TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

A PARAMETRIC STUDY USING A SIMPLIFIED LCA METHODOLOGY TO ASSESS THE INFLUENCE OF BUILDING PARAMETERS ON CARBON FOOTPRINT IN THE EARLY STAGES OF DESIGN

PARAMEETRILINE UURING, KASUTADES LIHTSUSTATUD OLELUSRINGI HINDAMISE METOODIKAT HOONE PARAMEETRITE MÕJUST SÜSINIKU JALAJÄLJELE DISAINI VARAJASTES STAADIUMITES

MASTER THESIS

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(*On the reverse side of title page*)

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THESIS TASK

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Thesis topic:

(in English) *A PARAMETRIC STUDY USING A SIMPLIFIED LCA METHODOLOGY TO ASSESS THE INFLUENCE OF BUILDING PARAMETERS ON CARBON FOOTPRINT IN THE EARLY STAGES OF DESIGN*

(in Estonian) *PARAMEETRILINE UURING, KASUTADES LIHTSUSTATUD OLELUSRINGI HINDAMISE METOODIKAT HOONE PARAMEETRITE MÕJUST SÜSINIKU JALAJÄLJELE DISAINI VARAJASTES STAADIUMITES*

Thesis main objectives:

1. To investigate the impact of different building morphologies on both carbon footprint and energy performance
2. To present solutions with regard to building morphology and material selection for achieving optimal carbon performance during the initial phase of the design process
3. To provide architects and engineers with ample information concerning the ultimate consequences of their choices concerning building morphology and material selection during the initial phases of design

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Reviewing pertinent literature and regulations and definition of research gap	30/01/2023
2.	Conducting a study on different approaches to parametric design in similar studies	15/02/2023
3.	Planning various parts of the parametric workflow	30/02/2023
4.	Performing a statistical analysis on buildings in Tallinn	10/03/2023
5.	Development of the parametric building model	30/03/2023
6.	Development of LCA parametric workflow	10/04/2023
7.	Development of energy assessment parametric workflow	20/04/2023

8.	Running all the necessary simulations	30/04/2023
9.	Writing the thesis manuscript	20/05/2023

Language: English **Deadline for submission of thesis:** “29” May 2023.a

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PREFACE

The present master thesis represents the culmination of an extensive research and exploration effort in the field of sustainable building design, with a particular focus on the impact of building parameters on carbon footprint during the early stages of design. The author initiated this topic in collaboration with distinguished supervisors and consultants, who provided invaluable guidance and support throughout the entire thesis process.

The main body of work for this research was carried out at Tallinn University of Technology, where the author had the privilege of working with Francesco De Luca, PhD, as the Principal Supervisor, and Viktoria Voronova, PhD, as the Co-Supervisor. The author would like to express his deepest gratitude to both supervisors for their exceptional expertise, unwavering support, and constant availability. Their direction was pivotal in defining the path and achievements of this analysis. The author acknowledges their invaluable contributions and insightful feedback, which significantly enhanced the quality and depth of this research.

The author also wishes to express gratitude to Kadri-Ann Kertsmik for her consultancy and valuable insights, which significantly contributed to the data collection and analysis process. Furthermore, the author extends their appreciation to Professor Kimmo Lylykangas, Professor Jarek Kurnitski, Martin Thalfeldt, PhD, and Simo Ilomets, PhD, for their helpful consultations and guidance, which enriched the research findings.

The author wishes to extend profound gratitude to Professor Karin Pachel, the manager of Environmental Engineering and Management program, for her invaluable guidance and for providing the opportunity to work on this brilliant thesis topic. Her support and encouragement were vital in the completion of this research.

The study aims to address the pressing environmental challenges posed by building-related carbon emissions. The research explores the intricate process of Life Cycle Assessment and its application in assessing embodied carbon and minimizing operational carbon through parametric design approaches. By eliminating stages with minimal impact on energy performance and carbon footprint, a streamlined LCA procedure was employed to examine the initial impacts of architects' choices on building carbon footprints. Given that buildings account for a significant portion of global energy usage and greenhouse gas emissions, it is crucial to comprehend the relationship between building parameters and carbon footprint in promoting sustainable design practices. This study investigates the most efficient architectural forms in terms of carbon footprint, explores the balance between embodied and operational carbon, and examines the effect of neighboring structures on carbon footprint.

Keywords: Parametric design, Life Cycle Assessment, Early-stage design, Carbon footprint, Building Parameters, Master Thesis

List of abbreviations and symbols

AAC	Autoclaved Aerated Concrete
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BIM	Building Information Modeling
BIPV	Building Integrated Photovoltaic
BREEAM	Building Research Establishment's Environmental Assessment Method
C30/37	Concrete with a characteristic compressive strength of 30 MPa after 28 days of curing
C40/45	Concrete with a characteristic compressive strength of 40 MPa after 28 days of curing
CF	Carbon Footprint
CLT	Cross-Laminated Timber
Cluster	Higher-level components created by grouping nodes together, enhancing organization and reusability in Grasshopper designs
Distortion R'W	An extension of the RW value that considers the effect of flanking transmission
DSS	Decision Support System
EC	Embodied Carbon
EED	Energy Efficiency Directive
EIA	Environmental Impact Assessment
Env/Vol	Envelope to Volume Ratio
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declarations
GFA	Gross Floor Area
HVAC	Heating, Ventilation, Air Conditioning
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LEED	Leadership in Energy and Environmental Design
Lux	unit of measurement for illuminance which is the amount of luminous flux (light) received per unit area
LWR	Length to Width Ratio
met	Metabolic equivalents (METs) which are used to express the energy expenditure of physical activities in relation to the resting metabolic rate
N.F.	Number of Floors
Node	Individual components that perform specific operations within Grasshopper
nZEB	Nearly Zero Energy Buildings
OC	Operational Carbon
P.R.	Primary Rectangle
RC	Reinforced Concrete

RW Value Sound Reduction Index

Workflow The sequence of steps or operations that you design and execute to achieve a specific outcome or result in Grasshopper

WWR Window to Wall Ratio

1. INTRODUCTION

Environmental issues are delineated as the circumstances under which human activity engenders the destruction of the fundamental ecological function of the ecosystem by collapsing its balance and regulations [1]. The same reference indicates that global-scale depredations, cataclysms, and deprivations are the repercussions of this tremendous, unprecedented incursion of humans. The flora and fauna have endured widespread misery. On a regular basis, new issues emerge, causing immense harm to the environment. Kumar et al. stated that an increase in greenhouse gas emissions, deforestation, production of waste, and overpopulation has caused the phenomenon of Climate Change, which is considered to be at the forefront of all environmental issues [2]. They also mentioned, in 2018, the Environmental Protection Agency of the United States recorded the release of 6,677 million metric tons of CO_2-equivalent of total greenhouse gases, with carbon dioxide accounting for more than 80% of the total emissions. In the list of emissions, methane and nitrous oxide placed second (10%) and third (7%), respectively. In addition, the global warming induced by greenhouse gases may be irreversible for millennia. Many existential dangers have emerged as a result of climate change, including an increase in global temperatures, the melting of glaciers and polar ice caps, an increase in sea level, the loss of biodiversity, catastrophic weather events, and the breakout of unfathomable diseases [2]. Amidst all human activities leading to the aforementioned calamity, buildings are to blame for approximately 27% of the world's energy consumption and around one-third of global greenhouse gas emissions which were found to be attributed mainly to building operations [3]. Furthermore, the same reference declares that, in 2021, buildings accounted for 30% of the world's ultimate energy consumption, with 8% of this energy consumption being directly emitted from buildings and 19% being indirectly emitted from the generation of electricity and heat utilized in buildings. Following a decline in the year 2020 due to restrictions imposed by the COVID-19 pandemic, there was a subsequent increase in both energy consumption and emissions, surpassing the levels recorded in 2019 [3]. They also mentioned that the trend towards decarbonization in the power industry has led to an increase in the implementation of efficient and renewable energy technologies in buildings and this has resulted in the development of more comprehensive and rigorous building energy codes and the establishment of minimum performance requirements. However, there is a pressing need for accelerated transformation in the buildings sector to align with the Net Zero Emissions by 2050 Scenario [3]. Achieving the requisite benchmarks, which specifically entails ensuring that all recently erected buildings and one fifth of the existing building inventory are equipped with zero-carbon readiness by 2030, would require an enormous effort throughout the upcoming decade [3].

Having comprehended the sheer quantity of energy consumption due to the operation of buildings since the 1970s oil crisis and the subsequent surge in the cost of energy carriers, authorities moved towards imposing constraints on the energy demand of buildings which have gradually grown more restrictive throughout the past decades [4]. Instances of reformative measures include, but are not limited to, thick insulation, thermal-insulated glazing, and mechanical ventilation, all of which entail consuming energy and resources for either their original manufacture or end-of-life disposal. This prompts the basic query on the legitimacy of the adopted approach: whether the redeeming features of this approach, particularly reduction in consumption, exceeds the required amount of resources for their manufacture. The query, the answer of which lies in the scope of Life Cycle Assessment [4].

1.1. Sustainable Built Environment

The term "sustainable built environment" pertains to the process of designing and constructing buildings whose construction and operation bring about a reduced ecological footprint while enhancing the physical and mental health of those who occupy them [5]. The design of sustainable buildings aims to create a built environment that, alongside minimizing its ecological footprint, fosters social cohesion and meets economic objectives [6]. The integration of sustainable features in the design, construction, and operation of buildings is a viable approach to achieving sustainability in the built environment. The sustainable attributes encompass energy efficiency, water preservation, utilization of renewable resources, and minimization of waste and pollution [7]. According to Kok et al. (2011), the initial stages of building development, including design and preconstruction, represent a pivotal juncture for determining the sustainability characteristics of a structure [8].

The prevalence of sustainable practices in the built environment is increasing as the market for green buildings expands. This trend is evidenced by recent developments [7]. The principles of green construction align with the methodological foundation for the development of smart cities and buildings. They advocate for the implementation of environmental technologies and ecological design, as well as the adoption of innovative approaches to promote sustainable development in the construction industry [9]. The implementation of a net-zero approach in the design and sustainability management of buildings can significantly mitigate the impacts on the building sector [10]. Numerous research studies have corroborated that the expenses associated with constructing green buildings exceed those of conventional buildings. However, it is noteworthy that the construction of a green-certified building can be economically advantageous if the objectives of sustainable design and the financial plan of the building are established during the design phase [11].

Ragheb et al. (2016) [12] define Green architecture, often known as green design, as an avenue of design that strives to alleviate the negative impacts of construction on both human health and the natural environment. Their study declares that the "green" architect or designer seeks to protect the environment, including the air, the water, and the land, by using environmentally friendly architectural materials and methods of construction. They enunciated that Green Architecture entails the following measures in order to ensure its defined goals:

- Efficiency in heating, cooling, and ventilation systems
- Efficiency in electricity
- Water-preserving irrigation systems
- Optimization of the landscape for augmentation of passive solar energy
- Minimization of harmful impacts on the natural environment
- Utilization of alternative energy sources (i.e., solar, wind, etc.)
- Employment of local construction materials
- Adaptive reuse of aging structures
- Considering the use of repurposed architectural remnants
- Coherent usage of space

The ultimate goal of architects is to implement as many aforesaid measures as possible in their design stage.

1.2. The challenge of Net-zero buildings

A feasible approach for mitigating the environmental effect of the construction industry is to use net-zero buildings [13]. A net-zero building system constitutes a system that generates all of the energy and water it needs throughout the course of its life [10]. Reducing energy demand by implementing efficiency measures and using renewable energy sources in order to create a net-zero energy building [14]. Net-zero energy buildings are those that can provide all of their energy needs from affordable, nearby, clean, and renewable sources [15]. However, creating net-zero buildings is a challenging endeavor that needs a multifaceted strategy that includes energy-efficient systems, passive measures, and renewable energy technology [16]. Building net-zero's assets is a tremendous challenge beyond anything the construction world has ever seen [17]. As a result, once the Energy Performance of Buildings Directive was published

[18], the promotion of entire building strategies that combine passive measures with energy-efficient systems and technologies utilizing renewable energy became a political strategy in Europe [16].

The concept of net-zero carbon is centered on the objective of achieving a carbon footprint of zero for buildings. The attainment of net-zero carbon is a formidable goal that necessitates a comprehensive strategy encompassing the utilization of low-carbon materials, low-energy systems, and renewable energy sources [19]. The same reference also states that the notion of achieving net-zero carbon emissions has originated from the field of physical climate science, and its implementation involves the integration of social, political, and economic frameworks. In order to attain a state of net-zero carbon, it is imperative to tackle the embodied carbon of construction materials, curtail operational carbon, and devise strategies for circularity [19].

The embodied carbon of building materials poses a significant obstacle in the pursuit of attaining net-zero carbon. The term "embodied carbon" pertains to the carbon emissions that are linked to the manufacturing, conveyance, installation, and elimination of construction materials [20]. It is stated by the same reference that in order to mitigate embodied carbon, it is imperative to employ materials with a low carbon footprint, including but not limited to timber, bamboo, and recycled materials, while simultaneously minimizing construction waste. Furthermore, they mentioned, it is crucial to take into account the carbon footprint associated with transportation during the process of choosing building materials. The utilization of locally sourced materials can result in a substantial reduction in carbon emissions [20].

One of the obstacles in attaining net-zero carbon is the carbon emissions linked to the functioning of buildings. In order to mitigate operational carbon, it is imperative to employ low-energy systems and technologies, such as LED lighting, high-efficiency HVAC systems, and smart controls [13]. Furthermore, the same reference mentioned that it is crucial to utilize renewable energy resources, such as solar, wind, and geothermal, to provide energy for the structure. The implementation of renewable energy sources enables the building to achieve energy self-sufficiency and mitigate the carbon footprint attributed to the utilization of non-renewable energy sources.

Ultimately, it is imperative to take into account the life cycle of buildings in the pursuit of achieving a net-zero carbon outcome. In order to mitigate the carbon emissions linked with demolition and disposal, it is imperative to conceive buildings with disassembly and reuse in mind and to employ materials that can be conveniently repurposed or recycled [20]. The implementation of circular design principles in the construction of buildings has the potential to mitigate the carbon emissions associated with the building industry, thereby facilitating a transition towards a more environmentally sustainable trajectory.

1.3. Thesis Outline

Chapter 1, introduction, elucidates the worldwide scenario concerning ecological concerns that arise due to human actions, specifically in the context of buildings and their substantial energy usage and greenhouse gas emissions and underscores the urgency of adopting sustainable practices and achieving net-zero buildings by means of energy efficiency, renewable energy sources, and tackling embodied carbon in construction materials.

Chapter 2, background, offers a comprehensive summary of Life Cycle Assessment (LCA) and its constituent phases. It also highlights the significance of sustainable practices and their influence on human well-being during every stage of a building's life cycle. Furthermore, it delves into the topic of embodied carbon, exploring potential strategies to mitigate its impact, addresses operational carbon and highlights various approaches to reducing it. Furthermore, it examines rating systems for green buildings and delves into an analysis of the regulatory framework of the European Union and Estonia pertaining to energy efficiency in buildings. Finally, it discusses diverse techniques and methodologies aimed at improving the ecological efficiency of buildings, encompassing multi-faceted, methodical, and parametric approaches and defines the research gaps.

In Chapter 3, novelty of the study, is expounded upon, with a focus on addressing research gaps and establishing the study's objectives. The study establishes explicit objectives, articulates research questions, and endeavors to expound on the originality of the investigation.

In Chapter 4, methodology, is expounded upon, specifically regarding the LCA methodological approach that has been implemented. The author provided a detailed explanation of all definitions and assumptions pertaining to the morphology, orientation, structure, and envelope parametric definitions. The text provides a comprehensive explanation of the embodied and operational carbon parametric workflows, with a detailed elaboration of definitions, assumptions, and calculations.

Chapter 5, results, presents the findings of the study, primarily by highlighting the highest and lowest values of all performance metrics for the buildings. Subsequently, a comparison is made between each shape and an analysis is conducted to examine the impact of shapes on the performance metrics. Ultimately, an analysis is conducted to assess the impact of the most significant building attributes on the performance of buildings.

Chapter 6, discussion, underscores the importance of the study's results in relation to previous research literature. Additionally, it elucidates the constraints of the study and aims to offer suggestions for future research endeavors.

Chapter 7, conclusion, offers a succinct summary of the study's objectives, key findings, the extent to which the research questions were addressed and endeavors to evaluate the outcomes. Ultimately, it expounds upon the pragmatic implementation and utilization of the findings.

Keywords: Parametric design, Life Cycle Assessment, Early-stage design, Carbon footprint, Building Parameters, Master Thesis

2. BACKGROUND

2.1. Life Cycle Assessment

Life Cycle Assessment (LCA) is an approach which is employed for quantifying a product's adverse impacts on the environment, consumption of energy, and resource use. It is used to methodically evaluate the effects of every component and procedure. LCA is a method for evaluating numerous product development-related facets and their possible effects from the procurement of raw materials through processing, manufacture, usage, and disposal of the product (i.e., from cradle to grave) [21]. The LCA comprises four primary stages, namely Goal and Scope Definition, Inventory Analysis, Impact Assessment, and Interpretation. The initial stage, known as the Goal and Scope phase, establishes the aim, targets, functional units, and system constraints. The second stage of the process, known as Inventory Analysis, involves the comprehensive collection of all relevant data pertaining to inputs, processes, emissions, and factors throughout the entirety of the life cycle. During the Impact Assessment phase, the quantification of environmental impacts and input resources is carried out based on the inventory analysis. The final stage of the assessment process, known as the Interpretation phase, involves the analysis and interpretation of the results obtained during the Impact Assessment phase. Based on the findings, appropriate recommendations for improvement may be proposed [22].

EN 15804 (EVS – EN 15804: Sustainability of buildings. Environmental declarations. General rules for the product category of construction products) [23] divides the lifecycle of a building into the following main stages:

- Product stage (A1 – A3)
- Construction process stage (A4 – A5)
- Use stage (building fabric) (B1 – B5)
- Use stage (building operation) (B6 – B7)
- End-of-life stage (C1 – C4)
- And a stage beyond the building life cycle (D)

The product stage (A1–A3) involves extracting raw materials, transporting them to manufacturers and producing construction materials and goods from them. As self-explanatory as its given name is, the construction process stage entails the steps and processes which are necessary for construction of a building, mainly, the logistics of transporting the finished building products from the factories to the construction site.

Upon the completion of the construction process (A4-A5), the use stage of the building starts. This stage can be broken up into two sub-stages: building fabric (B1-B5) and building operation (B6-B7). A building is regarded to be in operation when it is occupied, during which time massive amounts of energy and water are used. Maintenance and repairs are inevitable after the utilization of a building for some time in order to ensure that the building can continue to be used. Until the end of the life of the building, the operating and maintenance phases occur consecutively. Eventually, demolition is the last stage of the building's life cycle (C1-C4), after which the derived materials are either disposed of, recycled, or reused. All these stages and their corresponding sub-stages are summarized in figure (2.1).

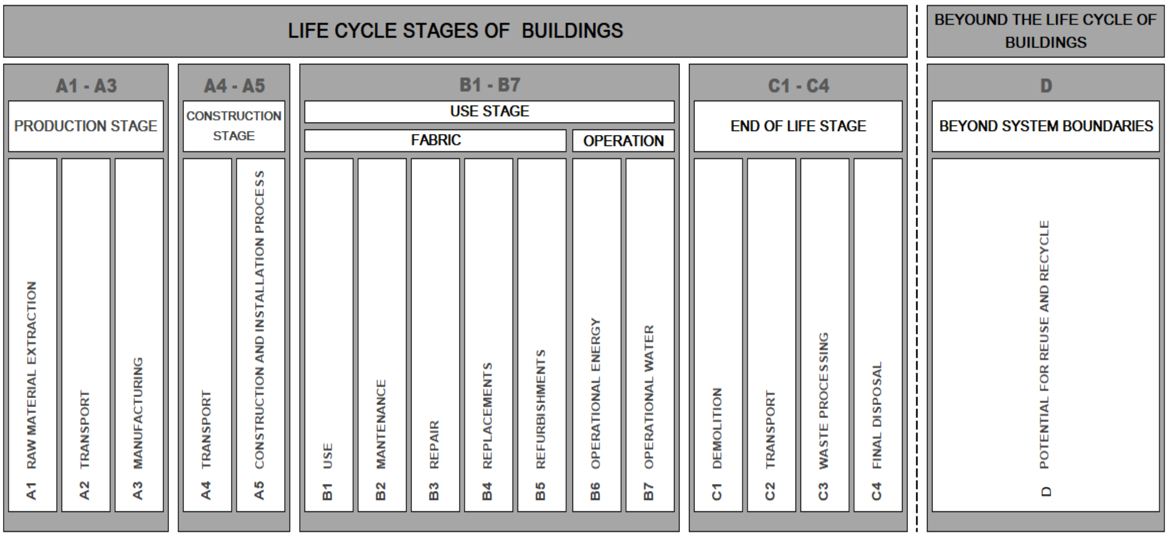


Figure 2.1. Life Cycle Stages of buildings

Energy, raw materials, and several other environmental assets are used in varied quantities in each of the aforementioned phases. At any of these stages, should unsustainable procedures be followed, it brings about a surge in waste, pollution, and environmental deterioration, all of which would have a severe influence on human health [24].

2.1.1. Goal and Scope Definition

The delineation of the system boundary is crucial in identifying the processes that must be incorporated in the LCA and must align with the study's objectives [21]. Identical to other commodities, the LCA system boundary of a building comprises either a cradle-to-grave, cradle-to-gate which is employed to assess building attributes, or gate-to-gate which is used to analyze the construction procedure.

The measurement of determined functions of a selected product is defined by the functional unit to ensure comparability, as stated in standard ISO-14040 (EVS-EN ISO 14040:2006/A1:2020 - Environmental management. Life cycle assessment. Principles and framework) [21]. The functional unit commonly employed by researchers for conducting an LCA of a building is the square meter (m^2) of floor area. Several studies have incorporated modifications to the square meter (m^2) functional unit. For instance, some studies have only considered the heated areas [25], while others have explicitly specified the number of occupants in the building [26].

The longevity of a building's existence holds noteworthy implications for the outcome of LCA investigation, primarily due to the aggregate energy utilization throughout its usage phase. The longevity of buildings has been found to be diverse in prior studies. Scholars have reported that the lifespan of residential buildings ranges from 40 to 100 years, with a majority of researchers applying a 50-year estimate [27], [28], [26], [29].

2.1.2. Inventory Analysis

The life cycle inventory analysis of buildings is recognized to be a highly intricate process, primarily due to the multitude of materials and procedures utilized, as well as the dynamic operational characteristics of buildings. The operational phase has been given significant emphasis in contrast to the construction phase, which presents several challenges, including missing data, difficulty in locating data, and the adoption of various calculation methods. Additionally, data may be unusable or subject to confidentiality restrictions, limiting the ability to modify it [30]. The inventory data pertaining to the construction phase of a building's LCA is predominantly reliant on the LCA data of the constituent building materials and components. Furthermore, various elements such as design, stakeholder requirements, the price, environmental objectives, and occupants' behavior, among others, have an impact on the list of contents of the distinct phases of a building's life cycle assessment [31], [32]. The common practice for obtaining the data of building materials is to derive them from the bill of materials. The collection of building inventory data is sourced from the building industry, databases, or environmental product declarations (EPD). The variations in building inventory data can be attributed not only to the source of the data, but also to factors such as the age of the data and the method of data collection. The reported variations have been deemed significant enough to potentially affect decision-making based on life cycle assessment outcomes, thereby posing challenges in the comparison of LCA results for buildings [33]. Silvestre et al., (2015) has put forth a set of guidelines for the selection of pertinent databases, taking into account the objective and extent of the life cycle assessment [30].

2.1.3. Impact Assessment

Conducting an impact assessment is a crucial stage in the Life Cycle Assessment process. During this stage, the potential environmental impacts will be assessed based on the results obtained from the inventory [21]. As per the Goal and Scope definition, the method and impact categories selection will be constrained in a manner identical to the inventory stage [34]. The majority of LCA experts tend to opt for utilizing established methods for assessment which were previously published, as opposed to creating new ones from the ground up [34]. Blengini and Di Carlo (2010) proposed that the process of selecting indicators is inherently subjective, but it should align with the impact assessment methodology recommended by the International Organization for Standardization (ISO) [25]. There exist two distinct approaches for conducting impact assessment, namely problem-oriented (midpoints) and damage-oriented (endpoint) methods. According to Bare et al. (2000), midpoints are regarded as a point within the cause-and-effect sequence of a specific impact category subsequent to the life cycle inventory (LCI) and preceding the end point. Various researchers have employed diverse impact categories in their studies, with eutrophication, ozone depletion, acidification, and global warming potential being the most frequently utilized categories [35]–[37].

2.2. Embodied Carbon

The term "embodied carbon" pertains to the carbon emissions that are linked to the manufacturing, transport, and installation of construction materials and constituents. The quantification of embodied carbon in buildings is a crucial element in assessing their carbon footprint, given its substantial contribution to the overall carbon emissions throughout the building's lifespan. The quantification of a building's embodied carbon can be achieved through the utilization of an LCA methodology, which takes into account both direct and indirect emissions [38].

Residential structures are a notable source of embodied carbon emissions due to their substantial demand for building materials and components. The embodied carbon emissions of residential structures can be impacted by several factors, including the building's dimensions, the materials utilized, and the construction techniques implemented. For instance, according to Omar et al. (2014), it has been observed that precast concrete wall panels exhibit a lower embodied carbon in comparison to cast-in-situ concrete walls [38].

The reduction of embodied carbon in buildings has garnered increasing attention due to its significant role in addressing the issue of climate change. Several approaches have been suggested to mitigate embodied carbon, including the utilization of low-carbon materials, the optimization of design to decrease material consumption, and the evaluation of the carbon footprint of material transportation and disposal [39].

The evaluation of the embodied carbon of buildings is gaining prominence due to its acknowledgement as a noteworthy factor in the carbon footprint of buildings. According to research, the lifetime greenhouse gas emissions of energy-efficient buildings can be predominantly attributed to embodied carbon, which can constitute as much as 80% of the total emissions [40]. Hence, it is imperative to take into account the embodied carbon during the process of building design and construction, with the aim of mitigating the carbon footprint associated with buildings.

Moreover, there is an increasing inclination towards the utilization of low-carbon materials in the realm of design and construction of buildings. As an illustration, timber is regarded as a material with low carbon content due to its relatively lower embodied carbon in comparison to conventional construction materials like concrete and steel [41]. Incorporating recycled and locally sourced materials is a viable strategy for mitigating the embodied carbon of buildings.

It is noteworthy that the mitigation of embodied carbon in buildings ought not to be pursued at the cost of compromising other sustainability objectives, including but not limited to conservation of energy and the quality of the indoor environment. Thus, it is imperative to adopt a comprehensive approach that can effectively reconcile these objectives.

2.3. Operational Carbon

The term "operational carbon" pertains to the carbon emissions that are produced during the routine utilization of a structure, encompassing the consumption of energy for heating, cooling, lighting, and appliances [42]. Residential buildings make a substantial contribution to operational carbon emissions, constituting roughly 20% of worldwide carbon emissions [43]. The carbon emissions generated during a building's operation are merely one component of its overall carbon footprint.

