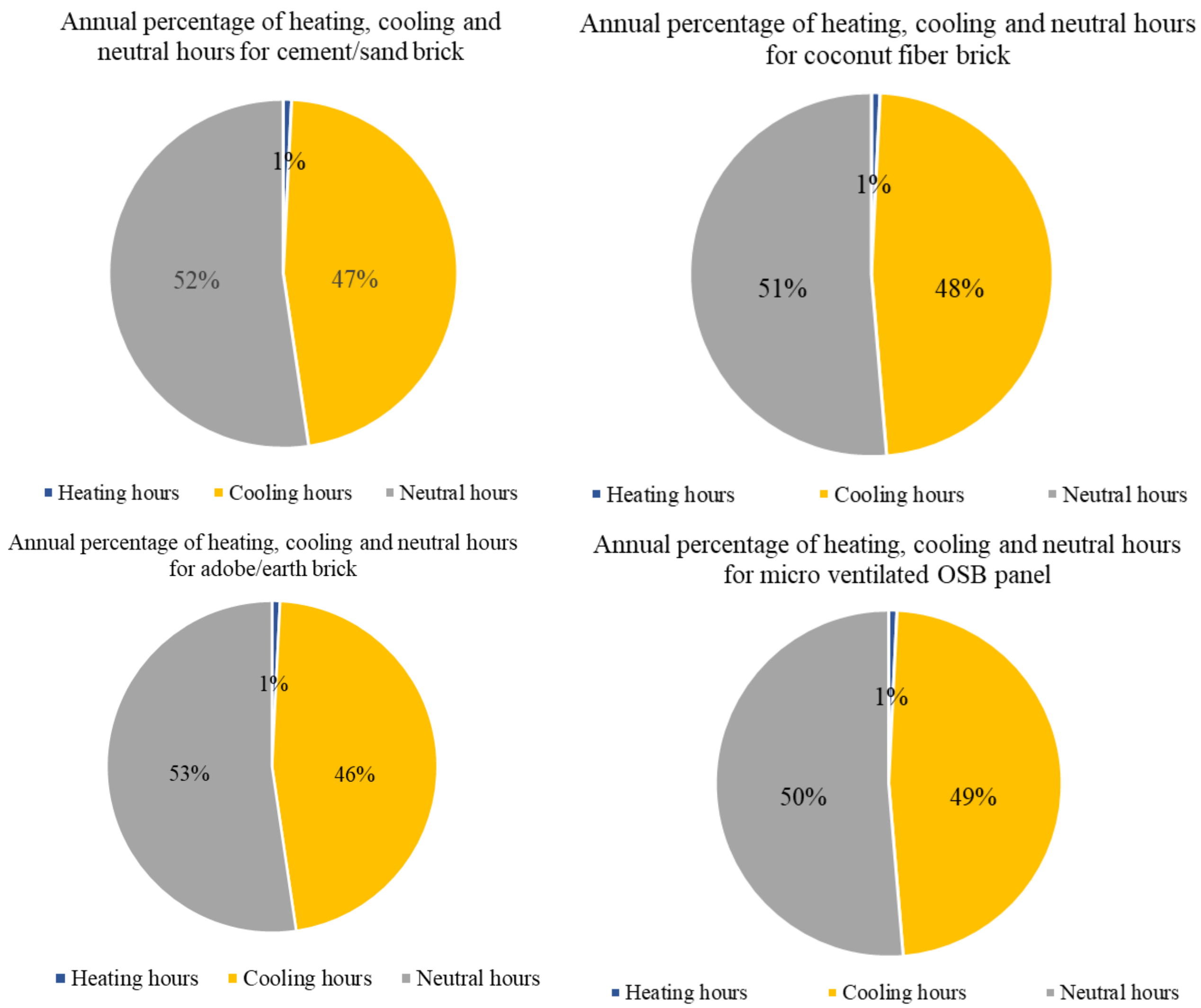


Figure 83 Annual percentage of heating, cooling,and neutral hours for all four opaque wall constructive systems, with natural ventilation

7.3.3. The third step: heat gains contribution to cooling loads

In third step, simulations are performed in order to understand different ways of heat transfer contributions including those across the building envelope. By understanding this, one can start to make decisions on how to reduce heat transfer and hence reduce energy demands.

An important note should be taken at this step of simulation: *although, simulations are supposed to be performed for all four opaque wall constructive systems, only the results of cement and sand mixture brick are plotted. This is due to the fact, at this step of simulation, the trend of the results for all wall systems are the same.*

A. Ardalan et al. (2016), pointed out that there are five methods in which heat and mass transfer in buildings:

i. Conduction through opaque elements including external walls, ceiling, floor slabs, roofs and partitions.
ii. Solar radiation and conduction through window glazing.
iii. Infiltration of outdoor air and air from adjacent rooms.
iv. Heat and moisture dissipation from the lighting, equipment, occupants and other materials inside the room.
v. Heating or cooling and humidification or dehumidification provided by the HVAC system

Moreover, the same authors outlined that 73% of the total heat/gain loss is contributed by the building envelope. This justifies the motivation of investigating the building envelope components in this study.

The following table summarises the input and output variables at this step of simulation.

Inputs			
Envelope technologies	**HVAC**	**Internal gains**	**Schedules**
cement and sand mixture brick wall as defined above without insulation		people, lighting and equipment as defined above	default schedules by ASHRAE for apartment building program
floor as defined above roof as defined above without insulation		infiltration rate: $0.0001 m^3/s$ per m^2 of exposed façade as recommended by ASHRAE for tight buildings	always on
window technology as defined above without shading device WWR: 40%	ideal loads system Cooling setpoint: 26 °C A standard (EN 15251) recommends a temperature range of 23 - 26°C for cooling energy calculations.		turned on during occupancy hours
Output			
Estimated cooling peak load components on a cooling design day (21/3 at 17:30)			

Table 24 Input and output parameters in third step of simulation

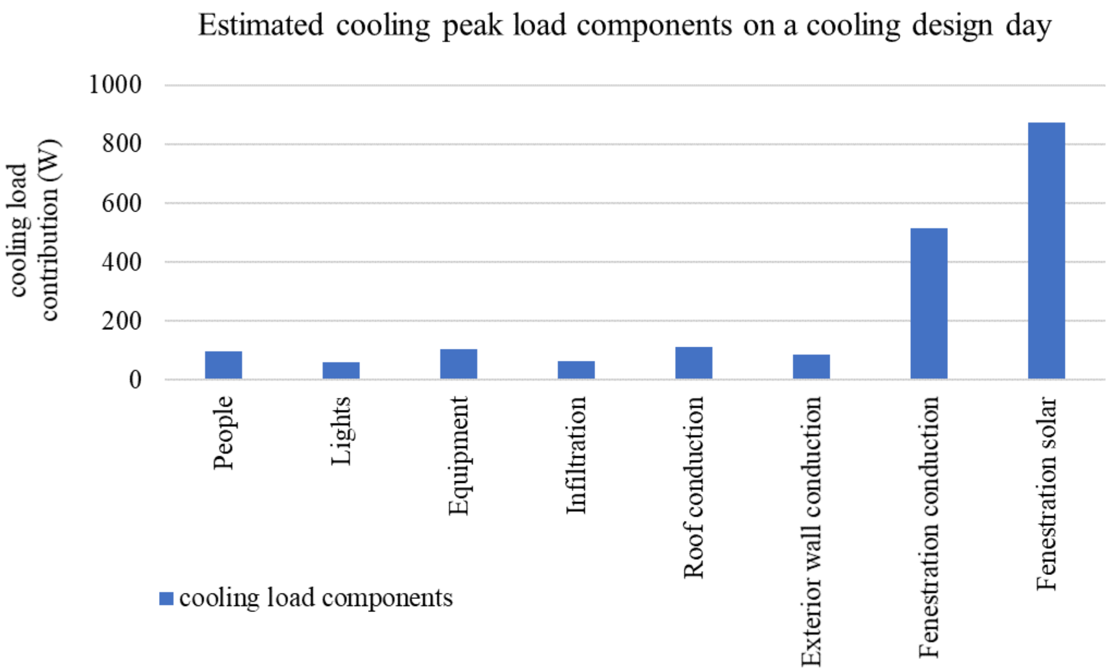


Figure 84 Cooling peak load component on a cooling design day, west facade

From the observed graph, it can be seen that the highest contribution to cooling loads is due to glazing solar radiation followed by glazing conduction. Since the thermal zone is located on the last floor, heat transfer through roof conduction is the third highest contributor to the cooling loads. The results obtained at this stage, are therefore the first point towards understanding passive strategies that can be applied to reduce energy demands.

7.3.4. The fourth step: comparing WWR

In fourth step, different values of WWR are applied as input variables in order to compare their performances. Normally, the size of the window depends on building type, local codes, climatic context and project objectives. In this study, the values of WWR are applied based on the already presented literature review on the size of windows in warm humid climatic context.

The following table summarises the input and output variables at this stage of simulation.

Inputs			
Envelope technologies	**HVAC**	**Internal gains**	**Schedules**
four opaque wall constructive systems as defined above without insulation		people, lighting and equipment as defined above	default schedules by ASHRAE for apartment building program
floor as defined above roof as defined above without insulation		infiltration rate: $0.0001 m^3/s$ per m^2 of exposed façade as recommended by ASHRAE for tight buildings	always on
window technology as defined above without shading device WWR: 20%, 30%, 40%, 50%	ideal loads air system Cooling setpoint: 26 °C		always on
Output			
Annual cooling loads			

Table 25 Input and output parameters in fourth step of simulation

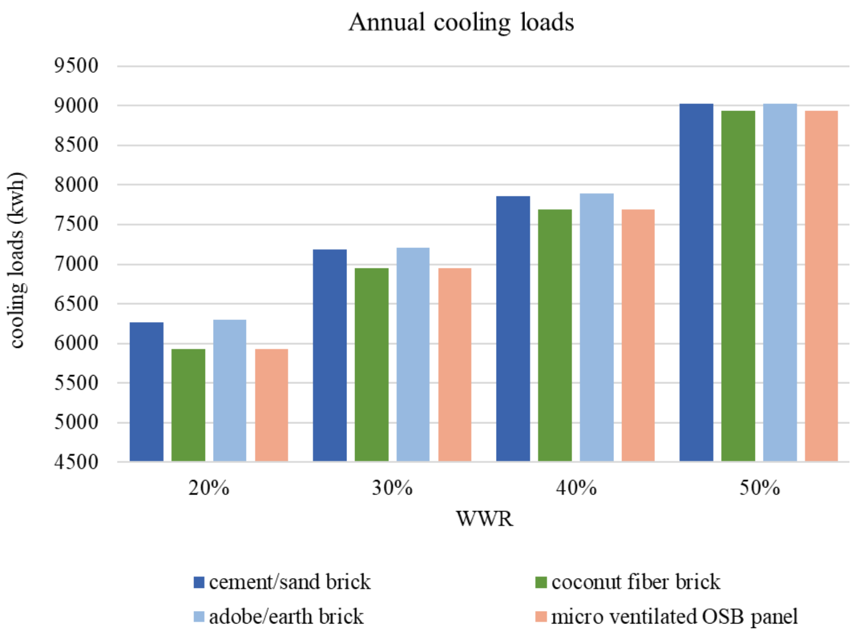


Figure 85 Annual cooling loads due to WWR, west facade

From the graph above, it can be observed that in hot climatic regions, smaller WWR is favourable in reducing energy demands. A smaller WWR means less glazing surface, which in turn reduces solar gains across the building envelope. However, the size of the window should also respect the building codes in a specific context (*in this context it does*), as well as other indoor comfort parameters such as visual comfort which at the moment is beyond the scope of this study. Moreover, a combination of active strategies such as HVAC systems and light wall construction systems seems to offer the better results.

7.3.5. The fifth step: comparing shading devices

As expressed in the literature review, in hot climatic regions, external shading are better in reducing energy demands than internal shading devices. In this study, the focus is limited to *external horizontal shading devices which are fixed*. As expressed later, the first length of the external overhang is obtained through climatic consultant software calculations. The rest of the shading devices are obtained based on the availability of the shading devices in the marketplace.

The following table summarizes the inputs and outputs variables at this stage of simulation.

Inputs			
Envelope technologies	**Cooling plant**	**Internal gains**	**Schedules**
four opaque wall constructive systems as defined above without insulation		people, lighting and equipment as defined above	default schedules by ASHRAE for apartment building program
floor as defined above roof as defined above without insulation		infiltration rate: $0.0001m^3/s$ per m^2 of exposed façade as recommended by ASHRAE for tight buildings	always on
window technology as defined above with shading device WWR: 20% (2m x 1.7m)	ideal loads air system Cooling setpoint: 26 °C		always on
Output			
Annual cooling loads			

Table 26 Input and output parameters in fifth step of simulation

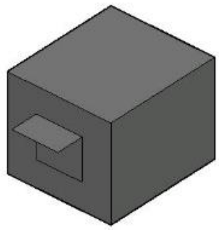
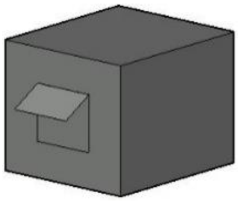
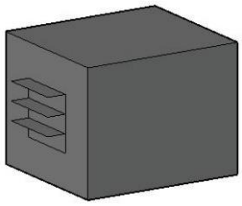
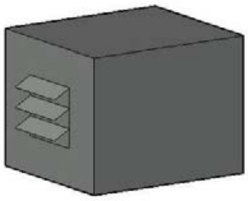
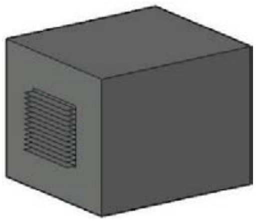
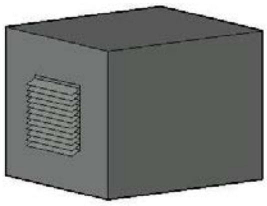
Types of shading devices	
single horizontal overhang • width/depth: 1200mm	
single inclined overhang • width/depth: 1200mm • Inclination angle: 30° from horizontal	
triple horizontal overhang • width/depth: 600mm • distance between each overhang: 400mm	
triple inclined overhang • width/depth: 600mm • distance between each overhang: 400mm • inclination angle: 30° from horizontal	
horizontal louvers • number of louvers: 12 • width/depth: 300mm • distance between each overhang: 150mm	
inclined louvers • number of louvers: 12 • width/depth: 300mm • distance between each overhang: 150mm • inclination angle: 30° from horizontal	

Table 27 Types of shading devices

Material of the selected shading devices (for both overhangs and louvers) is aluminium, which has the following optical properties needed as input during simulations: Solar reflectance: 0.482, visible reflectance:0.474, as obtained from LBNL window software

Calculations on overhangs and louvres dimensions

A software called Climatic Consultant is used to estimate the length of the window overhang. As shown in the figure below, if both the height of the window (H) and a sky view angle (α) are known, then it is possible to estimate the length of the window overhang (L).

The sky view angle is set based on the number of shaded hours, and a practicality on the length of the overhang. This means that even if let's say a 2.1m length of overhang shades the highest number of hours, it is not only costly but also architecturally unpleasant to build it compared to a 1.5m length of overhang even if it leads to a smaller number of shaded hours.

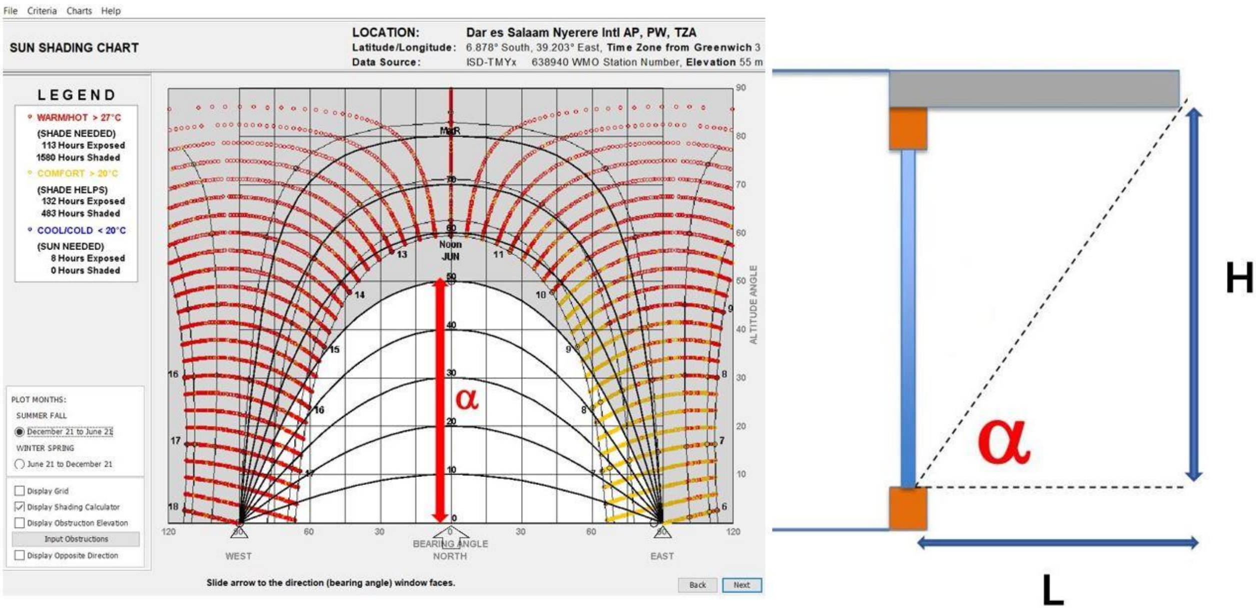


Figure 86 Climatic consultant sun shading chart

In this study, a 55 degrees sky view angle was selected, which resulted a 1.2m length of overhang. This length of overhang was then used as a starting point during simulations.

The following graph expresses the results of simulations performed with different shading devices above.

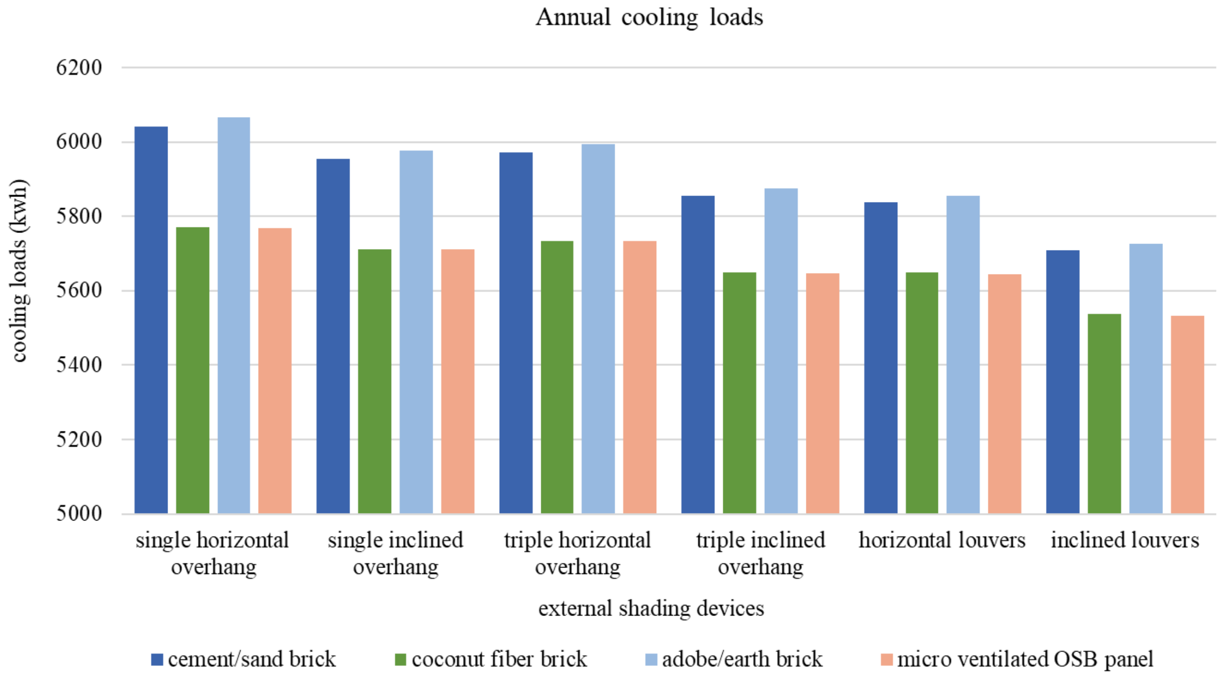


Figure 87 Annual cooling loads due to shading devices, west façade

The general trend shows that, inclined external shading devices perform better than horizontal external shading devices. This is due to the fact that, an inclined position increases the overall total blockage area for solar radiation reaching onto to the glazing surface. Moreover, having multiple horizontal external overhangs is better than single, even though the length of the single overhang may be longer than those of multiple overhangs. Multiple overhangs placed at various distances along the glazing surfaces increase the total blockage area for solar radiation at multiple sections of overall glazing surfaces compared to a single horizontal external overhang shading system. These are the reasons as to why multiple inclined louvres perform the best of overall shading devices.

7.3.6. The sixth step: comparing insulation thicknesses

Performances of variable corn insulation thicknesses are compared at this stage of simulation. The values of insulation thicknesses are obtained based on the already presented literature review on the application of insulation solutions in warm humid climatic context.

Inputs			
Envelope technologies	**Cooling plant**	**Internal gains**	**Schedules**
four opaque wall constructive systems as defined above with variable insulation thicknesses: 25 mm, 50mm, 75mm, 100mm		people, lighting and equipment as defined above	default schedules by ASHRAE for apartment building program
floor as defined above roof as defined above with insulation		infiltration rate: 0.0001m3/s per m2 of exposed façade as recommended by ASHRAE for tight buildings	always on
window technology as defined above with inclined louvers WWR: 20% (2m x 1.7m)	ideal loads air system Cooling setpoint: 26 °C		always on
Output			
Annual cooling loads			

Table 28 Input and output parameters in sixth step of simulation

The following graph expresses the results of simulations performed with different insulation thicknesses as defined above.

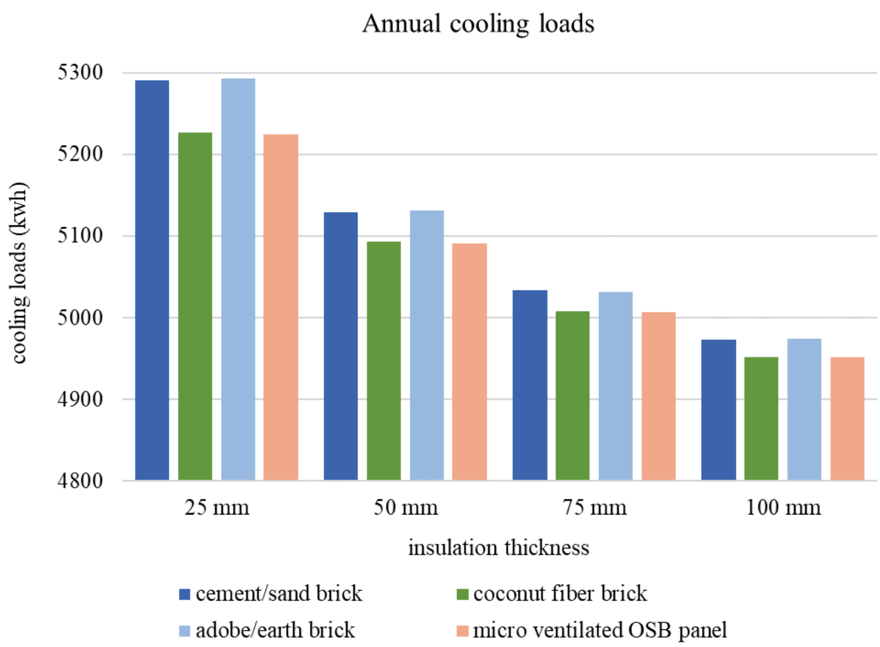


Figure 88 Annual cooling loads due to insulation thicknesses, west façade

From the graph above, it can be observed that the more the insulation thickness the less cooling energy demands. However, as noted earlier, attention should be taken when considering energy savings by applying insulation, as the cost of insulation increases with thickness. The study of the comparison between optimum insulation thickness and the relationship between energy saving and cost of insulation is however beyond the scope of this thesis.

7.4 Results and Discussion

A very important note should be taken from simulations of cooling energy demands above.

For the objectives of this study, the ideal loads air system is set to be always on. However, in reality, a good strategy in this particular type of climate for residential buildings will be hybrid ventilation and cooling strategy which combines natural and mechanical means of ventilation and cooling systems.

As already observed natural ventilation is significant in reducing cooling energy demands by lowering indoor temperatures to the comfort levels. Therefore, if the objectives of this study were to size an HVAC system for example, the cooling loads would have been much lower than the presented results because, a natural ventilation strategy would have been integrated in simulations.

Moreover, from the simulations performed above, the following observations on the performance of building envelope components on cooling energy demands in warm humid climatic context can be made:

- light wall constructive systems offer better performance than heavy solutions
- external inclined shading systems are better than horizontal
- higher insulation thickness is better, although attention should be made on the costs

In order to compare the performance of each of these building envelope components on all four opaque wall constructive systems, the following graph is hereby presented

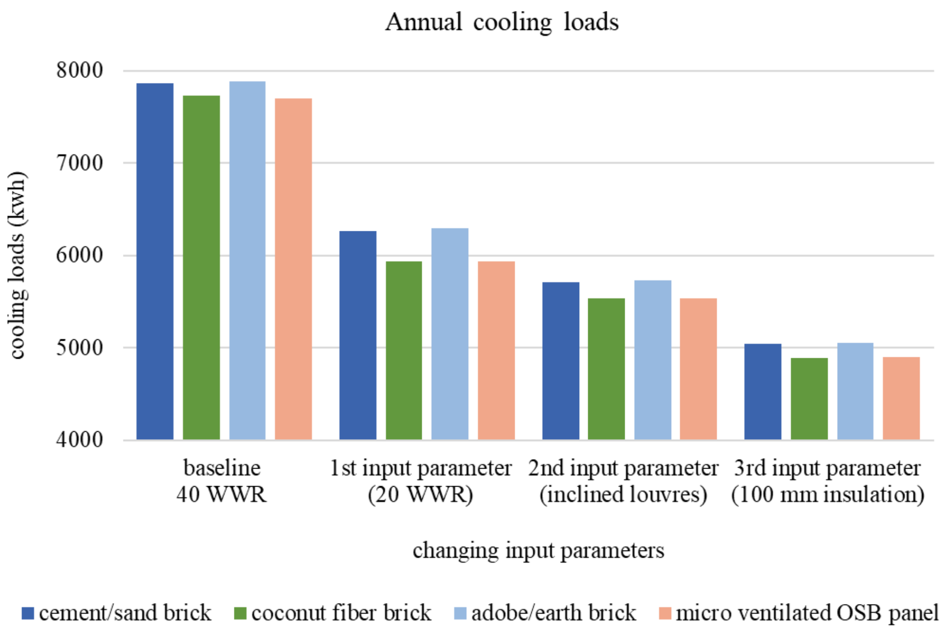


Figure 89 Impact of each input parameter on annual cooling loads, west façade

It can be observed that each input parameter (*WWR, shading device & insulation thickness*) has the potential to lower energy demands for all *four opaque wall constructive systems*. Moreover, reducing WWR offer the highest reduction of energy demands.

To further understand, how the annual cooling loads are distributed monthly, a figure below is presented. It can be observed that, for all wall systems, the highest cooling energy demands are experienced in the beginning and end of the year, while the lowest energy demands are experienced during the middle months of the year. This observation is also consistency with the already observed climatic analysis which showed that, July is the coldest month (*which means low cooling loads*) , while the beginning months of the year are the hottest (*which means high cooling loads*).

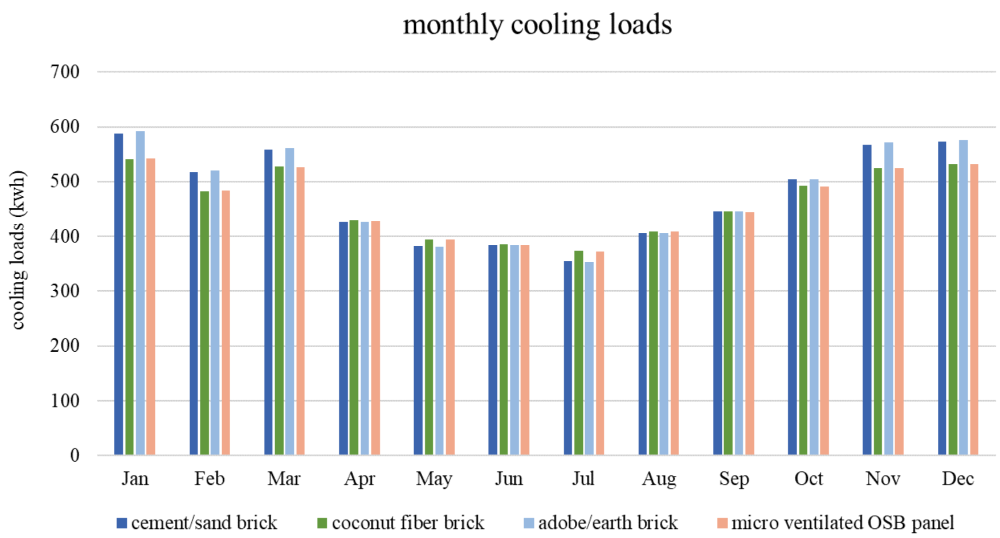


Figure 90 Impact of each input parameter on monthly cooling loads, west façade

In the next chapter all *four opaque wall constructive systems* with *20% WWR, inclined louvres* and *100mm insulation thickness*, are analysed using multi-criteria analysis methodology. The methodology analyses both *technical performances* and *project management methods* for all four opaque wall constructive systems.

8. Chapter 8: Application of Multi-Criteria Analysis approach to the case study

This chapter highlights how multi-criteria can be used to assess the performance of four opaque wall constructive systems, which are the case studies under investigation in this thesis. After performing BPS, the final *four opaque wall constructive systems* have *20% WWR, inclined louvres* and *100mm insulation thickness*. Therefore, multi-criteria analysis will assess both their *technical performances* and *project management methods*.

As already mentioned, the four wall systems are:

- Cement/sand brick wall
- Coconut fiber wall
- Adobe//earth wall
- Micro-ventilated OSB panel

The assessment first starts with each criterion separately, and then the final global evaluation follows for all four systems under study.

In each stage, comments on the evaluation performance are presented, by comparing all four-opaque wall constructive systems.

8.1 Criterion CC1- Simplicity of solution

In this criterion, an important change is made on the values of coefficient of facade typology Ci. As already shown, a coefficient Ci is assigned based on the type of façade in a particular context. The coefficient highlight the level of popularity (*and hence simplicity*),of a particular façade system, in a particular context. For example, a masonry façade in Singapore is given a coefficient, Ci of 0.5, this means that masonry façade system is not popular in this context. However, the same type of façade is given a coefficient, Ci of 0.9 in Tanzanian context, as the façade system is highly popular and therefore it is simpler for workers to execute this type of façade than other systems.

A new table, with new values of Ci, for Tanzanian context is hereby presented:

	$\Sigma S_{f,\,tot}[m^2]$	Ci	ΣSf, i*Ci	$\Sigma Sf,i*Ci/\Sigma S_{f,tot}$
adobe/earth brick	6086.358	0.9	5477.722	90
cement/sand brick	6086.358	0.9	5477.722	90
coconut fiber brick	6086.358	0.7	4260.45	70
micro-ventilated OSB panel	6086.358	0.5	3043.179	50

Table 29 Coefficients of façade typology, and façade are ratios

After performing all required calculations and analysis of sub-criteria, the following notes are therefore assigned for each of the four opaque wall constructive system:

adobe/earth brick

CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
1	1	5	6	3	1	1	2

cement/sand brick

CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
1	1	5	6	3	1	1	2

coconut fiber brick

CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
1	1	4	6	3	1	1	2

micro-ventilated OSB panel

CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
1	1	3	6	3	4	2	4

Table 30 Assigned notes for sub-criteria of criterion CC1

For all wall solutions, a high note (6) is given to sub-criteria CC1.4, as it is considered that, during design stage, all windows of the studied façade are standardised with the same technology and size. In fact, as already observed, the results of BPS determined the final size of the window (WWR), while glazing technology was fixed at the beginning. CC1.4, therefore, shows that if all windows are standardised in this way during design stage, it will be faster, and easier for the construction team to build, compared to let's say if there are different types of windows in terms of size and materials.

For CC1.3, a high note (5) is given to wall systems made of adobe/earth and cement/sand mixture bricks. This is due to high level of coefficient of façade typology (Ci) given to these two wall systems. A coefficient of 0.9 means that, it is easier for these wall systems to be constructed as they're the most conventional systems used. Therefore, they're highly standard mode of façade system compared to the other two systems.

For CC1.6, a high note (4) is given to micro-ventilated OSB panel wall system because of prefabricated panels. Moreover, this type of wall system is assembled by a combination of adhesion and C metallic profiles connections, the reason why it is also given a high note of 4 for CC1.8.

Since there are no prefabricated elements for both vertical and horizontal structural elements, a ratio of $\Sigma S_{sv, pref}/S_{sv, tot}$ and $\Sigma S_{sh, pref}/S_{sh,tot}$ give a result of < 30%, and hence a lowest note of 1 to both CC1.1 and CC1.2 respectively for all wall systems.

In this case study, vertical ducts are considered to be continuous, and they're designed near the vertical columns, hence a note of 3 is given to all wall solutions for CC1.5. All brick wall systems are completely realised on site, hence a note of 1 is given for CC1.7, while a note of 2 is given to micro ventilated OSB panel as it involves prefabrication of OSB panels even though the wall system is assembled on site.

From the resulting figure of all sub-criterion of CC1, micro ventilated OSB panel seems to perform better than the rest.

The resulting graph for all sub-criterion of CC1, for all wall systems is hereby presented:

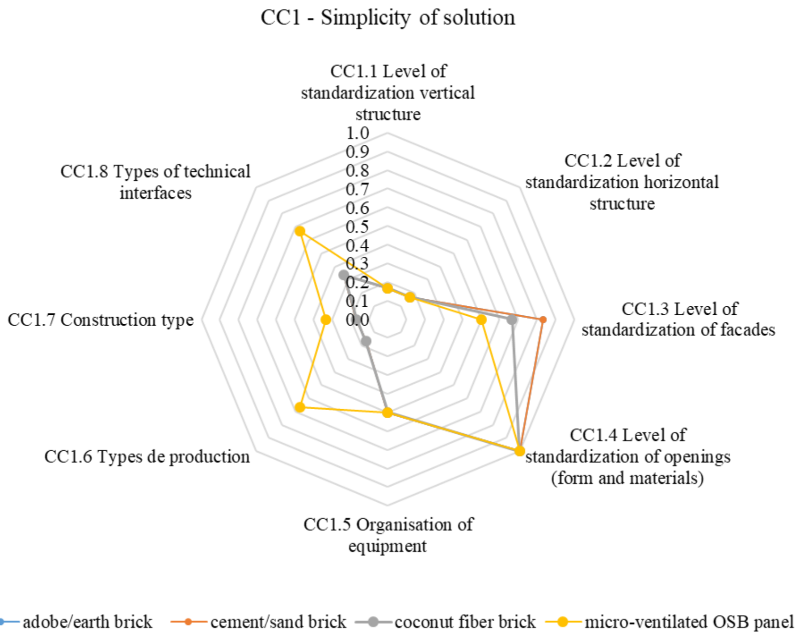


Figure 91 Evaluation of all envelope systems by criterion CC1

As already observed in previous paragraphs, in order to find the global final value of CC1, an aggregation method by AHP, should therefore be applied. The matrix of intensity is hereby presented for all sub-criterion of criteria CC1. One should note that, the matrix of intensity is the same for all wall systems.

	CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
CC1.1	1	5	1	3	3	3	3	1
CC1.2	1/5	1	1/3	1/3	1/3	1/3	1/5	1/3
CC1.3	1	3	1	5	3	3	3	1
CC1.4	1/3	3	1/5	1	1/3	1/3	1/3	1
CC1.5	1/3	3	1/3	3	1	1	3	1/3
CC1.6	1/3	3	1/3	3	1	1	3	1
CC1.7	1/3	5	1/3	3	1/3	1/3	1	1
CC1.8	1	3	1	1	3	1	1	1

Table 31 Intensity of importance, matrix of intensity for criterion CC1

The vector of the weighting coefficients W = $\{w_1, \cdots, w_5\}$ is calculated as already explained in the previous section. A figure below represents the values of calculated vector of the weighting coefficients. This vector is the same for all wall systems.

W_1	0.21
W_2	0.04
W_3	0.22
W_4	0.06
W_5	0.11
W_6	0.12
W_7	0.10
W_8	0.15

Table 32 Weighting coefficients, for criterion CC1

A final global normalised value for criterion CC1 for each of the four opaque wall systems is calculated by using a formula below, as already shown in previous section:

$$CC1 = \sum_{i=1}^{8} w_i \left[\frac{N_i}{N}\right]$$

A table below, represents global normalised values of criterion CC1 for each of the four opaque wall systems. The global values for all criteria, are represented in the global evaluation, in the last stage, as it is shown later.

wall system	CC1
adobe/earth brick	0.42
cement/sand brick	0.42
coconut fiber brick	0.39
micro-ventilated OSB panel	0.48

Table 33 Global normalised value of criterion CC1, for all envelopes

8.2 Criterion CC2 – Verifiability

The same procedures repeat for this criterion.

adobe/earth brick			
CC2.1	CC2.2	CC2.3	CC2.4
4	4	4	6

cement/sand brick			
CC2.1	CC2.2	CC2.3	CC2.4
4	4	4	6

coconut fiber brick			
CC2.1	CC2.2	CC2.3	CC2.4
4	4	4	6

micro-ventilated OSB panel			
CC2.1	CC2.2	CC2.3	CC2.4
4	4	4	6

Table 34 Assigned notes for sub-criteria of criterion CC2

In this criterion, all envelope solutions seem to have the same performance. For CC2.4, a high note is given to all wall systems, as it is assumed that all requirements related to verification, cleaning and maintenance procedures have been considered and all equipment and façade elements are easily accessible during buildings operation.

During design stage, the authors of this thesis, applied BIM and simulation tools, while the proposed envelope solutions were also reviewed by multiple actors. In addition to that, it is assumed that all future risks have been considered and therefore a commissioning plan on how to solve these challenges have been established. As a result, both CC2.1 and CC2.2 are given a note of 4.

During construction, laboratory and on-site tests are assumed to be prepared, while the real scale models are not considered, as a result CC2.3 is given a note of 4 for all wall design solutions.

From the resulting figure of all sub-criterion of CC2, all four wall systems have the same performance.

The resulting graph for all sub-criterion of CC2, for all wall systems is hereby presented:

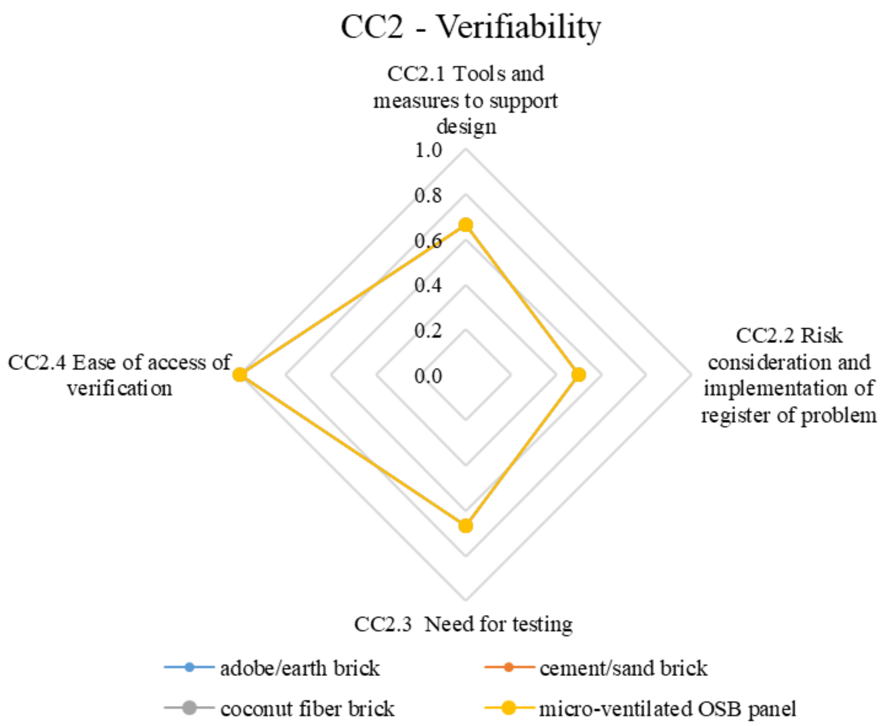


Figure 92 Evaluation of all envelope systems by criterion CC2

	CC2.1	CC2.2	CC2.3	CC2.4
CC2.1	1	3	3	3
CC2.2	1/3	1	3	1
CC2.3	1/3	1/3	1	1
CC2.4	1/3	1	1	1

Table 35 Intensity of importance, matrix of intensity for criterion CC2

W_1	0.48
W_2	0.22
W_3	0.13
W_4	0.16

Table 36 Weighting coefficients, for criterion CC2

wall system	CC2
adobe/earth brick	0.72
cement/sand brick	0.72
coconut fiber brick	0.72
micro-ventilated OSB panel	0.72

Table 37 Global normalised value of criterion CC2, for all envelopes

8.3 Criterion CC3 – Skills availability

The same procedures repeat for this criterion.

adobe/earth brick			
CC3.1	CC3.2	CC3.3	CC3.4
5	5	6	1

cement/sand brick			
CC3.1	CC3.2	CC3.3	CC3.4
5	5	6	1

coconut fiber brick			
CC3.1	CC3.2	CC3.3	CC3.4
5	5	6	1

micro-ventilated OSB panel			
CC3.1	CC3.2	CC3.3	CC3.4
5	5	5	1

Table 38 Assigned notes for sub-criteria of criterion CC3

In this criterion, all envelope solutions seem to have almost the same performance as well. As it is shown in chapter 8 which introduces all architectural design solutions, technical details concerning envelope systems are clear and exhaustive. However, only technical detail of the final best performing wall system is presented. For this reason, CC3.1 is given a note of 5. This means when technical details of proposed design solutions are clearly developed and exhaustive, it increases the chance of better execution at the construction site.

Modelling skills have clearly been portrayed in this study. BPS itself requires specific skills level in creating the model in simulation software, the same goes for architectural models as well. Hence, CC3.2 is given a note of 5. A high note is given to CC3.3 for all brick wall systems, as they do not require specialised team for execution, this is because as already observed, brick wall systems are the most conventional systems used in Tanzania. However, for the OSB panel, one needs to train or find specialised team for execution, the reason why it is given a note of 5 for CC3.3.

Since the wall systems are not associated with automation systems, there is no need for providing instructions to the end-users. Hence CC3.4 is given a note of 1.

From the resulting figure of all sub-criterion of CC3, all brick wall systems seem to perform equally better than micro ventilated OSB panel system.

The resulting graph for all sub-criterion of CC3, for all wall systems is hereby presented:

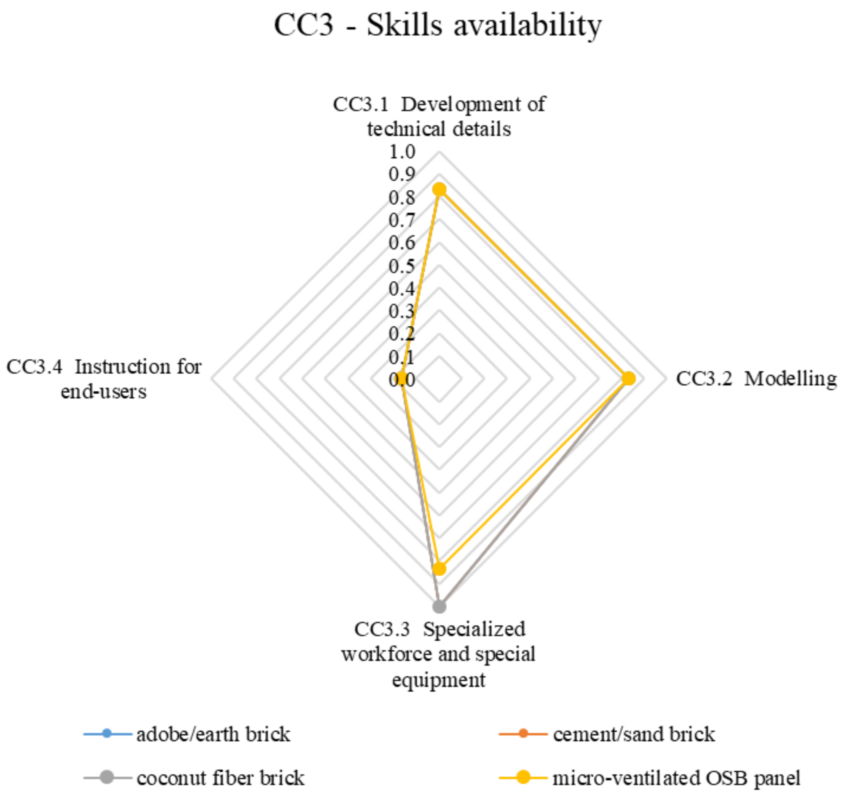


Figure 93 Evaluation of all envelope systems by criterion CC3

	CC3.1	CC3.2	CC3.3	CC3.4
CC3.1	1	5	5	5
CC3.2	1/5	1	1	3
CC3.3	1/5	1	1	1
CC3.4	1/5	1/3	1	1

Table 39 Intensity of importance, matrix of intensity for criterion CC3

W_1	0.61
W_2	0.17
W_3	0.12
W_4	0.10

Table 40 Weighting coefficients, for criterion CC3

wall system	CC3
adobe/earth brick	0.79
cement/sand brick	0.79
coconut fiber brick	0.79
micro-ventilated OSB panel	0.77

Table 41 Global normalised value of criterion CC3, for all envelopes

8.4 Criterion CC4 – Simplicity to manage

The same procedures repeat for this criterion.

adobe/earth brick						
CC4.1	CC4.2	CC4.3	CC4.4	CC4.5	CC4.6	CC4.7
6	3	1	1	1	6	6

cement/sand brick						
CC4.1	CC4.2	CC4.3	CC4.4	CC4.5	CC4.6	CC4.7
6	3	1	1	1	6	4

coconut fiber brick						
CC4.1	CC4.2	CC4.3	CC4.4	CC4.5	CC4.6	CC4.7
6	5	1	1	1	6	6

micro-ventilated OSB panel						
CC4.1	CC4.2	CC4.3	CC4.4	CC4.5	CC4.6	CC4.7
6	5	1	1	1	5	4

Table 42 Assigned notes for sub-criteria of criterion CC4

For all wall systems, it can be observed that CC4.3, CC4.4 are all given a lowest note (1), because analysis of assembly sequence and centralized management and control are not considered in design stage. Since there are not automation systems in all wall systems, CC4.5 is also given a lowest note.

The chosen materials for all wall systems are durable, meaning they're not destroyed by climatic conditions or aggressive environment. However, they do require protection such as plaster which has been integrated in all solutions. As a result, CC4.1 has a high note for all wall systems.

Both cement/sand and adobe/earth bricks are heavier than coconut fiber and micro ventilated OSB panel wall systems. However, during production and installation, they can be transported by one or two workers. Hence CC4.2 is given the same note for heavier wall systems.

In terms of maintenance, OSB panel wall system might need a specialized team for light maintenance such as cleaning, as it contains a bamboo cladding system. Hence a note of 5 is given to CC4.6 for this type of wall system, and a note of 6 for the others as they do not require such effort.

Both adobe and coconut fiber brick wall systems, contain biodegradable materials that can be easily separable and recyclable at the end of their service life. Hence a high note is given to both of them.

From the resulting figure of all sub-criterion of CC4, coconut fiber brick is performing better than the rest.

The resulting graph for all sub-criterion of CC4, for all wall systems is hereby presented:

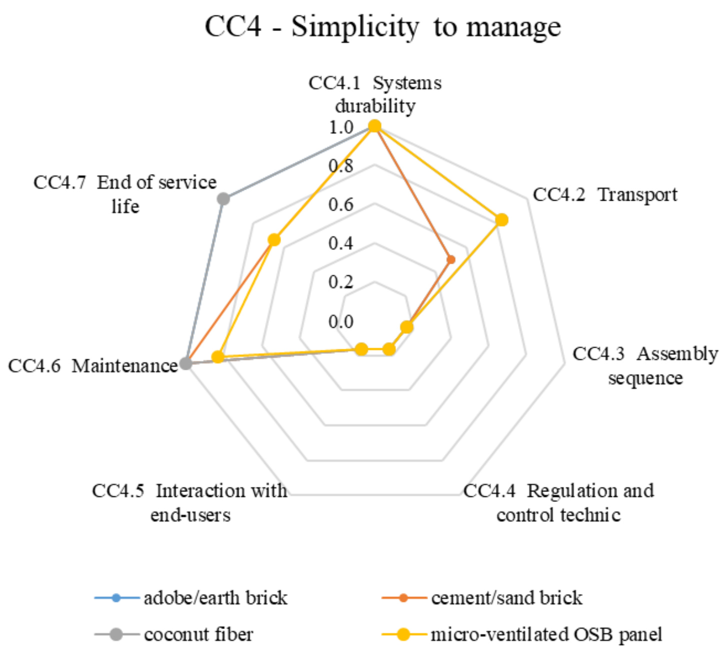


Figure 94 Evaluation of all envelope systems by criterion CC4

	CC4.1	CC4.2	CC4.3	CC4.4	CC4.5	CC4.6	CC4.7
CC4.1	1	1	1	3	3	1	3
CC4.2	1	1	1	3	3	1	1
CC4.3	1	1	1	3	3	1	1
CC4.4	1/3	1/3	1/3	1	1	1	1
CC4.5	1/3	1/3	1/3	1	1	1	1
CC4.6	1	1	1	1	1	1	1
CC4.7	1/3	1	1	1	1	1	1

Table 43 Intensity of importance, matrix of intensity for criterion CC4

W_1	0.21
W_2	0.18
W_3	0.18
W_4	0.08
W_5	0.08
W_6	0.14
W_7	0.12

Table 44 Weighting coefficients, for criterion CC4

wall system	CC4
adobe/earth brick	0.62
cement/sand brick	0.58
coconut fiber brick	0.68
micro-ventilated OSB panel	0.62

Table 45 Global normalised value of criterion CC4, for all envelopes

8.5 Criterion CC5 - Compliance with user-centric requirements

As already observed, only one indicator (*indoor thermal comfort*) is evaluated as an indicator for this criterion, whereby indoor operative temperature values to be observed are those below 26°C as recommended by EN 15251 (T<26°C).

Simulations are performed on a thermal zone defined during BPS. A ratio between the number of hours in which the temperature is below 26 (comfort hours), and total number of hours of occupation during a year is calculated as follows:

$$\mathrm{CC5.1} = \mathrm{n°hconf/n°hoccupation}$$

where:

n°hconf = number of hours of occupation below 26°C (*indoor comfort operative temperature limit*)
n°hoccupation = total number of hours of occupation in a year

Simulations are performed based on Adaptative comfort as recommended by EN 15251 (see *appendix A*). A table below shows the results of simulations for all wall systems under investigation.

From these results, adobe/earth brick wall system seems to perform best, but slightly close to cement/sand brick.

wall system	n°hconf	n°hoccupation	CC5
adobe/earth brick	3594	8760	0.41
cement/sand brick	3559	8760	0.40
coconut fiber brick	3188	8760	0.36
micro-ventilated OSB panel	3244	8760	0.37

Table 46 Global value of criterion CC5, for all envelopes

8.6 Criterion CC6 - Sustainability

As already observed, only one indicator (soil resource consumption) is evaluated by calculating a ratio between a built surface area and the available site surface as shown below:

$$\mathrm{CC6.1} = \mathrm{Sused} \ / \mathrm{Savailable}$$

where:
Sused = built surface area [m2]
Savailable = available site surface [m^2]

The value of this indicator is found to be the same for all envelope systems under investigation. However, if other sub-criteria of this criterion were considered, probably the results would have been different.

	Sused [m^2]	Savailable [m^2]	CC6
For all four-wall systems	8490	10000	0.84

Table 47 Global value of criterion CC6, for all envelopes

8.7 Criterion CC7 - Cost efficiency

As already observed, a final normalized value for this criterion, is obtained by calculating a ratio between *investment cost* and *global cost* of proposed design solutions as shown below:

$$\mathrm{CC7} = \mathrm{CO}inv\ /\mathrm{CG}$$

where:

$\mathrm{CO}inv$ = investment cost

CG = global cost

For the reasons of simplicity, only cost due to energy consumption (*only cooling, lighting are neglected*), are considered as a contribution of operation cost. All other costs are neglected. Therefore, the global cost formula becomes:

$$CG = CO_{inv} + \left[\sum_{i}^{t_{TC}} CO_{a(i)}(j) * (1 + RAT_{xx(i)}(j)\right]$$

where:

CG = global cost

$COinv$ = investment cost

$COa(i)(j)$ = operation cost in a year i for a component or service j (in *this case, only cooling energy costs are considered*)

$RATxx(i)(j)$ = inflation rate in a year i for a component or service j, (this can be related to cost of energy consumption, products, building systems, services, installations, maintenance etc.)

Façade surface area under study	14.6 m²
RAT (as per NCC standard)	5%
Price per kWh (as per TANESCO on 27/03/2020))	0.118 €/kWh

wall system	$COinv$/m²	Annual Cooling energy consumption [kWh]
adobe/earth brick	9.98€	5726.65
cement/sand brick	17.53€	5709.74
coconut fiber brick	13.81€	5536.93
micro-ventilated OSB panel	28.30€	5533.71

wall system	$COinv$	$COa(i)(j)/\mathrm{yr}$	CG	CC7
adobe/earth brick	145.68€	675.74€	855.21€	0.17
cement/sand brick	255.93€	673.75€	963.37€	0.27
coconut fiber brick	201.59€	653.36€	887.62€	0.23
micro-ventilated OSB panel	413.11€	652.98€	1098.74€	0.38

Table 48 Global value of criterion CC7, for all envelopes

**All currency exchanges are calculated as per BOT exchange rate on 27/03/2020.*
**All costs as per Tanzanian building market analysis as on 27/03/2020.*

From the resulting table above, micro ventilated OSB panel performs better than the rest. Also, it can be observed that, although the investment cost ($COinv$) for micro-ventilated OSB panel is the highest, its operation cost ($COa(i)(j)$) is the lowest. This can be attributed by the low cooling energy demands for this type of wall system as already observed in BPS chapter.

Moreover, it should be noted that, since maintenance insurance costs, costs due to replacement and end of service life costs are all neglected, the final results would probably change, if these costs were to be integrated.

8.8 Global evaluation of each system

The following figures show the global evaluation of each constructive wall system under investigation.

8.8.1. Global evaluation for adobe/earth brick

For adobe/earth brick, the highest normalised value obtained is 0.84 for criterion CC6 – Sustainability. The value of this indicator is found to be the same for all envelope systems under investigation because the chosen indicator (soil resource consumption) gives the same results for all wall systems under investigation. The results would have been different if either more indicators of this criterion were considered or if other design solutions such as buildings were under investigation.

The second highest performance is criterion CC3 – Skills availability. This is due to the fact that since brick wall systems are the most conventional in Tanzanian building industry, the available workforce is therefore highly skilled for design and execution for this type of wall system.

The third highest normalised value obtained for adobe/earth brick is 0.79 for criterion CC2 – Verifiability, which is also the same for all wall systems. The similarity is due to the fact that since all wall systems do not require physical models to test and they're simple to build in such a way that all façade elements are easily accessible during buildings operation, it is assumed that all requirements related to verification, cleaning and maintenance procedures have therefore been considered leading to high score.

A value of 0.62 is obtained for CC4 - Simplicity to manage, which is the next highest value. This can be attributed by the fact that adobe/earth brick wall contain biodegradable materials that can be easily separable and recyclable at the end of their service life. Moreover, this type of wall system does not need frequent maintenance.

A slight difference between CC1 and CC5 is also observed. For CC1, the low value of 0.42 is attributed by the fact; adobe/earth brick wall system does not apply prefabricated elements, the wall is actually realised on site. Moreover, the vertical and horizontal structural elements also do not apply prefabricated elements. These have highly contributed to the low value for this criterion.

Even though a value of 0.41 for CC5 is the highest for all wall systems, it is still low on the level of performance compared to other criteria for adobe/earth brick. This is simply due to the fact; the number of comfort hours of indoor temperature is quite small compared to the total number of hours of occupation in a year.