Numerous academic research have examined the influence of envelope systems of buildings on the embodied and operational carbon emissions of residential structures. A study conducted in Saudi Arabia demonstrated that the carbon footprint of residential buildings is significantly influenced by envelope variables, as evidenced by a parametric analysis [44]. In a separate investigation, the utilization of BIM-based lifecycle performance prediction and optimization was employed to examine the influence of varied materials and designs on the carbon footprint of residential structures [45]. Their findings indicate that the carbon emissions during the operational phase constituted a significant majority of the overall carbon emissions throughout the life cycle, amounting to 90%. On the other hand, the embodied carbon emissions constituted a relatively smaller proportion of 10%. The findings of the sensitivity analysis indicate that a 25% WWR results in a noteworthy rise of 47,4% in operational carbon. Furthermore, the carbon embodiment of the efficient block wall featuring marble is 10,7% higher than that of the base case. In a recent study, researchers proposed a comprehensive framework aimed at assessing the balance between embodied and operational carbon emissions in high-rise residential buildings [46]. Their findings suggest that the utilization of low carbon concrete is a viable strategy for mitigating the environmental impact by decreasing the embodied carbon (EC) by 5%-15% and conserving a modest proportion of operational carbon (OC). Thus, it is recommended to adopt this approach. Nevertheless, altering the thickness of the external walls results in a negligible reduction of the life cycle carbon emissions of 0,99%. They advised decreasing the U-value of building envelopes, as this can result in a reduction of approximately 2,84% to 2,89% in the life cycle carbon emissions. They also mentioned this reduction can be achieved by implementing insulation materials for external walls and installing triple-glazed windows.

The implementation of carbon mitigation tools and strategies is of paramount importance in the reduction of operational carbon emissions in residential buildings. According to a study conducted in China, the reduction of carbon emissions from residential buildings is contingent upon the presence of technological innovation and corporate competitiveness [47]. The study employed an empirical analysis to arrive at this conclusion. Research has demonstrated that the implementation of green building standards results in a noteworthy reduction of carbon intensity in residential buildings located in China [48]. Residential buildings' operational carbon emissions can be decreased by utilizing energy-saving technologies and optimization strategies [49]. The aforementioned tools and strategies encompass the enhancement of energy efficiency, utilization of low-carbon building materials, augmentation of resource recycling rates, and elevation of renewable energy source utilization [48].

Apart from policy interventions, retrofitting of extant dwellings is a viable approach to curtail operational carbon emissions. The process of retrofitting has the potential to enhance the sustainability of buildings and mitigate their carbon emissions. Retrofitting encompasses a range of measures such as the incorporation of energy-efficient lighting and appliances, insulation, and the integration of renewable energy sources like solar panels [50].

2.4. Rating Systems

Having developed the concept of green buildings, scholars noticed an urgent necessity to create a framework that could evaluate the performance and implementation of green buildings. Hence, the Building Research Establishment's Environmental Assessment Method, or BREEAM, was formed in 1990 [51]. This rating system analyses structures from a more detailed and exhaustive perspective. Since then, more green building rating systems, such as Leadership in Energy and Environmental Design (LEED) [52] and Green Star [53] have been developed. Studies claim that BREEAM is the most effective rating method that is presently available. In addition, these grading techniques evaluate sustainable design by considering a number of characteristics. It is typical for green grading systems to put a premium on characteristics such as the quality of the indoor environment, energy, and materials. In contrast, the bulk of these green building grading methods assess buildings in two stages. The first stage happens during the building's design, whilst the second refers to the project's actual construction [54], [55].

Today, the necessity of implementing sustainable measures to preserve natural resources is apparent. Sustainable measures can be outlined as the management of diverse environmental resources in a way that they are accessible for current and future generations [56]. Every stage of building design requires excogitation of a variety of approaches to conserve natural resources. Amidst all stages however, the design phase offers the highest potential to opt for sustainable alternatives which impact the entire life cycle of buildings. During this stage, analyses and simulations assist in minimizing the resource consumption to design utilitarian buildings. The objective of studies at this phase is to design a building that will utilize the least amount of material and energy over its lifetime [57].

2.5. EU Regulations

The European Union (EU) has established ambitious objectives to decrease greenhouse gas emissions and attain a competitive and environmentally friendly low-carbon economy by 2050 [58]. The difficulties and prospects for environmentally friendly construction are examined by Hayles and Kooloos (2005) [59]. One of the primary obstacles is the imperative transition towards more environmentally conscious construction methodologies. The adoption of sustainable building practices necessitates a shift in one's perspective and a readiness to allocate resources towards this end. An additional obstacle pertains to the requirement for a comprehensive and cohesive approach to residential energy refurbishment, which may entail intricate and substantial expenses. Nevertheless, this challenge also offers a prospect to optimize the renovation procedure and enhance its feasibility for homeowners. In addition, the issue of financing presents itself as a significant obstacle in the implementation of sustainable building practices. Bertoldi et al. (2021) conducted a comprehensive analysis of the extant and prospective financing mechanisms within the European Union (EU) that are aimed at facilitating the energy refurbishment of residential buildings [60]. The researchers discovered that a multitude of financing alternatives exist. However, the difficulty lies in aligning the appropriate financing mechanism with the particular requirements of the refurbishment endeavor.

An additional obstacle pertains to the practicality of refurbishment. The feasibility of converting a 22-story high-rise building from the 1960s into a near-zero energy building was evaluated by Poel et al. (2020) [61]. This was achieved by covering all usable parts of the facades and roof with building integrated photovoltaic (BIPV) components. The study determined that the refurbishment possesses technical feasibility. However, its economic viability is contingent upon the expenses associated with the building-integrated photovoltaic (BIPV) elements and the availability of subsidies.

The European Union has instituted certification schemes for building energy performance in order to encourage energy efficiency in buildings [62]. Upon evaluation of these initiatives, Li et al. (2019) determined that the schemes have played a significant role in augmenting cognizance regarding energy efficiency in constructions. However, there exists a scope for enhancement in the areas of standardization and implementation [63].

The European Union has placed emphasis on the refurbishment of the current residential stock as a strategy to attain their energy efficiency objectives [64]. The study conducted by D'Agostino et al. (2017) centered on the retrofitting of non-residential buildings [65]. The authors identified technical, financial, and regulatory factors as the primary obstacles to achieving deep energy renovation. The authors proposed that a blend of policy tools, including monetary inducements and regulatory measures, may effectively surmount these obstacles.

The amount of energy consumed in buildings is influenced by occupant behavior, which is a significant factor. In their study, Hu et al. (2020) performed a comprehensive analysis of occupant behavior in building energy policy and concluded that the energy consumption in buildings can be significantly influenced by occupant behavior [66]. Thus, it is imperative for policies to consider the human element and encourage energy-efficient conduct.

The European Union has mandated the use of digital building logbooks (DBL) as a means to promote deep energy renovations and surmount obstacles in building renovations [67]. They also introduced a novel data structure for the purpose of enhancing energy efficiency, sustainability, and intelligent functionality within buildings throughout the European Union. This proposal pertains specifically to the domain of DBL.

Pay-for-performance initiatives represent a novel policy-oriented strategy for the purpose of enhancing building renovations [68]. According to Anagnostopoulos and Tzani (2023), the implementation of such schemes has the potential to resolve the issue of split incentives and ensure that the energy efficiency objectives of building owners and tenants are in alignment [68].

The European Union endeavored to legislate and enact diverse policies and regulations pertaining to the enhancement of building energy efficiency within the European Union [69]. Since 2002, the European Union has implemented a unified policy aimed at encouraging energy conservation and reducing greenhouse gas emissions in the construction sector through the use of environmentally friendly materials and systems [70]. The aforementioned policy is conveyed via a sequence of directives, regulations, and policies.

The Energy Performance of Buildings Directive (EPBD) [62] is a significant policy pertaining to the enhancement of building energy efficiency within the European Union. Its inception dates back to 2002, and it has undergone multiple revisions subsequently [71]. The EPBD mandates that member states establish minimum energy performance standards for both new and existing buildings. Additionally, it requires that all newly constructed buildings meet the criteria for nearly zero-energy buildings by the year 2021 [69].

The Energy Efficiency Directive (EED) [69] is a significant policy that was implemented in 2012. It mandates member states to establish national energy efficiency targets and formulate energy efficiency plans [72]. In compliance with the Energy Efficiency Directive (EED), prominent corporations are mandated to perform energy audits and execute energy-conservation strategies.

The European Union (EU) has implemented several regulations pertaining to the energy efficiency of buildings. These include the Energy Labelling Regulation, which mandates energy labels [73] for various products, including boilers, and the Eco-design Regulation [74], which stipulates minimum energy efficiency standards for products such as lighting and ventilation systems [75].

It is imperative to accelerate the rate of building renovation while setting ambitious performance objectives in order to meet the European Union's climate change objectives for 2050 [76]. The study conducted by D'Oca et al. (2018) identified various technical, financial, and social obstacles and difficulties associated with deep building renovation. The authors recommended a comprehensive approach to address these barriers [76].

2.6. Regulations in Estonia

In 2008, Estonia proposed the first building energy efficiency regulations founded on primary energy consumption. In 2013, the criteria grew more stringent, and in 2019-2020, NZEB (nearly zero-energy buildings) regulations were introduced, first applicable to public buildings in 2019 and then to private premises in 2020. The Estonian Energy Sector Development Plan to 2030 (Energiamajanduse arengukava aastani 2030) outlines the country's energy conservation policies [77]. The goal of the strategy is to meet 50% of household power consumption and 80% of domestic heat using energy generated through renewable sources by 2030. The strategy emphasizes the significance of energy efficiency in the housing sector, which accounts for about 33.0% of national energy consumption. Estonia has established a goal to rehabilitate 3.0% every year of the floor area of public buildings, totaling 170,000 square meters by 2030, and to improve the energy efficiency of residential and commercial buildings. By the rehabilitation of multi-unit homes and small residential structures, Estonia is anticipated to lower its final energy consumption, resulting in reducing heating, electricity, and CO_2 emissions, and enhancing the living circumstances of occupants of such buildings [78].

In Estonia, regulations have been put in place to establish the minimum requirements for the energy performance of buildings. This includes both low energy buildings and nearly zero-energy buildings. The regulatory ambit encompasses newly constructed buildings equipped with indoor climate regulation systems, as well as pre-existing structures with indoor climate control which undergo substantial refurbishment. The stipulations are enforced on buildings designated for residential and non-residential purposes, in accordance with the intended function of the building in question. The verification of compliance with the minimum energy performance requirements for unlisted buildings necessitates an assessment of the purpose of use of the most analogous building type. The energy performance of a building is determined by the minimum requirements that are established for the building as a whole. These requirements are expressed through the energy performance indicator and other regulations that have been put in place. The energy performance indicator is a quantitative measure that assesses the total energy usage of a building for the purposes of maintaining indoor climates, supplying hot water, and powering residential appliances and other electronic equipment. The aforementioned metric is calculated on a per-unit-area basis of the heated space within the building, assuming standard usage. As per the regulation, the total energy consumption, and technical parameters of a building's purpose of use must be taken into account when determining the energy performance indicator for new constructions or buildings undergoing significant renovation. The established limit value for the energy performance indicator must not be exceeded.

The energy performance standards for multi-apartment buildings, defined as residential structures with three or more units, dictate that newly constructed buildings must adhere to a maximum energy performance indicator of 150 kWh/(m^2y), while buildings undergoing significant renovation must comply with a maximum energy performance indicator of 180 kWh/(m^2y). The regulatory framework also mandates stipulations for the overall specific heat loss caused by the envelope and ventilation systems in diminutive residential structures. The energy performance of low energy buildings is restricted to a maximum of 120 kWh/(m^2y), while nearly zero-energy buildings are limited to a maximum energy performance indicator of 100 kWh/(m^2y) for office, library, and research buildings, and 130 kWh/(m^2y) for business and commerce buildings [79].

2.7. Previous Research Approaches

The carbon footprint of residential buildings is a crucial issue in achieving the goal of low-carbon cities. The early stages of design are the most critical for reducing the carbon footprint of residential buildings [4]. Several studies have adopted a variety of approaches to incorporate LCA in early stages of design.

2.7.1. Multi-Objective Approach

The incorporation of a multi-objective approach during the initial phases of architectural design entails the simultaneous consideration of various environmental objectives while conducting a Life Cycle Assessment. The process encompasses a series of steps such as defining the objectives, establishing performance indicators, developing design alternatives, conducting a life cycle assessment, performing a multi-objective analysis, and optimizing the design. The aforementioned methodology empowers designers to evaluate and juxtapose the ecological ramifications of diverse design options, strike a harmonious equilibrium amidst competing goals, and arrive at judicious conclusions that foster sustainability in the realm of building design.

Płoszaj-Mazurek et al. (2020) employed a multi-objective methodology to enhance the carbon footprint of buildings within the context of regenerative architectural design [80]. They employed machine learning techniques, specifically Convolutional Neural

Networks, and utilized parametric design to examine the correlations between building parameters and the feasibility of integrating carbon footprint estimation and building optimization during the initial design phase. In their study, Gagnon et al. (2019) conducted a comparison between a sequential and a holistic design approach, utilizing multi-objective optimization techniques [81]. This was achieved through the case study of a residential building. The study revealed that the implementation of a holistic approach yielded a superior outcome in terms of energy efficiency, financial expenditure, and ecological footprint of the building. Eloranta et al. (2021) have devised a technique for optimizing building energy systems with multiple objectives, which involves sizing retrofit components for energy production and storage in a campus building located in Lahti, Finland [82]. The researchers determined that the approach was effective and suitable for mitigating the carbon emissions associated with buildings.

Magrassi et al. (2016) established a formalized multi-objective decision problem that incorporates life cycle assessment computations and aims to minimize expenses and greenhouse gas (GHG) emissions for typical structures [83]. A decision support system (DSS) was created by the researchers to incorporate life cycle assessment and optimization techniques for the purpose of designing environmentally sustainable buildings. The reduction of carbon footprint in multi-story residential buildings was investigated by Morales-Beltran (2023) through the implementation of hybrid timber-steel construction and designing for disassembly, as an alternative to reinforced concrete [84]. The researchers discovered that the implementation of these tactics leads to a noteworthy decrease in the carbon emissions associated with buildings. The assessment of the embodied carbon of an office building and the comparison of various design solutions were conducted by Przywózka et al. (2022) [85]. The study's findings suggest that the conclusions drawn may provide a foundation for the creation of building design principles aimed at mitigating the carbon footprint of forthcoming buildings. Frossard et al. (2020) conducted a comparative analysis of three distinct life cycle assessment methodologies that establish the multi-objective optimization problem for designing nearly zero-energy buildings (NZEBs) [86]. These approaches include static LCA, dynamic attributional LCA, and dynamic consequential LCA. The researchers determined that the dynamic consequential life cycle assessment methodology is the optimal approach for conducting multi-objective optimization.

2.7.2. Systematic Approach

A systematic approach to incorporation of Life Cycle Assessment into the initial phases of building design necessitates a methodical and structured approach. The process entails the establishment of objectives, acquisition of data, evaluation of effects, interpretation of findings, iterative development with consideration for sustainability, and providing of decision-making assistance. The proposed methodology guarantees a methodical and comprehensive incorporation of Life Cycle Assessment into the design process, thereby facilitating designers to contemplate environmental ramifications, enhance building efficacy, and arrive at informed decisions for sustainable design.

Dodoo et al. conducted a study aimed at investigating the potential constructive collaboration between structural engineering design solutions and the life cycle carbon footprint of cross-laminated timber utilized in multi-storey buildings [87]. The investigation employed a life cycle assessment methodology to evaluate the carbon footprint of diverse design alternatives. The findings indicate that the implementation of the synergy approach can lead to a decrease of as much as 43% in the carbon footprint over the entire life cycle. A study was conducted by Kuittinen (2016) regarding the utilization of recycled concrete in construction projects with a humanitarian focus [88]. The research employed a life cycle assessment approach to compute the carbon footprint of diverse concrete structure options and cement blends for a similar design of a school. In their study, Gardezi et al. (2021) investigated the assessments of carbon footprint throughout the life cycle of the housing sector in Malaysia [89]. The research employed a comprehensive methodology to evaluate the carbon footprint, encompassing all stages from planning and construction to operation, maintenance, and dismantling and disposal.

Mastrucci et al. (2020) have devised a framework for life cycle assessment that is spatio-temporal in nature and is intended for use in scenarios involving the renovation of buildings at the urban level [90]. The research employed a systematic approach to assess the ecological consequences of various building renovation scenarios. The LCA methodology was employed by the researchers to evaluate the carbon footprint of various building renovation scenarios. The findings indicated that the utilization of low-carbon materials and enhancement of the building's energy efficiency could potentially curtail the carbon footprint of the structure by as much as 70%.

2.7.3. Comparative approach

The adoption of the comparative approach in the inclusion of LCA during the early phases of building design refers to a technique that entails the evaluation of various design alternatives or options with respect to their environmental impact across their life cycle. Through using comparative methodology, architects and designers can assess and contrast the plausible ecological implications of diverse design alternatives, encompassing materials, construction techniques, energy systems, and end-of-life strategies.

In their study, Wang and Sinha (2021) utilized the Life Cycle Assessment methodology to evaluate the ecological ramifications of distinct prefabricated rates employed in the construction of buildings [91]. The study conducted by the authors revealed that the primary factor that had a significant impact on the water footprint was material extraction. This was particularly evident when there was an increase in the prefabricated rate. Using statistical methods of big data, Wang (2021) conducted an analysis of the energy consumption of HVAC systems and carbon emissions throughout the full life cycle of five residential buildings with varying building structures located in Beijing [92]. The researcher developed a comprehensive inventory of carbon emissions and a corresponding model for sustainable buildings throughout their operational lifespan.

The authors, Rasmussen et al. (2020), provided an environmental life cycle assessment of four design strategies with low carbon emissions that were implemented in the field of Danish architecture [93]. Various techniques were employed to improve the operational efficiency of structures. The design strategies that were subjected to testing encompassed the utilization of recycled materials, designing components for prolonged durability, creating adaptable designs, and designing for the reduction of operational energy demand. The study conducted by the authors revealed that the implementation of the aforementioned strategies resulted in a significant reduction of the carbon footprint of the buildings. Furthermore, the authors recommended the potential application of these strategies in other countries.

2.7.4. Parametric Approach

During the early stages of the design process, it is imperative to expeditiously assess various design options. Parametric modeling is a crucial aspect in this context. The process of parametric modeling entails utilizing computer software applications to generate a pliable and versatile digital representation of architectural design. This approach facilitates the examination of various design alternatives through the methodical manipulation of critical factors, including building configuration, positioning, constituent components, and mechanisms. The incorporation of Life Cycle Assessment within the parametric modeling procedure enables architects and engineers to evaluate the environmental efficiency of individual design alternatives in a more efficient and systematic approach. By establishing a linkage between the parametric model and LCA software or databases, the parametric approach facilitates the automated production of LCA outcomes for each design alternative. Real-time assessment and comparison of environmental impacts related to various design options can be facilitated through this approach.

The methodology proposed by Basbagill et al. (2013) endeavors to facilitate designers in comprehending environmental implications of their building component choices and devising an automated or semi-automated mechanism that furnishes environmental impact evaluations for numerous building designs [94]. The proposed methodology involves the integration of Building Information Modeling (BIM) software with Life Cycle Assessment, energy simulation, and sensitivity analysis software. The UniFormat 2010 categorization scheme is employed to classify building constituents under distinct building element groupings. The methodology solely accounts for the metric of global warming potential when assessing the environmental impact. The framework for classifying building components incorporates thickness as a dimensioning parameter, and thickness ranges are determined by referencing specifications from various suppliers of construction materials and equipment. The findings of this study provide designers with an impact allocation scheme and an impact reduction scheme. These schemes indicate the minimum and maximum embodied impacts that each building component can have across all designs considered. Additionally, they demonstrate the extent to which changes in material and thickness of each building component can lead to reductions in embodied impact. The suggested approach was exemplified through a case analysis of a multi-building residential complex with mid-rise buildings.

Hollberg and Ruth (2016) utilized parametric methodology in their implementation of a design-integrated life cycle assessment [4]. The model presented by the authors incorporates the parametrization of all input variables, such as building geometry, materials, and boundary conditions, and performs real-time calculations of the life cycle assessment. The researchers effectively showcased the efficacy of their methodology in identifying a solution that has the least possible environmental impact. They arrived at the conclusion that the integration of a simplified Life Cycle Assessment in the design process reduces the supplementary effort required for conducting LCA. The utilization of the parametric approach enables the architect to concentrate on the primary objective of designing the building, thereby rendering the Life Cycle Assessment practically advantageous for the purpose of design optimization. A framework was developed by Meex et al. (2018) for the application of life cycle assessment in early design stages of an environmental impact assessment (EIA) [95]. This framework takes into account user requirements and criteria for streamlining the LCA methodology. The framework proposed by the authors integrates two perspectives and outlines the necessary design-oriented environmental impact assessment tools for early design stages. The framework specifies the minimum methodological and calculation requirements that a simplified life cycle assessment must meet to be deemed suitable for evaluating the environmental impact of buildings. The researchers arrived at the conclusion that the utilization of Life Cycle Assessment based Environmental Impact Assessment tools in the process of making architectural design decisions can be advantageous. However, there exist certain inadequacies that must be resolved in order to satisfy the prerequisites of architects for early design.

Lobaccaro et al. (2018) examined the development of a workflow that facilitates the simultaneous enhancement of multiple performance factors in zero-energy buildings (ZEBs), including embodied emissions, solar radiation, daylighting, and building morphology [96]. The methodology employed involves the utilization of integrated design principles in the development of a Zero Energy Building (ZEB) conceptual model. The methodology employed in this study utilizes parametric tools to compute diverse performance metrics. Additionally, a parametric approach is devised to facilitate expedited and streamlined life cycle assessment analyses in the preliminary stages of the design process. The study applies a workflow to a residential building concept in Oslo, Norway, with the objective of achieving the Zero Emission Building - Plus Energy, Outdoor Module (ZEB-OM) standard. The article presents a comprehensive account of the study's methodology and findings, encompassing the utilization of generative algorithms for the parametric execution of LCA, the interrelation between structural solution and material quantities, and the computation of building component volume. The study's authors have determined that the workflow they have created can be utilized to enhance the design of Zero Energy Buildings (ZEBs). They have also noted that this workflow marks a noteworthy advancement in the creation of novel calculation techniques and three-dimensional models that can more effectively account for embodied impacts during the early stages and throughout the design process.

The study conducted by Röck et al. (2018) outlines a technique for identifying and visually conveying the potential of various construction types to enhance the embodied environmental impact of a building during its initial conceptual phase [97]. The proposed approach entails consolidating Life Cycle Assessment information at the level of building elements to align with the granularity of Building Information Modeling (BIM) elements. This involves devising a standardized nomenclature to streamline the process of automatic transferring of data between the LCA database and the BIM model. Additionally, a bespoke script is created to establish a connection between the two systems. The study employed a case study BIM model and an exemplary building element library to evaluate the method. The findings revealed that the embodied environmental impact of the building was primarily influenced by floors, external walls, and partition walls. The approach additionally facilitates the depiction of pertinent data through three-dimensional perspectives of the building model, accentuating the possibility of diminishing the overall embodied effect by opting for superior construction alternatives for specific element categories. The research recognizes the necessity of taking into account the effects on both embodied and operational impacts and proposes the integration of energy simulation with life cycle assessment of building materials for future investigations.

Zabalza Bribián et al. (2009) provided a state-of-the-art Life Cycle Assessment methodology for buildings [98]. The significance of Life Cycle Assessment in the assessment of building techniques was emphasized. The study also examines the potential stakeholders and applications of Life Cycle Assessment studies within the building industry. The primary beneficiaries of Life Cycle Assessment outcomes are individuals or entities involved in property development, architecture, and urban planning. The article additionally explores the factors that motivate or impede the utilization of Life Cycle Assessment in the construction industry. The article elucidates that there exist both facilitators and impediments, which may be tangible in nature, such as cost incentives, or intangible, such as perceived high expenses or convoluted, less efficacious outcomes. The article additionally addresses the development of life cycle assessment applications and the conduction of LCA studies within the building industry. The article posits a streamlined approach to Life Cycle Assessment methodology as a means of addressing the prevailing biases of architects and engineers towards the intricacies of LCA, the challenges associated with comprehending and implementing the outcomes, and the tenuous connection with energy certification applications.

2.8. Parametric and co-simulation workflow

The employment of parametric design, which is a computational design methodology, has gained significance in the realm of architecture. The process entails the utilization of algorithms for the purpose of generating and manipulating design parameters. This enables architects to investigate a broad spectrum of design alternatives and enhance the performance of buildings [99]. Parametric design has the potential to address sustainability concerns and environmental challenges in the context of building design by facilitating informed decision-making during the initial phases of building design [100]. Parametric design logic has emerged as a significant trend in the field of computational design research. This approach seeks to generate novel design solutions that enhance the performance of buildings, including bioclimatic considerations [99]. Investigation of the correlation between building design and bioclimatic principles in the context of spatial, functional, and morphological organization as well as building typology is another capability of parametric approach to building design [99]. Moreover, the implementation of parametric design in the realm of residential building design has the potential to mitigate energy consumption through the optimization of building orientation, envelope components, and window types [101]. The integration of parametric design tools with building simulation software is key to the parametric design methodology, which empowers designers to address various socio-environmental issues [102]. Hence, the utilization of parametric design can serve as a beneficial instrument for architects in the creation of ecologically sustainable residential buildings.

Grasshopper [103] is a programming language that utilizes visual elements and operates within the Rhinoceros 3D software [104], which is a computer-aided design (CAD) application. The manipulation of building design parameters is facilitated by a potent tool, which contributes significantly to the parametric generation of residential buildings [105]. Grasshopper is a widely utilized software application among architects and designers due to its ability to facilitate the creation of complex designs with relative ease. The aforementioned tool operates on a system that is structured around nodes, with each individual node serving the purpose of representing a distinct function or operation. Users have the ability to establish connections between nodes, which in turn facilitates the creation of a workflow that ultimately produces a design. The Grasshopper software is utilized in tandem with other software applications, such as Revit and AutoCAD, to produce intricate designs [105].

Grasshopper is a robust instrument for parametric design, which enables architects and designers to modify the parameters of building design. This implies that the building elements, such as walls, roofs, and windows, can be conveniently altered in terms of their dimensions, configuration, and positioning [106]. It also has the capability to automate design processes. Designers can enhance their productivity and save time by developing scripts that automate recurring tasks. An instance of automation can be implemented through the development of a script that generates building sections in an automated manner, utilizing a predetermined set of parameters. This approach eliminates the need for manual creation of each section, thereby reducing the time and effort expended by the designer.

The utilization of co-simulation workflows within Grasshopper has the potential to enhance the parametric design of residential dwellings by establishing valuable insights into building performance and the ramifications of preliminary design decisions [96]. Employing parametric design workflows in Grasshopper has enabled the execution of energy analyses, encompassing solar radiation and daylighting, as well as environmental impact analysis. These evaluations are conducted to assess the embodied and operational greenhouse gas emissions of the building [96], [107]. The Grasshopper-generated workflow enables parametric control over the building's shape, with the aim of optimizing several building performance as solar irradiations on the building envelope and minimizing embodied emissions [107]. Parametric design was used to realize a workflow with the potential to regulate venetian blinds through parametric design [108]. The utilization of building energy simulation is a viable approach to evaluate the energy efficiency of a building, as concluded from the outcomes of the simulation [109]. These elements have the potential to investigate the thermal efficiency of a building in relation to its orientation, envelope, and system alternatives [110]. The incorporation of Building Energy Modeling (BEM) software in the design process offers enhanced assurance to designers and building owners regarding the performance of the building. Additionally, it facilitates the development and construction of more environmentally sustainable buildings [111].