The lowest performing value of 0.17 is obtained for CC7 due to the fact that, the operation cost for adobe/earth brick wall system is much higher than the initial investment cost, this in turn lead to high global cost for this type of wall system.

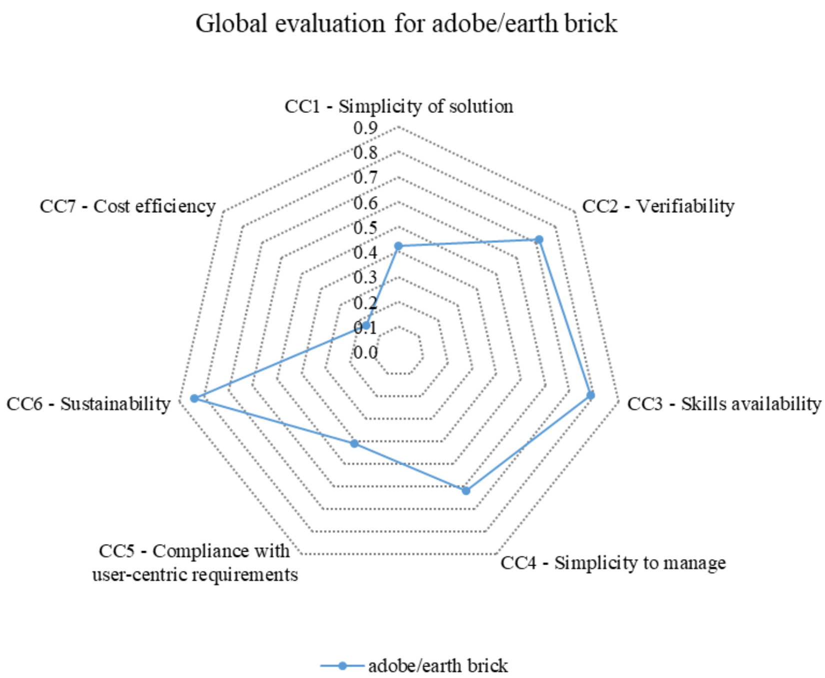


Figure 95 Global evaluation for adobe/earth brick

8.8.2. Global evaluation for cement/sand brick

For cement/sand brick, the same analysis as that of adobe/earth brick wall system applies for CC6, CC3, CC2 and CC1 as they all have the same normalised values. A fourth high value of 0.58 for CC4 - Simplicity to manage, is attributed by the fact that; cement/sand brick wall system is durable, does not need frequent maintenance, and it does not require such complex form of transportation.

Like in adobe wall system, event if a value of 0.40 for CC5 is still the second highest for all wall systems, it is still low on the level of performance compared to other criteria for cement/sand brick. As already observed, this is due to the fact; the number of comfort hours of indoor temperature is quite small compared to the total number of hours of occupation in a year.

The lowest performing value of 0.27 is obtained for CC7 due to the fact that, the operation cost for cement/sand wall system is also quite higher than the initial investment cost, this in turn lead to high global cost contributing to the low ratio value.

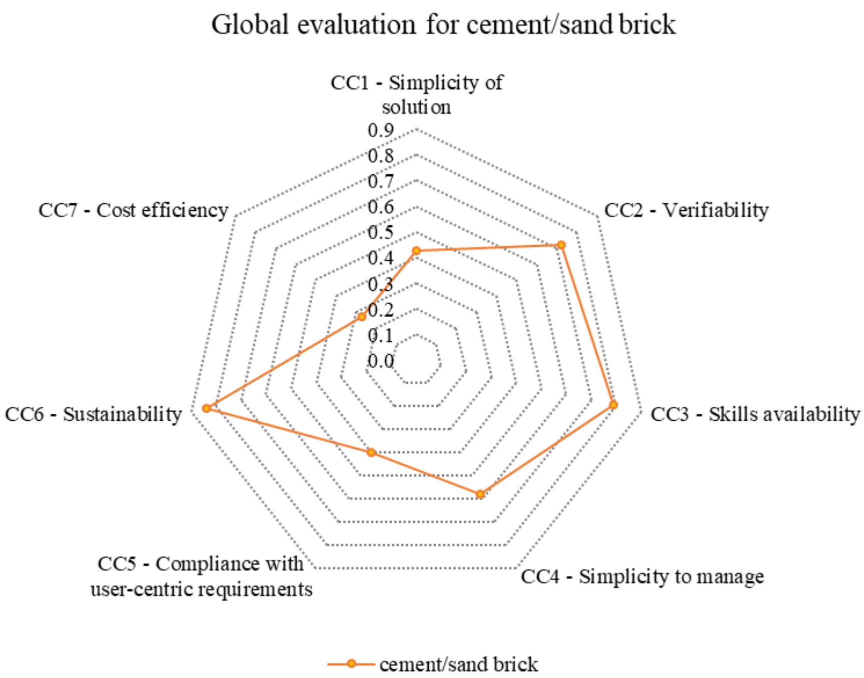


Figure 96 Global evaluation for cement/sand brick

8.8.3. Global evaluation for coconut fiber brick

For coconut fiber brick, the same analysis as those of other brick wall systems applies for CC6, CC3, and CC2 as they all have the same normalised values. A fourth high value of 0.68 for CC4 - Simplicity to manage, is attributed by the fact that; coconut fiber brick wall system is highly simple to manage in terms of transportation and recyclability as it contains biodegradable materials. Moreover, it does not need frequent maintenance.

The low values for CC5, is also due to the fact that; the number of comfort hours of indoor temperature is actually much smaller compared to the total number of hours of occupation in a year.

Although, the global cost for coconut fiber brick is comparative higher than the initial investment cost, the difference is not as high as for other brick wall systems. However, still CC7 obtained the lowest value for this type of wall system.

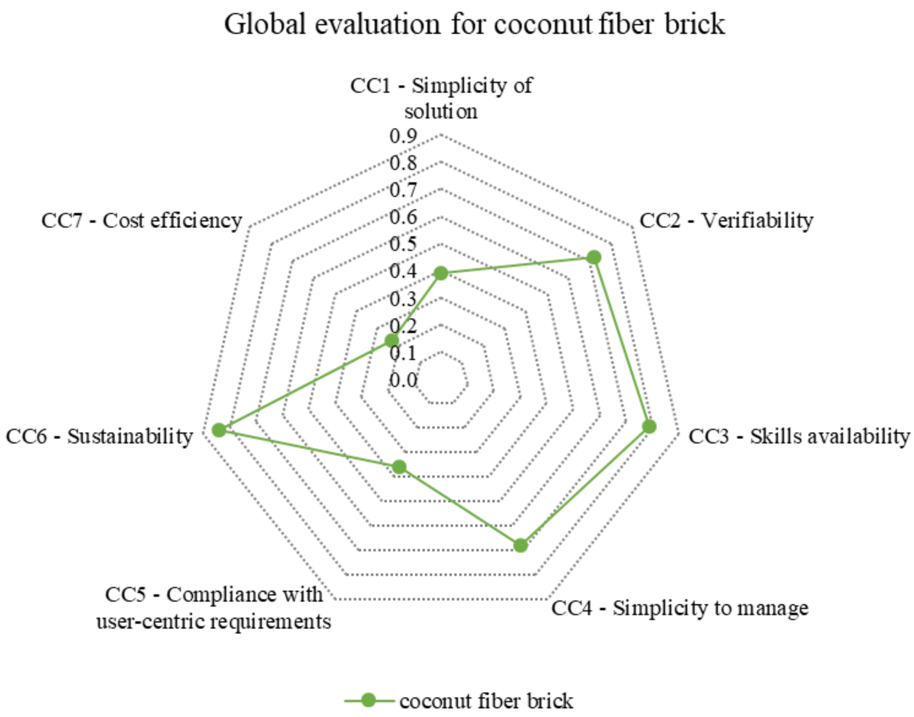


Figure 97 Global evaluation for coconut fiber brick

8.8.4. Global evaluation for micro-ventilated OSB panel

For micro-ventilated OSB panel, the same analysis applies for CC6 and CC2, as with other wall systems. Although, a second highest normalised value of 0.77 is obtained for CC3 - Skills availability, the value is slightly lower than the other wall systems due to the fact that, this type of wall system is not as popular as brick wall systems in Tanzania building industry.

A fourth highest value of 0.62 is recorded for CC4 - Simplicity to manage, as the prefabricated elements are easily separable at the end of service life. Moreover, the prefabricated OSB panels make this type pf wall system easy and fast to build at the construction site, leading to a value of 0. 48 for CC1, the highest among all wall systems.

Opposite to other wall systems, for CC7, the global cost is not so much higher than the initial investment cost due to lower operation costs contributed by lowest cooling energy demands costs. This leads to a value of 0.38 for CC7, the highest among all wall systems, but still the lowest among all sub-criteria for this type of wall system.

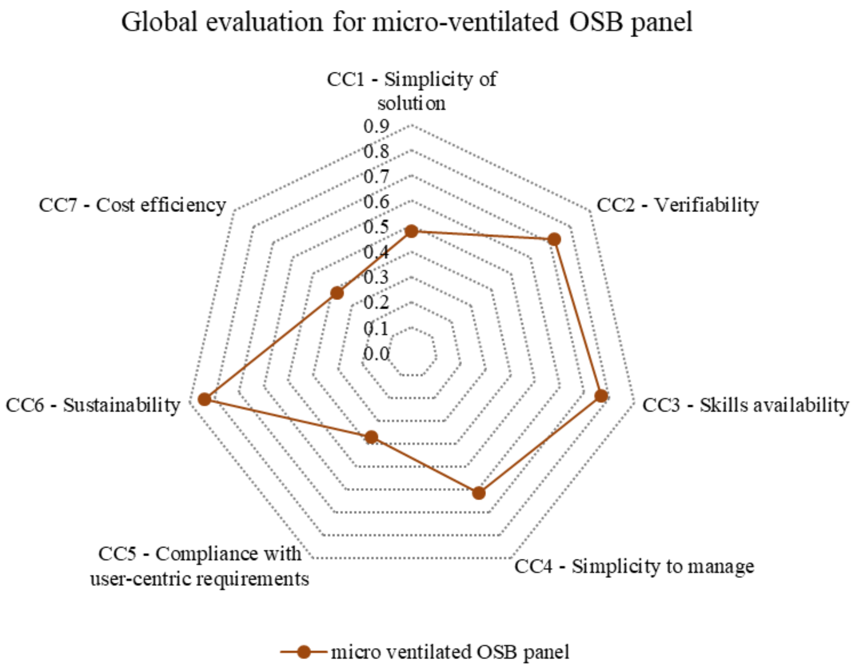


Figure 98 Global evaluation for micro-ventilated OSB panel

8.9 Global evaluation for all four opaque wall constructive systems

A table below demonstrates the global normalised values of all seven criteria for all wall systems under investigation. It can be observed that, adobe/earth brick, coconut fiber brick and micro-ventilated OSB panel perform best each in two criteria as highlighted by green colour, while cement/sand brick performs best in only criteria as highlighted by yellow colour. Moreover, all wall design solutions have the same performance in two criteria as highlighted by blue colour.

Another important observation is that all brick wall systems perform equally better in criteria CC3 with a score of 0.79. However, a micro ventilated OSB panel has a value of 0.77, which is not far from 0.79.

On the other hand, an important note should be taken on the performance of micro ventilated OSB panel system. Its leading global normalised values of 0.48 and 0.38 are much higher than 0.39 and 0.23 respectively, which are the next closest values. As a result, as shown in global evaluation figure for all wall systems, *micro ventilated OSB panel is indeed the best performing option.*

This in fact, is consistency with the results of BPS performed (*although it could have been different as well*). In this way, a final choice of an envelope solution is not only chosen based on BPS (performance based), but also on technical performance and project management methods (including cost effectiveness) using multi-criteria analysis approach.

A final note should be taken; as already observed, since maintenance insurance costs, costs due to replacement and end of service life costs were all neglected, the final results of CC7 would have probably changed, if these costs were integrated.

Evaluation	adobe/earth brick	cement/sand brick	coconut fiber brick	micro ventilated OSB panel
CC1 - Simplicity of solution	0.42	0.42	0.39	0.48
CC2 - Verifiability	0.72	0.72	0.72	0.72
CC3 - Skills availability	0.79	0.79	0.79	0.77
CC4 - Simplicity to manage	0.62	0.58	0.68	0.62
CC5 - Compliance with user-centric requirements	0.41	0.40	0.36	0.37
CC6 - Sustainability	0.84	0.84	0.84	0.84
CC7 - Cost efficiency	0.17	0.27	0.23	0.38

Table 49 Global values of all seven criteria for all wall desing solutions

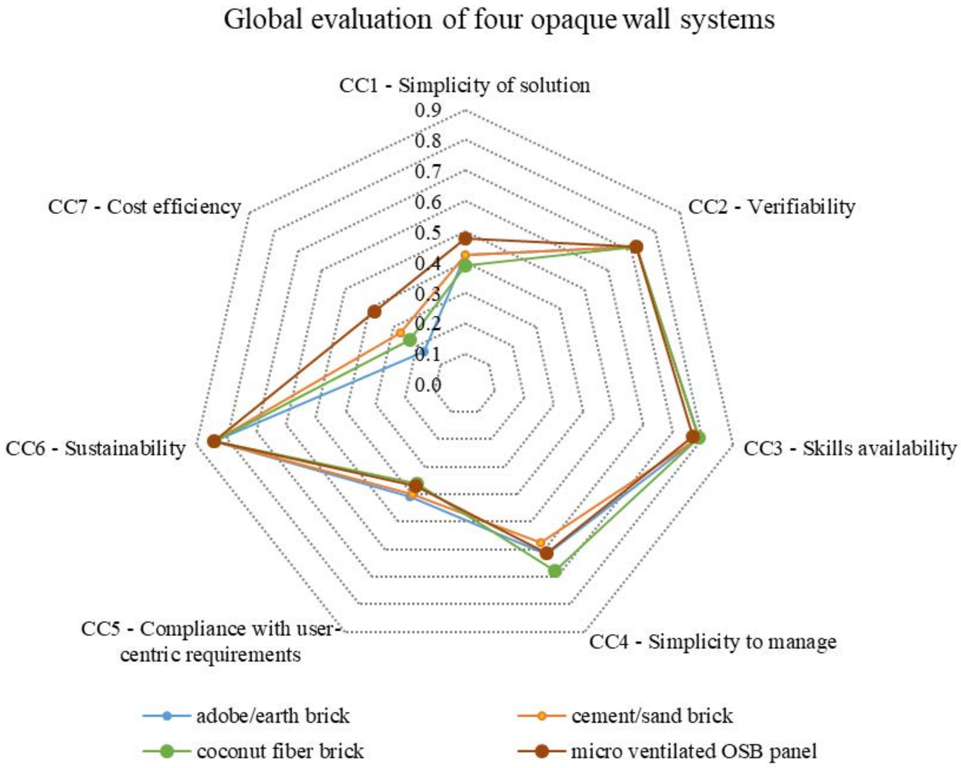


Figure 99 Global evaluation of all four opaque wall systems

8.10 Conclusion of chapter 8

8.10.1. Performance comparison

Chapter 7 has shown that, all four wall design solutions perform either in the same way or differently depending on the indicator, sub-criteria and criteria under consideration. In some cases, the difference is significant while in others it's not.

As a general result, adobe/earth brick performs best in CC3 - skills availability and CC5 - compliance with user-centric requirements, while coconut fiber brick performs best also in CC3 and CC4 - simplicity to manage. Simply this means that, the available workforce is skilled enough to design and build these two types of wall systems (CC3).

On the other hand, adobe/earth brick wall systems provides the highest number of indoor thermal comfort to the occupants (CC5). Coconut fiber brick seems to be the simplest wall system to manage (CC4) due to the fact that; its materials are not only durable but also light, hence no need for complicated mode of transport. Also, since, coconut is biodegradable material, its environmental footprint is simple to manage.

Micro-ventilated OSB panel perform best in CC1 - simplicity of solution and CC7 - cost efficiency. This means that OSB panel is the fastest and simplest wall system to build. This is due to its prefabricated elements. Also, in the long run, it is cost efficient to build this type of wall even though its investment cost is higher than the other systems. This is because, its running costs due to energy demands is the lowest, since this type of wall resulted the least cooling energy demands as observed in BPS chapter.

One the other hand, cement/sand brick performs best in only one criterion, CC3 - skills availability. Like in the case of other brick wall systems, brick is the most conventional wall technology available in Tanzania, hence the available workforce is highly skilled to design and build this type of wall system.

Moreover, all wall design solutions have the same performance in two criteria: CC2 – verifiability and CC6 – sustainability. In the end, a micro ventilated OSB panel seems to be the best performing option.

8.10.2. Significance of the method

One of the most important aspects of multi-criteria analysis methodology is its flexible ability to be customized based on specificities of the building industry in question and/or on design solutions intents. For example, even though, the methodology was developed in France, in this study it has been applied in Tanzanian context. Moreover, the intensity of importance for sub-criteria can be customised based on local building practices. The same goes for coefficients of façade typology as already observed. Also, sub-criteria of criterion CC5 and CC6 can be modified according to project's objectives. Apart from comparing the performance of building solutions, it can also be used to compare the performance of building sub-systems. As in the case of this study, it was used to compare the performance of building envelope design solutions.

Likewise, multi-criteria can also act as a reminder to the design team on what to consider during design. In fact, all indicators are supposed to be considered during early design stages. Therefore, even if someone decides not to use this methodology at all, still just by observing the lists of indicators, sub-criteria and/or indicators, they can adjust or make proper decisions on their design solutions.

8.10.3. Potential barriers

Although, multi-criteria methodology can be applied in different building industries, more research should be done on local context so as to establish better understanding such as on coefficients of façade typology or on other criteria and sub-criteria. If not, the methodology can mislead the final results, as the inputs won't reflect a building industry context in question.

Some criteria and/or sub-criteria may not be of necessity to the design solutions under investigation. For example, CC3.4 is highly practical for design solutions with automation systems. Or in this case study for example, CC4.3, CC4.4 and CC4.5 were not important. As a result, assumptions needed to be made, which may or may not reflect the exact reality.

9. Chapter 9: Final Architectural Design Solution

As already highlighted, the case study used in this thesis is not an existing building, but rather a design proposal which was developed by the authors of this thesis. And, since the overall objective of this study is to show how BPS and multi criteria analysis can be used by architects and engineers as supporting tools for design solutions, it is therefore, in the interest of this thesis to present the architectural design solution of the final building envelope components (*including window size, horizontal louvres system, micro ventilated OSB panel*) chosen after performing both BPS and multi-criteria analysis. Moreover, since the case study itself is not an existing building, therefore, the final architectural design solution of the overall case study is also presented in this chapter.

9.1 Location

9.1.1. City

As already observed, the case study is located in Dar es Salaam, a warm humid climatic city in coastal Tanzania. It is the main Tanzania's economic powerhouse, and the biggest city in terms of population size.

(See figure 16 and 17 for location of Dar es Salaam)

9.1.2. Site

The site itself is located in central business district of Dar es Salaam called Kariakoo (*within block 8 along the Kongo street*) , which is densely populated with buildings of high and medium rise heights.

(See figure 44 for Kariakoo Typomophological analysis plan)

A site analysis investigating site infrastructures and accessibility, solar path studies and contextual surroundings is presented in A3 sheets below.

9.2 Design program

9.2.1. Building types and uses

The proposed design solution consists of mixed-use development project to be constructed in an urban area. The mixed-use development project includes residential, office and commercial purposes. Although, only residential block was considered in BPS chapter, in this chapter, the overall project is presented.

The following are different functional requirements as highlighted in Design Brief by Ilala Municipal Council in 2019.

- Cinema halls
- Parking space for 130 cars
- Prominent pedestrian walkways and amenities
- Office building
- Mini supermarkets
- Commercial facilities
- Outdoor arcade-podium facilities
- Residential building

9.2.2. Building programs

Residential: Apartments with 80 rooms in total

Typical apartment (90m^2)

Total number of people	6
Space	Floor area (m^2)
Master bedroom	13
Bedroom 2	13
Bedroom 3	13
Lounge	25
Kitchen	9
Bath with toilet	5.5
Public toilet	1.5
Storage	4
Lobby	6
Balcony	6

Table 50 Typical apartment, space and floor area

Office : Open plan
Commercial : Open plan

Total floor areas

Functions	Total floor area (m^2)
Commercial	2400
Office	4000
Apartments	6400

Table 51 Total floor area for different fucntions

9.2.3. Proposed building design solution

A final building design solution consisting of residential curved block, U shaped office block and a commercial block is hereby presented.

The overall design process and architectural solutions are presented in A3 sheets below.

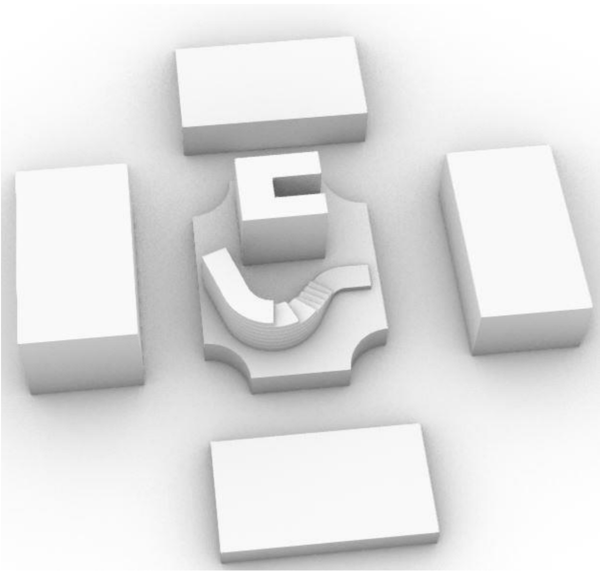
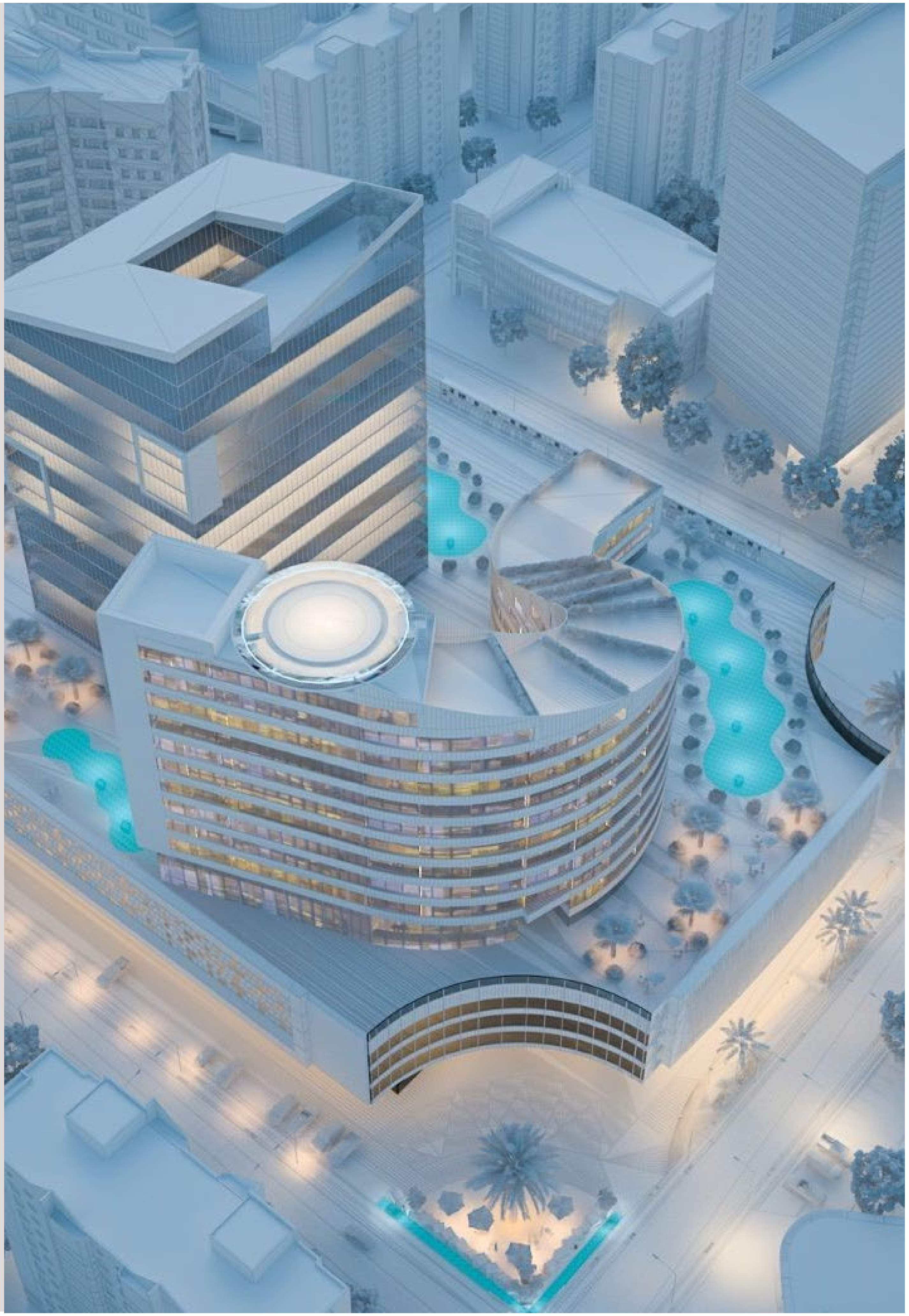


Figure 100 Mixed-use development design proposal and surrounding context

9.2.4. A3 sheets for the presentation of design process and architectural design solutions

PROPOSED
CASE
STUDY

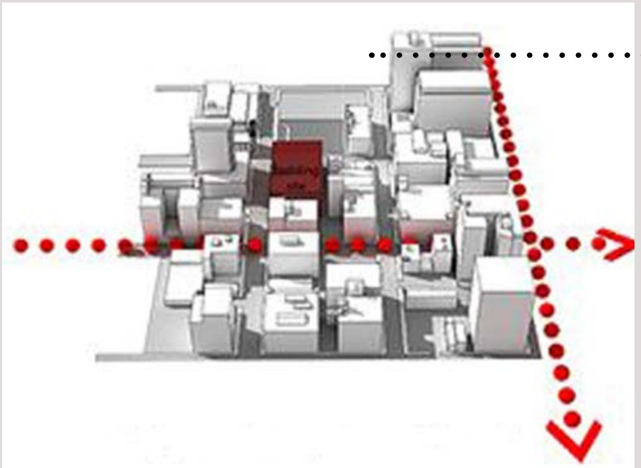
A R C H I T E C T U R A L   D E S I G N



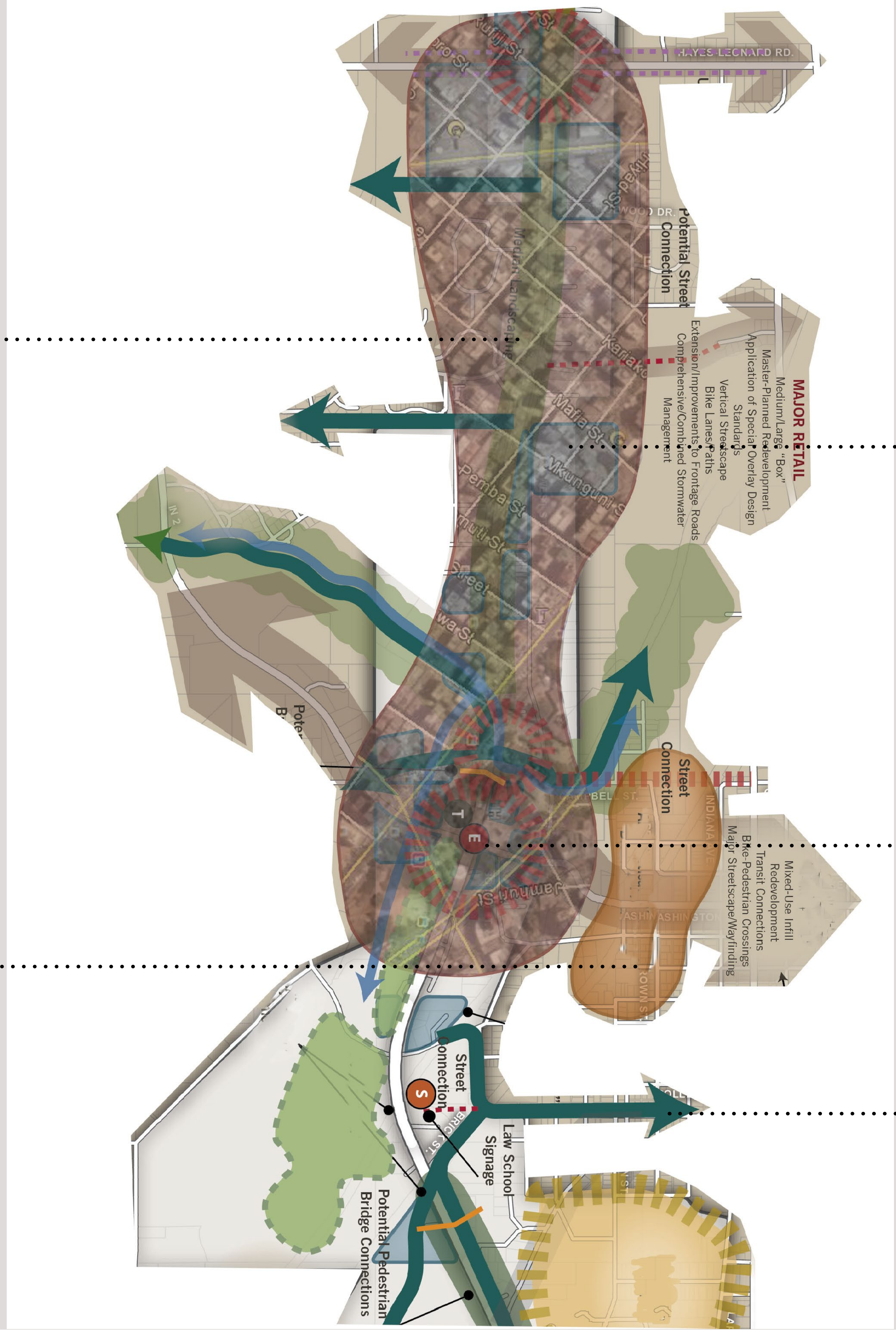
SITE INVENTORY

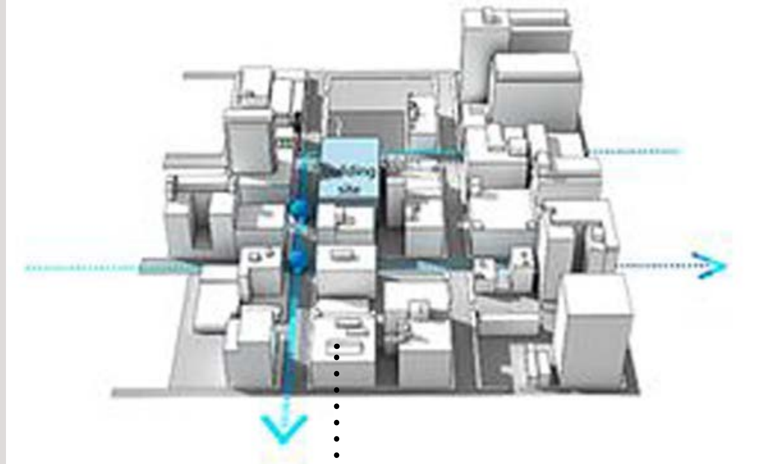
STREET NETWORKS

URBAN CONNECTIONS
FROM AND LINKS
INTER SECTIONS
ENTIRE THE CONTEXT



SECONDARY STREET NETWORKS

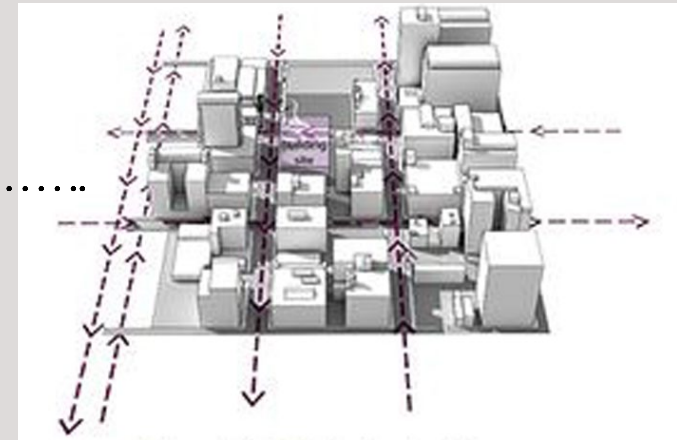




PRIMARY STREET NETWORKS

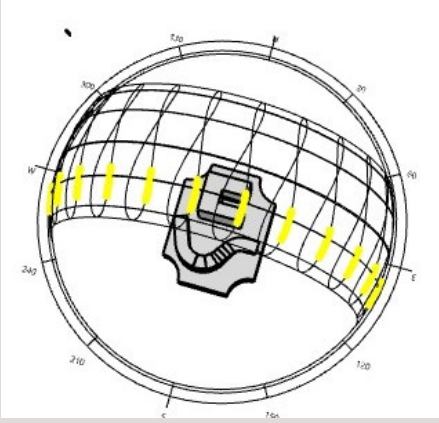
URBAN MORPHOLOGY

BUILDING TYPOLOGIES IN
THE CONTEXT
COMPARED TO THE GENERAL
CITY SKLINE

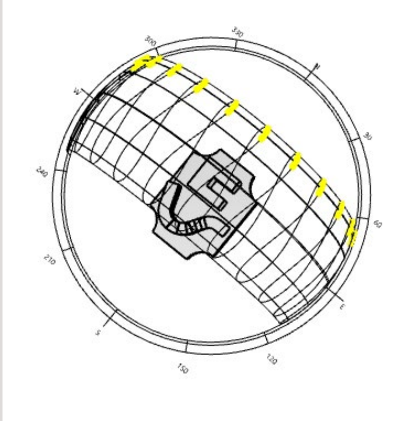


PEDESTRIAN NETWORKS

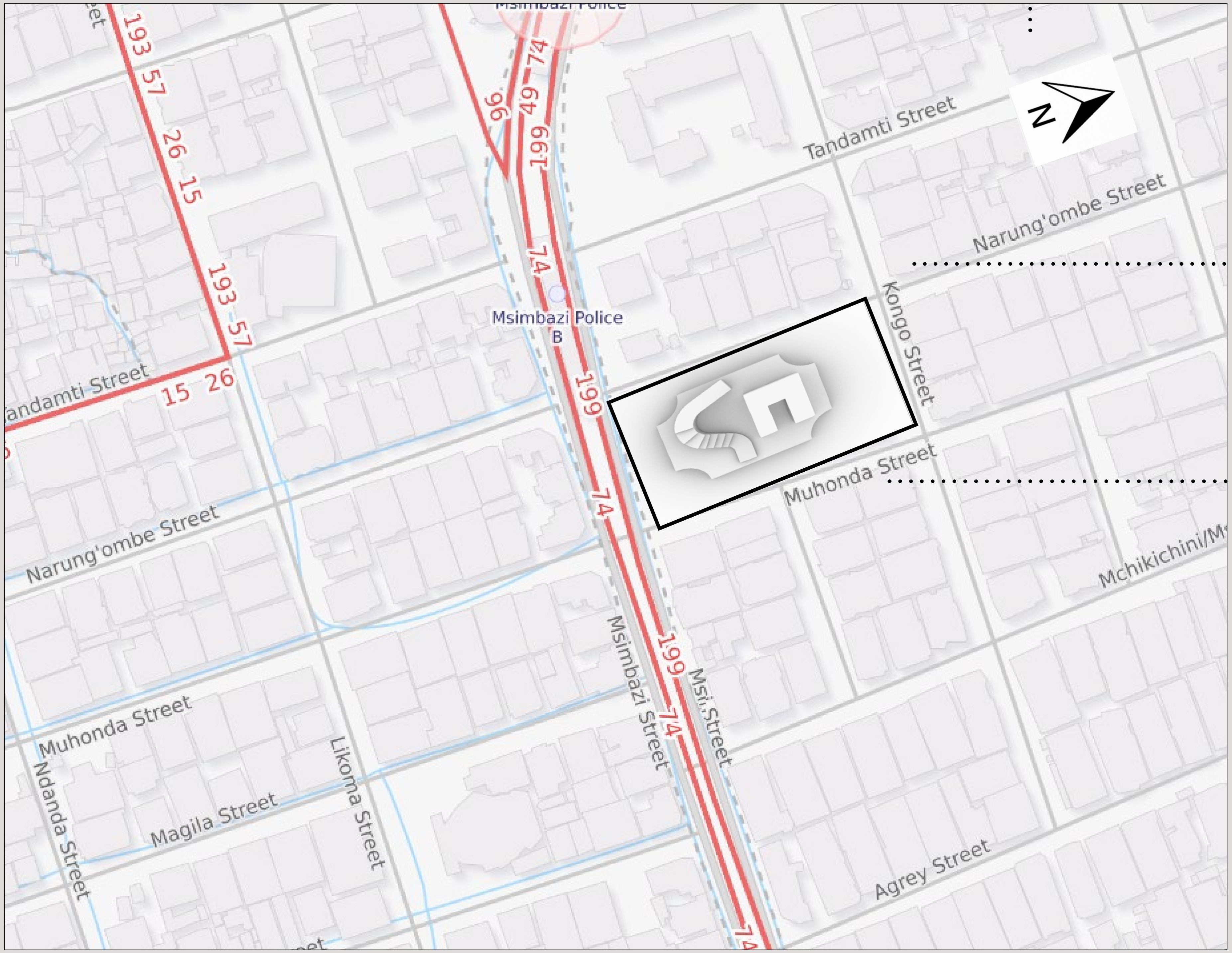
SITE ANALYSIS-CONTINUATION



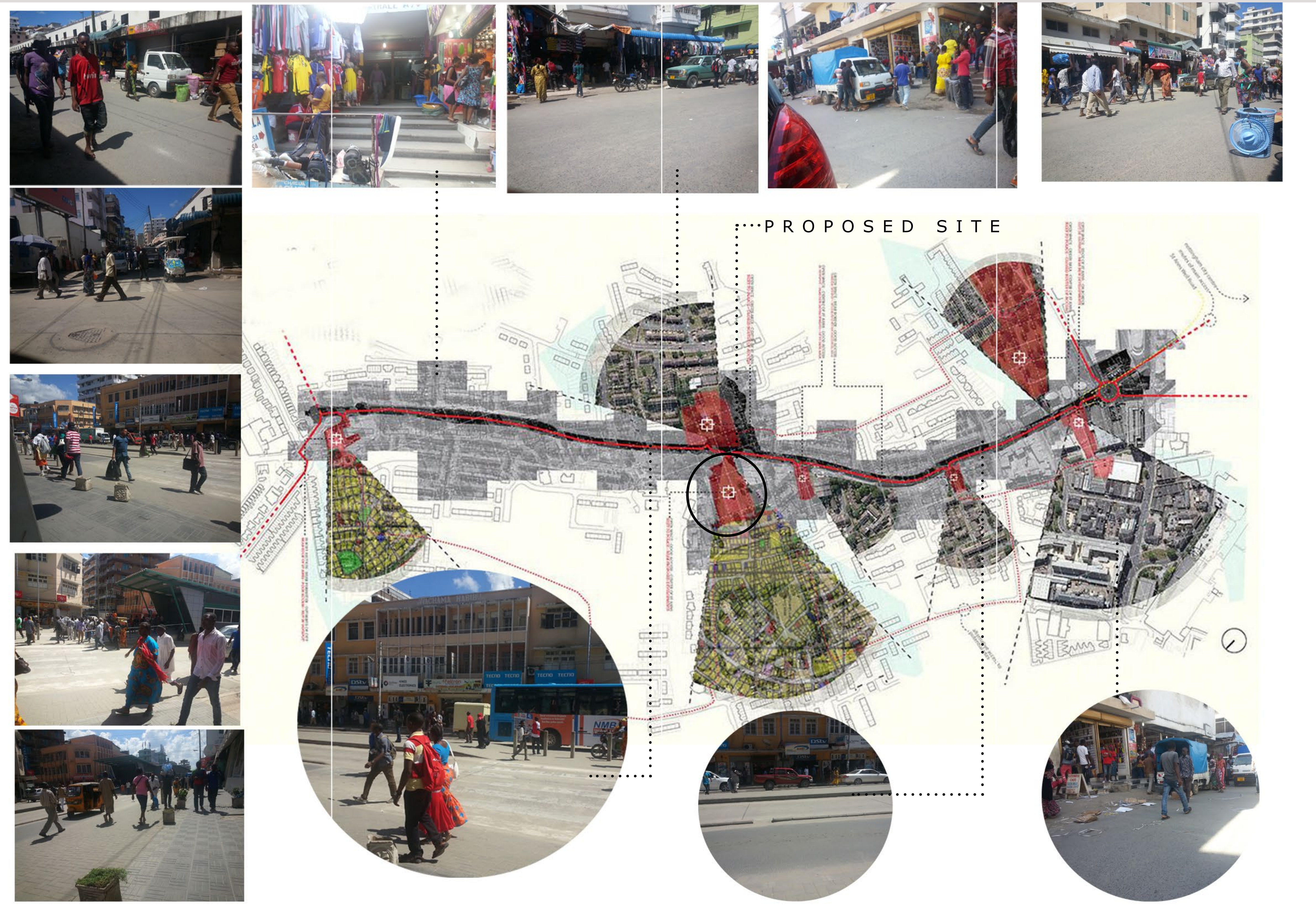
1ST FEB
HOTTEST DAY



23RD JULY
COLDEST DAY



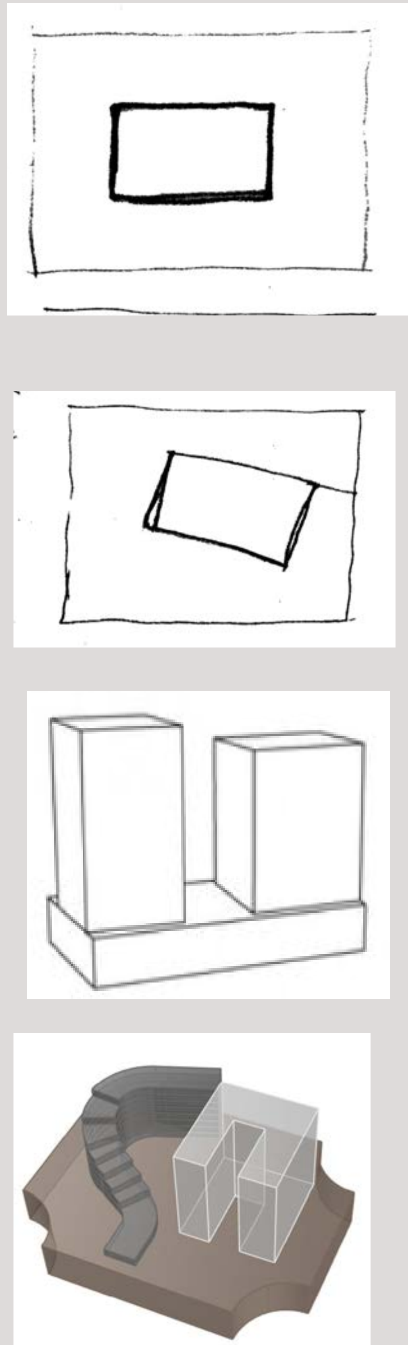
N E I G H B O U R H O O D - M A S T E R P L A N



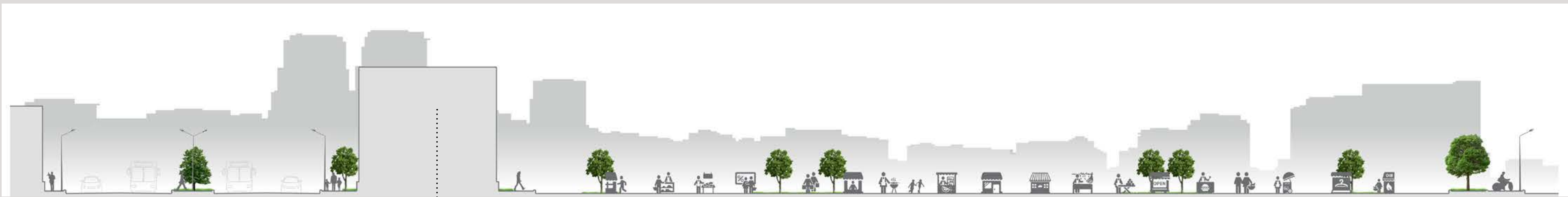
CONCEPT DEVELOPMENT

PUBLIC LIFE IN THE CONTEXT

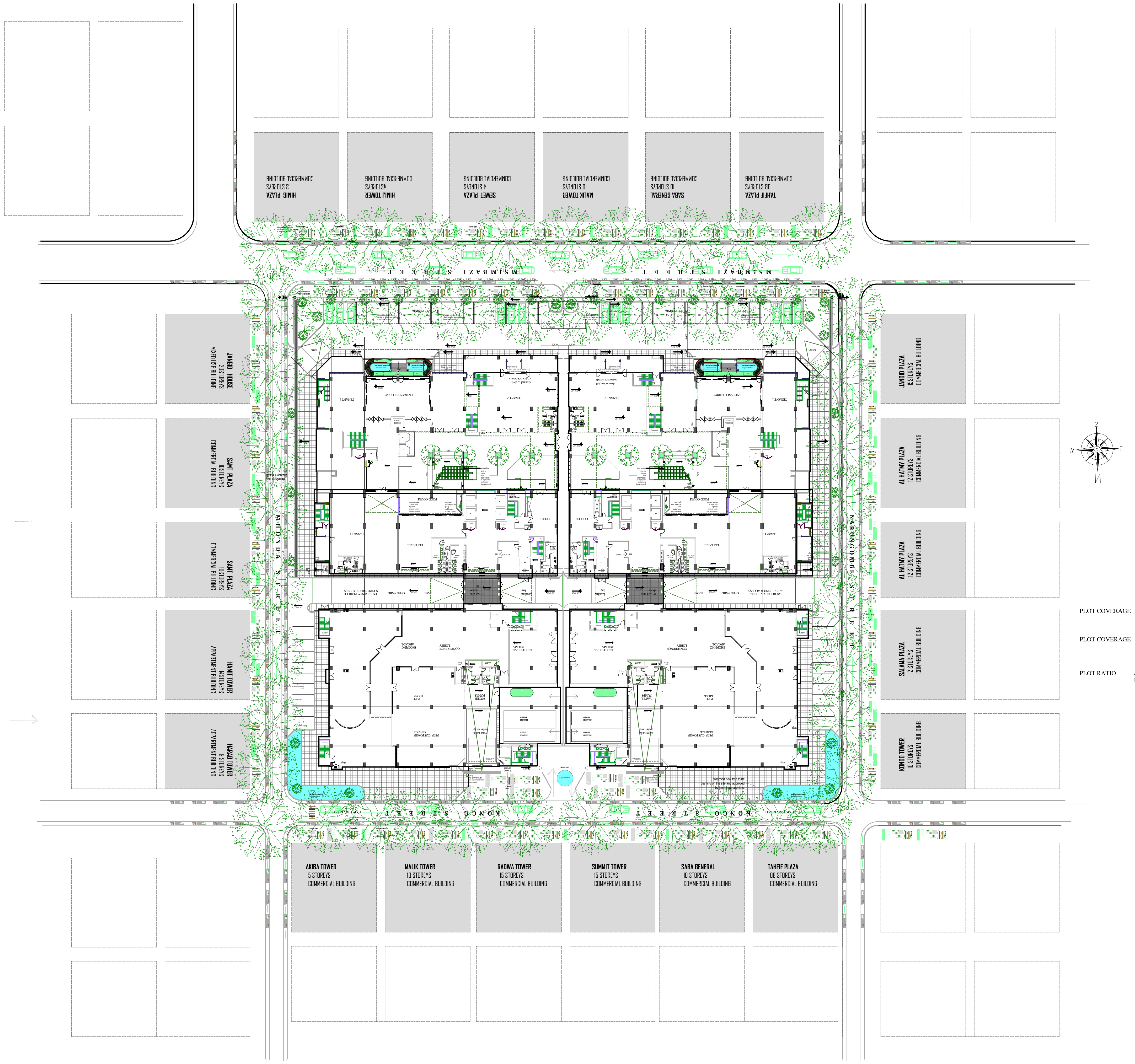
PUBLIC LIFE IN THE CONTEXT



URBAN CORRIDORS IN STREETS



PROPOSED CASE STUDY



SCHEDULE OF AREAS
Plot Calculations.

PLOT AREA = **10000M²**

PROPOSED BUILDING

Ground floor area =358.497m²

First Floor Area =346.412m²

Second Floor Area =346.412m²

Roof Terrace Floor Area =407.535m²

Total Floor Area **= 3,898.325m²**

Road Morrum area:
Interlocking blocks:
Carbstone length:

PLOT COVERAGE = TOTAL BUILT UP AREA x 100% / PLOT AREA

PLOT COVERAGE = **357.429 x 100% / 3914**

= 80.168%

PLOT RATIO = TOTAL FLOOR AREA / PLOT AREA

= 3,898.325 / 3914

= **2.014**

ARCH 01 PROPOSED MIXED USE BUILDING

DETAILED STREET LAYOUT PLAN

SCALE 1:100

Politecnico di Milano
Msc in Building and Architecture Engineering

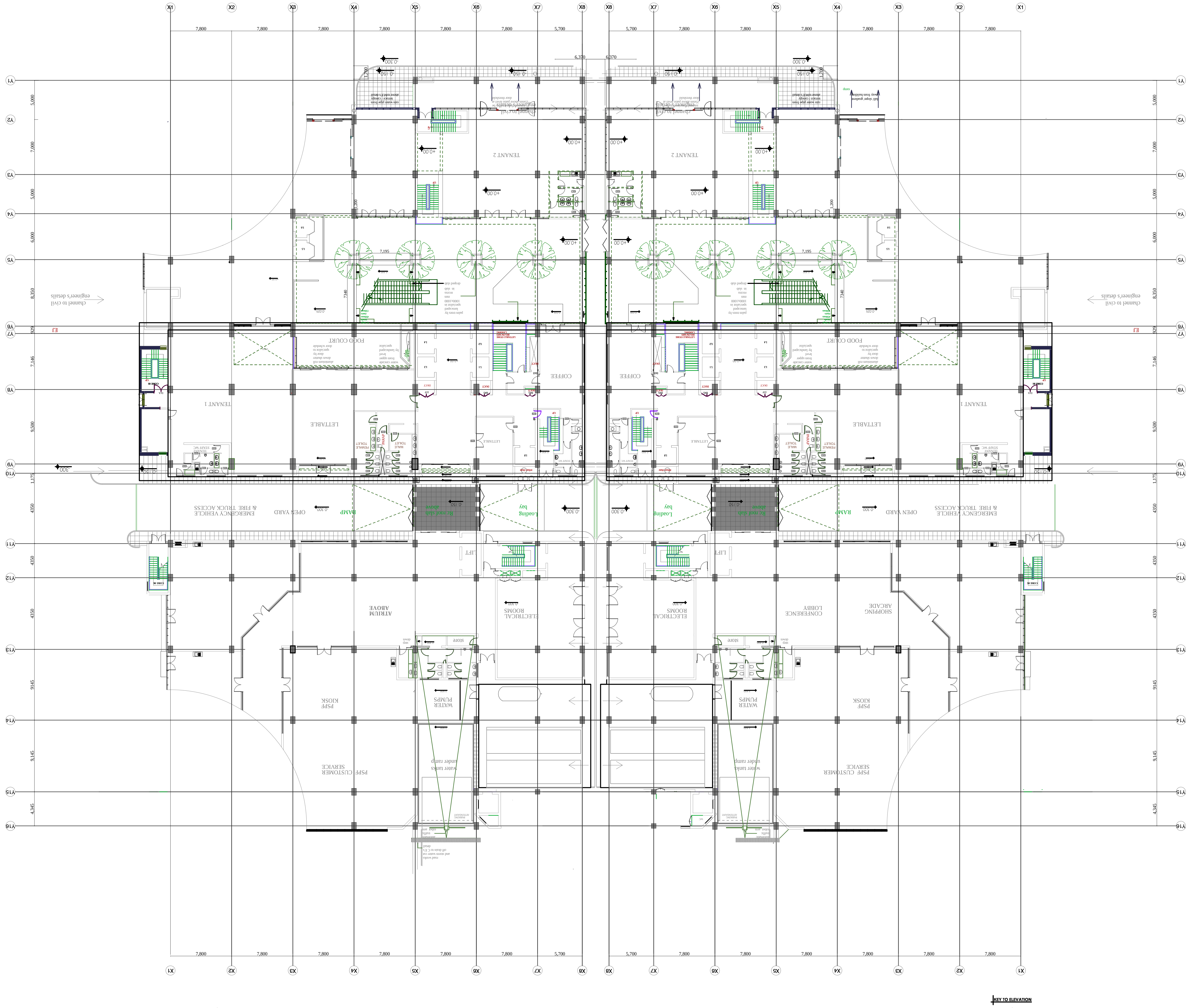
Final Thesis

Supervisor:
Prof Gabriele Masera

Emmanuel Morris Manko
Jamal Abdul Ngoyaro

Scala: 1:100

Titolo: Stratigrafie



ARCH | PROPOSED MIXED USE BUILDING
01 | TYPICAL 2ND TO 4TH FLOOR PLAN
SCALE 1:100

Politecnico di Milano
Msc in Building and Architecture Engineering

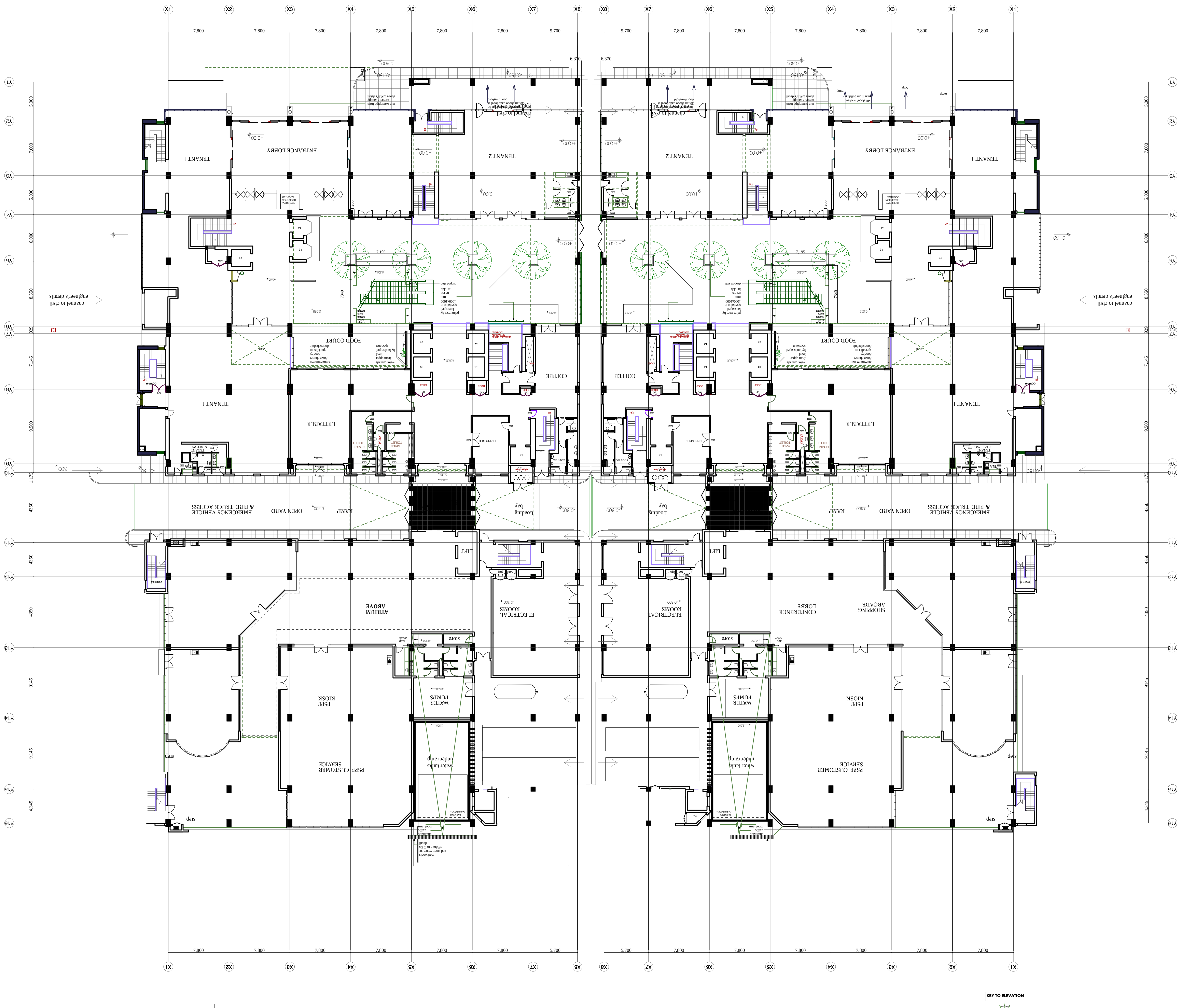
Final Thesis

Supervisor:
Prof Gabriele Masera

Emmanuel Morris Manko
Jamal Abdul Ngoyaro

Scala:
1:100

Titolo:
Stratigrafie

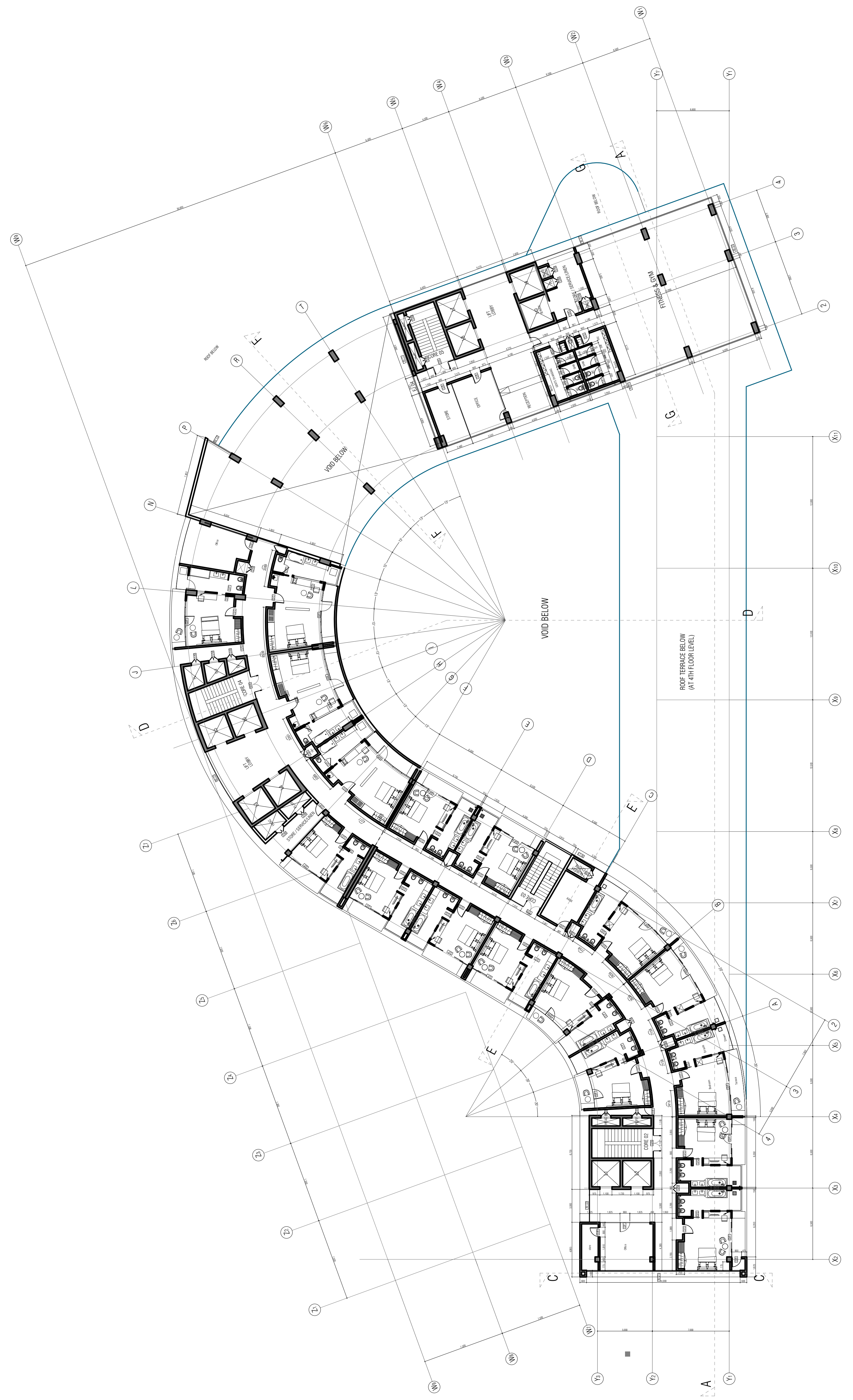


ARCH 01

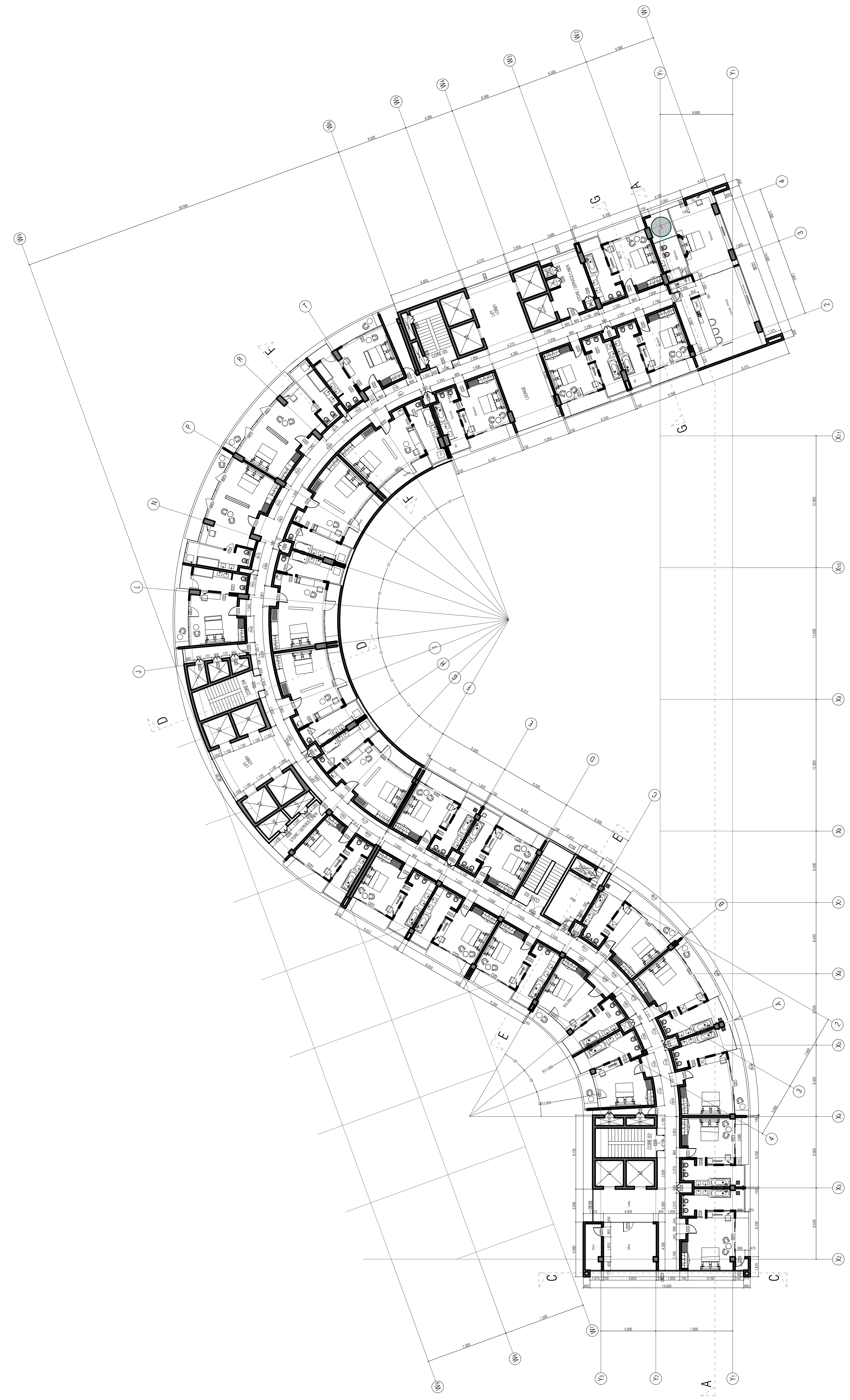
PROPOSED MIXED USE BUILDING

TYPICAL 2ND TO 4TH FLOOR PLAN

SCALE 1:100



ARCH 01 PROPOSED MIXED USE BUILDING
FIFTH FLOOR PLAN
SCALE 1:100



ARCH 01 PROPOSED MIXED USE BUILDING
SIXTH FLOOR PLAN
SCALE 1:100

Politecnico di Milano
Msc in Building and Architecture Engineering

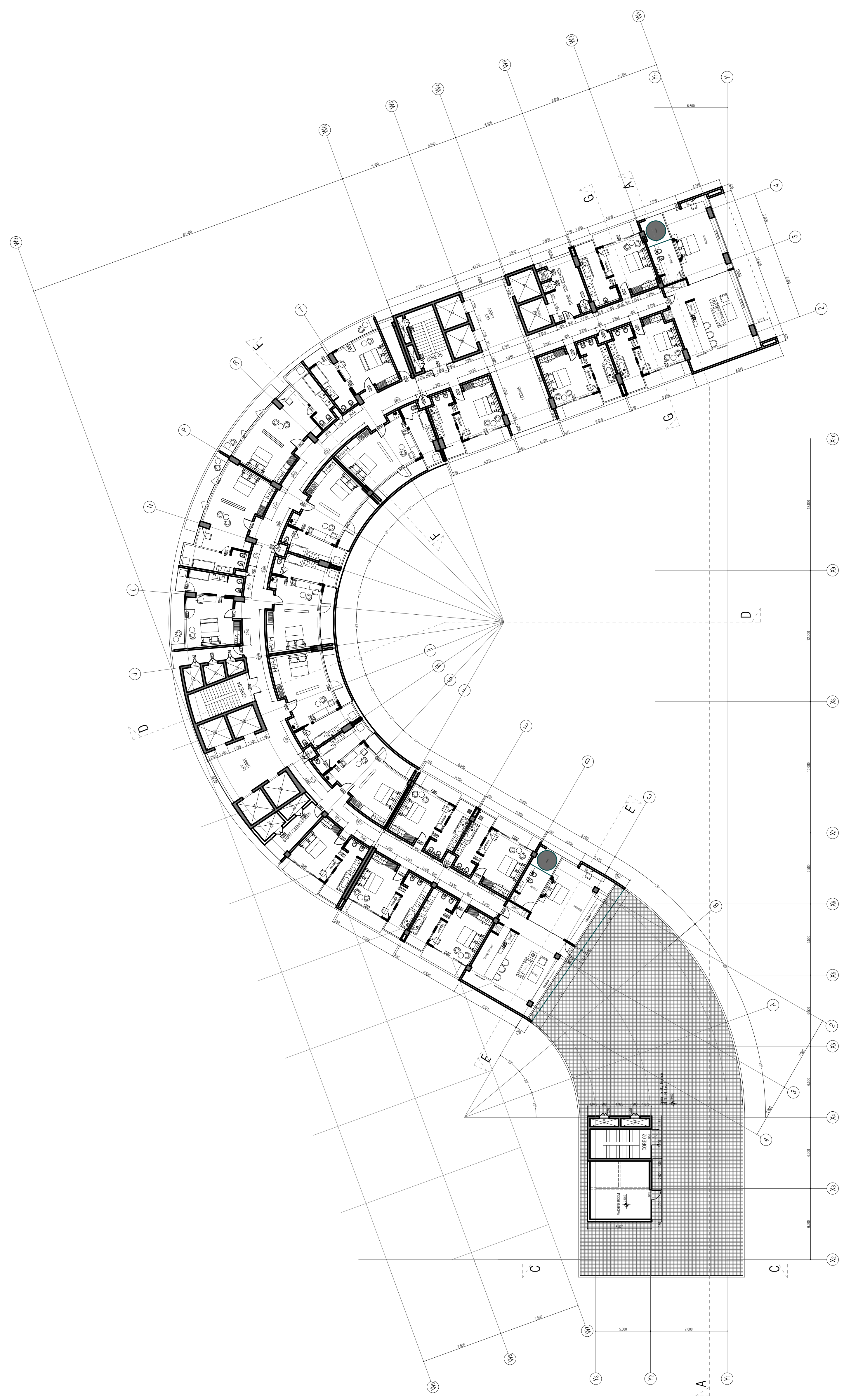
Final Thesis

Supervisor:
Prof Gabriele Masera

Emmanuel Morris Manko
Jamal Abdul Ngoyaro

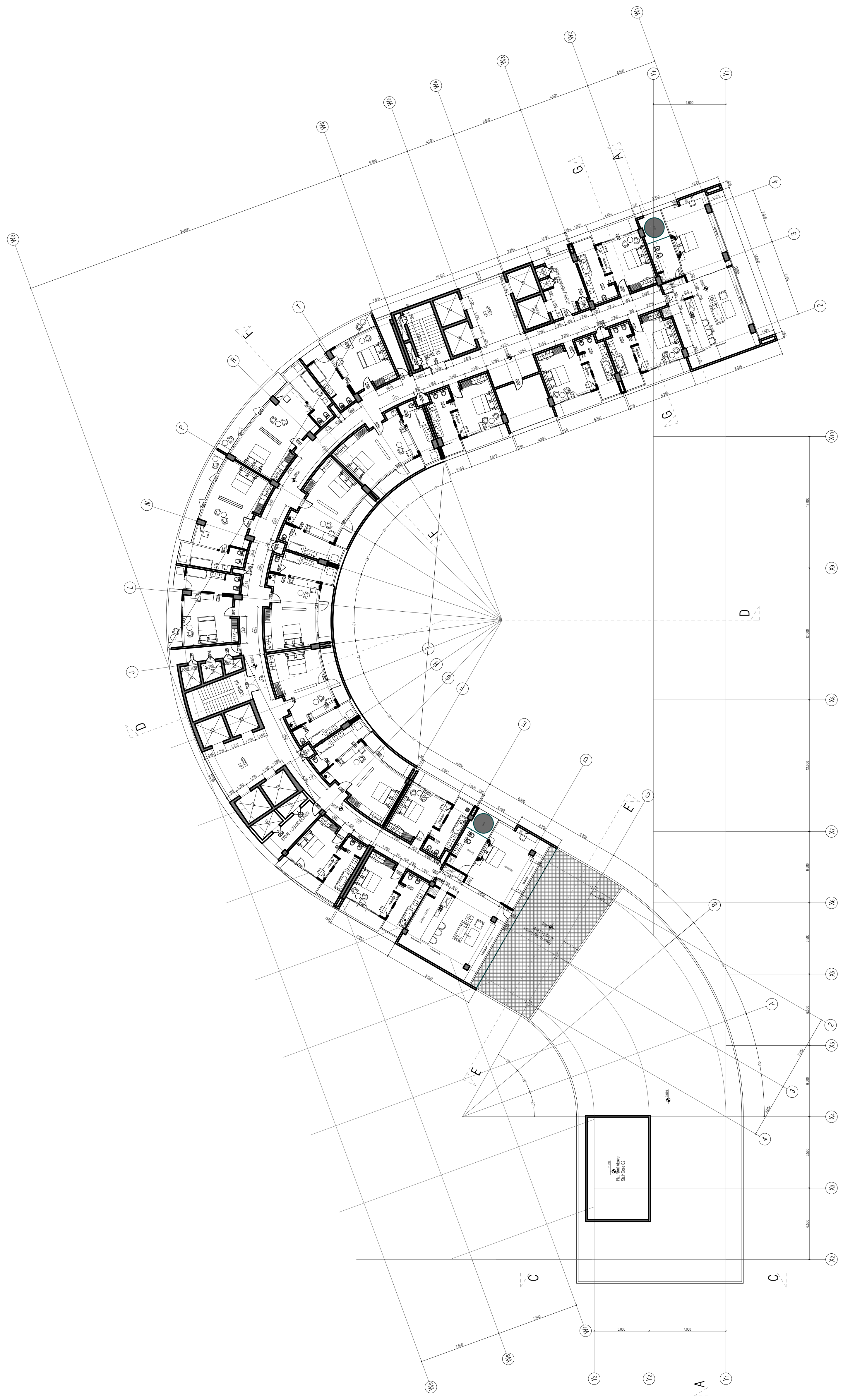
Scala: 1:100

Titolo:
Stratigrafie



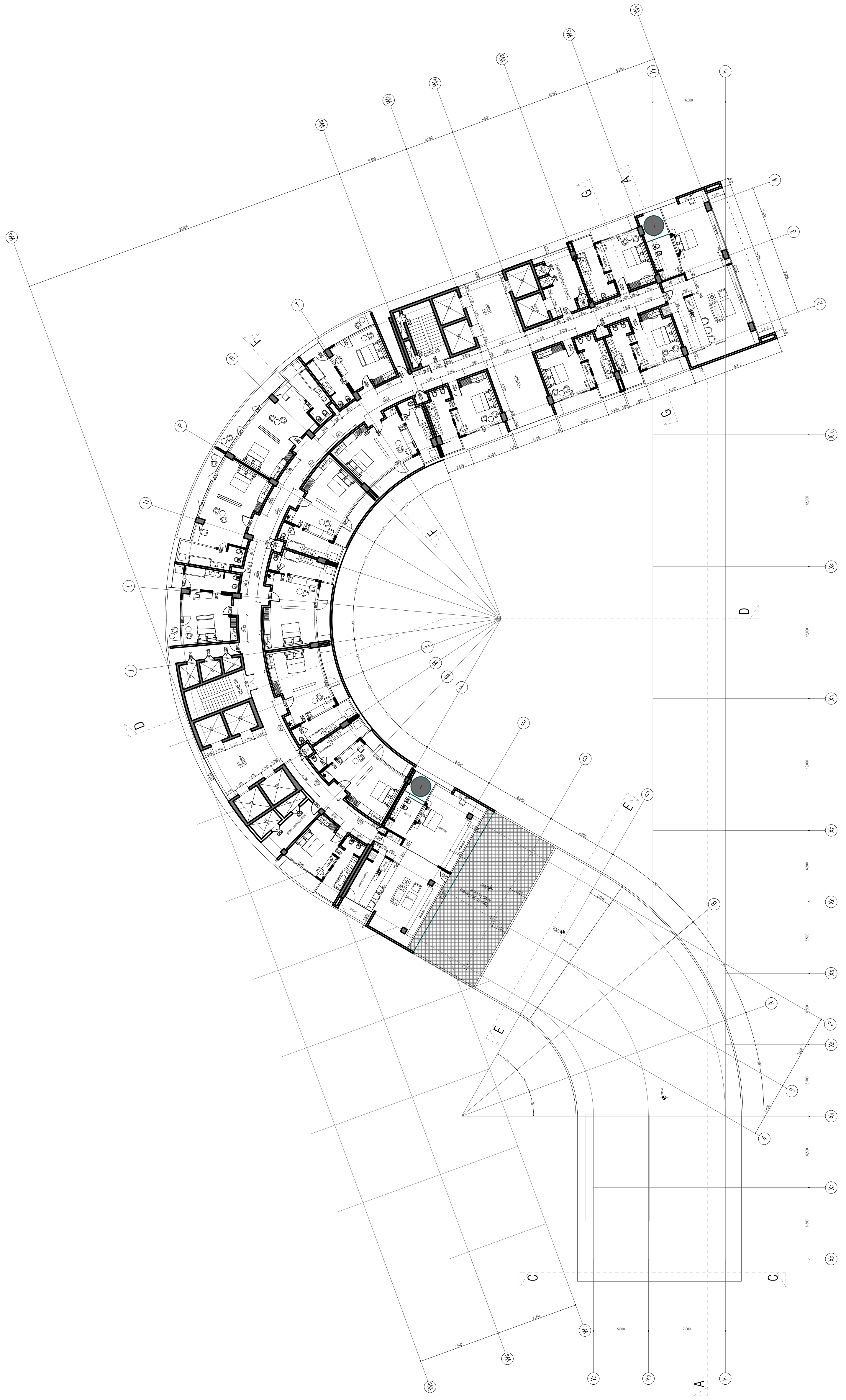
ARCH | PROPOSED MIXED USE BUILDING
01 | SEVENTH FLOOR PLAN
SCALE 1:100

KEY TO ELEVATION



ARCH | PROPOSED MIXED USE BUILDING
01 | EIGHTH FLOOR PLAN
SCALE 1:100

KEY TO ELEVATION



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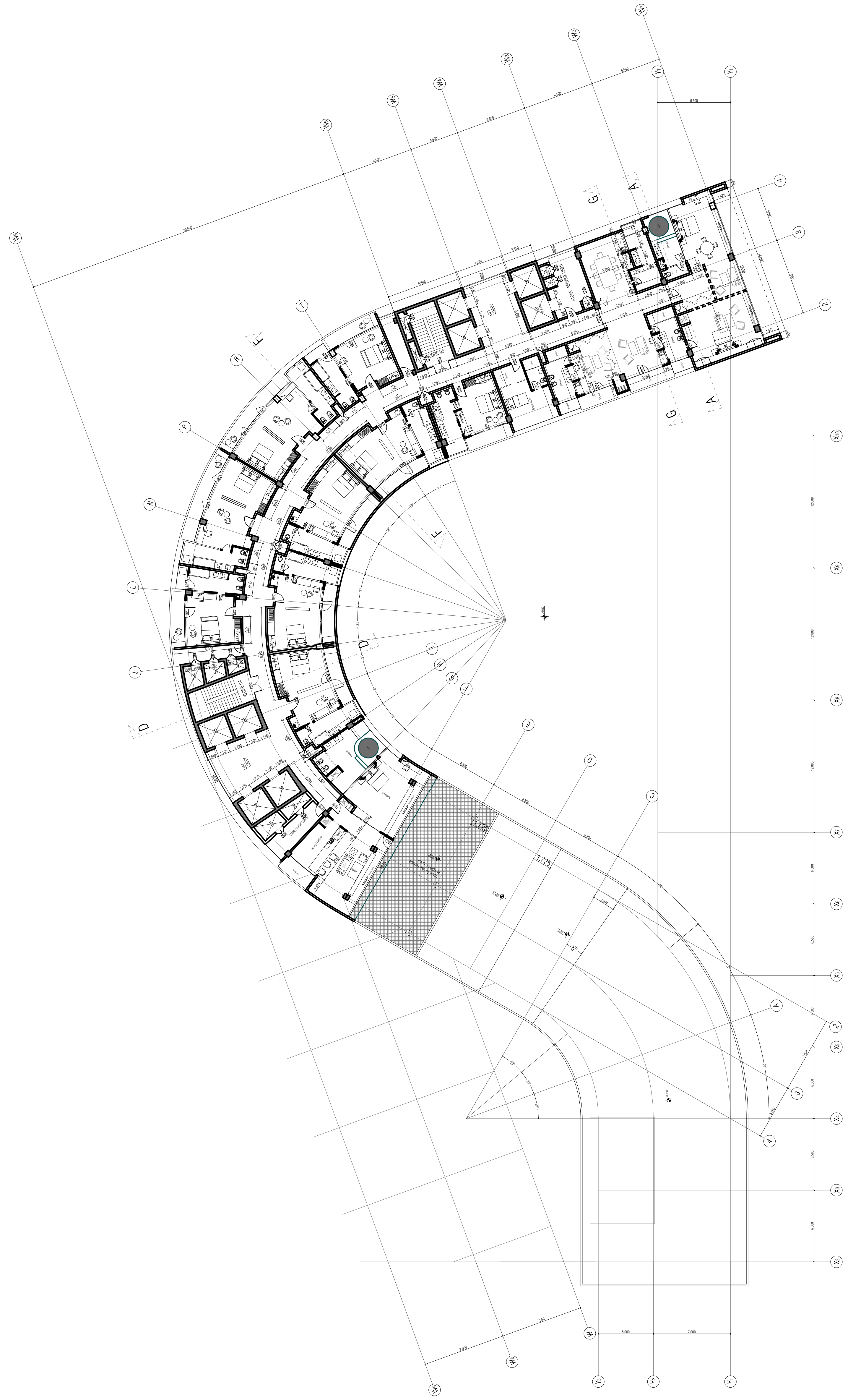

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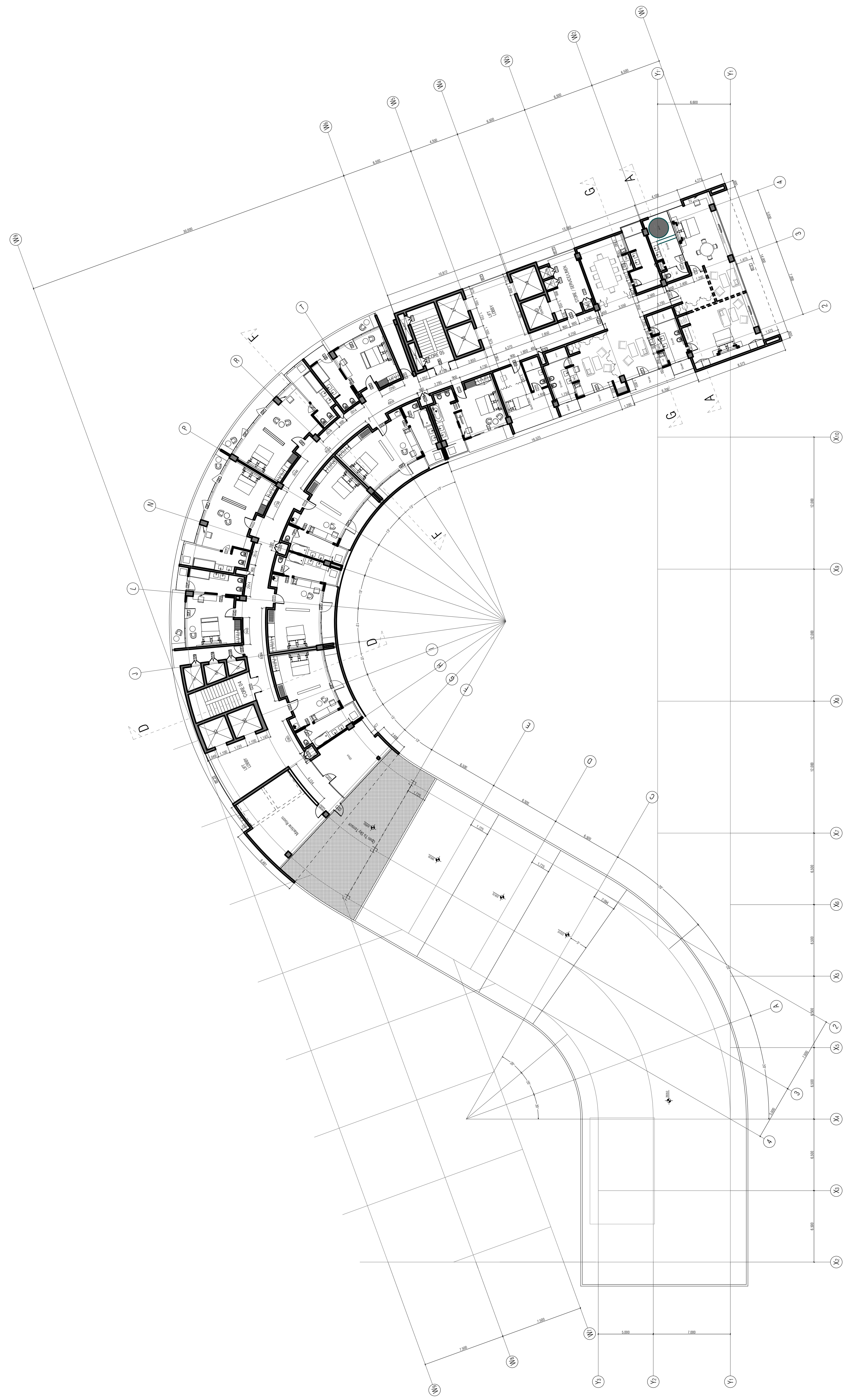