2.8.1. Embodied Carbon parametric workflow

As previously stated, the concept of embodied carbon in buildings pertains to the carbon emissions that arise from the manufacturing, conveyance, and installation of building materials, in addition to the energy consumption during the construction phase [112]. The software tool known as One Click LCA has the capability to compute the embodied carbon of buildings [113]. The assessment of the environmental performance of buildings can be conducted throughout their entire life cycle, encompassing the design, detailing, delivery, and deconstruction phases, by adhering to the ISO 14040-44 guidelines [112]. The One Click LCA software has been developed with a focus on facilitating usage during the initial phases of design. This enables professionals in the fields of architecture and engineering to make well-informed choices regarding the materials and systems they incorporate into their constructions [113].

The Grasshopper-based One Click LCA workflow comprises a series of distinct stages, each designed to execute a particular task. To initiate the process, the building geometry must be imported into Grasshopper, which is used for static environments rather than parametric variations such as urban areas. This can be accomplished through several file formats such as IFC, Rhino [113]. Parametric definition of the design in Grasshopper, which is employed for dynamic approach of changing form and features of design variations, is also a feasible approach. The subsequent stage involves the delineation of the construction materials and systems, which can be accomplished by utilizing the One Click LCA material library or by importing bespoke materials and systems [113]. The third procedural phase involves the allocation of materials and systems to the building geometry. This task can be accomplished by utilizing the visual scripting interface offered by Grasshopper [113]. The fourth procedure entails executing the One Click LCA analysis, which will produce a comprehensive account of the building's embodied carbon [113].

The One Click LCA software relies on various standards, such as ISO 14040-44, EN 15978, and EN 15804 [113]. The aforementioned standards offer a framework for conducting life cycle assessments pertaining to buildings and building materials, encompassing the computation of embodied carbon. The One Click LCA software integrates information from multiple databases, including the Ecoinvent [114], Boverket [115], EPiC [116], in addition to numerous other country-specific and global databases [117].

2.8.2. Operational carbon parametric workflow

As previously stated, the term "operative carbon" in the context of buildings pertains to the amount of carbon emissions that are generated by a building during its operational phase. Climate Studio [118] is a parametric tool utilized in the early stages of design to forecast energy consumption [119]. The Climate Studio software is founded on the principles of the Passive House standard, a stringent energy efficiency standard for buildings [120]. The Climate Studio methodology can also be utilized within Grasshopper, the visual programming language, to generate a parametric model of the building. Subsequently, the model is subjected to simulation via EnergyPlus [119]. The Climate Studio workflow in Grasshopper can be broken down into a series of comprehensive steps [119]. The first step is to establish the geometry and orientation of the building. The building envelope encompasses various components such as walls and windows. In the next step, it involves provision of a definition of the building systems, encompassing heating, cooling, and ventilation. Afterwards, a definition for the building occupancy and internal loads. The significance of every stage in the workflow cannot be overstated in the accurate prediction of the energy consumption of the building. The building envelope plays a crucial role in mitigating energy consumption [120]. EnergyPlus is a software tool designed for the purpose of simulating the energy consumption of a building and forecasting its overall performance. The tool in disputing is a parametric design software that enables designers to generate and assess architectural designs by utilizing predetermined parameters [96]. EnergyPlus is founded on the ASHRAE Standard 140-2017 [121], which furnishes a uniform approach for assessing the energy efficiency of buildings [113]. The software employs a simulation engine to compute the energy consumption of a structure, taking into account its architectural design, construction materials, and heating, ventilation, and air conditioning (HVAC) systems [113]. The outcomes of the simulation can be utilized for the purpose of enhancing the building's design and detecting methods for conserving energy [113]. The EnergyPlus workflow within Grasshopper encompasses multiple stages. The initial stage involves the establishment of the building's geometry, which can be accomplished through a range of software tools, such as Rhino, alongside the parametric definition of the building's geometry in Grasshopper. The subsequent phase entails generating an EnergyPlus model, which encompasses the delineation of the building's construction, HVAC systems, and other additional parameters. The third phase involves executing the simulation, which computes the energy consumption of the building during a designated timeframe. The ultimate stage entails scrutinizing the outcomes, which can be accomplished through a diverse range of instruments, such as Grasshopper, Ladybug or Climate Studio [96].

2.9. Research Gaps

Despite the considerable advancements achieved in the realm of LCA in recent decades, there remains a necessity for enhancing the early-stage design LCA. The reviewed academic literature pertaining to LCA has predominantly centered on the domains of materials selection and construction. It is axiomatic that the various stages of the building life cycle exert a substantial influence on the overall environmental efficacy of the building. The literature has given relatively little attention to the impact of building morphology and its more or less obstructing surrounding environment on carbon footprint, despite the significance of materials and construction. The term "building morphology" pertains to the physical characteristics of a building, including its shape, dimensions in an open landscape or urban environment, and positioning, as well as its spatial configuration within its surroundings. Various factors related to form and envelope can impact the energy consumption of buildings with regards to heating, cooling, and lighting, in addition to the feasibility of generating renewable energy. In addition, the massing of a building can significantly affect its embodied carbon.

Furthermore, there is a need for methodological simplifications in the construction of LCA to enhance its suitability for early design stages. This need stems from the aspiration to augment the applicability of LCA in the preliminary design phases of diverse projects. Through the optimization of the methodology employed in LCA, designers and architects can proficiently incorporate environmental factors into their decision-making procedures right from the outset. Moreover, it is imperative to underscore the necessity for enhanced usability of software tools for Environmental Impact Assessment based on LCA. The aforementioned tools are crucial in enabling the evaluation of the ecological ramifications linked to a specific project or design. For architects to effectively utilize these tools, it is imperative to synchronize them more closely with their work methodologies and practices. The integration of environmental factors into the design process would facilitate architects to seamlessly incorporate them into their workflows, leading to the production of more sustainable and environmentally conscious outcomes. Through the implementation of methodological simplifications in LCA and the alignment of Environmental Impact Assessment (EIA) software tools with architects' work methods, the efficacy and practicality of these tools can be improved.

3. NOVELTY OF THE STUDY

The intricacy of Life Cycle Assessment necessitates in-depth cognizance of the constituents of a building under scrutiny which customarily is listed in a document named bill of quantities. The corresponding environmental impact coefficients of the constituents are required to be found from the noted databases and multiplied by the quantity of the materials in order to calculate their impacts. The environmental emission factor from specific databases is utilized to multiply the material quantities. In general, every environmental factor entails a consideration of the regional circumstances and may, in certain cases, be tailored to suit the particular process. Databases normally offer national averages or broader evaluations of impact on the European Union or global scale. The intricacy involved in data collection and computation, coupled with the challenge of comprehension by non-specialists results in the usual practice of conducting LCA by specialists towards the end of the design phase [4], [122]. Nevertheless, those findings have limited usefulness in enhancing the design since the recommended modifications would entail excessive expenses. The aforementioned factor serves as a driving force behind the emergence of streamlined Life Cycle Assessment techniques, characterized by simplified data gathering and analysis procedures. These techniques hold the potential to be utilized by architects during the initial design phases, as this is the stage where LCA outcomes can have the most significant impact on the environmental sustainability of the design [4].

Furthermore, the minimization of both embodied and operational carbon of the buildings without shifting problem from one to another is a significant step in reduction of the carbon footprint of buildings. Architects' decisions in the early stage of design including building shape, orientation, number of floors, specifications of envelope, etc. have the most influential and principal impacts on buildings' carbon footprint [123]. The present study intends to investigate the preliminary effects of these decisions on residential buildings' carbon footprint employing parametric design in the context of Estonia.

3.1. Objectives of the research

According to aforementioned points, the primary objective of the research is to investigate and propose solutions to accomplishing optimal carbon performance by means of developing a workflow which facilitate decision-making by providing architects and engineers with sufficient information regarding the ultimate implications of their decisions pertaining to building morphology and material selection in the early stages of design.

Pursuing the objective, it will be endeavored to answer the following questions:

1. Which primary architectural forms return the optimal carbon footprint results?
2. Where is the trade-off between embodied and operational carbon to achieve the most optimal carbon footprint?
3. Which attributes of building, i.e., orientation, number of floors, envelope/volume ratio, window-to-wall ratio, external wall construction have more considerable impact on the carbon footprint of the building?
4. How does the presence of surrounding buildings affect the carbon footprint of a building?

3.2. Novelty of the Research

As far as current literature is concerned, there is a dearth of research that has evaluated the influence of building morphology on carbon footprint in conjunction with material selection in Estonia. The absence of literature on this topic is noteworthy, given that sustainable building design in the Estonian context is characterized by distinct challenges and opportunities. The Estonian climate is characterized by low temperatures and prolonged heating periods, necessitating the implementation of effective heating systems and optimal insulation measures.

4. METHODOLOGY

4.1. Goal and Scope Definition

The current investigation traces the path of Zabalza Bribián et al. [98] in order to streamline the LCA procedure. The aforementioned approach was implemented with the aim of surmounting the preconceived notions held by architects and engineers regarding the intricacies of Life Cycle Assessment (LCA), the challenges associated with comprehending and implementing the outcomes, and the tenuous connection with energy certification applications. The diagram depicted in Figure (4.1) portrays the fundamental phases that are considered in a comprehensive life cycle assessment (LCA) analysis, specifically the cradle-to-grave approach, for a building. The proposed simplified LCA methodology (Cradle-to-gate) aims to streamline calculations by removing stages that have a smaller influence on the level of primary energy and carbon dioxide emissions from the system. This study will solely evaluate the Carbon Footprint impact. The visualization of the stages involves the utilization of white color for the included stages and grey color for the not included.

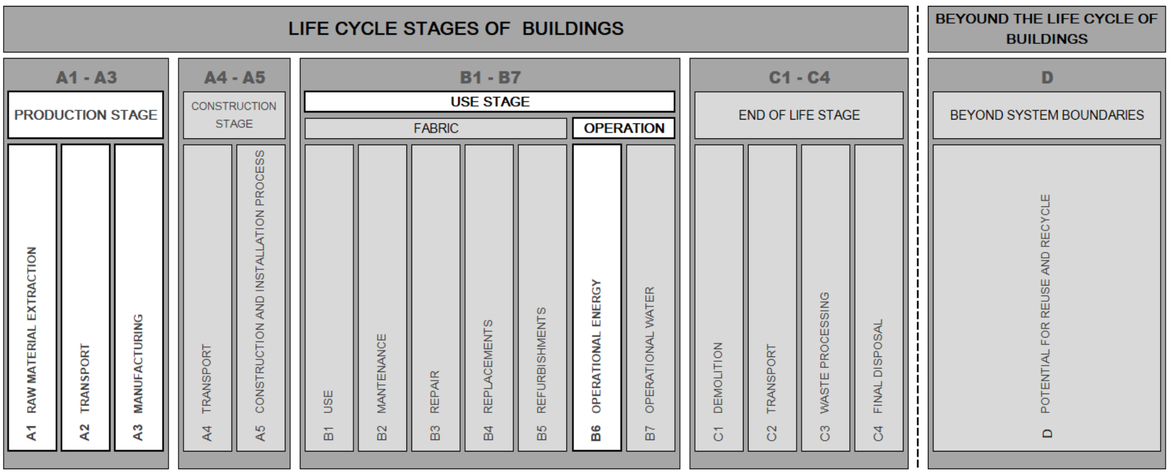


Figure 4.1. Included Life Cycle Stages of buildings

Two distinct parametric workflows were developed for calculating the carbon footprint of the designated stages. The OneClick LCA [124] workflow has been employed for the production stage (A1 - A3 stages, embodied carbon), while the Climate Studio and EnergyPlus [125] workflow have been utilized for the Operational Energy (B6, operational carbon) stage. The study provides specific sections where the workflows are expounded upon and elucidated.

The present study targets architects, engineers, and consultants as its primary audience. The study aims to provide workflows that can be utilized from the early stages of design until the detailed design stage, enabling collaboration among these professionals. The workflows can be employed to compare different design options, including form, orientation, and technical choices. This empowers the aforementioned experts to make educated choices at every stage of the design process and to opt for alternatives that have minimal possible implications.

Similar to numerous other Life Cycle Assessment (LCA) investigations [26]–[29], the present study regards the lifespan of the building variations as 50 years.

4.1.1. Functional Unit

The functional unit in both workflows is defined as one square meter (m^2) of the gross floor area for each building variation. The summation of embodied and operational carbon will yield the total carbon footprint of every building variant per unit area of its gross floor area.

4.1.2. Life Cycle Inventory and Impact Assessment

Since the design process is parametric and the inventory data of designs differ according to the specifications of the building variations, the process of obtaining the inventory and impact assessment results is outlined in the subsequent sections of the study.

4.2. Parametric design of building form

To investigate the relationship between the morphology of a building and its embodied and operational carbon, a parametric workflow has been defined in Grasshopper. The workflow is composed of six steps, including "Shape Definition," "Structure Generator," "Mass Generator," "Envelope Generator," "LCA Workflow," and "Energy Workflow." The building is defined by various parameters in each step. In order to control the number of variations to fit into the scope of this study, some parameters have been considered constant, and the others vary according to the ratiocinations, which are explained in the relevant parts of the study. The elements and their corresponding parameters, which define the building, are summarized in table (4.1).

Table 4.1. Summary of Buildings attributes, their corresponding parametric clusters, and parameters

Attributes	Corresponding Parametric Cluster	Parameters	Status	Number of Alternatives
Shape				
	Primary Curve Definition			
		Building Shape	Variable	6
		Orientation	Variable	4
		Size on X Direction	Variable	3
		Size on Y Direction	Variable	3
		Bay Width [a]	Variable	3
		Building Width [b]	Variable	3
		Primary Column Size	Constant	-
		Floor-to-Floor Height	Constant	-
Structure	(Reinforced Concrete)			
	Structure Generator			
		Primary Grid points [c]	Constant	-
		Columns Size [d]	Variable	-
		Floor-to-Floor Height	Constant	-
		Number of Floors	Variable	4
		Slab Thickness [e]	Variable	-
Envelope				
	Envelope Generator			
		Building Mass [f]	Variable	-
		Floor-to-Floor Height	Constant	-
		Number of Floors	Variable	4
		Window-to-Wall Ratio	Variable	4
		Perimeter Zone depth [g]	Variable	3

Notes:

a) The value of bay width is directly dependent on the size in both directions and changes accordingly.

b) Specific to Buildings with L-shape, C-shape and rectangular with a void in the middle. It is dependent on the bay width and changes in accordance with dimensions on both sides and bay width.

c) Primary Grid points are defined as the central points of columns so are depended on Bay width and size on directions.

d) Employing a python component in primary curve definition cluster, the primary column size is checked for all tolerance criteria of Eurocode 2 under typical load combinations of Eurocode 1 for Estonia.

e) Employing a python component in primary curve definition cluster the required slab thickness is calculated and checked for all tolerance criteria of Eurocode 2 under load combinations of Eurocode 1 for Estonia.

f) Building mass is defined using a cluster based on Building shape, Floor-to-Floor Height, and number of Floors.

g) The perimeter zone depth of each building variation is calculated using a parametric workflow.

4.2.1. Shape

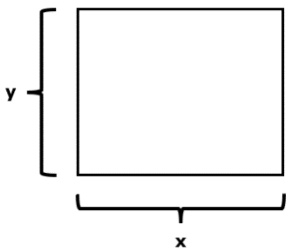
This section provides a comprehensive explanation of the rationale underlying the definition of various morphological variations.

Linear, Rectangular and Square Buildings

All the basic shapes analyzed and the ones under investigation in this study are defined based on a primary rectangle. The longer dimension of the rectangle is named the length of the shape, and the shorter dimension is called the width (Table 4.2). For rectangular shapes (linear, rectangular, and square), all the dimensions of the primary rectangle are present and define the boundaries of the shape. Since the shapes are rarely ideal geometrically, the following assumptions are made to define them:

- If the difference between the length and width of the shape is more than 20% of the length, the shape is defined as linear.
- If the difference between the length and width of the shape is between 10% and 20% of the length, the shape is defined as rectangular.
- If the difference between the length and width of the shape is less than 10% of the length, the shape is defined as square.

Table 4.2. Shape definition logic

Shape	Condition	Name
	$(x-y) > 0{,}2x$	Linear
	$0{,}1x \leq (x-y) \leq 0{,}2x$	Rectangular
$x > y$	$(x-y) \leq 0{,}1x$	Square

C and L shape Buildings

For shapes that are derived from the primary rectangle, depending on the nature of the shape, one or two dimensions are omitted. The terminology used is defined as follows:

- For C-shaped buildings, one dimension of the primary rectangle is omitted, and the final shape is defined by offsetting the remaining curve.
- For L-shaped buildings, in the same way, two dimensions of the primary rectangle are omitted, and the final building is defined by offsetting the remaining curve.

Figure (4.2) is a schematic illustration of the stages of concluding the aforementioned shapes.

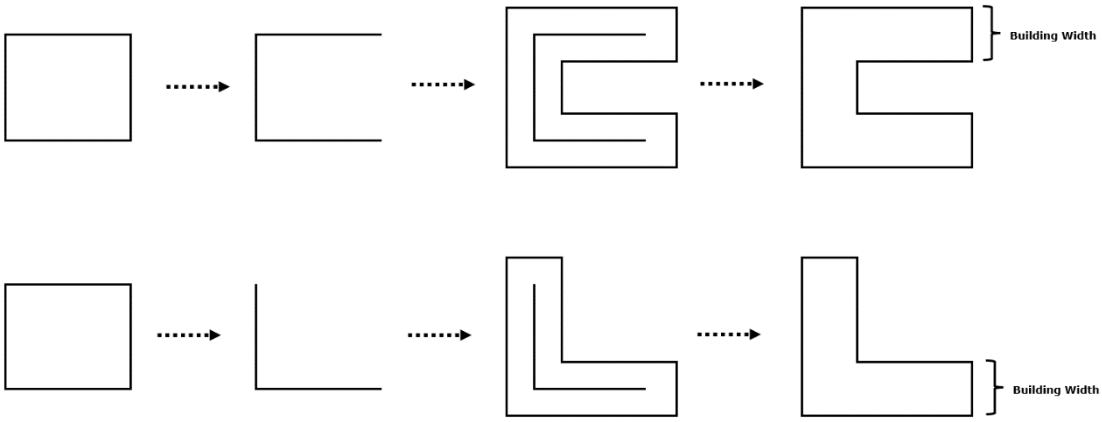


Figure 4.2. Stages of concluding C and L shapes buildings

Courtyard

The definition of this shape is quite similar to the C and L shapes. All dimensions of the primary rectangle are present, and the shape is defined by offsetting all dimensions. Figure (4.3) illustrates the stages of concluding the shapes schematically.

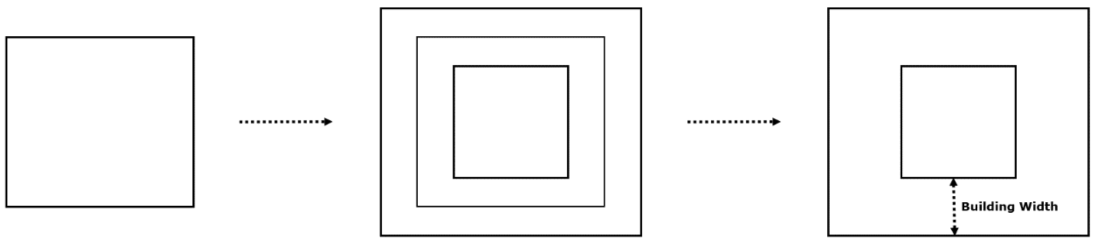


Figure 4.3. Stages of concluding courtyard buildings

Investigations on existing buildings in Tallinn

A total of 154 existing residential buildings constructed in Tallinn between 2015 and 2023 have been investigated using data from the Ehitisregister [126] to study the trend of building morphology. To conclude a number of viable alternatives for variable inputs of building attributes, data on building shape, orientation, length, width, height, materials, and facilities have been gathered. After cleaning the data set and employing a Microsoft Excel pivot table, a number of statistical analyses were performed. The results of the analyses provided meaningful length, width, thickness, number of floors, and building width to form the design alternatives. Table (4.3) summarizes the data collected and analyzed.

Table 4.3. Collected and analyzed data of existing buildings in Tallinn

		C-Shape	Irregular	L-Shape	Linear	Courtyard	Square	Rectangular	Trapezoid
Count		2	26	5	83	2	18	15	3
Percentage of the Shape Abundance		1,30%	16,88%	3,25%	53,90%	1,30%	11,69%	9,74%	1,95%
Length (m) [a]									
	Average	55,90	35,48	36,92	30,94	79,00	20,63	19,61	23,67
	Max	57,50	64,00	61,60	66,30	84,70	23,70	28,30	28,90
	Min	54,30	14,40	20,50	16,90	73,30	18,50	14,80	17,90
Width (m) [b]									
	Average	38,55	20,14	30,28	17,04	63,25	19,99	17,44	12,87
	Max	41,40	34,80	61,20	23,80	69,30	23,50	25,30	14,20
	Min	35,70	11,80	16,20	11,40	57,20	17,00	13,00	11,40
Height (m)									
	Max	22,00	48,60	20,00	29,50	22,00	22,40	29,40	19,50
	Min	17,80	7,00	12,00	7,60	21,00	9,00	10,10	10,20
Number of Above-ground Floors									
	Max	6	15	6	9	6	6	9	6
	Min	5	2	3	2	6	3	3	3
Length to width ratio (LWR) [c]									
	Average	1,45:1	1,84:1	1,39:1	1,84:1	1,26:1	1,04:1	1,12:1	1,83:1
	Max	1,52:1	4,35:1	2,71:1	4,60:1	1,28:1	1,1:1	1,19:1	2,04:1
	Min	1,39:1	1:1	1,01:1	1,18:1	1,22:1	1:1	1,09:1	1,57:1
Building Width (m) [d]									
	Average	16,75	11,10	12,24	-	13,00	-	-	-
	Max	18,00	14,60	20,70	-	14,00	-	-	-
	Min	15,50	7,60	7,10	-	12,00	-	-	-

Notes:

a) Please see the preliminary explanation section for the definition.
b) Please see the preliminary explanation section for the definition.
c) Please see the preliminary explanation section for the definition.
d) Specific to C-shape, Irregular, L-shape, and Courtyard buildings.

In order to reduce the level of complexity and control the number of alternatives to be sufficient for the study, the concentration is decided to be on the common and basic architectural shapes. To restrict the dimensions of the shapes, the maximum length of each shape category was considered, and using the minimum, average, and maximum length-to-width ratio (LWR) of the primary rectangle derived from the statistical analysis, the corresponding widths were calculated. If the width was within the range of widths in the statistical analysis, the alternative was accepted for further study; otherwise, the corresponding average length of the shape was considered for the LWR which did not return a width within the range in the first run. This resulted in alternatives with meaningful dimensions for each base shape of the buildings, which are within the actual range of shapes that are practiced in Tallinn. Figure (4.4) summarizes the logic in a flowchart.

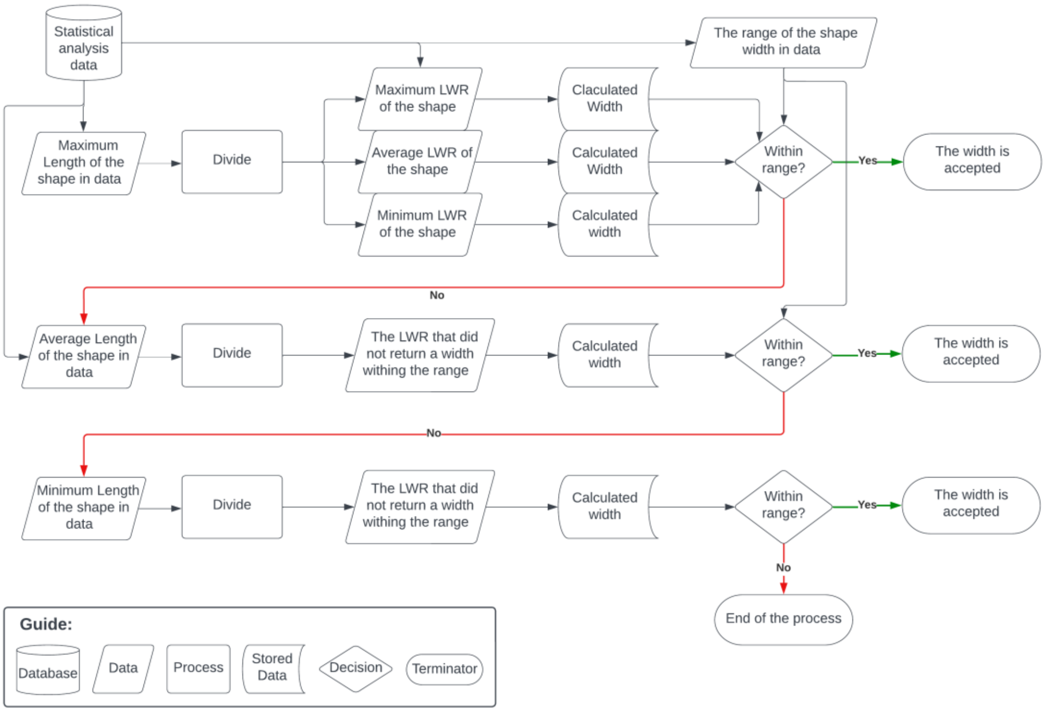


Figure 4.4. Flowchart of the logic of defining building variation dimensions

The results of the logic returned an unequal number of variations for each shape. Therefore, following the logic of the optimal option, three variations were chosen for each shape category. The optimal logic is illustrated in figure (4.5).

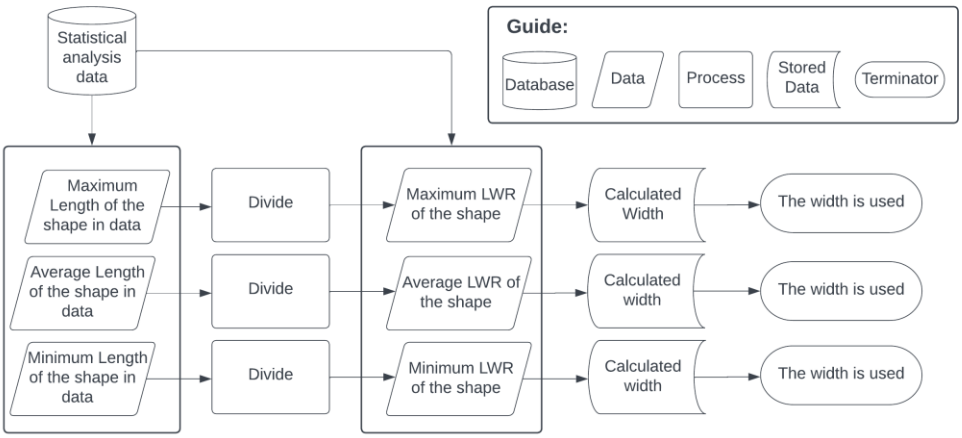


Figure 4.5. Flow chart of the selection of optimal options

The floor-to-floor height is considered 3,2 m constantly, and the number of floors is limited to 5, 7, and 9. For the shapes that require building width as an input, the corresponding average width of the specific shape is considered for the building's width. Table (4.4) summarizes the shape alternatives and their corresponding dimensions.