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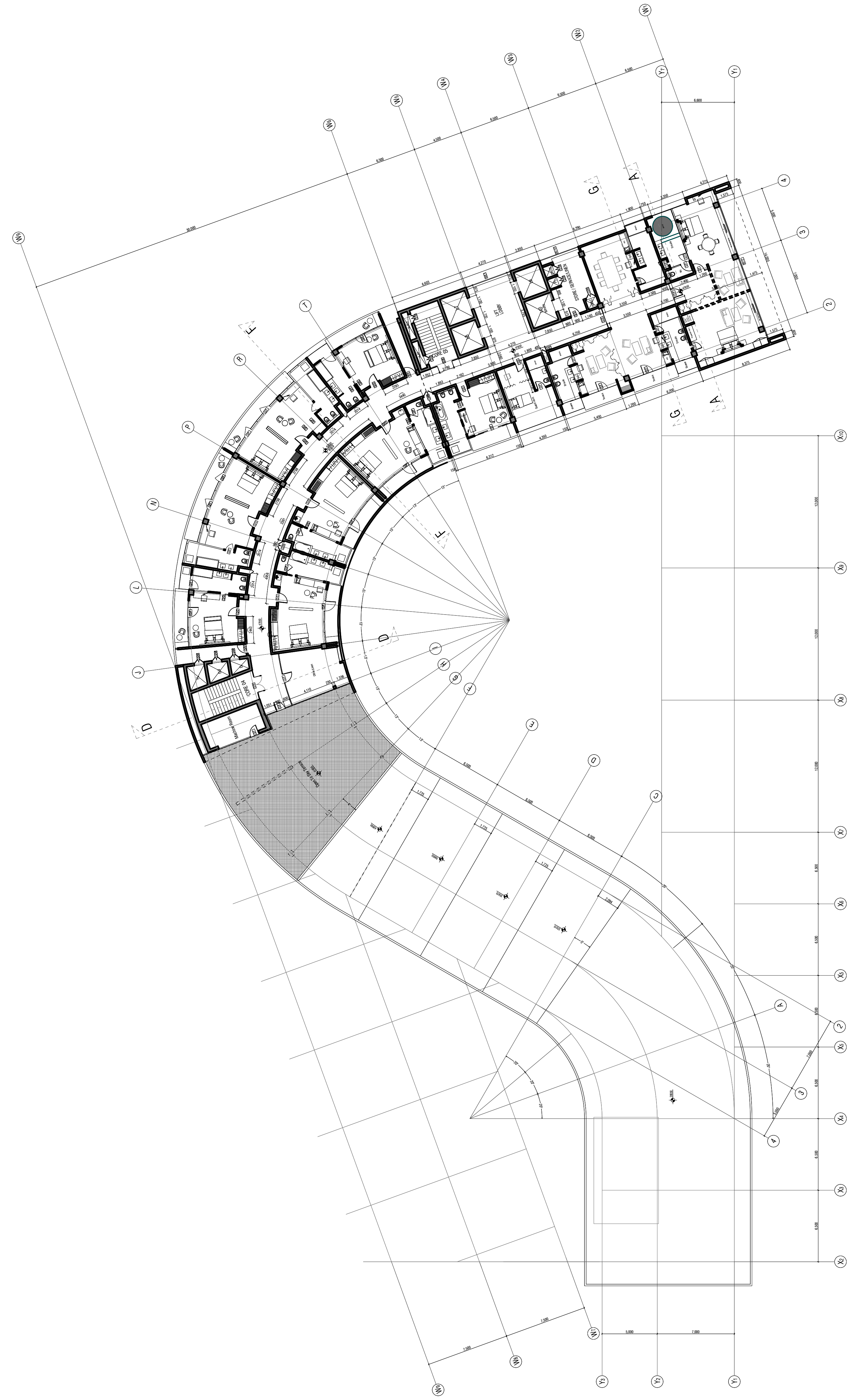

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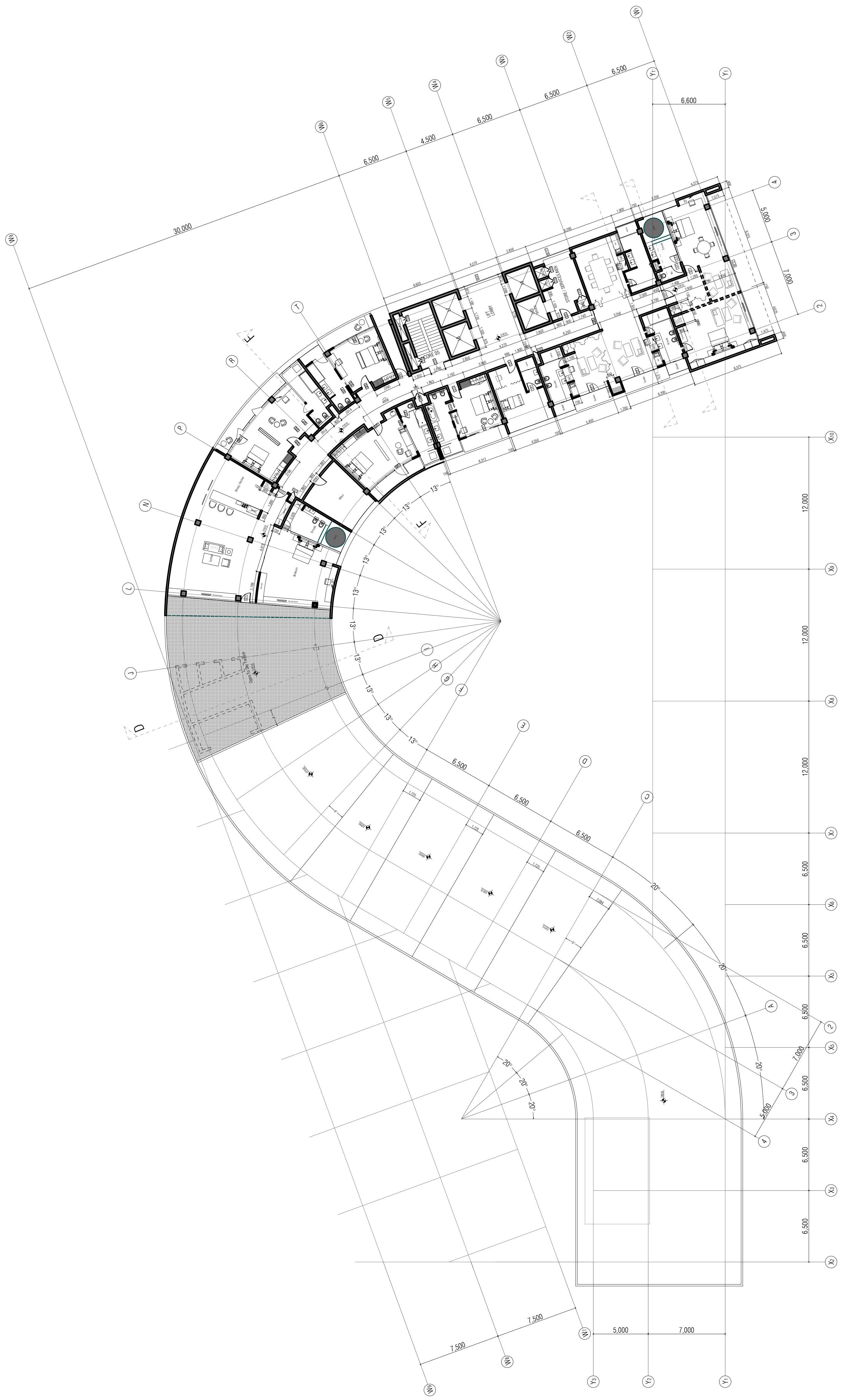

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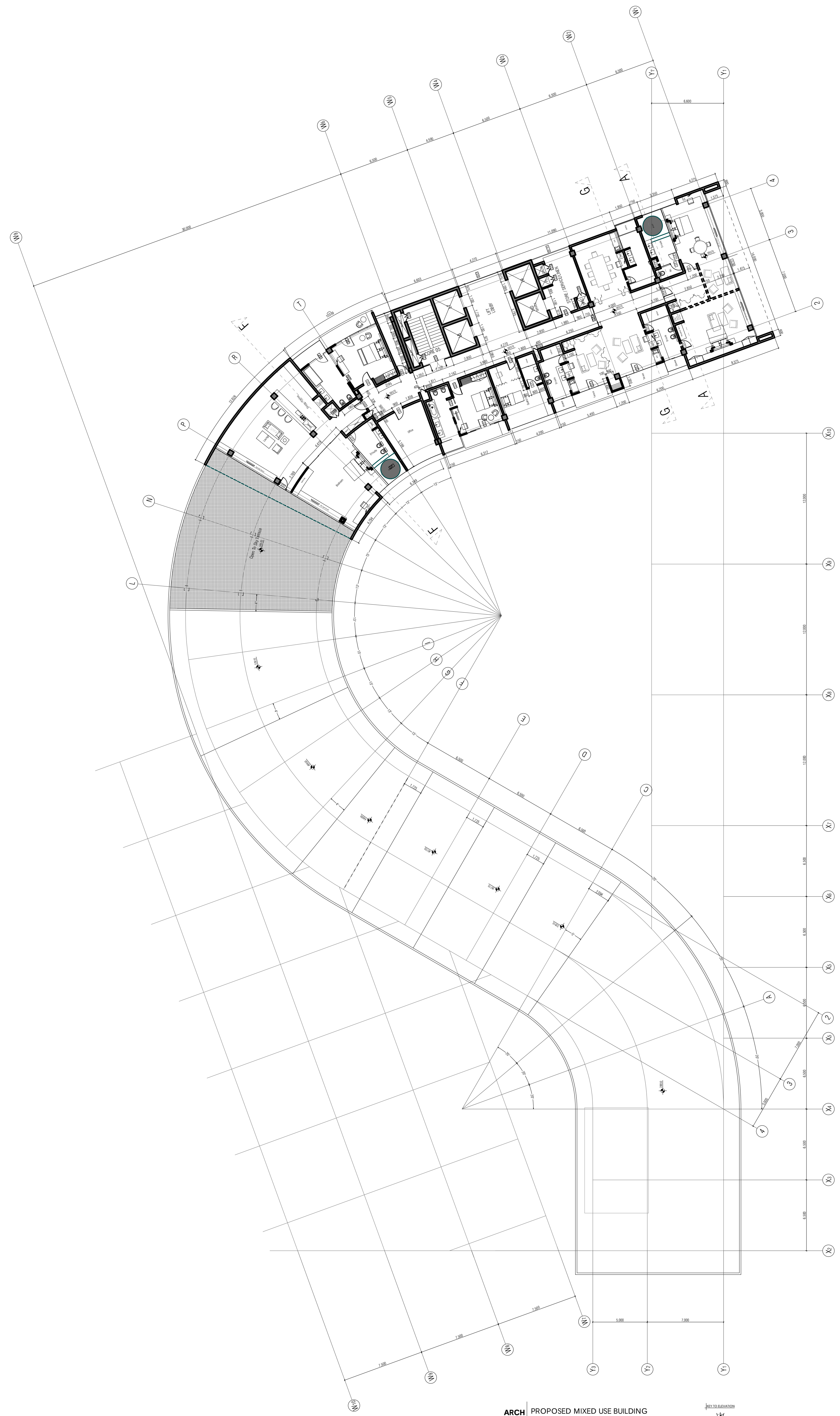

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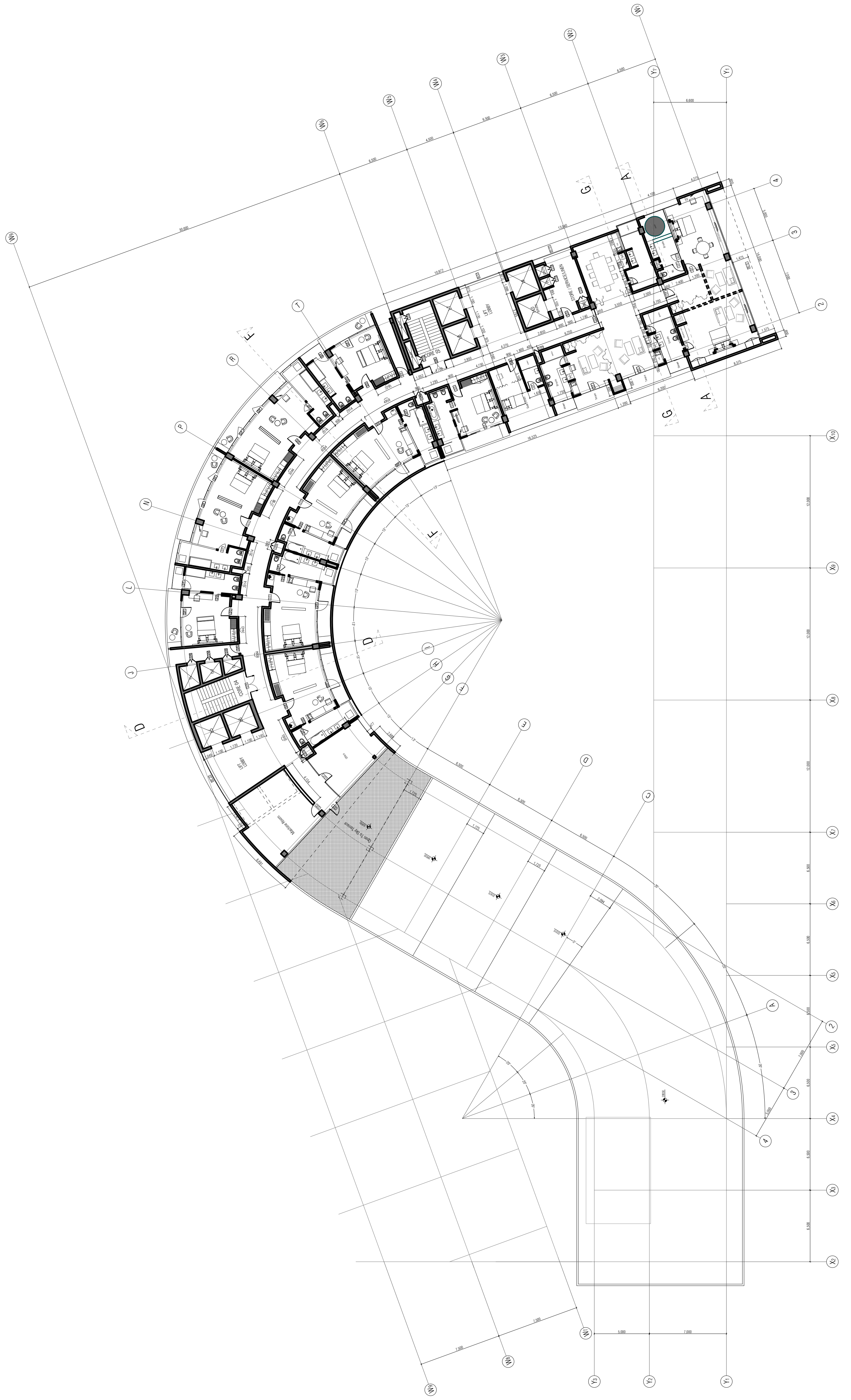

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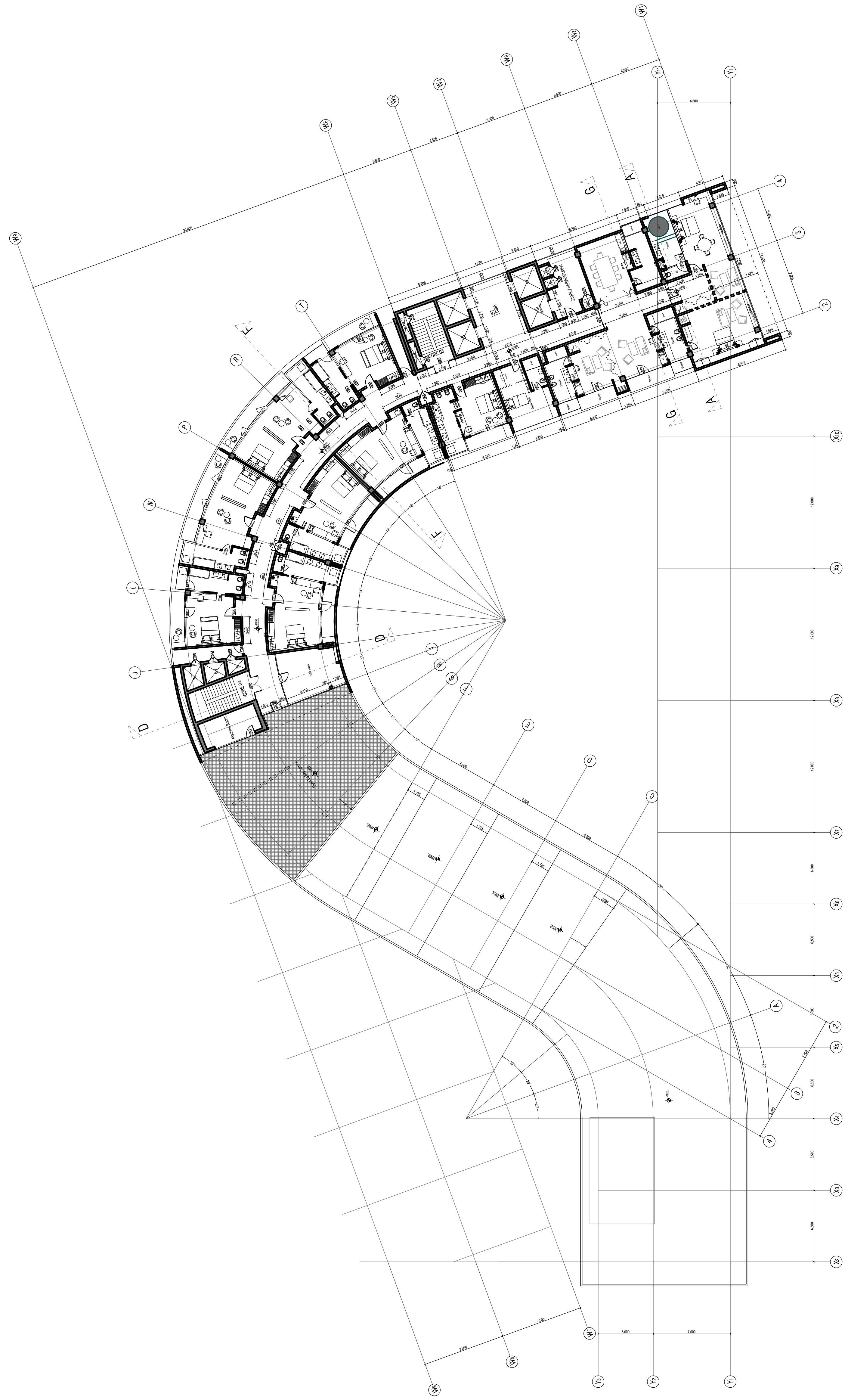

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Final Thesis

Supervisor:
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Jamal Abdul Ngoyaro

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Titolo:
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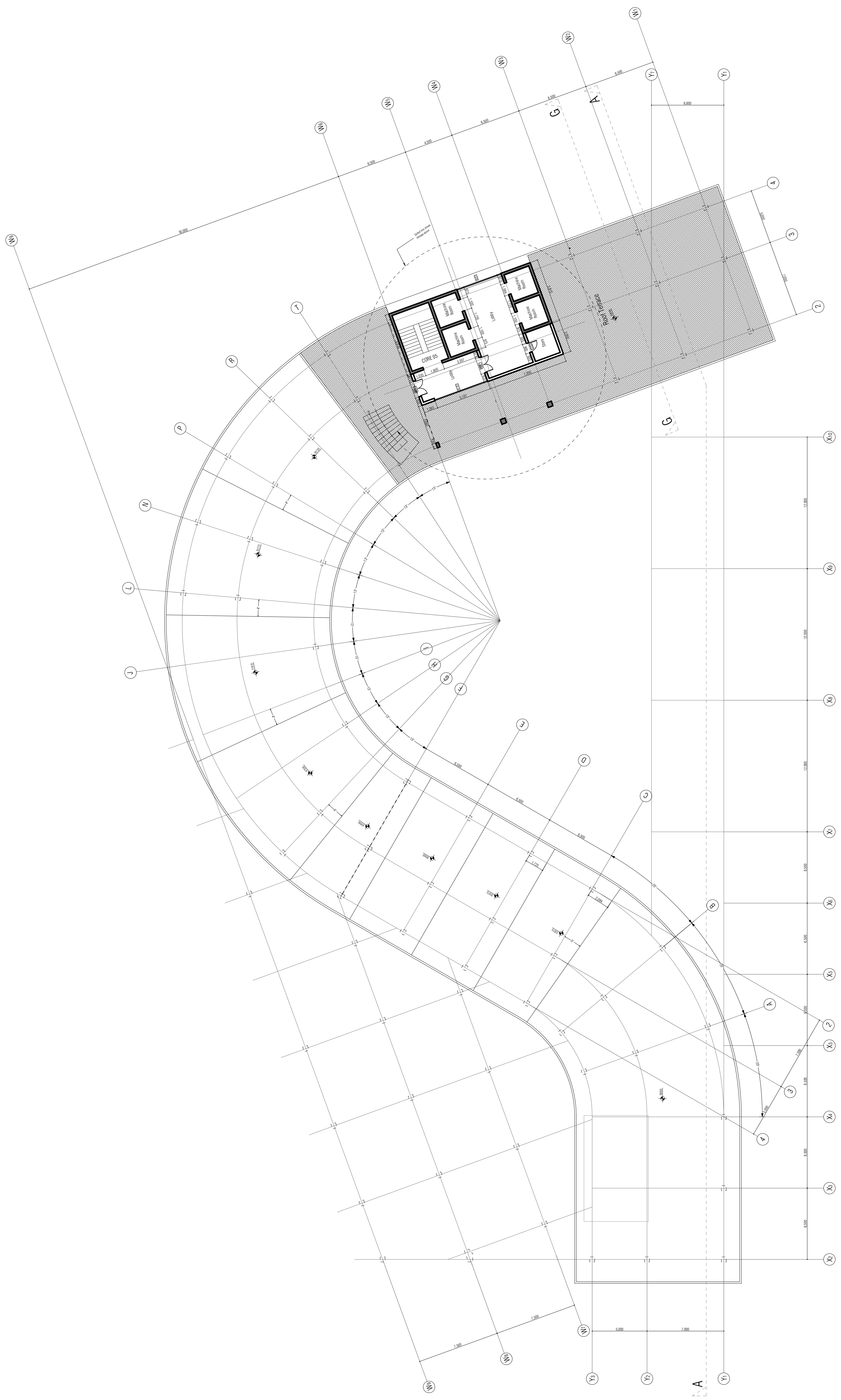

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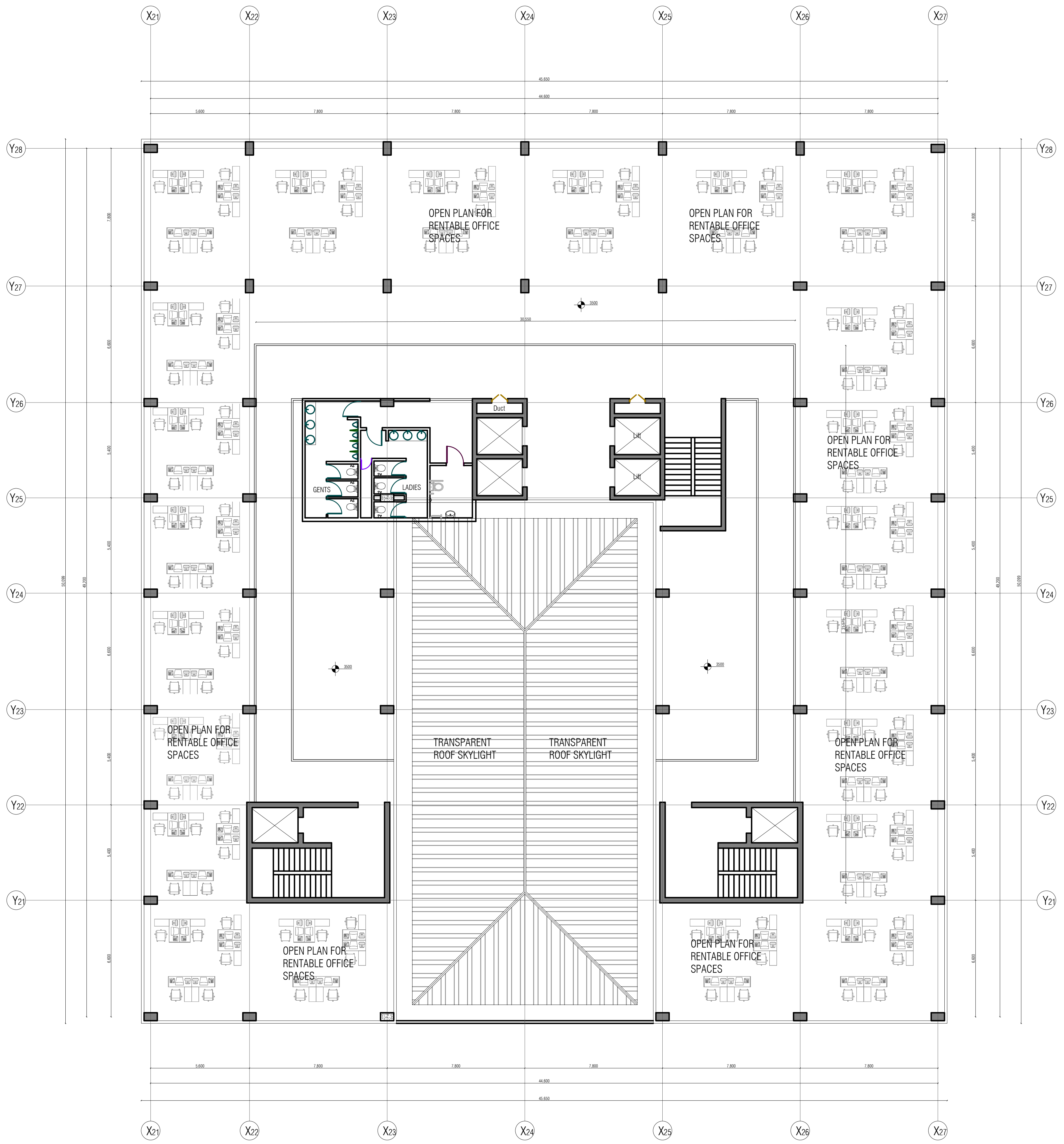

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5TH FLOOR PLAN
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KEY TO ELEVATION

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6TH -10TH FLOOR PLAN
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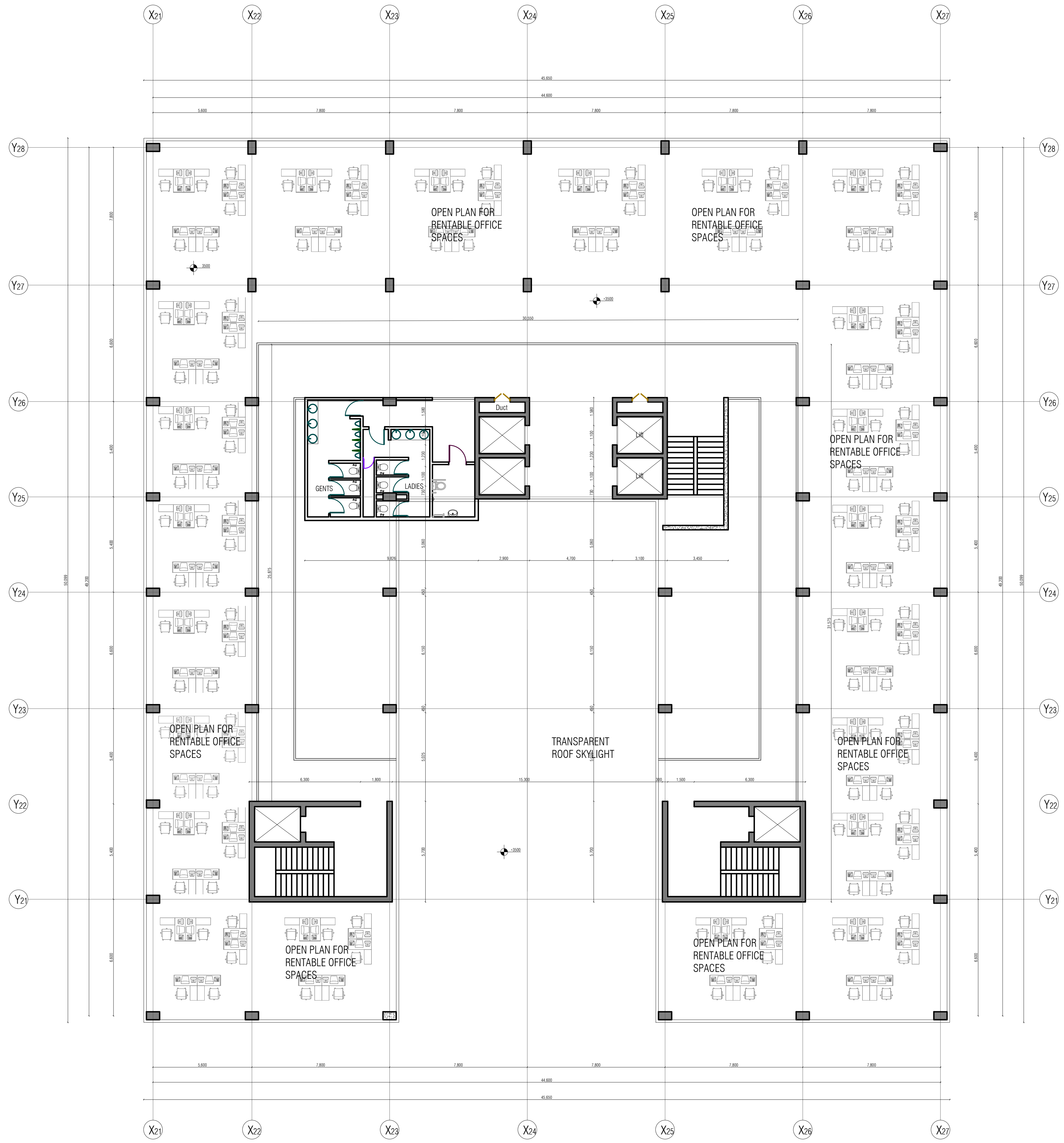

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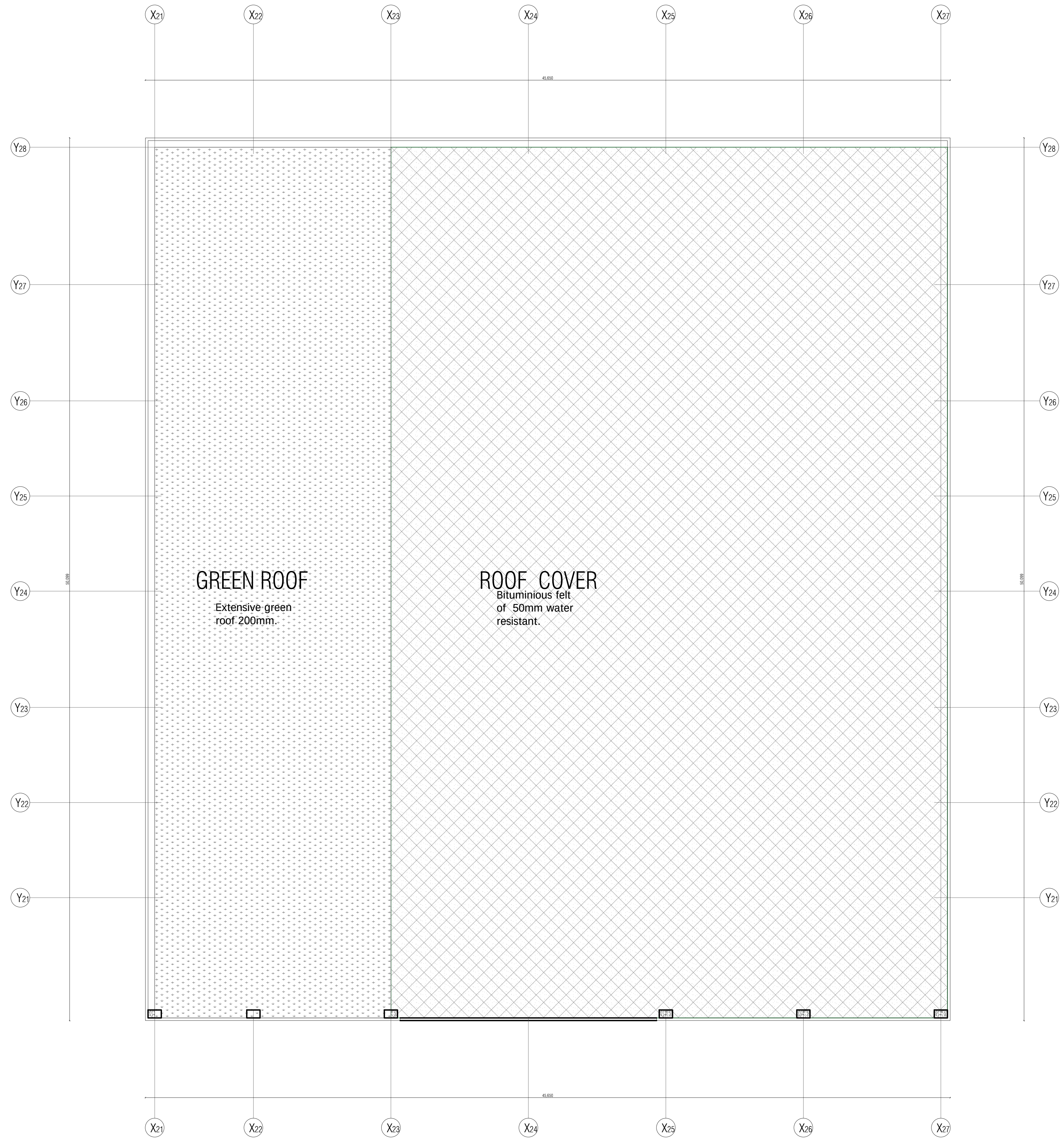

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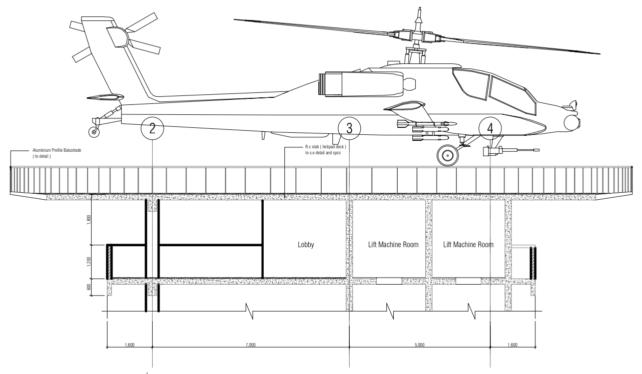

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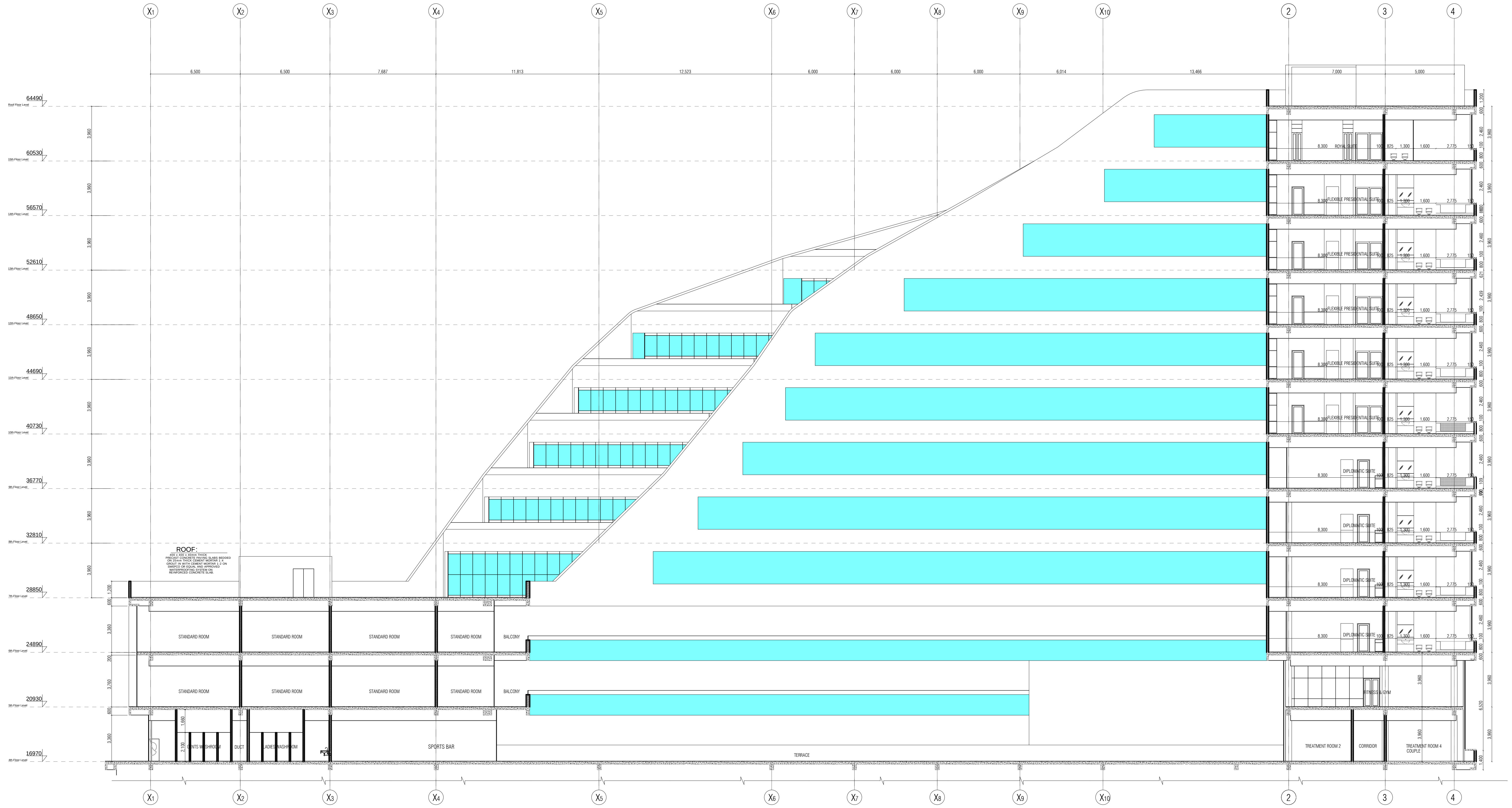
01 | HELIPAD CROSS SECTION
SCALE 1:50



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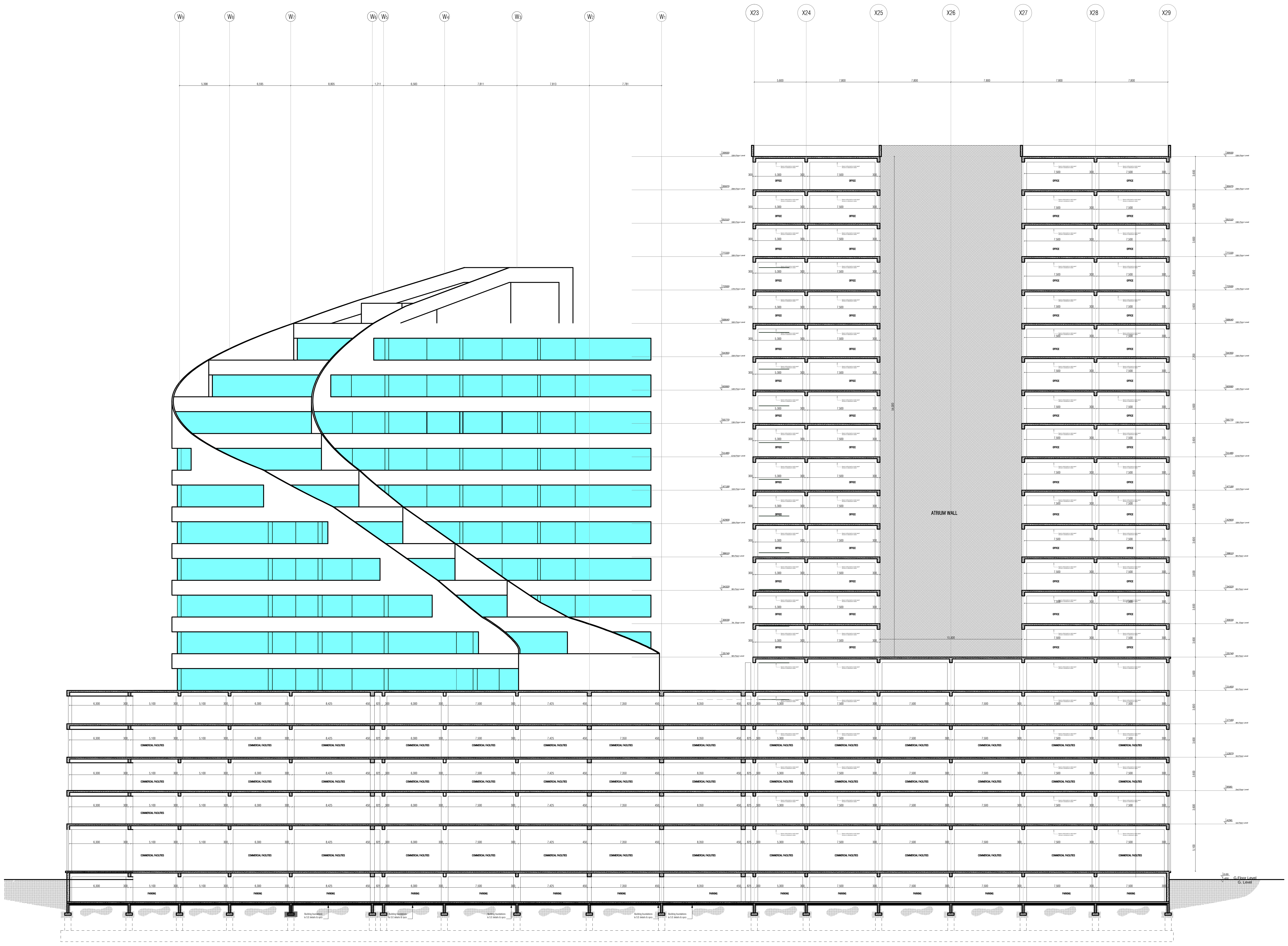
01 SECTION A-A

SCALE 1:50



ARCH PROPOSED MIXED USE BUILDING

01 SECTION H-H

SCALE 1:50

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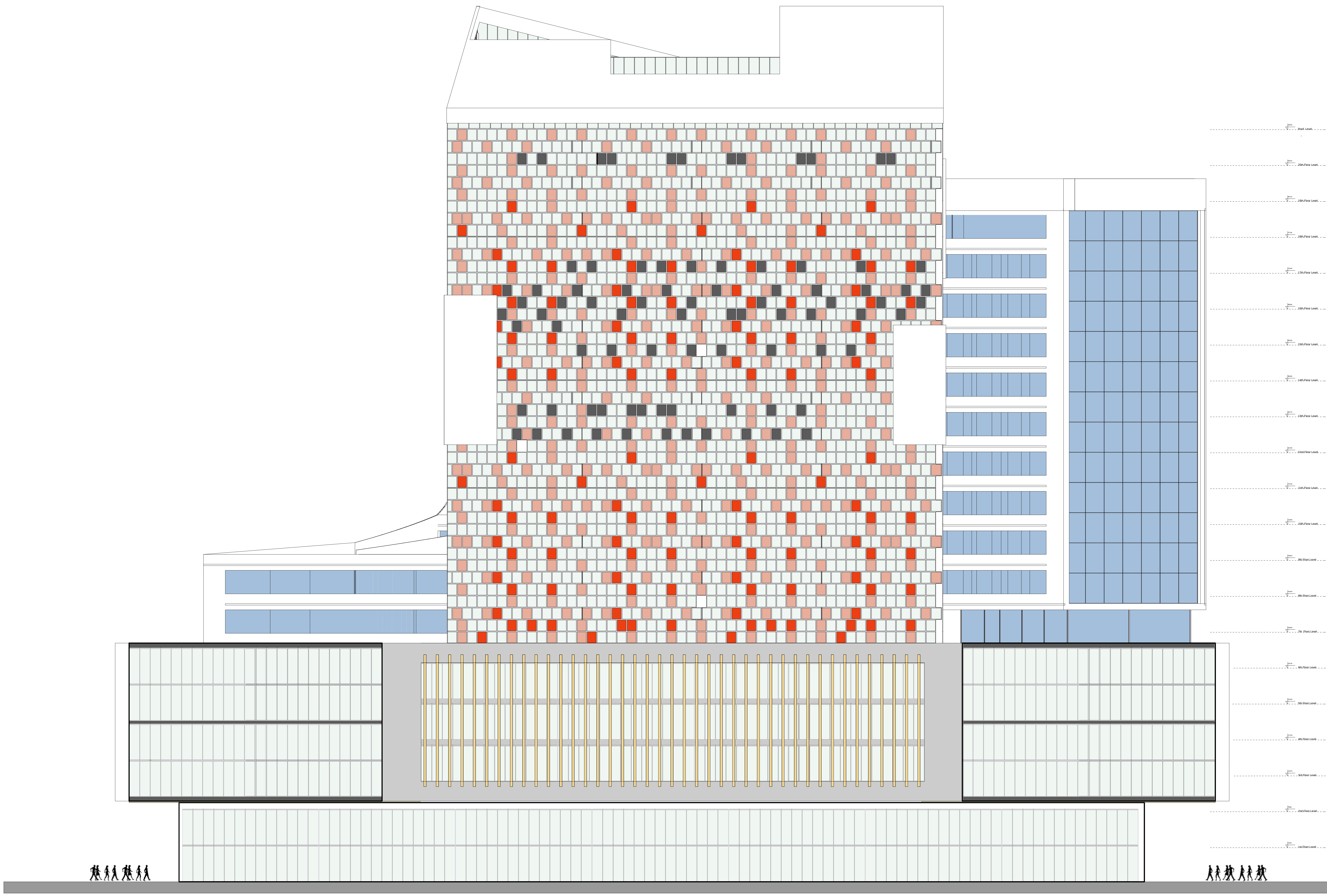

ARCH | PROPOSED MIXED USE BUILDING
01 | R.H.S ELEVATION
SCALE 1:200

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Scala:
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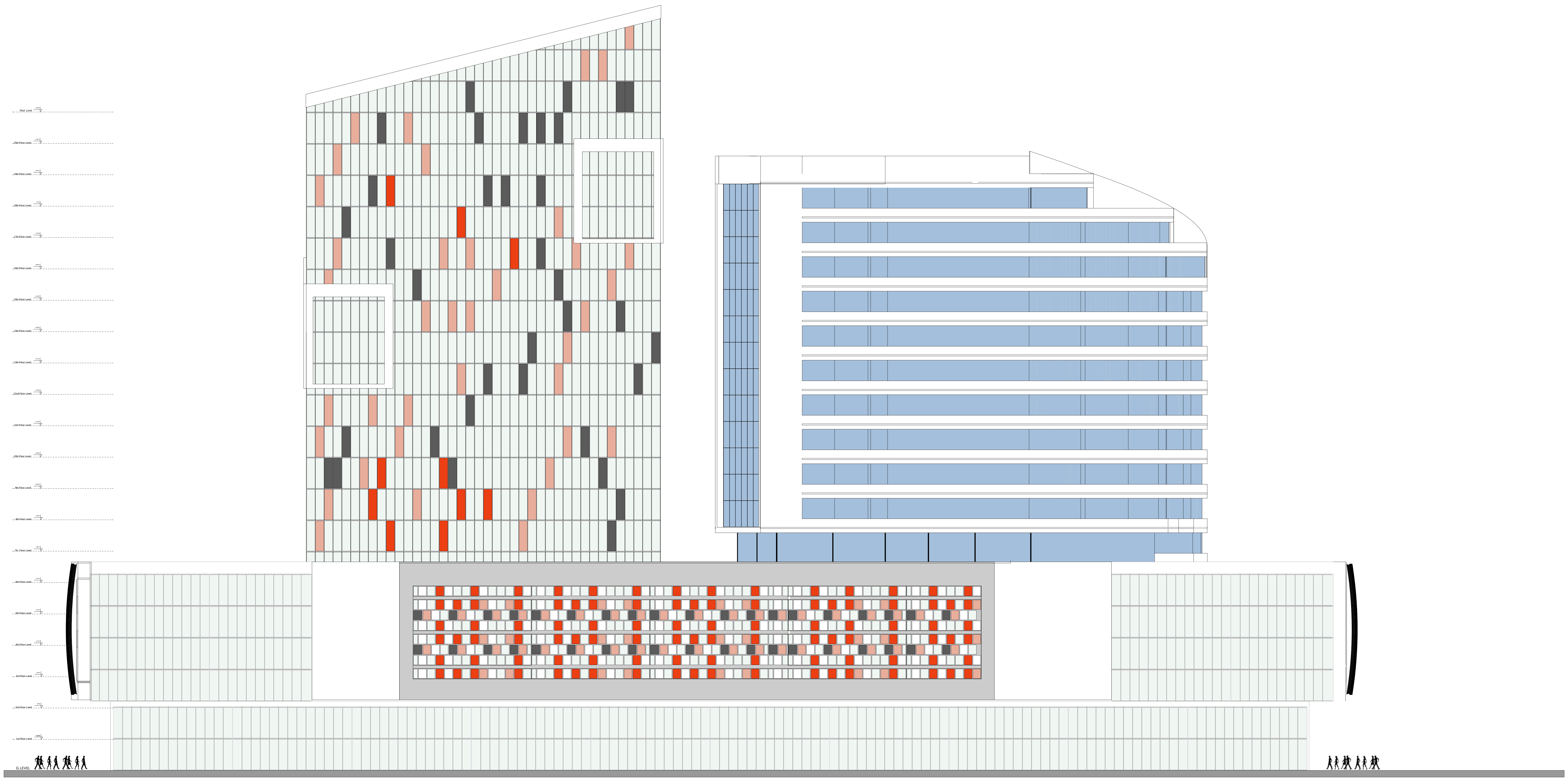
Titolo:
Stratigrafie



ARCH

01

PROPOSED MIXED USE BUILDING

REAR SIDE ELEVATION
SCALE 1:200

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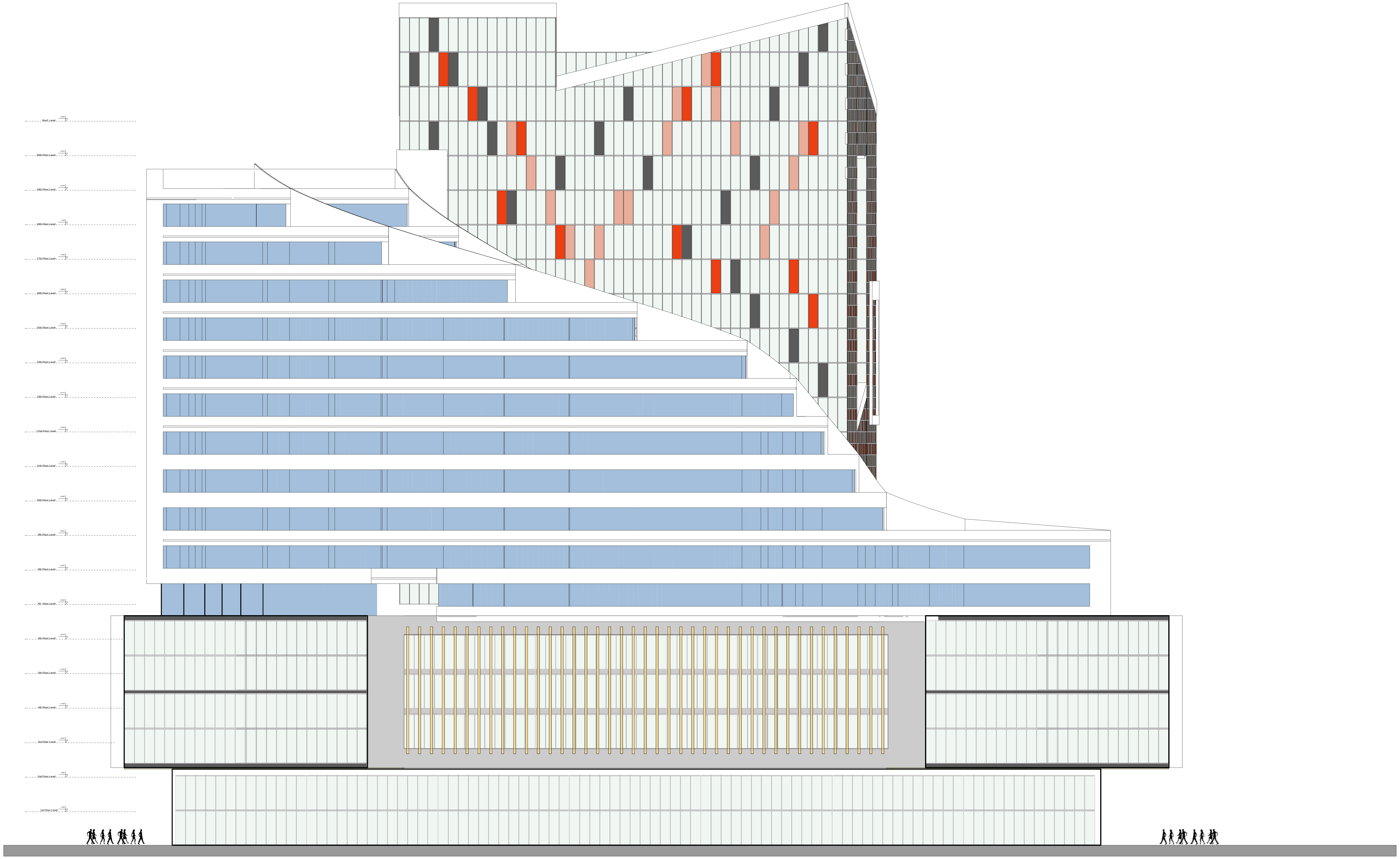