Table 4.4. Summary of shape alternatives and their corresponding specifications

	Alternative code	Length (m)	Width (m)	LWR[1] of P.R.[2]	No. of Floors	Height (m)
Square						
	SQ 01	23,7	21,55	1,10:1	5	16
	SQ 02	20,63	19,84	1,04:1	5	16
	SQ 03	18,5	18,50	1,00:1	5	16
	SQ 04	23,7	21,55	1,10:1	7	22,4
	SQ 05	20,63	19,84	1,04:1	7	22,4
	SQ 06	18,5	18,50	1,00:1	7	22,4
	SQ 07	23,7	21,55	1,10:1	9	28,8
	SQ 08	20,63	19,84	1,04:1	9	28,8
	SQ 09	18,5	18,50	1,00:1	9	28,8
Rectangular						
	RC 01	28,3	23,78	1,19:1	5	16
	RC 02	19,61	17,51	1,12:1	5	16
	RC 03	14,8	13,58	1,09:1	5	16
	RC 04	28,3	23,78	1,19:1	7	22,4
	RC 05	19,61	17,51	1,12:1	7	22,4
	RC 06	14,8	13,58	1,09:1	7	22,4
	RC 07	28,3	23,78	1,19:1	9	28,8
	RC 08	19,61	17,51	1,12:1	9	28,8
	RC 09	14,8	13,58	1,09:1	9	28,8
Linear						
	LN 01	66,3	14,41	4,60:1	5	16
	LN 02	30,94	16,82	1,84:1	5	16
	LN 03	16,9	14,32	1,18:1	5	16
	LN 04	66,3	14,41	4,60:1	7	22,4
	LN 05	30,94	16,82	1,84:1	7	22,4
	LN 06	16,9	14,32	1,18:1	7	22,4
	LN 07	66,3	14,41	4,60:1	9	28,8
	LN 08	30,94	16,82	1,84:1	9	28,8
	LN 09	16,9	14,32	1,18:1	9	28,8
Courtyard						
	CY 01	84,7	66,17	1,28:1	5	16

Alternative code	Length (m)	Width (m)	LWR[1] of P.R.[2]	No. of Floors	Height (m)
					Table 4.4 Continued
CY 02	79	62,70	1,26:1	5	16
CY 03	73,3	60,08	1,22:1	5	16
CY 04	84,7	66,17	1,28:1	7	22,4
CY 05	79	62,70	1,26:1	7	22,4
CY 06	73,3	60,08	1,22:1	7	22,4
CY 07	84,7	66,17	1,28:1	9	28,8
CY 08	79	62,70	1,26:1	9	28,8
CY 09	73,3	60,08	1,22:1	9	28,8
C-Shape					
CS 01	57,5	37,83	1,52:1	5	16
CS 02	55,9	38,55	1,45:1	5	16
CS 03	54,3	39,06	1,39:1	5	16
CS 04	57,5	37,83	1,52:1	7	22,4
CS 05	55,9	38,55	1,45:1	7	22,4
CS 06	54,3	39,06	1,39:1	7	22,4
CS 07	57,5	37,83	1,52:1	9	28,8
CS 08	55,9	38,55	1,45:1	9	28,8
CS 09	54,3	39,06	1,39:1	9	28,8
L-Shape					
LS 01	61,6	22,73	2,71:1	5	16
LS 02	36,92	26,56	1,39:1	5	16
LS 03	20,25	20,05	1,01:1	5	16
LS 04	61,6	22,73	2,71:1	7	22,4
LS 05	36,92	26,56	1,39:1	7	22,4
LS 06	20,25	20,05	1,01:1	7	22,4
LS 07	61,6	22,73	2,71:1	9	28,8
LS 08	36,92	26,56	1,39:1	9	28,8
LS 09	20,25	20,05	1,01:1	9	28,8

Notes:

1) LWR: Length-to-Width Ratio
2) P.R.: Primary Rectangle

4.2.2. Orientation

The analysis of the buildings in Tallinn reveals that buildings feature quite diversified orientations. Furthermore, various considerations are involved in specifying the orientations of buildings, though in order to determine the impact of orientation on the final carbon footprint of a building, this study investigates each shape variation in 4 different orientations. The primary definition of each shape is oriented toward the north. Employing a parametric definition, the shape will rotate around its geometrical center towards all main cardinal directions. Figure (4.6) depicts the described directions.

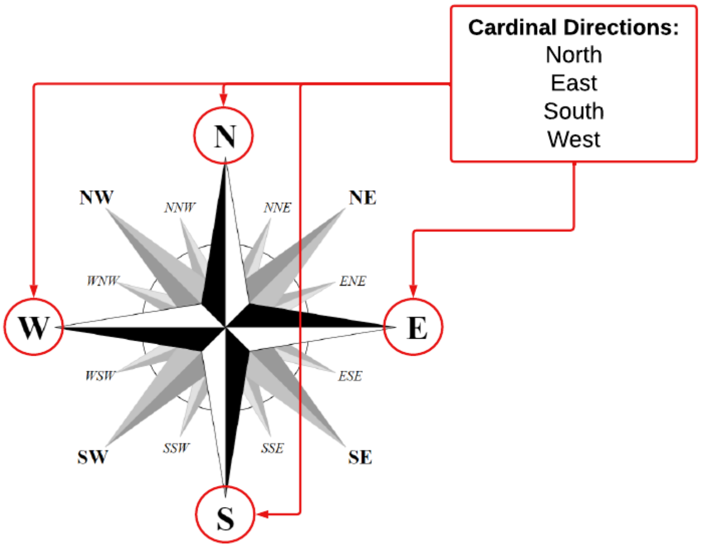


Figure 4.6. Illustration of Cardinal directions

Figure (4.7) demonstrates the schematic rotation of a shape around its central point.

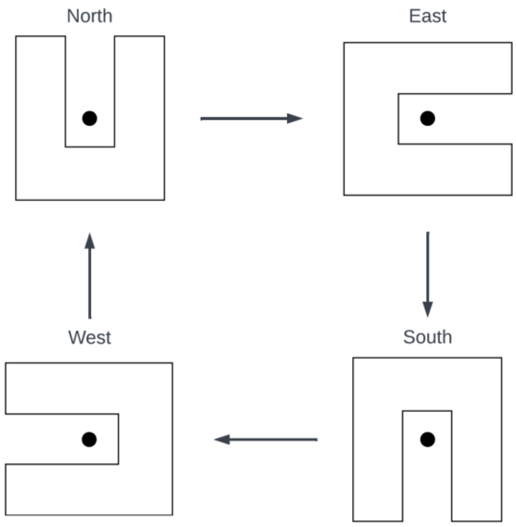


Figure 4.7. Schematic illustration of the rotation of a shape around its geometrical central point

4.2.3. Structure

As mentioned earlier, the concentration of this study is on building morphology. Therefore, it is decided that the structure of the building is constantly considered to be reinforced concrete in all iterations and variations. Designing reinforced concrete structures is a highly specialized field that necessitates a thorough comprehension of material properties, structural behavior, and design codes and standards. Several factors contribute to this complexity, including the variability of material properties, the complexity of the loads the structure must withstand, and the need to conform with safety codes and regulations. Due to the specific considerations and requirements that must be addressed, the incorporation of reinforced concrete structures into parametric design can be complex. The nonlinear behavior of concrete and steel under load is one of the primary challenges in designing reinforced concrete structures. In contrast to steel, concrete exhibits significant nonlinear properties, such as fracture, compression, and contraction. This behavior can make it difficult to anticipate the structure's performance under different loading conditions and can also contribute to design errors and overestimations of load capacities. In addition, the use of steel in concrete structures adds complexity to the anchorage, detailing, and positioning of the reinforcement. The need to conform with safety codes and regulations is an additional difficulty in designing reinforced concrete structures. These codes and regulations stipulate the minimum requirements for structural design, including material properties, structural behavior, and construction methods. Noncompliance with these requirements may result in hazardous structures that endanger public safety. Despite these impediments, simplified methodologies exist for estimating the performance of reinforced concrete structures. While parametric design tools can facilitate the design process, certain considerations and constraints must be taken into account, and empirically based methods are typically employed for preliminary design and estimation. However, these methods are not a replacement for a comprehensive analysis and design process that considers all of the building’s particular considerations and constraints. In this study, the structure is considered to be comprised of a system of flat slabs and columns. Figure (4.8) illustrates the described structure for a sample C-shaped building.

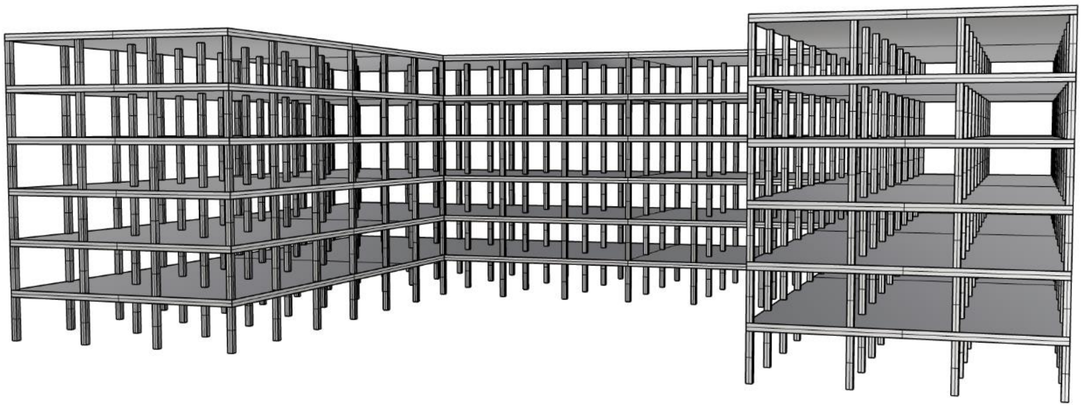


Figure 4.8. An illustration of structure for a sample C-shape building

In order to facilitate the design of structures within the parametric workflow, some simplifications were postulated. The bay width (distance between columns) is uniform and identical in both directions. In addition, the dimensions of the building on both sides, as well as the building width in C-shape, L-shape, and courtyard, are always divisible by the bay width, as ascertained by a workflow cluster (i.e., a parametric tool included in the workflow as a node) with the precisely specified function. In order to estimate the thickness of the slab, a simplified design approach based on EVS-EN 1991-1-1-1:2002 (Eurocode 1: Actions on structures - Part 1-1: General actions - Densities, self-weight, imposed loads for buildings) [127] and EVS-EN 1992-1-1:2005+A1:2015/NA:2015 (Eurocode 2: Design of concrete structures. Part 1-1: General rules and rules for buildings) [128] was adopted. Using a Python script component (i.e., a programmed tool included in the workflow as a node) in Grasshopper and inside the primary curve definition cluster, the slab was designed in accordance with hand-design calculations based on the aforementioned guidelines for Estonia. Since the bay width is the same in both directions and for all slab spans, the script designs the slabs with length and breadth equal to the bay width. Figure (4.9) depicts a slab section span sample and an example of Eurocode 2 slab design considerations for a 6-meter bay width.

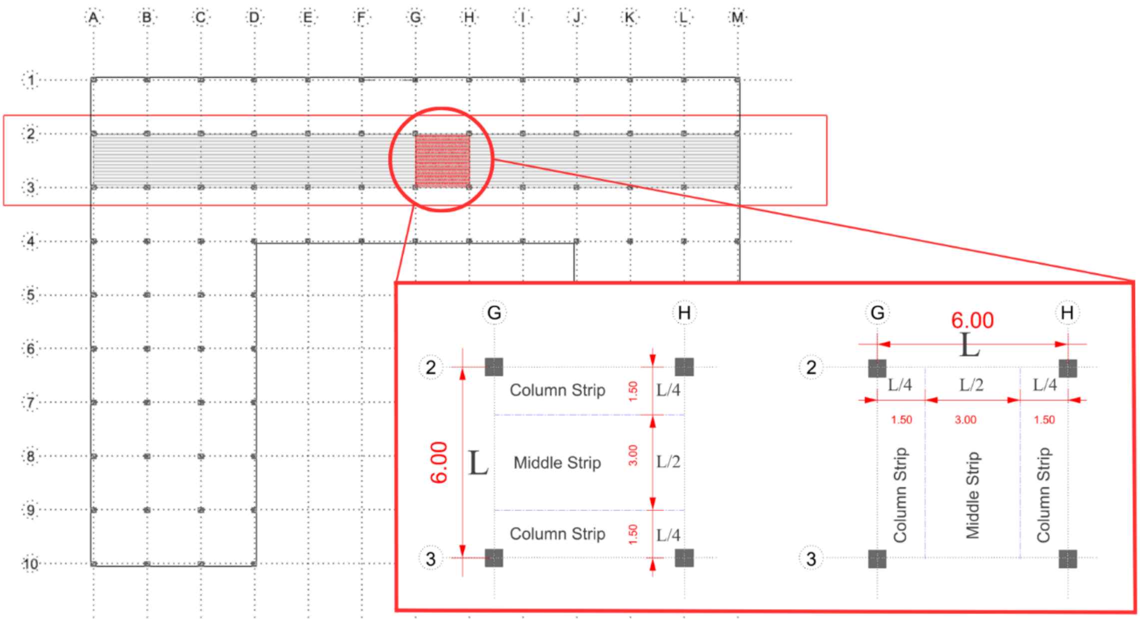


Figure 4.9. Slab span details and Eurocode 2 slab design considerations for a sample 6-meter bay width

The Python script generate the reinforced concrete slab composed of concrete with a strength of C30/37 based on load combinations of Eurocode 1 (Eurocode - Basis of structural design) [129] for Estonia and assumes the load is distributed uniformly over its span. The typical values of the loads used in the design process were assumed based on the design structures of the elements considered for building attributes. In addition, the constants of the materials' characteristics were retrieved from Eurocode 2. (Table 4.5) is a summary of all pertinent information.

Table 4.5. Design specifications of slabs

Slab (RC C30/37)	Constant	magnitude	Unit
Loads			
	Self-Weight	Weight of Slab Construction	kN/m²
	Finishes Weight	1	kN/m²
	Partitions Weight	1	kN/m²
	Live Load	4	kN/m²
	Snow Load	1	kN/m²
Partial Load Factors			
	dead	1,35	-
	Live	1,5	-
Partial Safety Factors			
	Concrete	1,50	-
	Steel	1,15	-

The slab's suitable thickness and needed reinforcement are determined through the design process. Then, a Python script was built in another component to design the slab's necessary shear reinforcement. Subsequently, two more controlling scripts were created in two distinct Python components to validate the proposed slab based on Eurocode 2 requirements for deflection and punching shear under critical circumstances and loads. The controlling Python components modify the slab in regions where Eurocode 2 required criteria are not satisfied and finalize slab thickness and reinforcement. Figure (4.10) depicts the procedure inside Grasshopper.

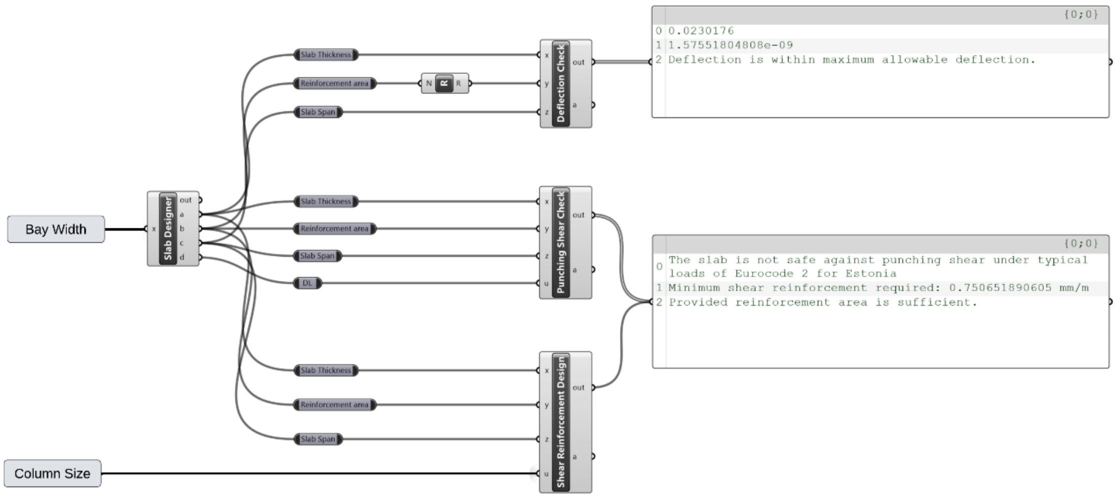


Figure 4.10. Slab design workflow inside Grasshopper

Similarly, a Python component was used in order to design columns. The component assumes that the columns are designed using C40/45 concrete and that loads are transferred directly from slabs to columns. Thus, the span of the slab that impacts the column is considered to be half the bay width in each direction. Since they are the most crucial, the middle columns on the first level of the building are taken into consideration. Figure (4.11) depicts a chosen sample column and the corresponding zone expected to have an effect on the column, as well as thorough details of the selected area and its measurements for a sample column with a bay width of 6 meters.

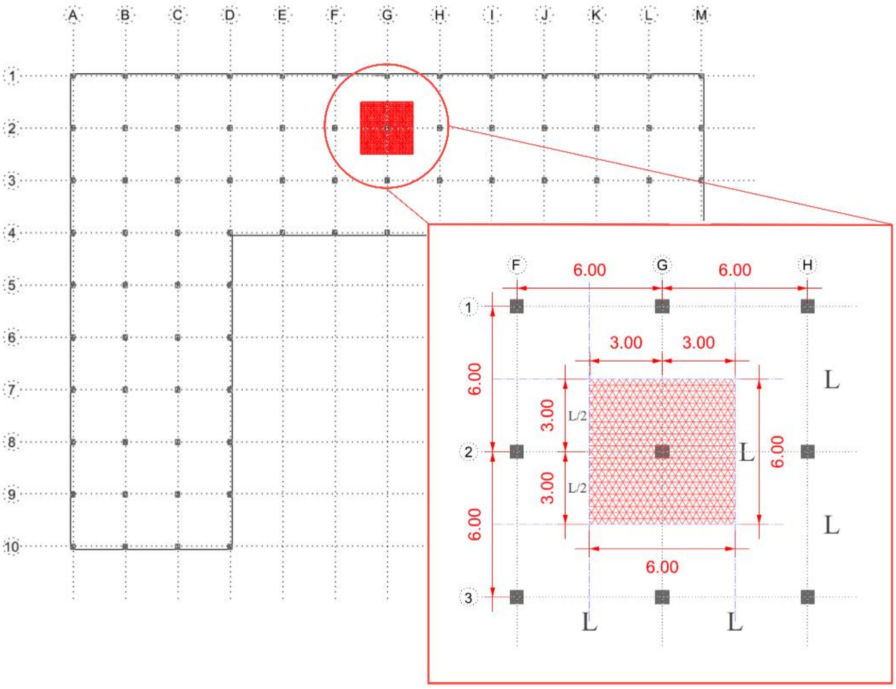


Figure 4.11. A sample column span for a 6-meter-wide bay width

The column check and design Python script receives a given size of column, verifies it against all Eurocode 2 criteria (strength, slenderness, compression, bending, and deflection) based on load combinations of Eurocode 1 for Estonia, modifies the column for the weaknesses, and offers the proper size and reinforcement. In table (4.6), pertinent constants, assumptions, and considerations are presented.

Table 4.6. Column design specifications

Column RC (40/45)	Constant	magnitude	unit
Loads			
	Permanent	$(Weight_{Slab} + Weight_{Column}) \times N.F.$[1]	kN/m^2
	Variable	5	kN/m^2
	Snow	0,7	kN/m^2
	wind	0,6	kN/m^2
Partial Load Factors			
	Permanent	1,35	-
	Variable	1,5	-
Partial Factors			-
	Material (γ_m)	1,0	-

Column RC (40/45)	Constant	magnitude	unit
		Table 4.6 continued	
	Concrete (γ_c)	1,5	-
	Steel (γ_s)	1,15	-
	Axial compression (γ_{cc})	1,0	-
Reduction Factors			
	Axial compression (α_{cc})	1,0	-
	Tension (α_{ct})	0,85	-
	Bending (α_{cw})	1,0	-

Notes:

[1] N.F.: Number of Floors above the column

Figure (4.12) illustrates the corresponding components in Grasshopper.

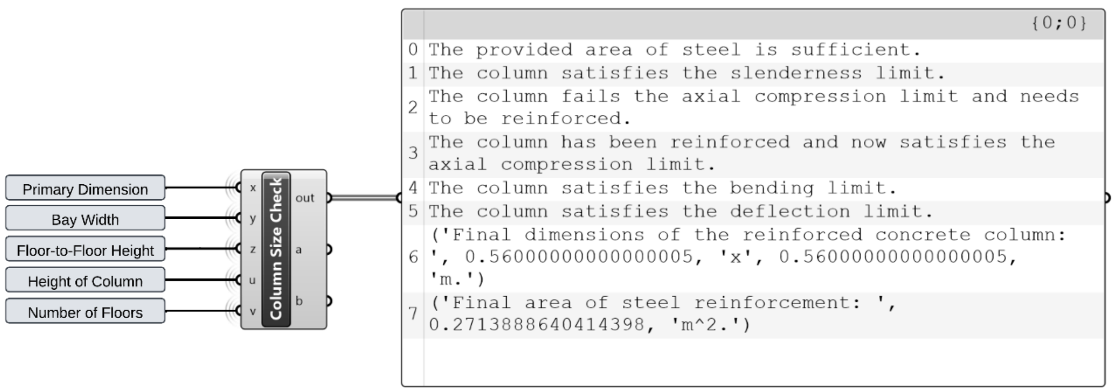


Figure 4.12. An illustration of column designer component inside Grasshopper

4.2.4. Envelope

Designing the building envelope employing parametric design involves considerable hurdles, especially in designing energy-efficient, environmentally sustainable buildings with low carbon footprints. The building envelope denotes the physical barrier between the interior and exterior, consisting of walls, roofs, and windows. To achieve energy efficiency, the envelope must be designed to decrease energy use and encourage sustainability. However, the complexity of parametric design and the variety of parameters that influence the performance of the building envelope make it challenging to improve energy efficiency. To design an appropriate building envelope, architects must consider thermal comfort, daylighting, ventilation, and insulation. In addition to optimizing the envelope, other elements of the building's design, including the selection of materials, the use of renewable energy sources, and the building's orientation, form, and massing, must be considered in designing a low-carbon and sustainable building. Architects, engineers, and environmental experts must collaborate to create solutions that promote energy efficiency and sustainability in building design to overcome these obstacles. Noting that improving insulation levels in building envelopes in compliance with requirements might lead to an increase in embodied carbon despite a reduction in operational carbon. Therefore, a strategy that addresses both operational and embodied carbon emissions is required. Incorporating life cycle assessment in the early phases of design may assist in discovering the potential for decreasing both kinds of emissions by evaluating the entire life cycle of the building, from material extraction through decommissioning. By adopting a Life cycle assessment approach, designers are able to make educated decisions about material selection, design strategies, and construction procedures, resulting in buildings with low carbon footprints.

In order to streamline the scope of this research and minimize the intricacy of the analysis, and since these factors are known to have a substantial influence on the energy efficiency and sustainability of buildings, the research focuses exclusively on the roof, exterior and interior walls, and windows. This study intends to develop design strategies that could optimize the performance of the building envelope, minimize energy consumption, and reduce the total carbon emissions by analyzing these critical attributes. This allows for a more comprehensive investigation of the influence of each parameter on the overall energy performance and supports a more focused approach to building envelope design. The outcome of the parametric analysis in Grasshopper, which enables the exploration of several design variations, serves as a benchmark for designers, offering insights into the performance of different design decisions and their influence on the building's energy consumption and carbon footprint.

The workflow in this study employs a parametric cluster in Grasshopper which considers the building's mass, floor-to-floor height, number of stories, window-to-wall ratio in each cardinal direction, and perimeter zone of the floor area. The parametric cluster facilitates the design of a flexible and adaptable building envelope that can be modified for energy efficiency and other important considerations.

Roof

Data from the analysis of the buildings in Estonia (Ehitisregister) [126] reveals that the common practice of constructions for roofs are either bitumen or PVC sheet or roll material. In compliance with the regulations for minimum requirements for energy performance of buildings [130], one insulation construction was considered for roofs in this study. The construction is derived from a well-known company in Estonia-ROCKWOOL [131].

Specifications

ROCKWOOL 7.1.1 was chosen. Figure (4.13) depicts the cross section of this alternative and the specifications of its layers are summarized in table (4.7).

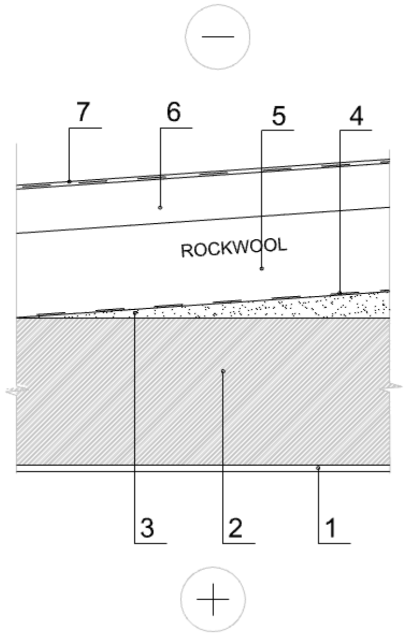


Figure 4.13. Details of selected roof construction

Table 4.7. Specifications of the layers of selected roof construction

Layer	Specification	Thickness (mm)
1	Interior finish - plaster	10
2	Reinforced concrete slab	300
3	Slope layer	-
4	Vapor insulation	-
5	ROOFROCK 30 E	50
6	ROOFROCK 80	30
7	Roof waterproofing	-

Windows

The complexity and variety of window types and material of which windows are made in buildings is axiomatic. Due to the plethora of available materials and the necessity to control variations to suffice for the scope of the study, a particular window profile was selected. This choice was intended to accomplish the requisite degree of rigor and oversight for legitimate academic research. An inspection of the prevalent architectural trends in Estonia reveals a preference for the use of natural and sustainable materials, especially in the construction of residential buildings. Observations of the local built environment indicate a predominance of wooden and wood-aluminum window frames, which is consistent with the country's historic emphasis on timber-based construction and the rising worldwide interest in eco-friendly building techniques. In compliance with minimum requirements for energy performance regulation of Estonia, which restricts the range of 0,6 to 1,1 W/(m2K) for thermal transmittance of windows for residential buildings, figure (4.14) illustrates the NTech triple-glazed passive window profile [132] from NorDan company [133] considered for both simulations and table (4.8) summarizes the specifications of the window.

Figure 4.14. Details of window profile

Table 4.8. Details and specifications of layers of windows

Glazing layers		Thickness (mm)
	Energy coated glass	4
	Vacuumed gap (filled with Argon gas)	16
	Glass	4
	Vacuumed gap (filled with Argon gas)	16
	Energy coated glass	4
Specifications		
	Exterior material	Timber
	Interior material	Aluminum clad timber
	Ventilation	Yes
	Thermal transmittance	0,7 W/m²K

External walls

The exterior wall design of a building has a considerable influence on its overall energy efficiency, thermal performance, and sustainability. Architects and engineers may find it difficult to select the most appropriate wall structure due to the availability of a wide variety of wall structures on the market nowadays. The early consideration of various wall structures is one of the most complex components of the parametric design process, which entails constructing several design variations and putting them through a series of tests to see which one generates positive results.

To address this issue, it has been decided to use the wall construction designs developed by Annemari Tatra who has kindly consented to share the data to help the investigations of this study [134]. The three wall constructions considered for this study were selected on the basis of their demonstrated performance in previous applications and their modifiability through parametric design.

Figure (4.15) illustrates the cross section of the construction of variation 1 and table (4.9) summarizes the specifications of the wall.

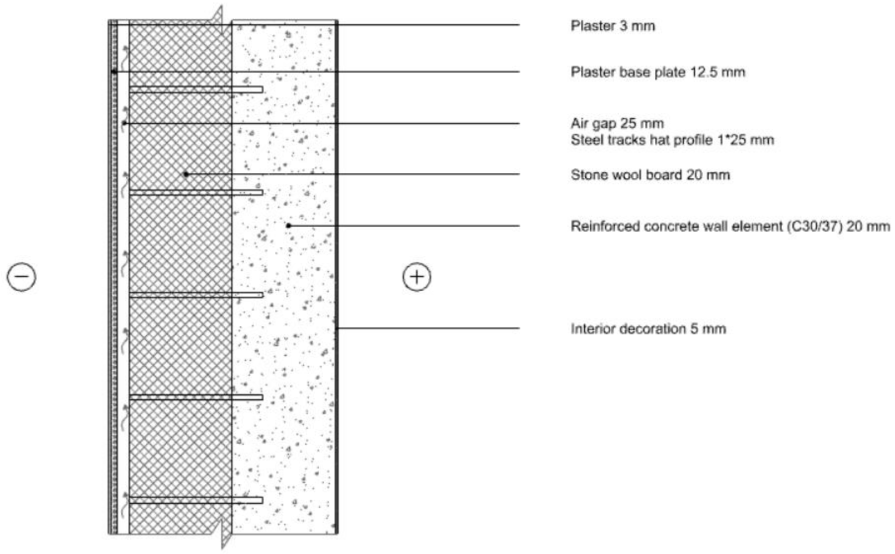


Figure 4.15. Details of layers of Reinforced Concrete Wall (V1)

Table 4.9. Details and specifications of the layers of Reinforced Concrete walls (V1)

Reinforced Concrete – V1			
	Layers	Thickness (mm)	Thermal transmittance W/(m*K)
	Plaster	3	-
	Plaster base plate	12,5	-
	Air gap/steel tracks	25	-
	Stone wool board (μ=1)	200	0,034
	Reinforced concrete element wall (C30/37)	200	2,3
	Interior decoration	5	-

The cross-section of Variation 2 construction is shown in Figure (4.16) and the wall's parameters are summarized in Table (4.10).

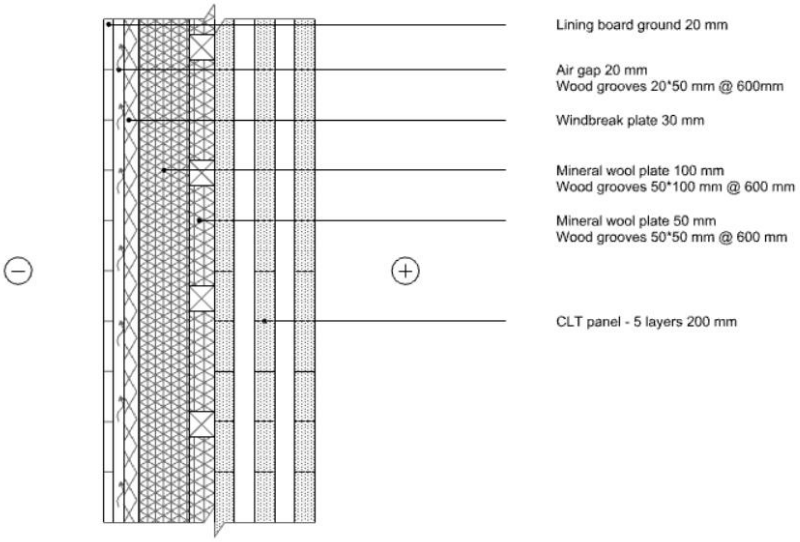


Figure 4.16. Details of layers of Cross-Laminated Timber Walls (V2)

Table 4.10. Details and specifications of the layers of Cross-Laminated Timber walls (V2)

CLT – V2			
	Layers	Thickness (mm)	Thermal transmittance W/(m*K)
	Chipped Plywood	20	-
	Air gap/ wooden grooves	20	-
	Windbreak plate (μ=1)	30	0,031
	Mineral wool plate (μ=1)	100	0,035
	Mineral wool plate (μ=1)	50	0,035
	CLT panel, 5-layer (C24; ρ=480 kg/m3)	200	0,13

The cross-section of Variation 3 construction is shown in Figure (4.17) and the specifications of the wall are reported in Table (4.11).

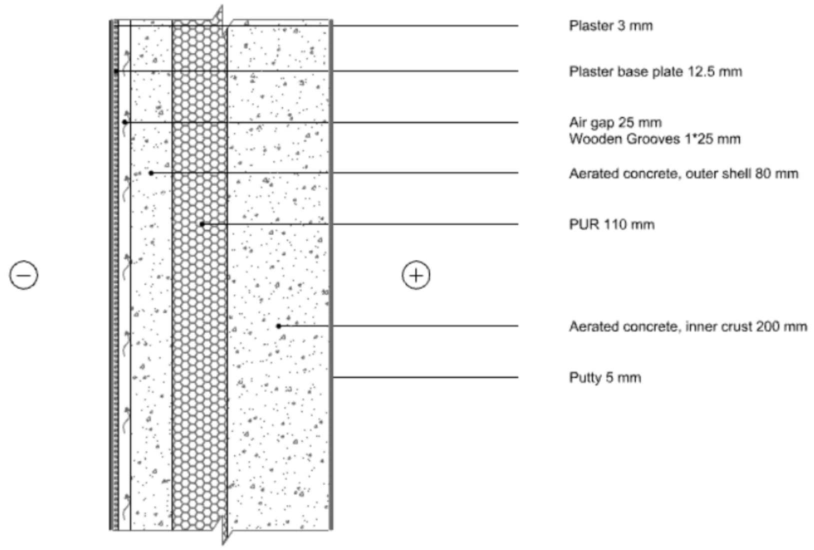


Figure 4.17. Details of layers of Autoclaved Aerated Concrete Walls (V3)

Table 4.11. Details and specifications of the layers of Autoclaved Aerated Concrete walls (V3)

Aerated concrete – V3	Layers	Thickness (mm)	Thermal transmittance W/(m*K)
	Plaster	3	-
	Plaster base plate	12,5	-
	Air gap/wooden grooves	25	-
	Aerated concrete, outer shell (ρ=500 kg/m3)	80	0,13
	PUR (specific conductivity of water vapor=1.8-12 kg/(m·s·Pa))	110	0,029
	Aerated concrete, inner crust (ρ=500 kg/m3)	200	0,13
	Putty	5	-

Internal walls

During the early phases of a building design, there is indeed a significant amount of uncertainty regarding the placement and dimensions of interior walls. This uncertainty is perhaps associated with a number of parameters, such as the requirement to distribute the building's various functions and enhance natural lighting. Consequently, architects and designers may encounter difficulties in generating realistic 3D models of a structure at this point.

This research employs a technique derived from a prior investigation by Hollberg et al. [135]. The application of simplified digital building models, commonly known as early BIM, for LCA was examined in their research. The aim was to facilitate the expeditious enhancement of environmental sustainability during the preliminary stages of design, when numerous variables required for traditional BIM-LCA methodologies remain indeterminate. Subsequently, the proposed methodology was implemented in a case study pertaining to the conceptualization of a residential community.

In their study, internal walls were not included in the building's 3D model during the early stages of design. Rather, these walls were numerically inserted utilizing overall mean factor of 0,4 m/m^2 of Gross Floor Area (GFA), in accordance with the Swiss Minergie regulation [136]. By adhering to this methodology, designers are able to maintain flexibility and adaptability in the design process while guaranteeing compliance with applicable norms and standards.

The Swiss Minergie guideline [136] is a collection of criteria intended to encourage construction energy efficiency. By employing the value of 0.4 m/m^2 of GFA for the length per square meter area of the building for interior walls, it is possible develop energy-efficient parametric building design without sacrificing architectural flexibility or freedom. This strategy has been thoroughly explored and examined, and it is generally recognized as a good method for attaining the optimal balance between energy efficiency and design flexibility.

To simplify the simulation process and decrease the required number of iterations, an interior wall structure based on Paroc [137], a well-known Estonian insulating materials manufacturer, has been used. The selected wall structure includes a double layer of 25 mm gypsum board, 100 mm of PAROC Ultra insulation, and a 100 mm metal frame. This structure has been tested and certified to have a fire resistance rating of EI 90, as well as a laboratory steel RW value of 55 dB and a predicted distortion R'W value of 44 dB. Using a pre-established architecture from a trusted source simplifies the simulation procedure and improves the reliability of the findings. This has the additional advantage of facilitating comparisons between models and permitting more precise forecasts of building performance.

Figure (4.18) depicts the cross-section of the internal walls and table (4.12) summarizes its specifications.

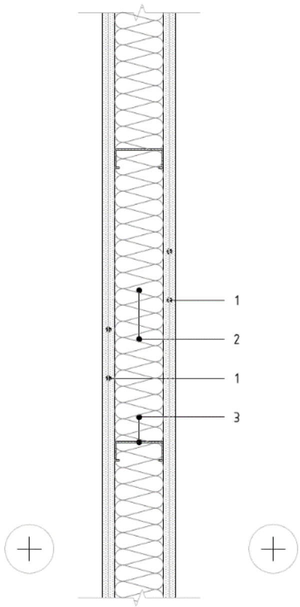


Figure 4.18. Details of selected PAROC internal wall construction

Table 4.12. Details and specifications of the layers of selected PAROC internal walls

Internal Walls			
	Layers	Thickness (mm)	Thermal conductivity (W)/mK
1	Gypsum board (2X)	25	0,19
2	PAROC Ultra	10	0,036
3	Metal frame	10	50
Specifications			
	Technical basis	ETA-07/0071	
	Fire resistance class	EI 90	
	RW of laboratory steel	55 dB	
	Predictable distortion R'W	44 dB	
	Total R-value	3,56 m^2.K/W	
	Total U-value	0,28 W/ m^2.K	
	Total thermal capacitance	72,25 kJ/ m^2.K	

Floors

The selection of flooring systems is one area of design where this uncertainty is very prevalent and there are a plethora of constructions to opt for. The flooring system is an important interface between the building envelope and the inhabitants. It serves an important role in regulating the interior environmental quality of the building, controlling heat and moisture transmission, and providing inhabitants with a durable and serviceable floor.

In order to solve the issue of complexity due to abundance of variations, this study analyzes one floor construction that is a modified version of a floor detail offered by PAROC [137], a well-known Estonian corporation. This strategy seeks to decrease the complexity and number of simulation iterations by adopting a tried-and-true, extensively implemented solution. The chosen structure consists of a parquet surface, an adhesive layer, a reinforced smoothing layer, a separating filter film, PAROC SSB 1 insulation, a leveling layer, a reinforced concrete ceiling, and a plaster interior finish.

Using this strategy, the research seeks to create a more streamlined and efficient design process that may enhance the simulation findings' precision and dependability. Early in the design phase, the implementation of a well-established flooring system with known performance indicators may decrease the risk of design mistakes and increase the degree of assurance. Ultimately, this strategy may assist in maximizing the building's overall efficiency while reducing its environmental effect and providing residents with a pleasant interior atmosphere.

Figure (4.19) illustrates the details of the floor structure, and a summary of the layers and specifications has been provided in table (4.13).

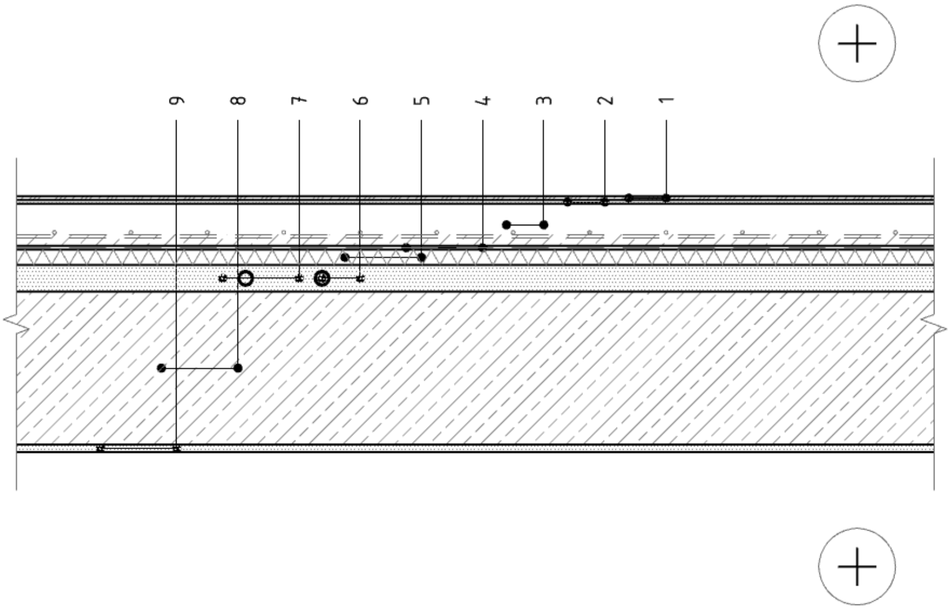


Figure 4.19. Details of selected PAROC floor construction

Table 4.13. Details and specifications of the layers of the selected PAROC floor construction

Floors			
	Layers	Thickness (mm)	Thermal conductivity (W)/mK
1	Floor parquet covering	10	0,15
2	Adhesive layer	4	0,2
3	Reinforced leveling layer	≥ 50	0,7
4	Separating filter film	-	0,15
5	PAROC SSB 1	20	0,045
6	Communications pipelines	-	0,15
7	Leveling layer	≥ 30	0,7
8	Reinforced concrete ceiling	300	2
9	Interior finish - Plaster	5	0,5
Specifications			
	Sound insulation index RW	62 dB (Ct-1; Ctr-5)	
	Reduced impact noise level index L'n, w	48 dB	
	Total R-value	4,64 m^2.K/W	
	Total U-value	0,216W/ m^2.K	
	Total thermal capacitance	810,68 kJ/ m^2.K	

4.2.5. Embodied Carbon parametric workflow

The present study utilizes the OneClick LCA [124] plugin in grasshopper to evaluate the embodied carbon of the aforementioned samples. As elucidated, the workflow receives the building attributes as input and establishes an LCA profile for each. Subsequently, diverse materials are allocated to each profile based on the construction particulars in the ensuing stage. The materials utilized in construction serve as inputs for the creation of building attributes, which are then subjected to LCA analysis. The analysis component facilitates real-time monitoring of embodied carbon emissions from A1 to A3 stages of constructions, enabling the comparison of different construction solutions. Figure (4.20) depicts a schematic process of OneClick LCA workflow in Grasshopper.

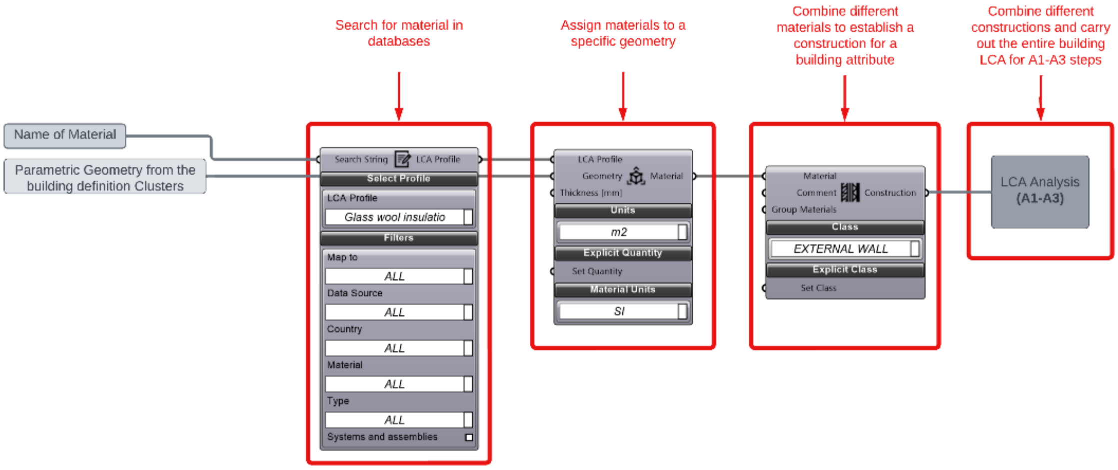


Figure 4.20. Schematic process of OneClick LCA workflow

4.2.6. Operational carbon parametric workflow

The Estonian regulations pertaining to the methodology for calculating the energy performance of buildings [138] offer clear directives for determining buildings' energy consumption. The present investigation adheres to the established regulations for determining the inputs of the EnergyPlus model. The energy zones of the building were established according to the occupant, equipment, lighting, and hot water specifications outlined in Table 2 of Chapter 3 of the aforementioned regulations. The HVAC system's settings in the workflow are derived from Article 10 of the Estonian regulations outlining the minimum requirements for energy performance [130].

The energy parameters utilized were derived from the Estonian directive were those specified for the residential buildings. Table (4.14) provides a summary of the settings, assumptions, and considerations pertaining to the energy section of the workflow. The notes section offers explanations regarding the resources that informed the choices made in this regard.

Table 4.14. Summary of settings, assumptions and considerations for energy workflow based on Estonian regulations for residential buildings

Zone Setting		Parameter	Value	Unit	Reference
Loads					
	Occupants				
		People density	0,035 [b]	P/m²	Referring to EMEPB [a], Article 6, Table 1
		Metabolic rate	1,2	met	Referring to EMEPB, Article 6
		Occupancy Schedule	-	-	Referring to EMEPB, Article 6, Table 2, Residential Building Occupants
	Equipment				
		Equipment power density	3	W/ m²	Referring to EMEPB, Article 6, Table 1, Appliances
		Equipment availability schedule	-	-	Referring to EMEPB, Article 6, Table 2, Residential Building Equipment
	Lighting				
		Lighting power density	8	W/ m²	Referring to EMEPB, Article 6, Table 1, Lighting [c]
		Light availability schedule	-	-	Referring to EMEPB, Article 6, Table 2, Residential Building Lighting
		Illuminance target	300	Lux	Author’s assumptions and considerations
		Dimming type	Stepped	-	Author’s assumptions and considerations
	Hot water				
		Energy demand (constant)	30	kWh/m²y	Referring to EMEPB, Article 7, Table 5, energy need for multi-apartment buildings
Conditioning (HVAC)					
	Heating				
		Heating setpoint	21	°C	Referring to MREP [d], Article 10, subsection 4, Heating setpoint for multi-apartment buildings
	Cooling				
		Cooling setpoint	27	°C	Referring to MREP, Article 10, subsection 4, Cooling setpoint for multi-apartment buildings
	Mechanical ventilation				

Zone Setting	Parameter	Value	Unit	Reference
				Table 4.14 continued
	Minimum fresh air per person	14,15 [e]	L/s/P	Referring to EMEPB, Article 6, Table 1, Occupants and MREP, Article 10, subsection 4, outdoor flow rate for multi-apartment buildings
	Minimum Fresh air area	0,5	L/s/m²	Referring to MREP, Article 10, subsection 4, outdoor flow rate for multi-apartment buildings
	Natural ventilation			
	Window opening ratio	10	percent	Author's assumptions and consideration
Envelope [f]				
	Infiltration	Parametrically variable [g]	ACH [h]	Referring to EMEPB, Division 3, Article 13, Determination of the infiltration air flow rate

Notes:

a) Estonian Methodology for calculating the energy performance of buildings.
b) The Estonian Methodology for calculating the energy performance of buildings, in its Article 6 and Table 1, specifies that the area value allocated for occupants is 28.3 square meters per person. To obtain the people density value as required in the workflow settings, it is necessary to invert the numerical value.

$$\text{People density} = \frac{1}{\frac{\text{m}^2}{\text{Person}}} = \frac{\text{Person}}{\text{m}^2}$$

$$\text{People density} = \frac{1}{28{,}3} = 0{,}035\ \frac{\text{Person}}{\text{m}^2}$$

c) The notes section of the aforementioned table elucidates that the usage rate for lighting in residential buildings is 0,1. Nevertheless, Given the significant correlation between daylight availability and electricity usage in lighting within residential buildings, this study intends to deviate from regulations in order to obtain results with distinguishable significance from the simulation.
d) Minimum requirements for energy performance
e) In Article 10, subsection 4 of Minimum requirements for energy performance, the minimum fresh air per area is declared to be 0,5 Liters per second per square meter and in Table 1, Article 6, of Estonian Methodology for calculating the energy performance of building, the area value allocated for occupants is 28,3 square meters per person. Therefore, the minimum fresh air per person can be calculated as follows:

$$\text{minimum fresh air per square meter } (\text{L/s/m}^2) \times \text{minimum required area per person } (\text{m}^2/\text{P})$$

$$0{,}5\ (\text{L/s/m}^2) \times 28{,}3\ (\text{m}^2/\text{P}) = 14{,}15\ (\text{L/s/P})$$

f) All envelope attributes are set as defined in the section of envelope construction details.
g) Please see the calculations and explanations in the infiltration item.
h) ACH stands for Air Change per Hour

Infiltration

Estonian Methodology for calculating the energy performance of buildings provides the following formula as a means of calculating the infiltration air flow rate:

$$q_i = \frac{q_{50}}{3,6 \times x} \times A \qquad (4.1)$$

where:

q50 represents the mean rate of air leakage in cubic meters per hour per square meter of the building envelope, which in accordance with article 9, Table 6 of the same regulations is considered 3 m^3/hm^2.

A represents the total area of the building envelope, which also includes all floors, measured in square meters.

X varies depending on the number of stories in a building. For a single-story building, x is equal to 35. For a two-story building, x is equal to 24. For buildings with three or four stories, x is equal to 20. Finally, for buildings with five or more stories, x is equal to 15. It is important to note that the height of each story is 3 meters. In this study, since the stories of the building variations varies between 5 to 9 stories, x can be considered 15. Since we require the infiltration in m^3/h, we do not consider the factor of 3.6, which is used to convert m^3/h to L/s. Therefore, the formula to calculate infiltration changes to:

$$q_i = \frac{q_{50}}{x} \times A \qquad (4.2)$$

In order to calculate Air Change Per Hour, it is required to divide the infiltration, which is calculated based on Estonian regulations, on the volume of the building.

$$ACH = \frac{q_i}{V_i} \qquad (4.3)$$

Where:

q_i is the infiltration of the entire building envelope including its floors.

V_i is the volume of the same building.

A special parametric workflow was defined to calculate ACH for each building variation parametrically and the corresponding ACH was employed in the EnergyPlus workflow.

Specifications and Calculations of HVAC systems

Given the previously mentioned variables, the workflow calculates the energy demand per square meter of each building for its heating, cooling, and electricity separately. The calculation of delivered energy in each section is based on the coefficients of each part, as per the regulations outlined in the Estonian methodology for calculating the energy performance of buildings and is contingent upon the author's assumptions regarding HVAC systems.

Table (4.15) presents an overview of the HVAC systems that were taken into consideration, along with their respective coefficients and the corresponding sections of the aforementioned regulations that pertain to each coefficient value.

Table 4.15. Assumptions and considerations of HVAC systems

Heating and Cooling Systems	Assumptions	Efficiency Factors
Heating		
	District Heating Substation	0,9
	Radiators	0,97
Cooling		
	Cooling System emissions and distribution losses	1,1
	Compressor-driven Cooler	3,5

Subsequently, the calculated delivered energy for each part of the building energy demand was multiplied by the corresponding Future scenario for the CO_2 emission factors of the energy carrier [139], [140] within the scope of 50 years and calculates the entire CO_2 emission of the usage stage (B6) of each building variation. Figure (4.21) depicts the stages of the calculations.

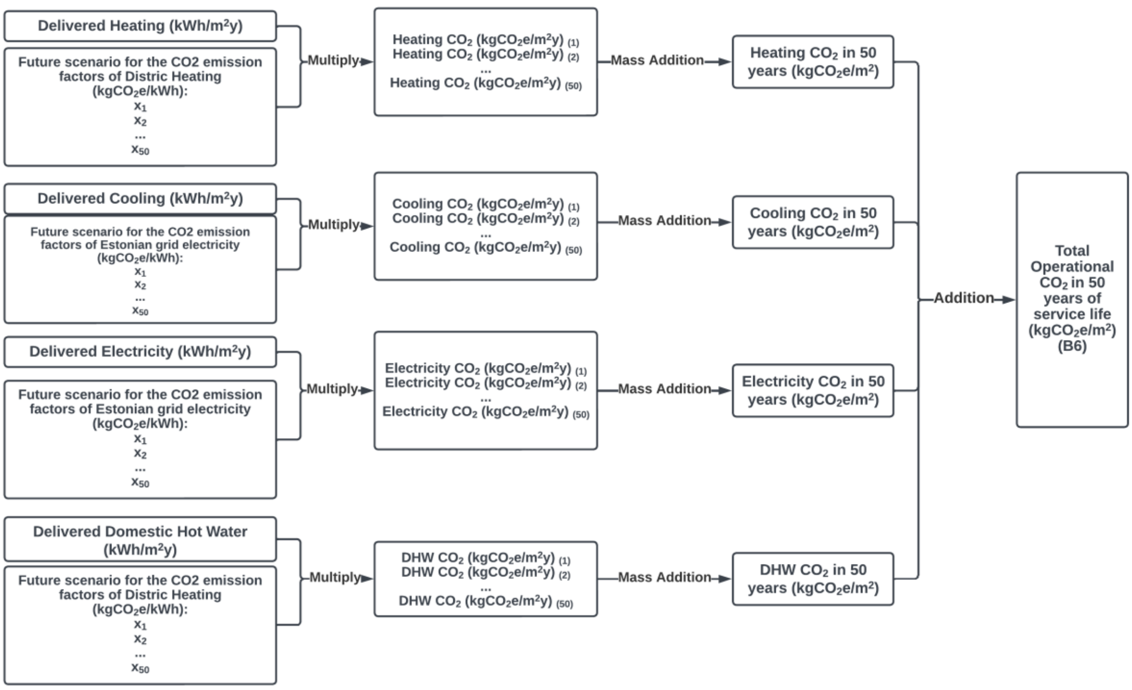


Figure 4.21. Stages of calculation of Operational Carbon

Furthermore, in order to foresee and compare the energy performance of each variation, the primary energy demand of each building variation was calculated using the energy carrier conversion factors declared in Article 9 of Minimum requirements for energy performance regulations in Estonia. Table (4.16) summarizes the energy carriers and their corresponding conversion factors based on the aforementioned regulation.