ARCH PROPOSED MIXED USE BUILDING

01 L.H.S ELEVATION
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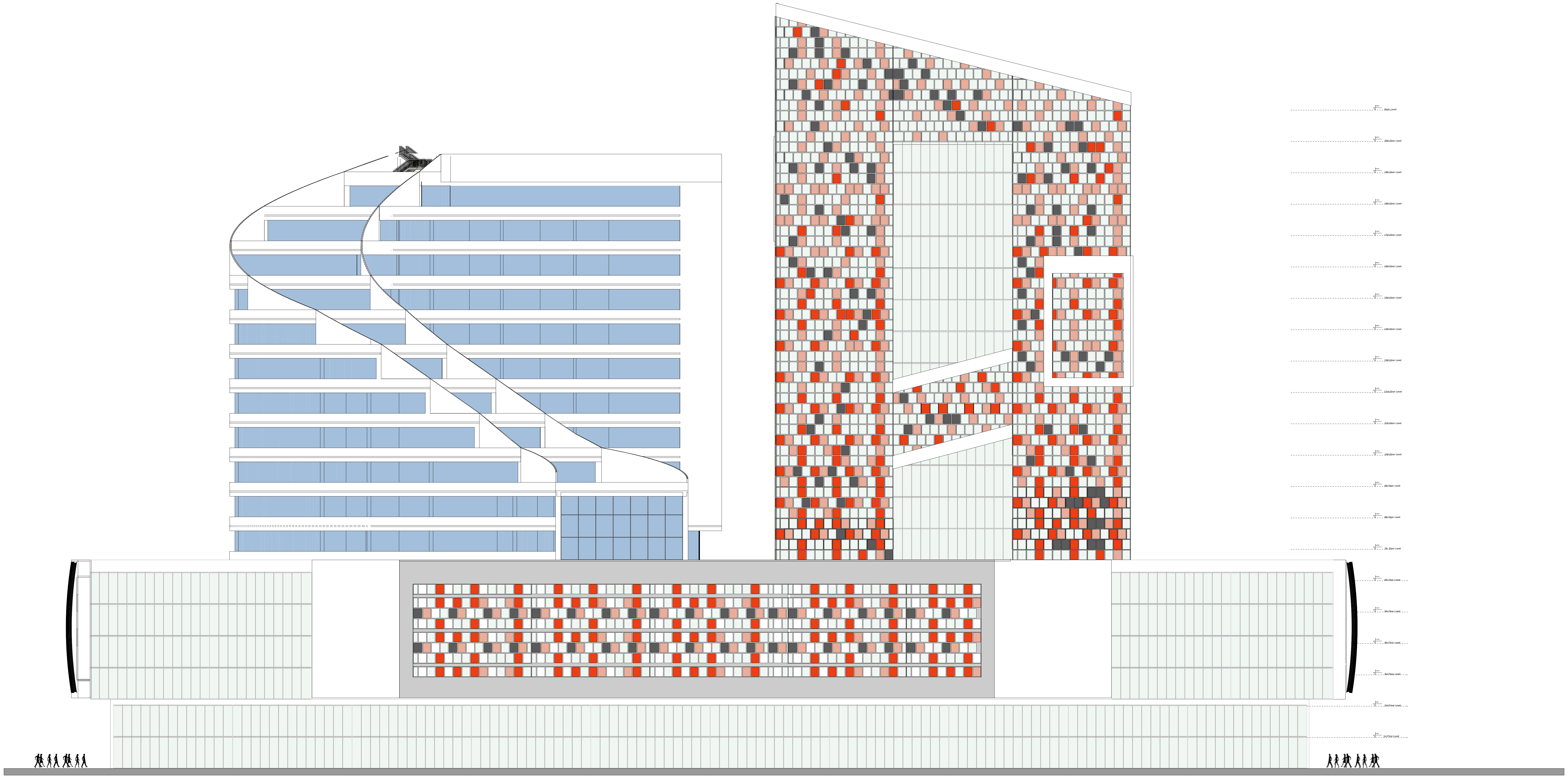

ARCH PROPOSED MIXED USE BUILDING

01 FRONT SIDE ELEVATION
SCALE 1:200

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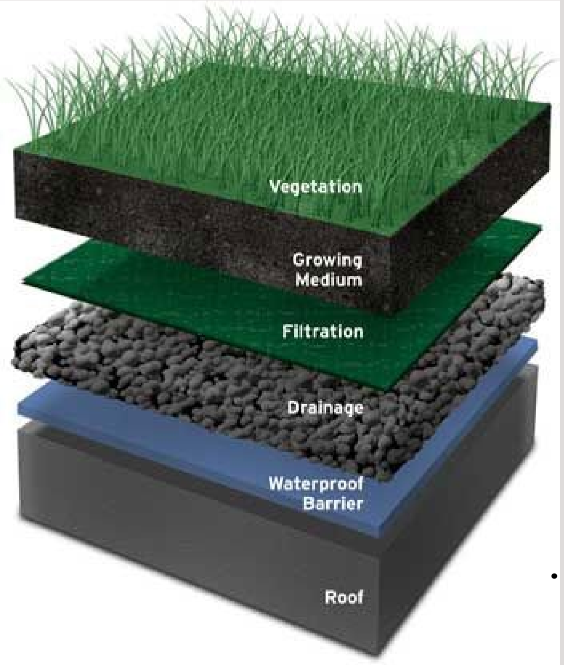
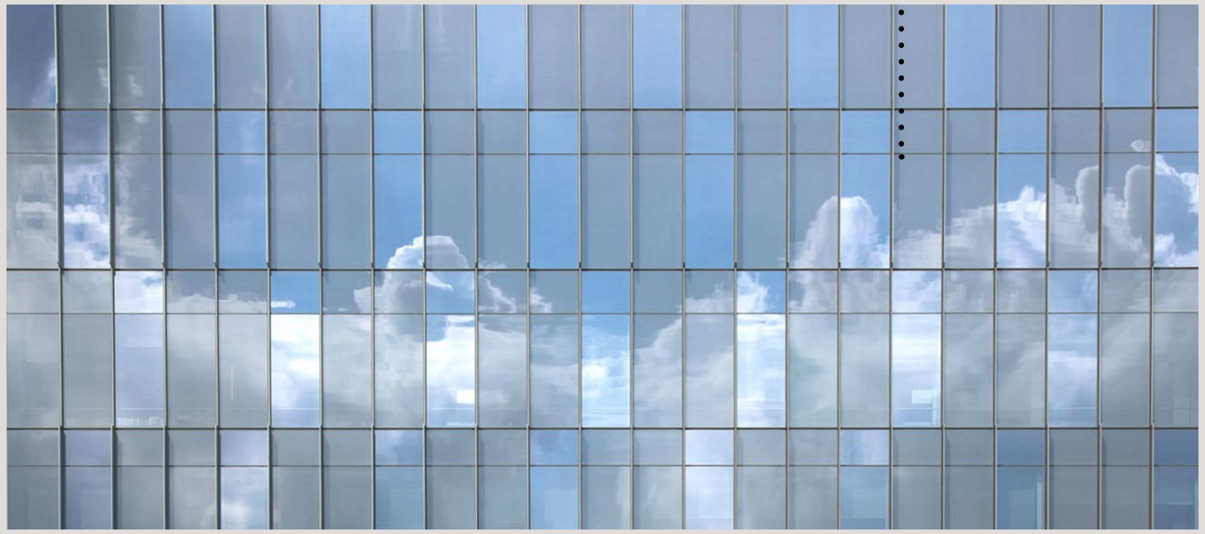
INTERGRATED TECHNOLOGIES



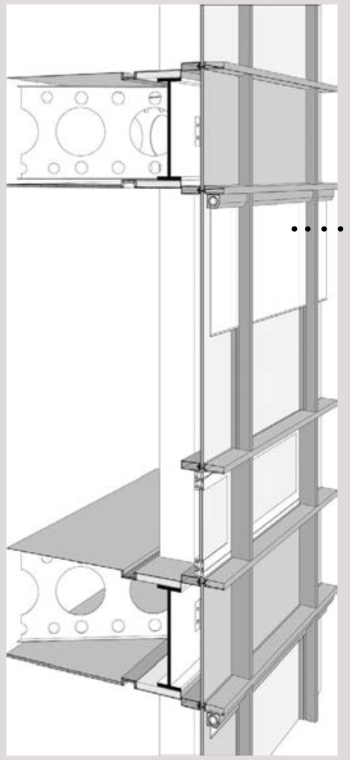
EXTENSIVE GREEN ROOF

INTENSIVE GREEN ROOF

INTERGRATED TECHNOLOGIES



STICK SYSTEM CURTAIN WALL



CURTAIN WALL-SECTION


DISPLAY


T 938 AFE


Fashion
Cafe

Conclusion and further studies

The thesis provides an analysis of application of Building Performance Simulation and Multi-Criteria Analysis as supporting tools in the choice of building envelope components during early-design stage. The proposed approaches help building project collaborators to compare multiple design solutions and eventually make decision using a performance-based approach. In total, the proposed methodologies analyse sustainability and technical performance, as well as project management methods of design solutions.

Expected final project performance as well as cost effectiveness are higher when the proposed tools are applied during the early design stage. At this stage, project collaborators have an opportunity to test the feasibility of proposed design solutions and anticipate different challenges that can be encountered later in the next stages of building life cycle. In this way, designers and engineers can either modify or improve their proposed design solutions early on.

Despite, these advantages, there are shortcomings associated with the application of proposed approaches especially in early design stage. At this stage, volatility of design ideas is so high, as ideas come and go so fast, important input information is either inaccurate or insufficient, and time is always a limited resource.

In this study, for example, input information for the simulations such as schedules were chosen from ASHRAE standard, while thermal and physical properties of layers of walls, roofs and floors were chosen from literature review. This can lead to inaccurate output results due to the fact that, ASHRAE standard for schedules do not reflect the behaviour of occupants in Tanzania due to cultural differences. Moreover, the input from literature review may not reflect the final performance of proposed solutions in Tanzanian context. The input properties should come from certified manufactures, in a specific context, in the case of Tanzania they are not sufficient if not non-existing at all.

The same concern goes for the proposed properties of window technology which were chosen from LBNL window software. The software contains database from American or international manufactures, which may not be the players in Tanzanian building industry.

Moreover, the proposed opaque wall solutions such as coconut fiber brick, corn insulation, bamboo cladding and micro-ventilated OSB wall system are still unpopular in Tanzanian building industry. However, it is the interest of this thesis, to show that these solutions are promising towards the future of energy-efficient and sustainable building practice in general. Further research should, therefore, be done in order to analyse the cost aspects, skills and technical feasibility of proposed solutions in Tanzanian building industry.

BPS output performance for this study are only limited to energy demands. However, in order to better understand the effectiveness of the proposed building envelope components such as shading devices, future studies can be concentrated on adding other output performance such as daylighting, visual and glare comfort, which are important aspects of indoor comfort.

The same goes for the input variables, whereby in this study, the concentration was put on building envelope components, specifically opaque wall constructive system, external horizontal shading devices and window size. Further research can therefore be done to compare the performance of other building envelope components such as glazing technologies, internal shading devices or external vertical shading devices, roof systems etc. Furthermore, future research can be used to compare the performances of other passive and active design solutions such as building forms and HVAC systems respectively.

In multi-criteria analysis, further studies can focus more on applying other sub-criteria. For example, in criterion 5 (CC5), future research can add visual comfort, air quality or acoustic performance in the assessment of performance of design solutions. In criterion 6 (CC6), future research can investigate other sub-criteria such as water and primary energy consumption, or emitted quantity of CO_2. However, one should note that, the assessment objectives depend on the requirement of a particular project. This means, one can even add other parameters as they see fit. Moreover, as already expressed the procedures in finding the limiting values of sustainability parameters will depend on local or international regulations guidelines. This make, the two criteria flexible and easily adaptable to different contexts.

Furthermore, for the last criterion (CC7), more research can be done on operations and end of service life cost assessment of proposed design solutions. By doing this, the overall global cost can be obtained, and the exact economic analysis can be more accurate.

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Annex A – Criteria definition

The following paragraphs present all criteria of multi-criteria analysis methodology under investigation as already demonstrated by (Contrada, 2019; Contrada et al, 2019).

CC1 - Simplicity of solution

It considers the technical aspects of design solutions during design and construction phases. In design phase, these aspects include the level of standardisation, modularity and regularity of building sub-systems such as structure and building envelope. In construction phase, it includes prefabrication level, number and kind of technical connections, and component production and assembly of building sub-systems.

The assessment of performance (level of simplicity of solution) is done in a *qualitative* manner. For example, a high note is given to a more standardised design solution. This means that, the more standardised the design solution, the simpler it is to build at the construction site and vice versa. Or the more prefabricated the solution is, the easier it will be to construct.

CC2 - Verifiability

This criterion considers the capability to verify, examine and control the project progress in design, construction and operation phases of building project. In design phase, verification can be done through commissioning protocols, physical models, BIM or simulations.

During construction phase, verification of buildings technical components such as façade or equipment can be done through onsite or laboratory tests. A verifiable project considers the possible tests that will verify the technical performance of proposed design solutions.

In operation stage, verification can be done by observing the possibility of accessing maintenance systems which should be considered during design stage.

The assessment of performance for this criterion is done in a *qualitative* manner. For example, a high note is given to a design solution which anticipate possible verification procedures in all building life cycle stages.

CC3 - Skills availability

This criterion considers availability of skills in design, construction and operation stages of a project. In design phase, this criterion observes tools applied for technical details specification and modelling of design solutions. For example, a high note is given to a design solution in which the technical details are exhaustively elaborated.

During construction phase, analysis is made on the available workforce and machines that are used during installations or execution of design solutions on site. A high note is given to a design solution which does not need very high level of expertise or a complicated and special equipment to execute.

In operation stage, emphasis is put on the level of information availability to the final end-users or occupants. A high note is given to a design solution which provide enough information to the end-users on how to operate a building component or system, for example, how to clean a façade or how to control indoor temperature by using installed devices. The assessment of performance for this criterion is also done in a *qualitative* manner.

CC4 - Simplicity to manage

This criterion assesses the levels in maintaining performance and control of technical solutions throughout building life cycle. In design stage, the criterion evaluates aspects such as durability of construction materials applied in a particular design solution. For example, a high note is given to a design solution whose materials are not easily destroyed by environmental conditions or weather patterns.

During construction stage, the criterion evaluates aspects such as transportation. For example, a high note is given to a design solution which doesn't involve complicated modes of transportation.

In operations, aspects such as end-user interaction is observed. Here, a high note is given to a design solution which is easy for building occupants or facility managers to operate.

This criterion can be useful when dealing with high-tech building envelope components such as dynamic facades or HVAC control systems. The assessment of performance for this criterion is also done in a *qualitative* manner.

CC5 - Compliance with user-centric requirements

This criterion evaluates the capacity of design solution to meet the required performance objectives that will ensure acceptable levels of indoor environmental comfort for occupants. Therefore, this criterion evaluates the performance of design solutions in operation stage, however, the design decisions which results in those performances are made in design stage. As illustrated by F. Contrada (2019), indoor environmental comfort conditions can be observed by checking the following aspects:

- Indoor thermal comfort
- Visual comfort
- Air quality
- Acoustic comfort

In each aspect, there is an indicator or a set of indicators which are defined by either local or international standards, and environmental certifications. These guidelines define the values of different indicators that should be respected according to different building types and environmental contexts. Therefore, by calculating the values of these indicators and compare them with the limiting values defined by guidelines, one can assess the performance of design solutions using CC5.

For further elaboration on how to assess the indoor environmental comfort performance by using some of the indicators above, refer to *Francesca Contrada. (2019). L'apport de la constructibilité au pré-design. Evaluation et support au choix des solutions techniques. PhD Thesis in Science de l'Ingénieur Université Paris Est.*

CC6 - Sustainability

This criterion is related to environmental sustainability performance of design solutions. The assessment is focused on resource consumption (water, soil and energy) and environmental impact (emission of CO_2). This means, the assessment involves the calculation of volume of water used [m^3], surface of soil used for the construction [m^2], primary energy consumption [kWh/m^2. yr], and quantity of emissions of CO_2 [kgCO2eq].

The assessment is done by comparing the calculated values of environmental parameters of design solutions to limit values defined by authorities, guidelines or project's environmental performance objectives. As a result, the procedures in calculating these environmental parameters may differ from one context to another. For example, as expressed by F Contrada et al. (2019), CO_2 emissions of proposed design solutions may be assessed using Life Cycle Assessment tools or simplified methods via existing environmental data defined by manufactures for construction components.

For further elaboration on how to assess the environmental sustainability performance by using the list of indicators above, refer to *Francesca Contrada. (2019). L'apport de la constructibilité au pré-design. Evaluation et support au choix des solutions techniques. PhD Thesis in Science de l'Ingénieur Université Paris Est.*

CC7 - Cost efficiency

This criterion assesses the global cost of the proposed design solutions. Normally, during construction project, the cost analysis involves only the initial investment cost of proposed design solutions. However, there are other costs related to building operations such as energy consumption (gas, electricity), and those related to end of service life such as costs of waste disposal or recycling of materials. Therefore, it is of paramount importance to include these costs, during economic assessment of proposed design solutions. Currently, methodology such as Life Cycle Cost Analysis (LCCA) can be used to assess the overall cost of a project for the entire life cycle.

As expressed by F. Contrada (2019), a standard NF EN 15459-2017 proposes a method to evaluate a global cost of proposed design solutions. This method is valid for a building with service life of about 30 to 50 years. According to this method, the global cost can be calculated as shown in the following equation:

$$CG = CO_{inv} + \sum_{j} \left[\sum_{i}^{t_{TC}} \left(CO_{a(i)}(j) * \left(1 + RAT_{xx(i)}(j)\right) + CO_{co2(i)}(j) \right) * D\_f(i) + CO_{disp(TLS)}(j) - VAL_{ft_{TC}}(j) \right]$$

where:

CG = global cost

$COinv$ = investment cost

$COa(i)(j)$ = operation cost in a year i for a component or service j

$RATxx(i)(j)$ = price inflation in a year i for a component or service j, (this can be related to cost of energy consumption, products, building systems, services, installations, maintenance etc.)

$CO_{CO2(i)(j)}$ = cost of emission of CO_2 in a year i related to energy consumption j

$D\_f(i)$ = discount rate in a year i

$CO_{disp(TLS)}(j)$= cost at the end of service life related to deconstruction, transportation and recycling, in the end year TLS of a component j, or of a building reported in the first year T_0

$VALftTC(j)$= residual value of a component j in a year TC, at the end of a period of calculation (and reported in the first year T_0)

The formula can be simplified as follows:

Global cost = Investment cost + Operation cost + End of service life cost

Investment cost is related to all costs until delivery of a project. It includes costs related to design, procurement, execution and professional fees.

Operation cost is related to all costs during operations phase of a project. It includes costs related to maintenance and replacement costs.

Operation cost = maintenance cost + replacement costs

Maintenance cost	=	maintenance insurance cost	+	energy consumption costs (gas, electricity)	+	related tax costs

Replacement cost relates to all costs in a period of a year, applied for replacing all or part of building systems.

End of service life cost involves deconstruction, transportation and recycling of waste materials at the end of service life of a project

Annex B – Example of aggregation and evaluation of criteria

For *all qualitative criteria CC1, CC2, CC3,CC4*, a final normalised value is calculated according to the following steps:

i. A note between 1 and 6 is first assigned to each qualitative sub-criteria based on chosen indicator
ii. For each sub-criterion, an intensity of importance is assigned through AHP
iii. Aggregation
iv. Normalisation of a criteria

As an example, the first criteria CC1 is hereby considered:

Firstly, it is assumed that the notes were applied as follows for each sub-criteria

CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
6	5	4	6	4	5	6	6

Secondly, by using AHP, a relationship is established among sub-criteria by assigning the intensity of importance, hence establishing the intensity matrix below:

	CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
CC1.1	1	5	1	3	3	3	3	1
CC1.2	1/5	1	1/3	1/3	1/3	1/3	1/5	1/3
CC1.3	1	3	1	5	3	3	3	1
CC1.4	1/3	3	1/5	1	1/3	1/3	1/3	1
CC1.5	1/3	3	1/3	3	1	1	3	1/3
CC1.6	1/3	3	1/3	3	1	1	3	1
CC1.7	1/3	5	1/3	3	1/3	1/3	1	1
CC1.8	1	3	1	1	3	1	1	1

0.221	0.192	0.221	0.155	0.250	0.300	0.206	0.150
0.044	0.038	0.074	0.017	0.028	0.033	0.014	0.050
0.221	0.115	0.221	0.259	0.250	0.300	0.206	0.150
0.074	0.115	0.044	0.052	0.028	0.033	0.023	0.150
0.074	0.115	0.074	0.155	0.083	0.100	0.206	0.050
0.074	0.115	0.074	0.155	0.083	0.100	0.206	0.150
0.074	0.192	0.074	0.155	0.028	0.033	0.069	0.150
0.221	0.115	0.221	0.052	0.250	0.100	0.069	0.150

The vector of the weighting coefficients W = {$w_1, \cdots, w_5$} is calculated by first dividing each intensity of importance in the matrix above by their sum in the same colon (*as shown by yellow colour*), and then calculating an average by dividing the sum of obtained value in each row (*as shown by blue colour*) and the total number of sub-criteria (in this case its 8).

W_1	0.21
W_2	0.04
W_3	0.22
W_4	0.06
W_5	0.11
W_6	0.12
W_7	0.10
W_8	0.15

As already noted, if it is assumed that the notes for each sub criteria were applied as shown below

N_1	N_2	N_3	N_4	N_5	N_6	N_7	N_8
6	5	4	6	4	5	6	6

Then, a final normalised value of criterion CC1 can be calculated as follows:

$$CC1 = \sum_{i=1}^{8} w_i \left[\frac{N_i}{N}\right] = 0,86$$

where;

N is the maximum note that can be assigned, in this case its 6.
N_i is the note for sub-criterion i
W_i is vector of the weighting coefficients of sub-criterion i, evaluated through AHP

For the quantitative criteria CC5, CC6, CC7, the aggregation and normalisation of sub-criteria is done as follows:

$$CCk = \sum_{i=1}^{n} w_i \cdot CCk_i$$

where:
n = number of sub-criteria
wi = vector of the weighting coefficients of sub-criterion i, evaluated through AHP
$CCki$, = value obtained from calculated ratios

Annex C – Assigning the intensity of importance for sub-criteria

The following paragraphs explain how the intensity of importance is assigned to sub-criteria of criterion CC1, CC2, CC3 and CC4. Since there is only one sub-criterion for each of criterion CC5, CC6 and CC7, the order of importance is therefore just 1.

For CC1 - Simplicity of solution, the intensity of importance is assigned to 8 sub-criteria:

- CC1.1 Level of standardization of vertical structure
- CC1.2 Level of standardization of horizontal structure
- CC1.3 Level of standardization of facades
- CC1.5 Organization of technical equipment
- CC1.6 Type of production technology
- CC1.7 Construction type
- CC1.8 Types of technical interfaces

A shown by two yellow rows in the figure below, a strong importance is given to the level of standardization of vertical structure (CC1.1) and façade (CC1.3). This is due to the fact that, both sub-criteria optimise the execution of technical building components at the construction site. Organisation of technical equipment (CC1.5) in terms of vertical ducts continuity is moderately important compared to the type of construction (CC1.7). The vertical continuity of ducts optimise the use of internal spaces and reduce interferences with other building sub-systems.

	CC1.1	CC1.2	CC1.3	CC1.4	CC1.5	CC1.6	CC1.7	CC1.8
CC1.1	1	5	1	3	3	3	3	1
CC1.2	1/5	1	1/3	1/3	1/3	1/3	1/5	1/3
CC1.3	1	3	1	5	3	3	3	1
CC1.4	1/3	3	1/5	1	1/3	1/3	1/3	1
CC1.5	1/3	3	1/3	3	1	1	3	1/3
CC1.6	1/3	3	1/3	3	1	1	3	1
CC1.7	1/3	5	1/3	3	1/3	1/3	1	1
CC1.8	1	3	1	1	3	1	1	1

Table 52 Intensity of importance, matrix of intensity for criterion CC1

For CC2 - Verifiability, the intensity of importance is assigned to 4 sub-criteria:

- CC2.1 Tools and measures to support the design
- CC2.2 Risk consideration and implementation of register of problem
- CC2.3 Need for testing
- CC2.4 Ease of access to verification (during operational phase)

The moderate level of importance is given to the first sub-criterion CC2.1, as shown in yellow colour in the figure below, in comparison to the other sub-criteria. This is due to the fact that, if design tools such as BIM are used early in design process, and other risk assessment procedures are undertaken, the risk of having challenges at later stages of design are hugely reduced.

	CC2.1	CC2.2	CC2.3	CC2.4
CC2.1	1	3	3	3
CC2.2	1/3	1	3	1
CC2.3	1/3	1/3	1	1
CC2.4	1/3	1	1	1

Table 53 Intensity of importance, matrix of intensity for criterion CC2

For CC3 - Skills availability, the intensity of importance is assigned to 4 sub-criteria:

- CC3.1 Development of technical details
- CC3.2 Modelling of elements
- CC3.3 Use of a specialized workforce and special equipment (site)
- CC3.4 Instruction planned for end-users

Strong intensity of importance is given to sub-criteria CC3.1, as shown in yellow colour in the figure below, because elaboration on technical detailing is highly important during execution at the construction site. Moreover, sub-criterion CC3.2 is also moderately important over sub-criterion CC3.3 because, modelling expertise is critical in achieving good design and eventually better execution at the construction site.

	CC3.1	CC3.2	CC3.3	CC3.4
CC3.1	1	5	5	5
CC3.2	1/5	1	1	3
CC3.3	1/5	1	1	1
CC3.4	1/5	1/3	1	1

Table 54 Intensity of importance, matrix of intensity for criterion CC3

For CC4 – Simplicity to manage, the intensity of importance is assigned to 7 sub-criteria:

- CC4.1 Systems durability
- CC4.2 Transport
- CC4.3 Assembly sequence
- CC4.4 Regulation and control technic
- CC4.5 Interaction with end-users
- CC4.6 Maintenance
- CC4.7 End of service life

As highlighted by yellow colour in the figure below, the application of durable materials (CC4.1), means of transport (CC4.2) and assembly sequence (CC4.3) are moderately important over CC4 and CC5. This is because, application of durable materials optimises performance while reducing the need for frequently maintenance. Transportation and assembly sequence reduces challenges at the construction site.

	CC4.1	CC4.2	CC4.3	CC4.4	CC4.5	CC4.6	CC4.7
CC4.1	1	1	1	3	3	1	3
CC4.2	1	1	1	3	3	1	1
CC4.3	1	1	1	3	3	1	1
CC4.4	1/3	1/3	1/3	1	1	1	1
CC4.5	1/3	1/3	1/3	1	1	1	1
CC4.6	1	1	1	1	1	1	1
CC4.7	1/3	1	1	1	1	1	1

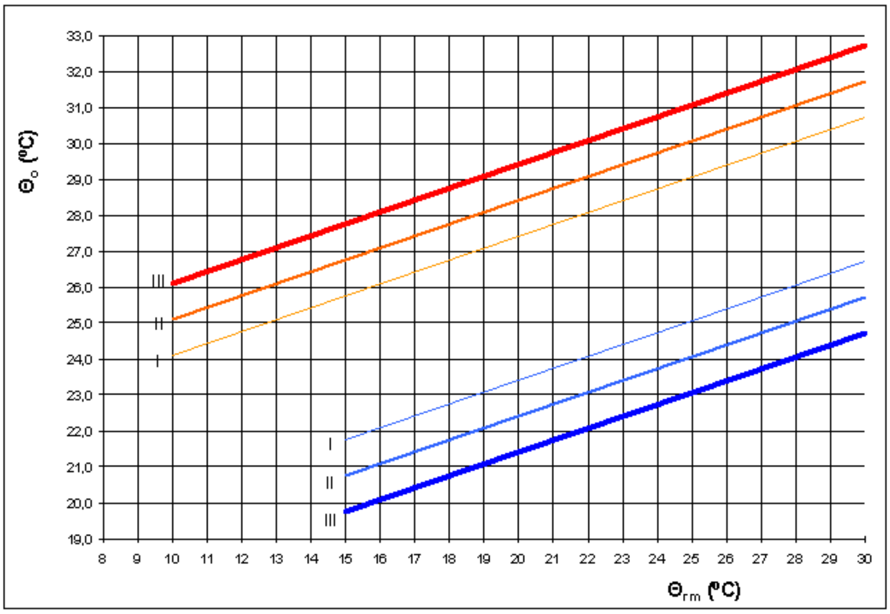
Table 55 Intensity of importance, matrix of intensity for criterion CC4

Annex D – Adaptive comfort model

A standard (EN 15251) recommends that the design values of the indoor operative temperature for new buildings and renovations should be 20°C minimum for heating (winter season) and 26°C maximum for cooling (summer season). These temperature limits are valid for buildings without mechanical cooling systems used for human occupancy with mainly sedentary activities and dwelling, where there is easy access to operable windows and occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions. The reason why it is called adaptive comfort model.

Overall, this means that when the indoor temperature is between 20°C and 26°C, occupants will feel thermal comfort by either opening windows or adapting their cloth based on how they feel. However, when the indoor temperature is above 26°C, a cooling system should be turned on to reduce the temperature or when the indoor temperature is less than 20°C, a heating system should be turned on to raise the temperature. When the mechanical cooling or heating is turned on, adaptive comfort model with these temperature ranges cannot be applied to measure indoor thermal comfort.

The chart below shows adaptive comfort model as described in EN 15251



Adaptative comfort chart, source : EN 15251

The x-axis represents the values of indoor operative temperatures, Θ [°C]
The y-axis represents exponentially weighted running mean of the daily outdoor temperature, Θ_{rm} [°C]
Category I represents high level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons
Category II represents normal level of expectation and should be used for new buildings and renovations
Category III represents an acceptable, moderate level of expectation and may be used for existing buildings

In this thesis, the building considered is in category II

For the category II, the equations which representing the lines are:

$$\text{upper limit: } \Theta_{i,\,max} = 0{,}33\ \Theta_{rm} + 18{,}8 + 3$$
$$\text{lower limit: } \Theta_{i,\,min} = 0{,}33\ \Theta_{rm} + 18{,}8 - 3$$

where Θ_i represents limit value of indoor operative temperature, oC
Θ_{rm} represents running mean outdoor temperature, oC

These limits apply when $10 < \Theta_{rm} < 30$ oC for upper limit and $15 < \Theta_{rm} < 30$ oC for lower limit.

Appendix E–A table of surface areas for CC1 calculations

$\Sigma S_{sv,pref}$	Total surface area on plan of prefabricated elements of the vertical structure (columns and/or shear walls, retaining walls if any, only if prefabricated)(m^2)	0
$S_{sv,tot}$	Total surface area on plan of all elements of the vertical structure (columns and/or shear walls, retaining walls non prefabricated and prefabricated if any) (m^2)	381
$\Sigma S_{sh,pref}$	Total surface area on plan of floor slab occupied by prefabricated elements only if any (m^2)	0
$S_{sh,tot}$	Total surface area on plan of floor slab (m^2)	12153
$\Sigma S_{f,i}$	Total surface area of facade of the same type (m^2)	6086
$\Sigma S_{f,tot}$	Total surface area of all facades (m2)	6086
ΣNb_s	Total number of windows of the same size	250
Nb_{tot}	Total number of all windows	250
ΣNbs/Nbtot	The same for all wall systems	1
S_1	Total Site Area (m^2)	10000
S_2	Total Built Area (m^2)	8490