Table 4.16. Summary of considered energy carriers and their corresponding conversion factors

Energy demand	Energy carrier	Conversion factor
Heating		
	Efficient District Heating	0,65
Cooling (Compressor-driven Cooler)		
	Estonian grid electricity	2,0
Electricity		
	Estonian grid electricity	2,0
Domestic Hot Water		
	Efficient District Heating	0,65

Figure (4.22) illustrates the method for the calculation of the primary energy and the performance of each building variation based on the simulation as well as the Estonian methodology.

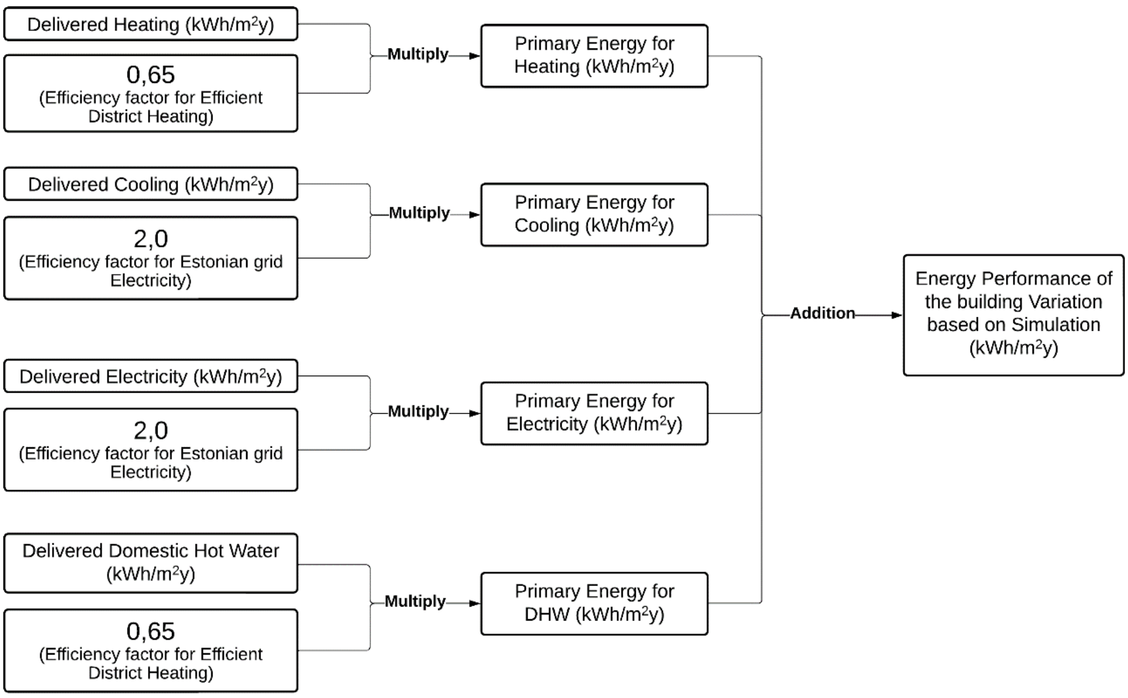


Figure 4.22. Flow chart of the methodology of the calculations of primary energy demand and energy performance of building variations based on simulations

In table 1 of article 6 in chapter 3 of Estonian Methodology for calculating the energy performance of buildings, which is pertinent to standard use of buildings, the maximum values of heat gain per square meter of heated area of buildings were summarized.

The values for multi-apartment buildings which are under investigation in this study are briefed in table (4.17).

Table 4.17. Summary of the usage rate of residential buildings based on Estonian regulations

Type of Building	Occupied hours			Usage	Lighting	Appliances
	Hours	Hours/24h	Days/7d	rate	W/m^2	W/m^2
Multi apartment building	00:00 – 00:00	24	7	0,6	8 [a]	3

Notes:
a) *The usage rate of lighting for residential buildings is considered 0,1 based on note c of the table 1 of the regulation.*

The aforementioned regulation calculates the use of electricity by considering it equal to the heat release of the lighting for lighting electricity use and divides the appliance heat release by the factor 0.7 for the electricity use of appliances in residential buildings. According to the aforesaid regulation the heat release of the lighting and appliances is calculated using the following formula:

$$\boldsymbol{Q = kP\frac{\tau_d}{24}\frac{\tau_w}{7}\frac{8760}{1000}} \qquad (4.4)$$

where
k is the usage rate
P is the heat release W/m^2
τ_d is the number of occupied hours of the building per 24 hours of a day
τ_w is the number of days of occupancy of the building per week

According to table (4.17) and equation 4, the electricity use of lighting and appliances were calculated.

$$Q_{Lighting} = 0{,}1 \times 8 \times \frac{24}{24} \times \frac{7}{7} \times \frac{8760}{1000} = 7{,}008\, kWh/m^2y = Electricity\ usage\ of\ lighting$$

$$Q_{Appliances} = 0{,}6 \times 3 \times \frac{24}{24} \times \frac{7}{7} \times \frac{8760}{1000} = 15{,}768\, kWh/m^2y = 0.7\ Electricity\ usage\ of\ Aplliances$$

$$Electricity\ usage\ of\ Aplliances = \frac{Q_{Appliances}}{0{,}7} = 22{,}526\ kWh/m^2y$$

The Estonian Methodology for calculating the energy performance of buildings, considers the above numbers alongside energy usage of all HVAC auxiliary device. The latter requires detailed design, and since this study intends to focus on early stage of design, the author considers some experienced assumptions for this part of calculations. Table (4.18) summarizes the assumptions.

Table 4.18. Assumptions of HVAC auxiliary devices

Auxiliary devices	Value	Unit
Pumps	1,0	kWh/m^{2}y
Fans	11,0	kWh/m^{2}y
Supply air heating	7,2	kWh/m^{2}y

Note:

The values are derived from a practice lecture at TALTECH by Martin Thalfeldth, PhD.

The sum of values of the table alongside 30 kWh/m^{2}y of energy demand for Domestic Hot Water results in the value of 78,7 kWh/m^{2}y for the fixed primary energy demand of residential buildings. Adding the final calculated primary energy demand for Heating in each building variation to this fixed value returns the energy performance of the building variations based on Estonian regulations. Figure (4.23) illustrates the procedure.

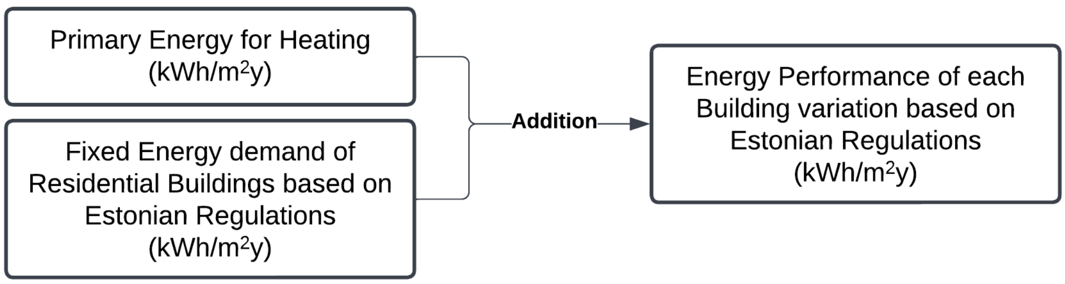


Figure 4.23. Methodology of calculating building variations energy performance based on Estonian Regulations for residential buildings

Calculating the energy performance based on Estonian Regulations provides an opportunity to primarily compare the results of the simulation with the results calculated based on regulations. Moreover, it provides a measure to compare the energy performance of different building variations based on a practiced and experienced methodology.

4.3. Assumptions of the study

The undertaking of research in any given field is frequently intricate and demanding. This is notably accurate with regards to parametric design. Undoubtedly, various limitations and challenges have arisen during the course of developing models and deriving eloquent conclusions from the research. As a result of the intricate nature of the investigation, the author of the study was compelled to integrate several assumptions into the parametric methodology. The aforementioned assumptions were employed with the intention of streamlining the model and rendering it more amenable to scrutiny. Although the assumptions were imperative for the progression of the study, they may have contributed to a certain level of uncertainty which is bound to occur in the findings. However, efforts have been made to mitigate these uncertainties. Table (4.19) provides a briefing on all the assumptions of the study.

Table 4.19. Summary of the assumptions of the study

Building attribute	Sub-Category	Assumptions	Explanations
Shape		Subjective definitions Basic architectural shapes	-
	Dimensions	Limited to the boundary of studied buildings in Tallinn	-
	Building width	Only average width for each shape	-
	No. of Floors	Only 5, 7, and 9 floors	-
Structure		Only reinforced concrete structure	-
	System	Only flat slab and columns system	-
	Loads	Only typical loads for Estonia	-
	Design	Based on single elements and concentrated on the size of elements.	-
Envelope			
	Roof	Only one roof construction details	Efforts have been made to be close to what happens in construction market in Estonia.
	Windows	Only one type of window	It is based on the minimum requirements for energy performance in Estonia.
	External walls	Three different constructions for external walls	The constructions are based on a brilliant study by TALTECH student Annemari Tatra.
	Internal walls	The length of internal walls assumed to be 0.4 m/m^2 of the gross floor area of the building based on Swiss Minergie Regulations. Only one construction was considered.	Reduction of the complexity was the purpose.
	Floors	Only one floor construction was considered.	Efforts were made to consider the floor construction completely close to what happens in Estonian construction market.

5. RESULTS

The study entailed conducting a total of 3888 simulations encompassing various building shapes and their respective variations and specifications. This section will provide a detailed presentation of the exceptional findings obtained from the study. Initially, the carbon performances' maximums, averages, and minimums are presented, along with the corresponding morphologies that led to these outcomes. The subsequent presentation outlines the optimal, median, and suboptimal energy performance, as well as the corresponding morphologies that yielded these outcomes, among all other morphologies. Afterwards, a comparison between various shapes and their significant discoveries is delineated. Following that, an analysis is conducted on the impact of shape on performance. The maximum, average, and minimum outcomes of each shape are presented alongside the corresponding morphologies that yielded declared outcomes. The parallel coordinates graphs in Figures (5.1) and (5.2) depict the complete set of outcomes derived from the simulations in both no surrounding condition and urban context.

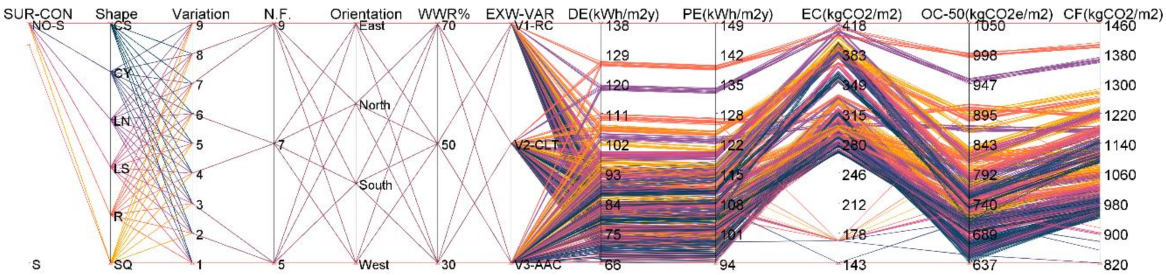


Figure 5.1. An illustration of results for all shapes in no surrounding condition

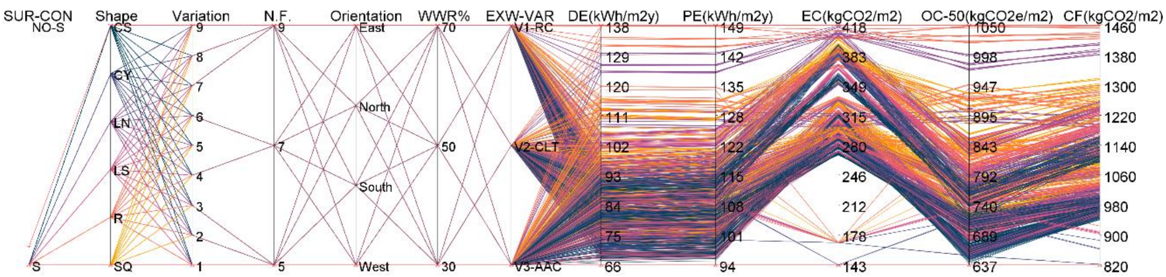


Figure 5.2. An illustration of results for all shapes in an urban context

Guide:

SUR-CON: Surrounding Condition
NO-S: No Surrounding
S: In an Urban Context
N.F.: Number of Floors
WWR%: Window-to-Wall Ratio

EXW-VAR: External Wall Variation
DE: Delivered Energy
PE: Primary Energy
EC: EC (A1-A3)
OC-50: OC(B6) over the period of 50 years
CF: CF (A1-A3 & B6)

CS: C-shape Buildings
CY: Courtyard Buildings
LN: Linear Buildings
LS: L-Shape Buildings
R: Rectangular Buildings
SQ: Square Buildings

The second part of the section presents findings pertaining to the morphologies of buildings. The subsequent segment of this section involved an analysis and comparison of the impact of various parameters including orientation, window to wall ratio, external wall constructions, number of floors, and envelope to volume ratio on the outcomes. Furthermore, the optimal, median, and suboptimal solutions for each shape were presented.

5.1. Carbon Footprint

Over a span of 50 years, the value of Carbon Footprint (CF) among all variations ranges between 820,05 and 1411,17 $kgCO_2e/m^2$ in no surrounding condition. The range surges to 822,39 to 1460,32 $kgCO_2e/m^2$ in an urban context. The results obtained regarding the maximum, average, and minimum of CF values for each shape served as a metric for assessing the differences in their respective ranges. The figure (5.1) illustrates that in no surrounding condition and out of the 1944 variants of various shapes, the variant with the minimum CF was a 25606,18 m^2 courtyard building with seven floors which was oriented towards the North and whose Window-to-wall Ratio (WWR) was 30% and had a construction of Cross-Laminated Timber (CLT) external walls. A rectangular building with 1789,52 m^2 of Gross Floor Area (GFA) with an orientation towards the East which was 5 floors high with WWR of 30% and Autoclaved Aerated Concrete (AAC) external walls exhibited the mean amount of 1077,98 $kgCO_2e/m^2$ of CF among all variants. Furthermore. The worst variant with regards to having the highest CF among all other variations was a rectangular building with the height of 5 floors and was oriented towards the East with 1062,77 m^2 of GFA, WWR of 70% and the construction of its external walls was AAC. Additionally, it was observed that in an urban context (Figure 5.2), the maximum and minimum CF was observed to associate with the same explained variants explained in no surrounding condition. However, a 5 floors high square shape building with 1787,94 m2 GFA which was oriented towards the North and had a WWR of 30% and external walls of CLT exhibited the average value of 1091,34 $kgCO_2e/m^2$ as its CF.

5.2. Operational Carbon

Additionally, upon analysis of the Operational Carbon (OC) ranges, it has been determined that the quantity ranges from 637,15 to 999,62 $kgCO_2e/m^2$ across all variations in no surrounding condition within a 50-year period. A C-Shape building oriented towards the North with 9 floors and WWR of 30% and external wall construction of AAC exhibited the least amount of OC emission. On the other hand, a 5-floor high rectangular building with CLT external walls, 70% of WWR and 1062,77 m^2 of GFA which was oriented towards the East had the highest amount of OC emission. The average value of OC in no surrounding condition which was 756,62 $kgCO_2e/m^2$ belonged to a rectangular building with an orientation towards the East, 5 floors, WWR of 30% and external wall construction of Reinforced Concrete (RC) which had 1789,52 m^2. The same explained variations owned the maximum and minimum amount of OC in an urban context as well. Nevertheless, the mean value was observed to be connected with a 9-floor high courtyard building with 36472,80 m^2 of GFA and orientation towards the East. The envelope specifications of this building were 70% of WWR and AAC external walls.

5.3. Embodied Carbon

The building with the lowest Embodied Carbon (EC) was identified as a courtyard building with 5 floors and 18977,08 m^2 of GFA and envelope specifications of 50% WWR and CLT external walls. The average amount of EC was exhibited by an L-shape building with 7 floors and GFA of 5203,21 m^2. The external walls of the building had a construction of AAC, with a WWR 30%. The building with the highest EC was a 5-floor high linear building. Having 1273,91 m^2 of GFA, this building had a WWR of 70% and the external walls construction was AAC. Since transportation is not considered in the scope of the study, as axiomatic it is, surrounding conditions do not have any contribution to the EC emissions of the studied buildings.

5.4. Delivered Energy demand

The study revealed that the delivered energy demand for all shapes in no surrounding condition was found to vary from 66,09 to 126,91 kWh/m^2y. The least demand was for a C-Shape building with 21311,88 m^2 GFA, 9 floors and WWR of 30%. The orientation of the building was towards the South and its external walls had a construction of AAC. The mean value of delivered energy was also connected to a C-Shape building. The building with mean value, however, had 17751,79 m^2 of GFA and was 7 floors high and was oriented towards the West and had a WWR of 70% and external wall construction of CLT which demonstrated a demand of 86.34 kWh/m^2y. The worst variant pertaining to delivered energy demand was a 5-floor high rectangular building with a GFA of 1062,77 m^2 and WWR of 70% as well as CLT external walls which was oriented towards the East. In an urban context, a surge was observed in the range of delivered energy increasing it to span between 66,85 to 138,13 kWh/m^{2}y. The maximum and minimum values in the urban context were connected to the same variant which were explained in no surrounding condition, while a 9 floors high C-shape building with 22372,89 m^2 of GFA which had a WWR of 70% and external walls constructed of RC and was oriented towards the East demonstrated 89,63 kWh/m^{2}y of delivered energy demand which was the average of the range.

5.5. Primary Energy demand

The primary energy demand of variations in no surrounding condition exhibits a range of 94,17 to 139,57 kWh/m^{2}y. The study revealed that the optimal variant in respect of primary energy demand was L-Shape building with 13967,90 m2 of GFA and AAC external walls, WWR of 30% and 9 floors which was oriented towards the North. The average value of 109,64 kWh/m2y was exhibited by a C-Shape variant with 9 floors, CLT external walls, WWR of 70% and an orientation towards the East which had a GFA of 22823,73 m^2. The variant exhibiting the greatest primary energy demand coincided with the one displaying the highest delivered energy demand in no surrounding condition. A consistent pattern of increase in the range of primary energy demand was observed by positioning the buildings in an urban context. The minimum value was found related to the same building which had the minimum value of energy demand in no surrounding. The average value of 112,52 kWh/m^{2}y was connected to a 9-floor high linear building with WWR 30%, AAC external walls and 2293,04 m2 of GFA which was oriented towards the East. The maximum amount of primary energy demand belonged to a rectangular building with the same specifications as the maximum delivered energy demand except for its external walls which had a construction of CLT.

5.6. Comparison of performances based on morphologies

The comparison among different shapes is presented in Figures (5.3) and (5.4). The presented figures effectively illustrate the ranking of building performances, ranging from the highest performing courtyard shape to the lowest performing rectangular shape.

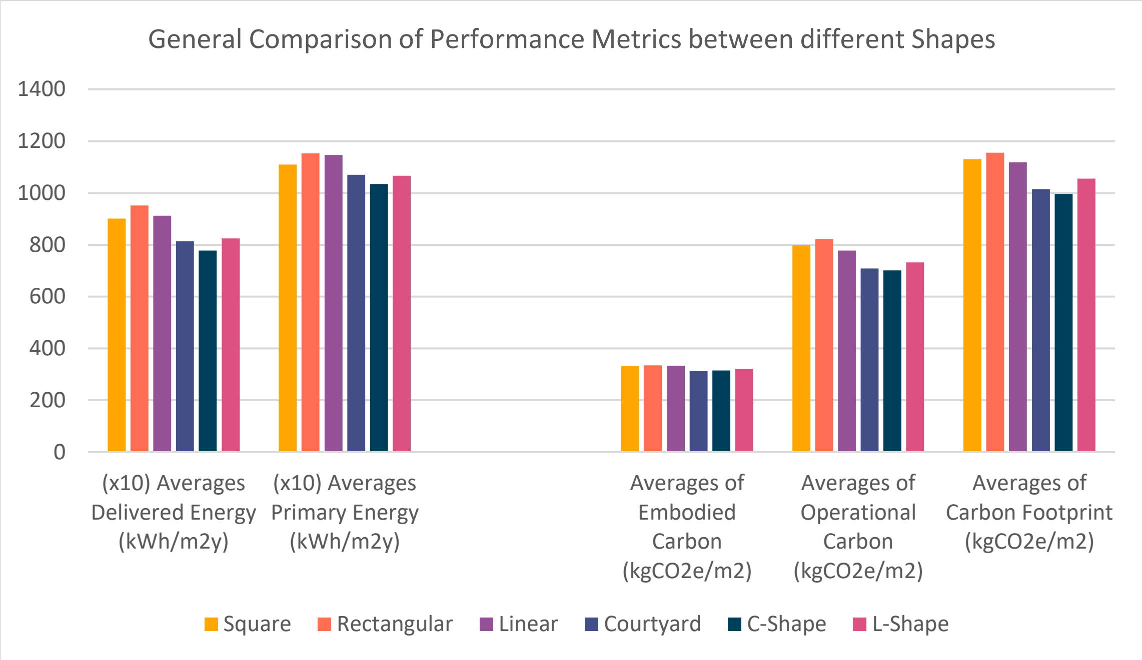


Figure 5.3. Comparison in no surrounding condition

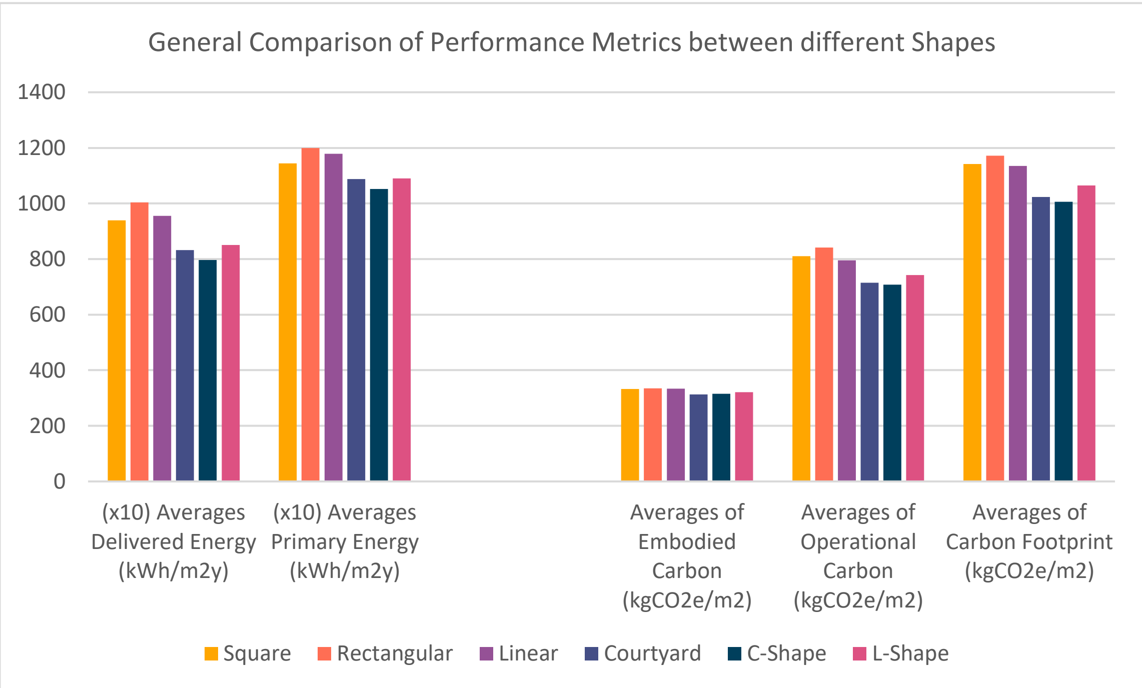


Figure 5.4. Comparison in an Urban Context

A noteworthy observation indicates that, overall, the CF and operational carbon, as well as delivered and primary energy demand metrics in urban areas, are slightly higher than those of counterparts without any surrounding. The rationale behind this phenomenon is that the shading effect caused by adjacent buildings results in a reduction in the requirement of cooling energy. Conversely, it brings about an elevation of energy consumption for the purposes of indoor heating and electric lighting. As a result, the context in which these metrics are accounted for has a significant impact on their outcomes, which tend to be unfavorable in an urban setting. The delivered energy exhibits a greater percentage change between the two distinct surrounding conditions compared to the primary energy. Similarly, the percentage change in OC is higher than that of the CF. Figure (5.5) illustrates a comparison between the percentages of increase in the four above-mentioned performances.

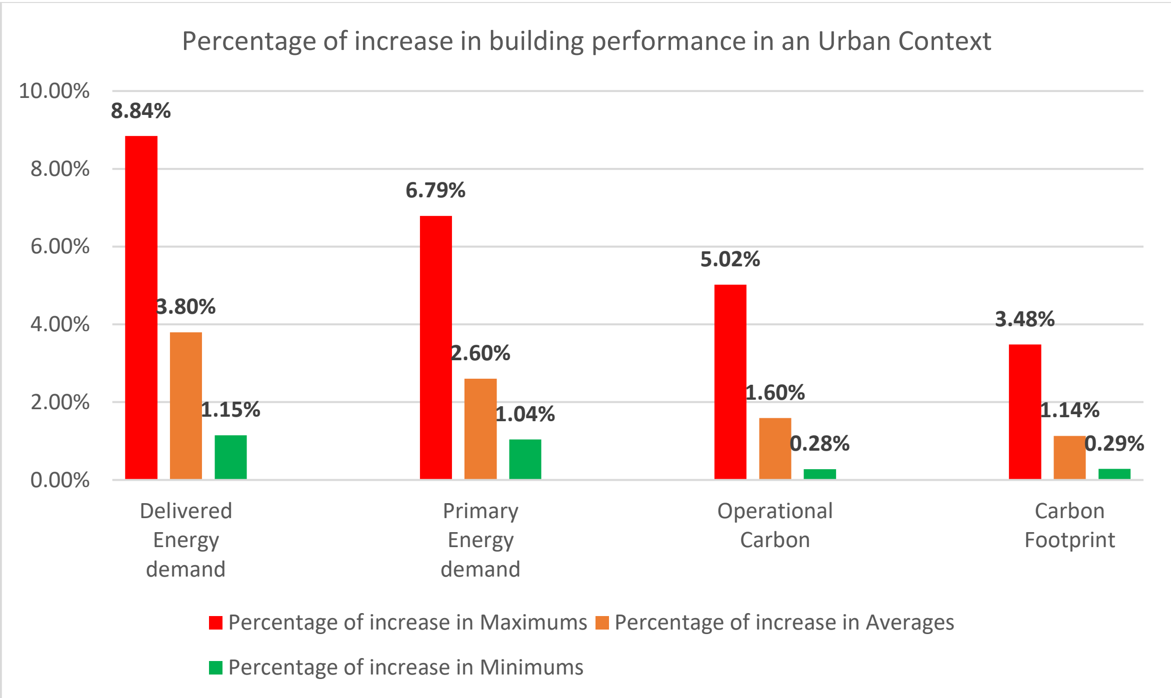


Figure 5.5. Percentage of increase in building performance in an urban context comparing to no surrounding condition

Another notable observation is that the percentage alteration in the maximum values of shapes across all aforementioned outcomes is considerably greater than the percentage of change observed in the minimum and average values. The aforementioned observation suggests that the impact of the adjacent buildings on buildings with an optimal level of energy consumption and carbon emissions is comparatively less than that on buildings with elevated energy demands and CF.

5.7. The effect of shape

As delineated in the methodology section, each geometric shape has nine distinct variations that vary in their dimensions of length, width, and height. This section provides a comprehensive report on the outcomes of performances for each shape derived from the simulations in the subsequent subsections. The diagrams depicted in Figures (5.6) to (5.11) present a comprehensive overview of the outcomes obtained for various building configurations. The shapes and surrounding conditions have been differentiated using a color-coded scheme, and the analysis has been conducted with respect to the individual shape and its surrounding conditions.

5.7.1. Square Buildings

A total of 648 variations of square buildings were examined across all simulations. The outcomes pertaining to CF exhibited a range of 940,96 to 1286,18 $kgCO_2e/m^2$ with an average of 1155,13 $kgCO_2e/m^2$ in no surrounding condition. The range for EC was between 168,93 and 413,58 $kgCO_2e/m^2$ and the average value was 334,37 $kgCO_2e/m^2$. Furthermore, the OC spanned between 689,95 and 999,62 $kgCO_2e/m^2$. As can be observed in figure (5.6) the minimum value of both CF and EC belongs to variation 2 with GFA of 2127,37 m^2, external wall construction of CLT and WWR of 50% which was oriented towards the North. Variation 2 in square buildings is 5 floor high. Conversely, variation 1 with 5 floors and GFA of 2641,89 m2 which had an orientation towards the North, WWR of 70% and external wall construction of AAC displayed the maximum EC among square buildings. The average value of CF was connected to variation 3 which has a height of 5 floors and its orientation is towards the North with a WWR of 50%, AAC external walls and GFA of 1787,94 m^2. The same variation exhibited the average of 332,14 $kgCO_2/m^2$ of EC while having a WWR of 30%. The maximum CF was associated with variation three with the same specifications except for the WWR of 70%. The same variation also demonstrated the maximum OC emission when its external walls construction is RC. The average OC emission of 798,3 $kgCO_2/m^2$ is connected to variation 8 which is 9 floors high and has a GFA of 3829,27 m^2. This building had external wall construction of AAC, WWR of 50% and was oriented towards the North. The same variation 8 exhibited the lowest OC when it was oriented towards the East and had a WWR of 30%. As it is clear in figure (5.6), ranges of CF and OC are slightly higher in an urban context spanning between 924,29 and 1460,32 $kgCO_2e/m^2$ for CF, and 691,82 to 1049,84 $kgCO_2e/m^2$ for OC with averages of 1171,76 $kgCO_2e/m^2$ and 841,51 $kgCO_2e/m^2$, respectively. The same variations and specifications exhibited the maximum, average and minimum values. The only difference was observed in the average value of the CF which was obtained from the same variation while it had a WWR of 50%.

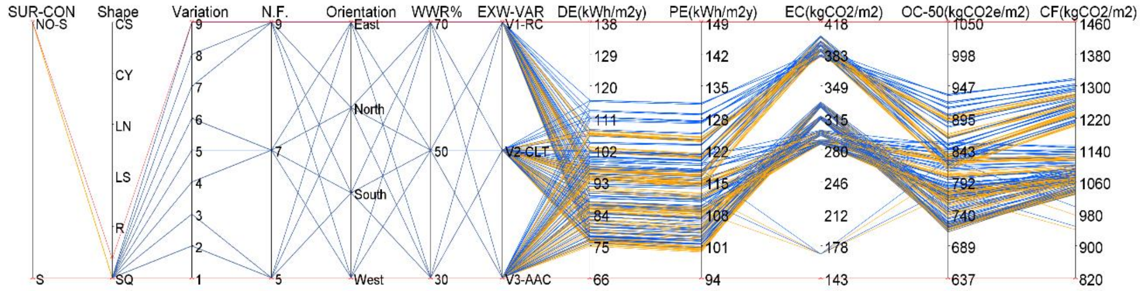


Figure 5.6. Results of Square buildings (No Surrounding condition and Urban Context)

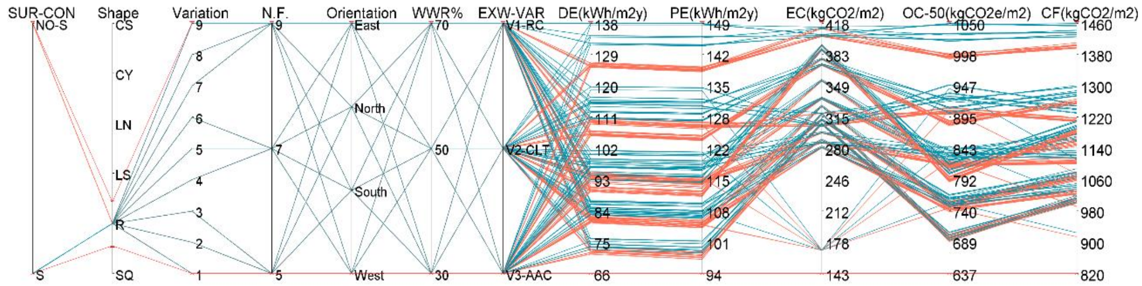


Figure 5.7. Results of Rectangular buildings (No Surrounding condition and Urban Context)

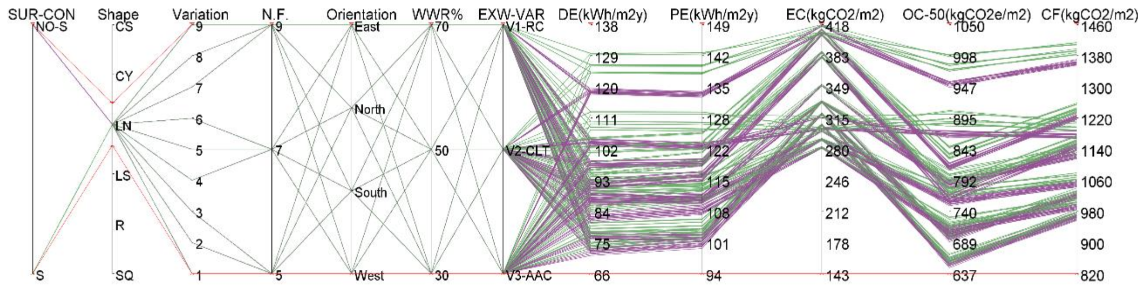


Figure 5.8. Results of Linear buildings (No Surrounding condition and Urban Context)

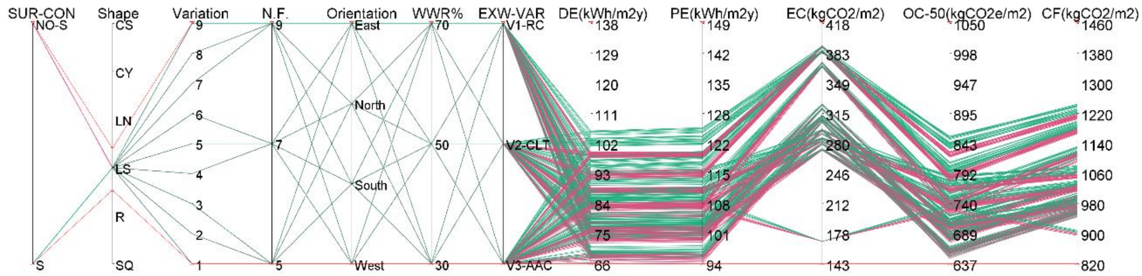


Figure 5.9. Result of L-Shape buildings (No Surrounding condition and Urban Context)

Guide:

SUR-CON: Surrounding Condition
NO-S: No Surrounding
S: In an Urban Context
N.F.: Number of Floors
WWR%: Window-to-Wall Ratio
EXW-VAR: External Wall Variation
DE: Delivered Energy
PE: Primary Energy
EC: EC (A1-A3)
OC: OC(B6)
CF: CF (A1-A3 and B6)

Square Shape with No Surrounding
Square Shape in an Urban Context
Rectangular Shape with No Surrounding
Rectangular Shape in an Urban Context
Linear Shape with No Surrounding
Linear Shape in an Urban Context
L-Shape with No Surrounding
L-Shape in an Urban Context

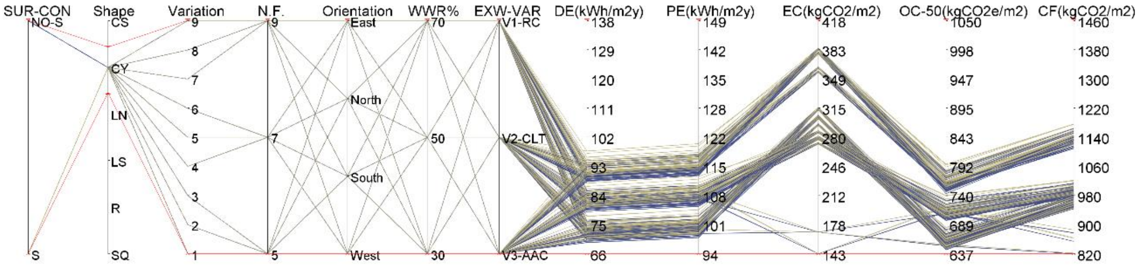


Figure 5.10. Results of Courtyard buildings (No Surrounding condition and Urban Context)

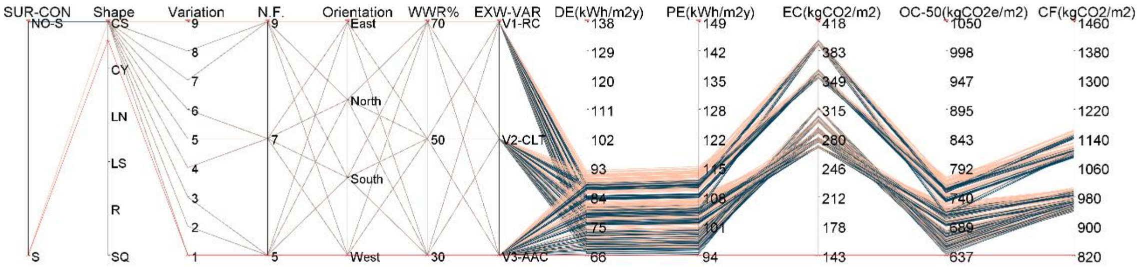


Figure 5.11. Results of S-Shape buildings (No Surrounding condition and Urban Context)

Guide:

SUR-CON: Surrounding Condition
NO-S: No Surrounding
S: In an Urban Context
N.F.: Number of Floors
WWR%: Window-to-Wall Ratio
EXW-VAR: External Wall Variation
DE: Delivered Energy
PE: Primary Energy
EC: EC (A1-A3)
OC: OC(B6)
CF: CF (A1-A3 and B6)

Courtyard Shape with No Surrounding
Courtyard Shape in an Urban Context
C-Shape with No Surrounding
C-Shape in an Urban Context

5.7.2. Rectangular Buildings

An equivalent quantity of variations pertained to the group of rectangular buildings. The results exhibited a range of 913.99 to 1411.17 $kgCO_2e/m^2$ in the absence of any surroundings. Similarly, the embodied and OC emissions of each rectangular building variation have been gathered individually, in accordance with the established trajectory. EC ranged between 168,93 and 413,58 $kgCO_2e/m^2$, and OC spanned between 689,95 and 999,62 $kgCO_2e/m^2$. The highest value of the CF was observed to be connected to variation 3 with GFA of 1062,77 m^2, WWR of 70%, AAC external walls and 5 floors which was oriented towards the East. The same variation had the highest OC with CLT external walls and the highest EC with AAC external walls. The minimum CF was attributed to variation 4 which had 4849,41 m^2 of GFA, WWR of 50%, external wall construction of RC, 7 floors and was oriented towards the North. Variation 3 with WWR of 30%, external wall construction of CLT exhibited the average of 1155,13 $kgCO_2e/m^2$ of CF. The minimum OC was connected to variation 7 with 9 floors, GFA of 6234,95 m^2, external wall construction of AAC, WWR of 30% and oriented towards the North. Variation 2 with 1789,52 m^2, 5 floors, WWR of 50%, external wall construction RC and oriented towards the North. The minimum amount of EC was exhibited by variation 2 with 5 floors, 1789,52 m^2 of GFA, external wall variation of RC, WWR of 50%. The average amount of 334,37 $kgCO^2e/m^2$ of EC was attributed to variation 9 with 1912,99 m^2 of GFA, 9 floors, WWR of 30% and external wall variation of CLT.

In congruence with square-shaped buildings, rectangular buildings demonstrated marginally elevated levels of carbon emissions within urban settings. The observed CF spanned from 924.29 to 1460.32 $kgCO_2e/m^2$. OC ranged from 691,82 to 1049,84 $kgCO_2e/m^2$. The variations which attributed to the maximums, averages and minimums of carbon emissions were largely consistent except for average of 1171,76 $kgCO_2e/m^2$ for the minimum of CF which was derived from variation 9 with GFA of 1912,99 m2, 9 floors, external walls of AAC, WWR of 30% that was oriented towards the East, and maximum of OC which is connected to variation 3 with the same specifications as in no surrounding condition with the exception of the external wall construction of RC.

5.7.3. Linear Buildings

The subsequent category comprised of linear buildings. The number of variations within this particular group was comparable to that observed in the preceding groups. Linear Buildings exhibited a diverse spectrum of CFs. The study found that buildings with no surroundings had a minimum value of 957,23 $kgCO_2e/m^2$ and a maximum value of 1371.65 $kgCO_2e/m^2$ and an average value of 1118,33 $kgCO_2e/m^2$. The range of EC in linear buildings was between 281,66 and 417,6 $kgCO_2e/m^2$ with an average of 334,06 $kgCO_2e/m^2$, while the OC spanned from 647,24 $kgCO_2e/m^2$ to 955,86 $kgCO_2e/m^2$ having an average of 777,69 $kgCO_2e/m^2$. The minimum value of EC, OC and CF was connected to variation 7 with 8855,11 m^2 of GFA, 9 floors, and orientation towards the North, but with different envelope specifications. The minimum value in CF is attributed to external walls construction of CLT and WWR of 30% while the same WWR exhibited the minimum OC with external wall construction of AAC. The maximum EC was connected to variation 3 with a GFA of 1273,91 m^2, height of 5 floors, AAC external walls and a WWR of 70%. The same variation exhibited the maximum CF while being oriented towards the East. Furthermore, with the exception of having RC external walls and being oriented towards the East, the same variation was also found to demonstrate the maximum operational carbon. The average value of CF belonged to variation 6 with GFA of 1783,48 m2, 7 floors, CLT external walls, having a WWR of 30% and being oriented towards the North. The average value of OC was attributed to variation 9 with 2293,04 m^2 of GFA, the height of 9 floors and external walls construction of AAC, a WWR of 30% and was oriented towards the North. The maximum value of EC demonstrated by variation 3 with a GFA of 1273,91 and 5 floors, RC external walls, WWR of 30% and orientation towards the North.

Similar findings were observed regarding the marginally greater operational carbon, as well as the increased CF, in urban settings for linear buildings. The study found that the CF of linear buildings in urban areas ranged from a minimum of 963,39 $kgCO_2e/m^2$ to a maximum of 1414,89 $kgCO_2e/m^2$ with an average of 1134,48 $kgCO_2e/m^2$. The values pertaining OC spanned between 653,06 and 1000,51 $kgCO_2e/m^2$ which had an average of 795,83 $kgCO_2e/m^2$. All the same variations demonstrated the minimum, and maximums of all metrics with the exception of the average in CF and OC which had different external walls and orientations. The same variation 6 RC external walls and orientation towards the East was observed to have the average CF. The average for OC was also attributed to variation 9 with the same specifications with the exception of having RC external walls.

5.7.4. Courtyard Buildings

Similar to previous building groups, the courtyard buildings fell into 648 distinct variations. The results of the study indicate that buildings without surroundings exhibited a lower range of CF per square meter, with a minimum value of 820.05 $kgCO_2e/m^2$, a maximum value of 1164.68 $kgCO_2e/m^2$ and an average of 1014,52 $kgCO_2e/m^2$ compared to the preceding building categories. The values of OC in this group of buildings spanned between 644,2 $kgCO_2e/m^2$ and 783,5 $kgCO_2e/m^2$ with an average of 708,47 $kgCO_2e/m^2$. The EC, however, ranged between 143,29 $kgCO_2e/m^2$ which was the minimum among all variations of all shapes and 385,69 $kgCO_2e/m^2$ as the maximum and an average of 312,7 $kgCO_2e/m^2$. The maximum values of CF, embodied, and OC were all connected to variation 1 with GFA of 20262,67 m^2, 5 floors, WWR of 70% and an orientation towards east, but with different external wall constructions. AAC external wall was observed to result in maximum EC emissions and CF while maximum OC was derived from RC external walls. Variation 9 with a GFA of 32922,24 m^2, 9 floors, AAC external wall construction, a WWR of 30% and oriented towards the North exhibited the minimum OC as well as the average EC. The minimum amount of EC was attributed to variation 2 which had 18977,08 m^2 of GFA, 5 floors, CLT external walls and WWR of 50%. Moreover, the average value in OC belonged to variation 3 with a GFA of 18290,13 m^2, 5 floors, CLT external walls, WWR of 50% which was oriented towards the North. The average CF was observed to be connected to variation 1 having 20262,67 m^2, 5 floors, AAC external walls, a WWR of 50% and an orientation towards the East. The minimum CF, however, was connected to variation 6 which had a GFA of 25606,18 m^2, 7 floors, CLT external wall construction, WWR of 30% and was oriented towards the North.

Similar to prior building typologies, courtyard buildings exhibited slightly greater CF and OC emissions within an urban context. The numerical values exhibited a conspicuous decrease in comparison to prior architectural configurations. The observed CF stretched from 822.39 to 1177.02 $kgCO^2e/m^2$ with an average of 1023,04 $kgCO^2e/m^2$. OC demonstrated a minimum of 645,87 $kgCO^2e/m^2$, the average of 713,14 $kgCO^2e/m^2$ and the maximum of 795,85 $kgCO^2e/m^2$. The values were obtained from a set of variations, which were largely similar to the no surrounding condition, with the exception of two variables. The average value for OC was derived from the same variation 3, which featured AAC external walls. Additionally, the maximum CF was associated with variation 1, which had RC external walls, but the rest of its specifications were completely identical.

5.7.5. C-Shape buildings

The following group consisted of C-shape buildings. Likewise, the quantity of variations within this specific collection amounted to 648. Buildings with a C-shape configuration demonstrated a more limited range of CFs. The research revealed that buildings not having surroundings exhibited a lower bound of 940,34 $kgCO_2e/m^2$, the mean value of 996,27 $kgCO_2e/m^2$ and an upper bound of 1150.02 $kgCO_2e/m^2$, which were comparatively proximate figures in contrast to the broader range of values detected in the antecedent categories. The OC ranged from 637,15 $kgCO_2e/m^2$ to 760,72 $kgCO_2e/m^2$ with an average of 701,2 $kgCO_2e/m^2$. The minimum, average and maximum values of EC for C-shape buildings were 269,65 $kgCO_2e/m^2$, 315,37 $kgCO_2e/m^2$ and 396,53 $kgCO_2e/m^2$, respectively. Variation 1 with a GFA of 11839,9 m^2, 5 floors, AAC external walls, WWR of 70% and oriented towards the North exhibited the maximum level of EC and CF. The same variation with WWR of 50% was connected to the average CF. Variation 7 which featured 21311,9 m^2 of GFA, height of 9 floors, AAC external walls demonstrated various significant values by having different WWRs and orientations. With a WWR of 30%, it was observed to have the average EC and having the same WWR and oriented towards the South it had the minimum OC while with WWR of 50% and orientation towards the East, it showed the average OC. The minimum EC was attributed to variation 9 with a GFA of 22372,9 m^2, 9 floors, CLT external walls and WWR of 50%. Furthermore, the maximum amount of OC was demonstrated by variation 3 featuring 12429,4 m^2 of GFA, RC external walls, WWR of 70% which was oriented towards the North. Finally, the minimum CF was derived from variation 8 with GFA of

22823,7 m^2, height of 9 floors, CLT external walls, WWR of 30% and its orientation was towards the South.

Comparable results were noted with respect to the slightly higher OC and amplified CF in urban areas for C-shaped buildings. The research revealed that the CF of C-shaped buildings situated in urban areas varied between 941,77 kgCO_2e/m^2 and 1164,83 kgCO_2e/m^2 with an average of 1006,36 kgCO_2e/m^2. OC ranged from 638,93 kgCO_2e/m^2 as minimum to 708,43 kgCO_2e/m^2 as the average and 776,81 kgCO_2e/m^2 as the maximum amount. The aforementioned variations explicated in no surrounding condition exhibited the highest, lowest, and mean values, with the sole exception of the minimum CF. This particular value was obtained from variation 8, which had identical specifications but was oriented towards the West.

5.7.6. L-Shape buildings

In all simulations, a comprehensive analysis was conducted on 648 different configurations of L-shaped buildings as well. The results regarding CF demonstrated a range between 895,64 to 1220,21 kgCO_2e/m^2 and an average of 1054,95 kgCO_2e/m^2 when there were no surroundings. Furthermore, an independent analysis has been conducted on the EC and OC emissions of various variants. OC spanned between 646,55 kgCO_2e/m^2 as the minimum, 732,17 kgCO_2e/m^2 as the average and 829,88 kgCO_2e/m^2 as the maximum values. The minimum EC was 168,93 kgCO_2e/m^2, its average value was 321,16 kgCO_2e/m^2 and maximum EC was 392,35 kgCO_2e/m^2. Variation 7 with GFA of 12459,11 m^2, 9 floors, CLT external walls, WWR of 50% demonstrated the minimum EC and when it was oriented towards the East it demonstrated the average value for OC. Also, the same variation with WWR of 50%, AAC external walls and orientation towards the South exhibited minimum value of CF. Variation 1 which featured 6921,73 m^2 of GFA, height of 5 floors, AAC external walls was connected with two significant values with two distinct WWR. Having a WWR of 70% it showed the maximum EC, but with WWR of 30%, it demonstrated the average value of EC. Moreover, variation 3 with GFA of 3716,58 m^2, 5 floors height and WWR of 70% was connected to the maximum of OC with RC external walls and maximum of CF while having AAC external walls. Variation 8 with 13967,90 m^2 of GFA, height of 9 floors, AAC external walls and WWR of 30% exhibited the minimum OC while it was oriented towards the North. The average CF, however, attributed to variation 9 with GFA of 6689,84 m^2, 9 floors, AAC walls and WWR of 50% which was oriented towards the South.

Conversely, simulations carried out in an urban environment revealed that the range of CF was observed to be between 903,16 and 1246,09 kgCO_2e/m^2 with an average of 1064,83 kgCO_2e/m^2. OC in urban context spanned from 647,82 kgCO_2e/m^2 as minimum, 742,16 $kgCO_2e/m^2$ as the average and 856,49 $kgCO_2e/m^2$ as the maximum value. Similar variations were connected to maximum, minimum and average values with a number of exceptions. Average OC was connected to variation seven with identical specifications with the exception of having RC external walls and being oriented towards the West. Maximum CF attributed to the same variation 3 while it was oriented towards the West and finally the average CF was connected to the same variation 9, but with orientation towards the East.

5.8. Findings associated with building morphologies

An additional noteworthy discovery pertains to the ratio of embodied and OC present in the optimal variant of each configuration. As elucidated in the introductory section, it is not uncommon for engineers to augment the insulation of a building as a means of reducing its operational carbon. However, this approach often results in a significant increase in EC, thereby exacerbating the building's overall CF. The subject of inquiry pertains to the precise location of the threshold for augmenting insulation, as well as the optimal equilibrium between EC and OC that results in the most minimal CF. To investigate this inquiry, an analysis was conducted on the proportions of EC and OC that contribute to the CF, considering the highest, mean, and lowest values. The study's results indicate the necessary trade-off between the two variables in order to achieve the optimal level of ultimate CF.

Figure (5.12) presents a summary of the aforementioned proportions of various shapes. As it is obvious from the figure, the trade-off in optimal solutions of each shape is 80% of OC and 20% EC in the ultimate CF. It is noteworthy to mention that the circumstances were identical in an urban context.

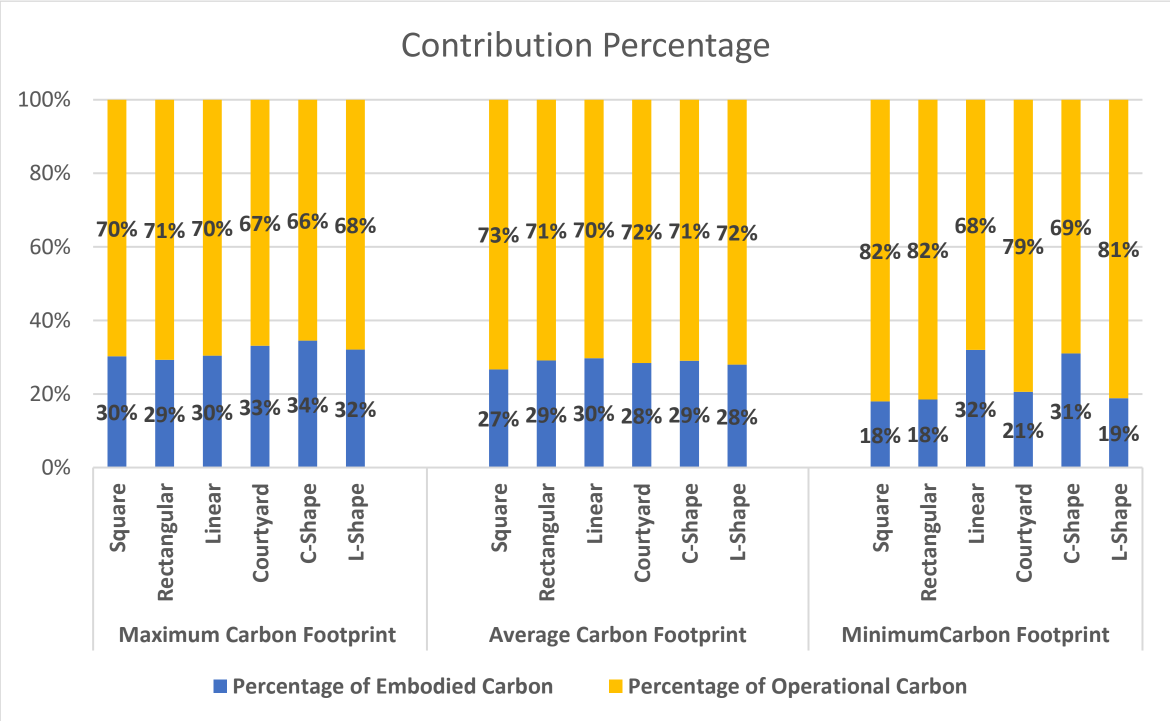


Figure 5.12. Contribution percentage of Embodied and Operational Carbon in final Carbon Footprint in optimal, average and suboptimal performances

Another notable finding of the study is that a discrepancy exists in the percentage of increase in buildings performance metrics among various shapes and building forms. Figure (5.13) depicts the percentage of shifts in maximums, averages, and minimums of building performances when situated in an urban context as compared to a non-surrounding condition.

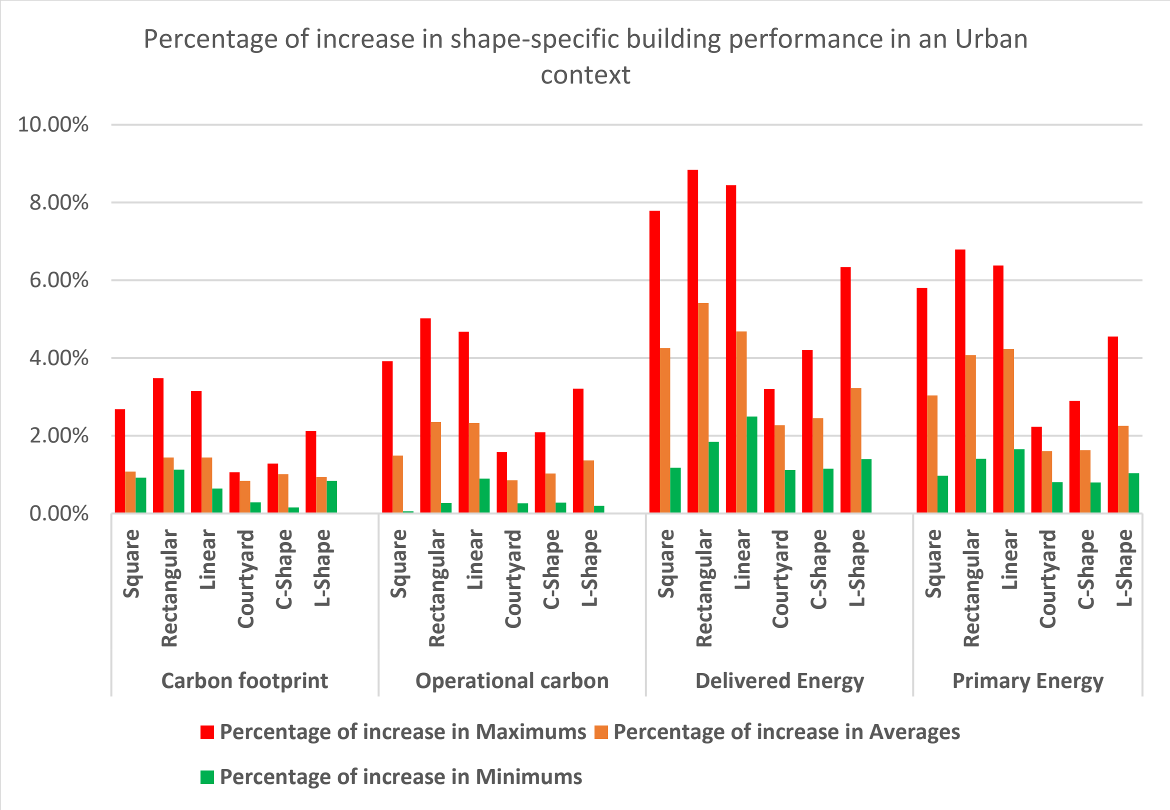


Figure 5.13. Shape-specific percentage of increase in building performances in an urban context comparing to no surrounding condition

The graphical representation indicates that rectangular buildings exhibit the greatest disparity between their maximum and minimum values, with square and linear buildings following in second and third place, respectively. In an urban context, it can be inferred that the placement of a rectangular building, which may not exhibit optimal performance metrics during the initial design phase in comparison to alternative options, may result in a greater decline in performance relative to buildings of other shapes. Conversely, courtyard buildings exhibit a minimal disparity, functioning in direct contrast to rectangular buildings. The explanation behind the observed phenomenon is that structures with rectangular, square, and linear configurations are more susceptible to the influence of neighboring buildings due to their limited capacity for self-shading. Conversely, structures with alternative shapes, such as courtyards, exhibit greater self-shading capabilities, thereby causing them to be less susceptible to the effects of surrounding buildings. The aforementioned figure substantiates the notion that buildings which demonstrate subpar performance in no surrounding condition are more likely to exhibit even poorer performance in urban settings. Furthermore, the depicted figure illustrates that the magnitude of the rise in delivered energy surpasses that of other metrics.

5.9. Analysis of buildings' parameters

To investigate the impact of various morphological factors on building performance metrics, the mean metrics of individual attributes were computed along with their corresponding standard deviations against the average value of the building shape category. The outcomes were juxtaposed to present a comprehensive analysis of the impact of individual morphological features on the metrics. The subsequent sections provide a detailed exposition of the findings obtained from the analysis. The negative percentages indicate a lower value of the analyzed metric of the buildings when compared to the average values of the variations of the same parameter, signifying a superior performance of the building for that particular parameter option. Conversely, positive values indicate a higher value, implying a poorer performance. The investigation involved a comparison of building performances for each specific parameter option, with separate evaluations conducted for both non-surrounding conditions and urban contexts.

5.9.1. The effect of Orientation

The comparative analysis of building performances was conducted with respect to their corresponding orientations. The results indicate the optimal orientation for every building shape. Figures (5.14) and (5.15) present a comprehensive summary of the impact of orientation on individual building shapes.

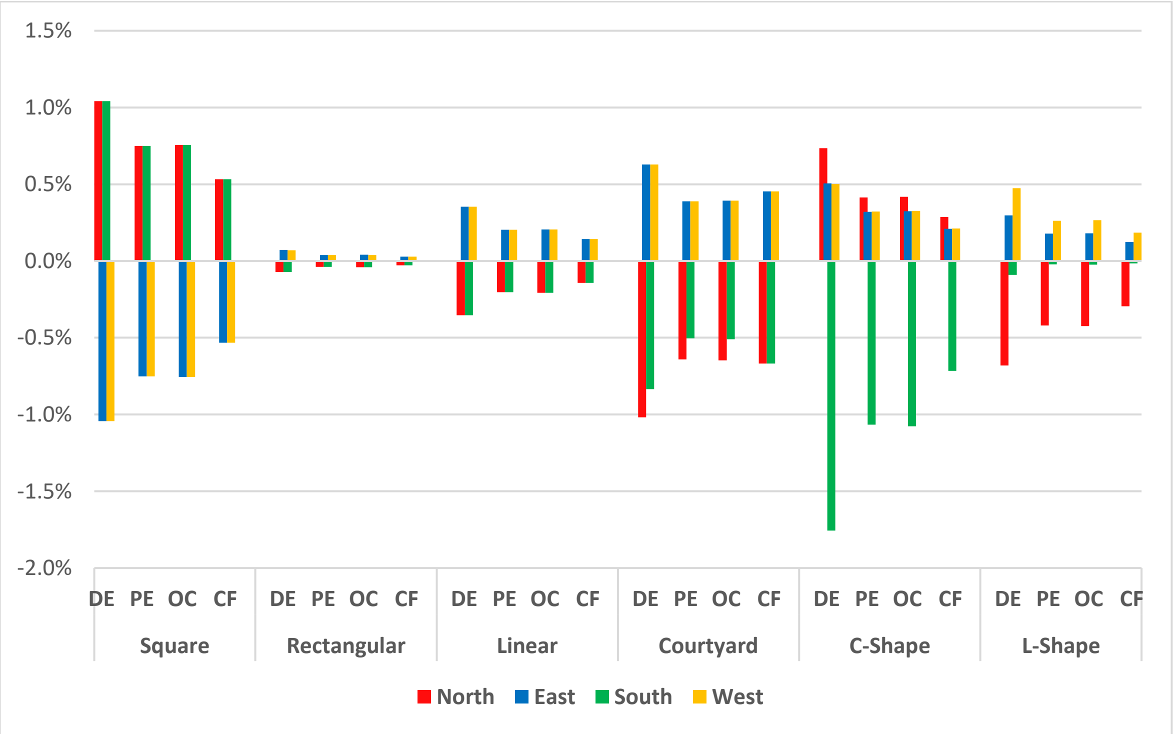


Figure 5.14. Comparison of the effect of Orientation on each shape in No Surrounding condition

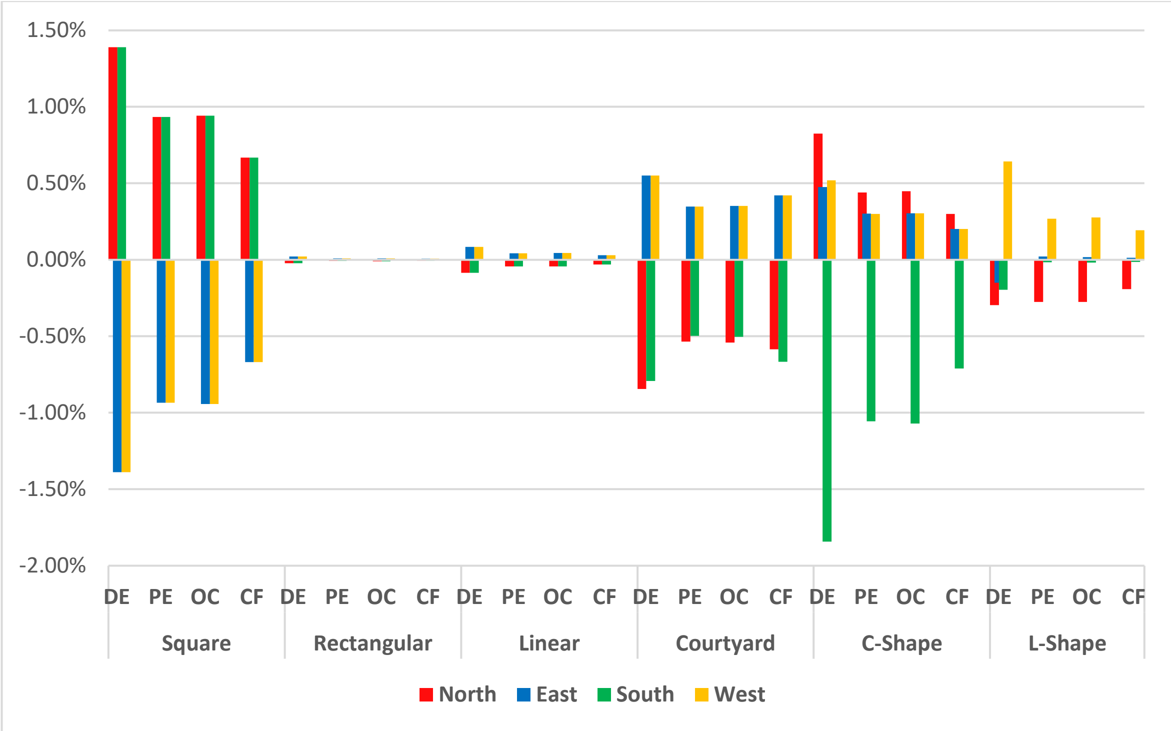


Figure 5.15. Comparison of the effect of Orientation on each shape in Urban Context

Upon general examination of the scale depicted in the charts provided, it can be observed that the impact of orientation on the metrics is generally negligible. Nevertheless, the chart remains a useful tool for comparing the impacts of different orientations. Upon initial observation, it is evident that the impact is more pronounced in an urban setting when compared to no surrounding condition. The observed phenomenon is attributed to the fact that the presence of adjacent buildings accentuates the difference in the exposure of the buildings to sunlight in the South, West and East orientations. Thus, those buildings that receive greater solar radiation exhibit reduced energy requirements in comparison to those with less exposure. Furthermore, the chart illustrates that the metric that is significantly impacted by orientation is the delivered energy, in comparison to the other metrics.

Upon a closer inspection of the results, it can be observed that buildings with square shape exhibit better performance when their extension is oriented towards the North-South axis, with their longer dimensions facing the East-West direction while rectangular, linear, and courtyard shapes demonstrated a diametrically opposed outcome. Research indicates that C-shaped buildings demonstrate optimal performance when the building is extended towards East-West direction and its extrusions are extended towards the South, whereas L-shaped buildings demonstrate superior performance with the same extension though their extrusion is being extended towards the North. By applying a similar logical approach, insights regarding the diverse building performances can be extracted from the chart that has been presented.

5.9.2. The effect of Window-to-Wall Ratio

An analysis was performed to examine the results of building metrics depending on their shape and relative window-to-wall ratio (WWR). Figures (5.16) and (5.17) present a visual representation of the outcomes obtained from two distinct surrounding conditions.

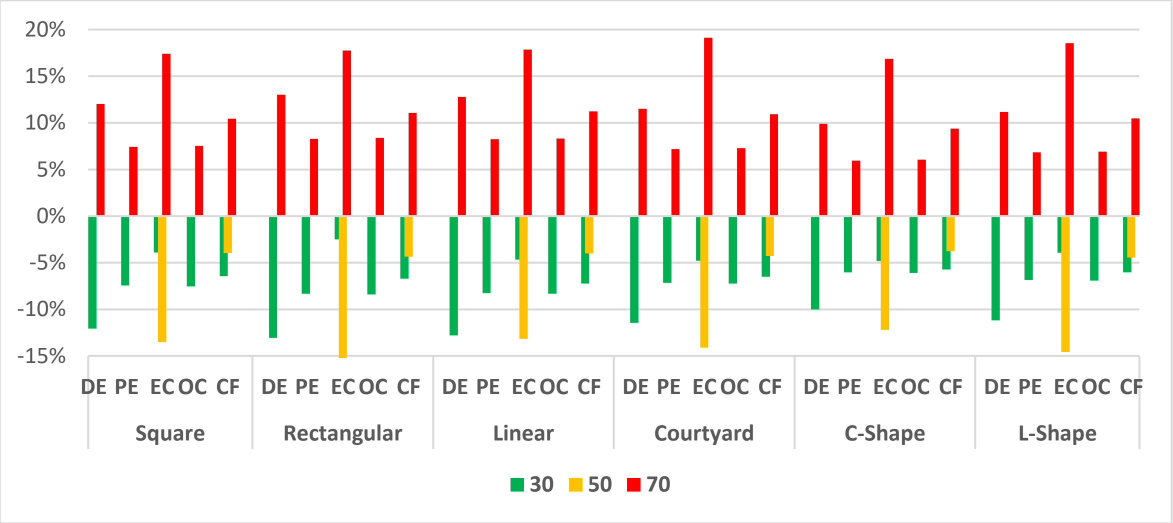


Figure 5.16. Comparison of the effect of WWR on each shape in No Surrounding condition

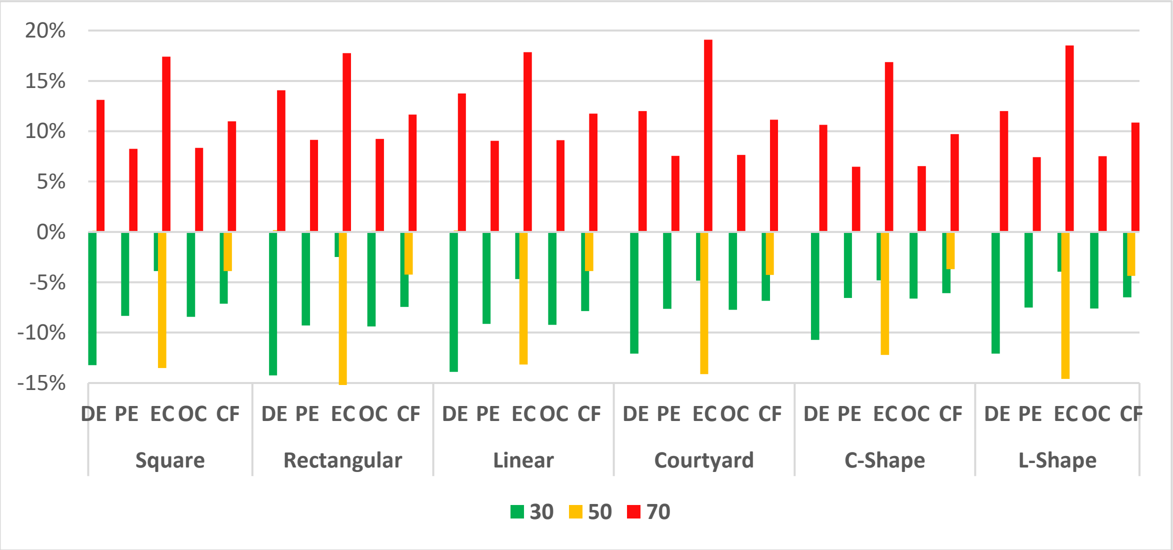


Figure 5.17. Comparison of the effect of WWR on each shape in Urban Context

Initially, it can be observed that the magnitude of the percentage of deviation indicates a substantial impact of WWR on the metrics. Additionally, it is noteworthy to mention that the degree of deviation is slightly greater in urban settings, as evidenced by the chart. There is a significant disparity in the levels of delivered and primary energy, as well as operational carbon, between the compared entities. However, the difference is comparatively minor in other metrics. This suggests that the aforementioned metrics are significantly impacted by the joint alteration of WWR and the surrounding condition.

Moreover, the EC is notably impacted by the WWR metric more than any other performance metric. According to the chart, a WWR of 70% is associated with inferior performance across all shapes, whereas a WWR of 30% has an opposite effect on the metrics. The impact of a WWR of 50% exhibits dissimilar trends across various metrics and shapes. A common observation across various shapes and metrics is that a WWR of 50% leads to a reduction in EC and CF, while exhibiting an opposite effect on energy-related metrics. However, the marginal impact it has on energy performance and operational carbon emissions is typically negligible, and therefore does not result in a significant increase in the overall carbon footprint of buildings. It is noteworthy to mention that the reduction in magnitude caused by a 50% WWR across all shapes is less than that of a 30% WWR. Generally, the optimality of WWR can be ranked in the order of 30%, 50%, and 70%, respectively. The optimal performance of buildings is achieved with a WWR of 30%, whereas a WWR of 70% results in suboptimal performance. This effect is further accentuated in an urban context.

5.9.3. The effect of External Wall Constructions

A similar trajectory has been pursued to investigate the impact of three distinct external wall constructions on the performance metrics of buildings of varying shapes. The findings of the study indicate that there exists a lack of uniformity among various metrics in terms of their comparability with respect to external wall constructions. The performance metrics of various external wall constructions across different shapes in two distinct surrounding conditions are compared in Figures (5.18) and (5.19).

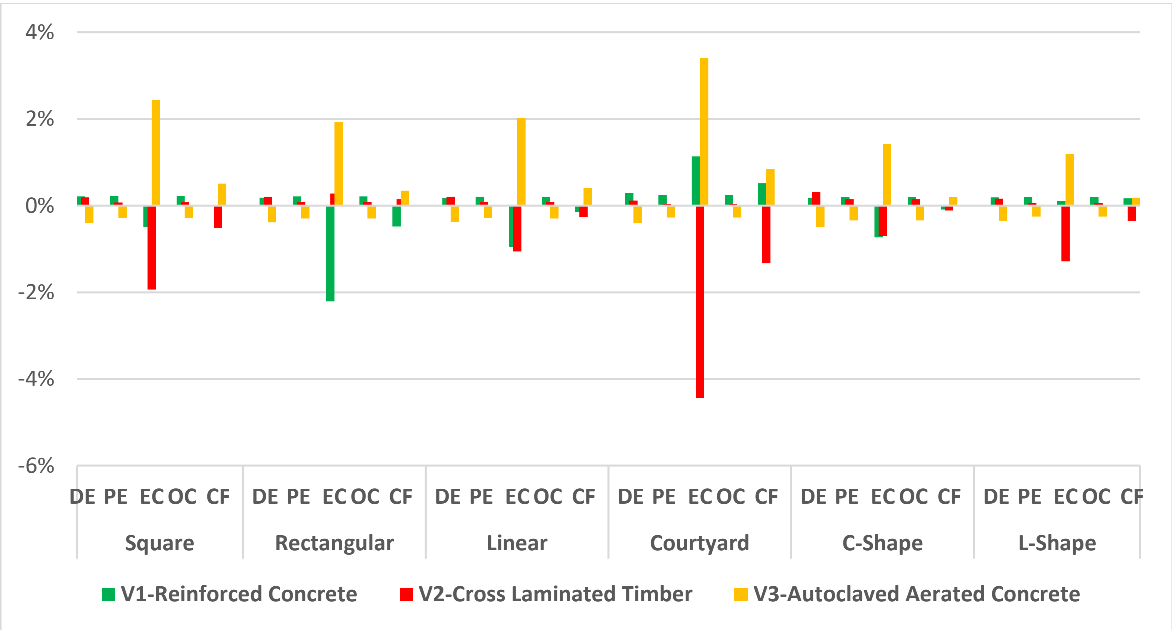


Figure 5.18. Comparison of the effect of external wall construction on each shape in No Surrounding Condition

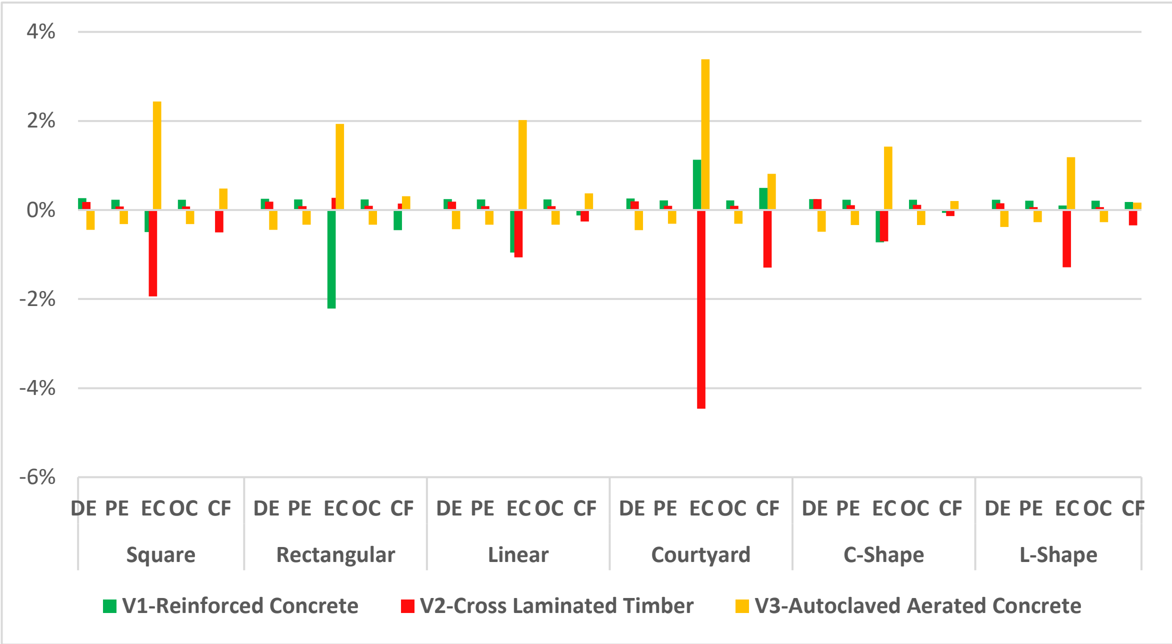


Figure 5.19. Comparison of the effect of external wall constructions on each shape in Urban Context

Upon initial observation, it appears that the charts demonstrate that the influence of external wall construction on the metrics is comparatively less significant than that of WWR, yet larger than that of orientation. As per the chart, it can be observed that EC holds a significant impact on the overall CF across all shapes, as compared to other performance metrics. The aforementioned statement implies that the construction exhibiting the least EC ultimately yields the lowest CF, while the construction characterized by a higher EC culminates in a comparatively elevated final CF. This phenomenon occurs due to the significantly greater impact of external wall construction on EC in comparison to other performance metrics, particularly those related to energy. According to the chart, it can be inferred that CLT is the most optimal choice for external wall construction in all shapes, with the exception of rectangular buildings, where reinforced concrete external walls exhibit superior performance.

The charts reveal a significant and noteworthy discovery that AAC external walls have a negative impact on energy-related performance metrics across all shapes though due to the observed increase it caused in EC in all shapes, results in a higher final CF. AAC external walls comprise of concrete and cement, which serves as its primary component. Global awareness regarding the significant contribution of cement to greenhouse gas emissions is widely acknowledged. According to the author's perspective, the higher contribution to the EC which is observed in AAC walls as compared to CLT walls, is due to the presence of cement in the former. Nevertheless, this subject matter and the rationale behind it holds significant importance and presents intriguing avenues for further exploration in future academic studies. Consequently, AAC external walls may not be the most optimal option to consider.

5.9.4. The effect of Number of Floors

Figures (5.20) and (5.21) illustrate a comparison of the heights of shapes in two distinct surrounding conditions. The study pertaining to the number of floors indicates that the degree of variation is comparable to that of building orientation in terms of performance metrics. However, it is noteworthy that the impact of the number of floors on individual metrics is distinct.

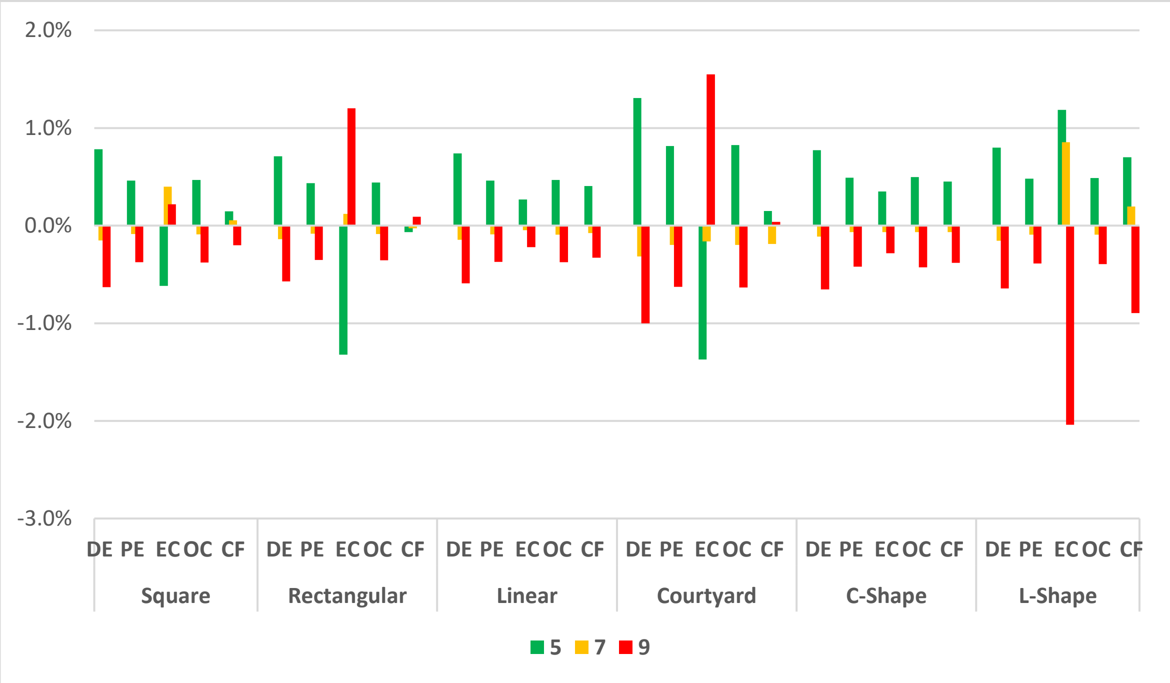


Figure 5.20. Comparison of the effect of number of floors on each shape in No Surrounding Condition

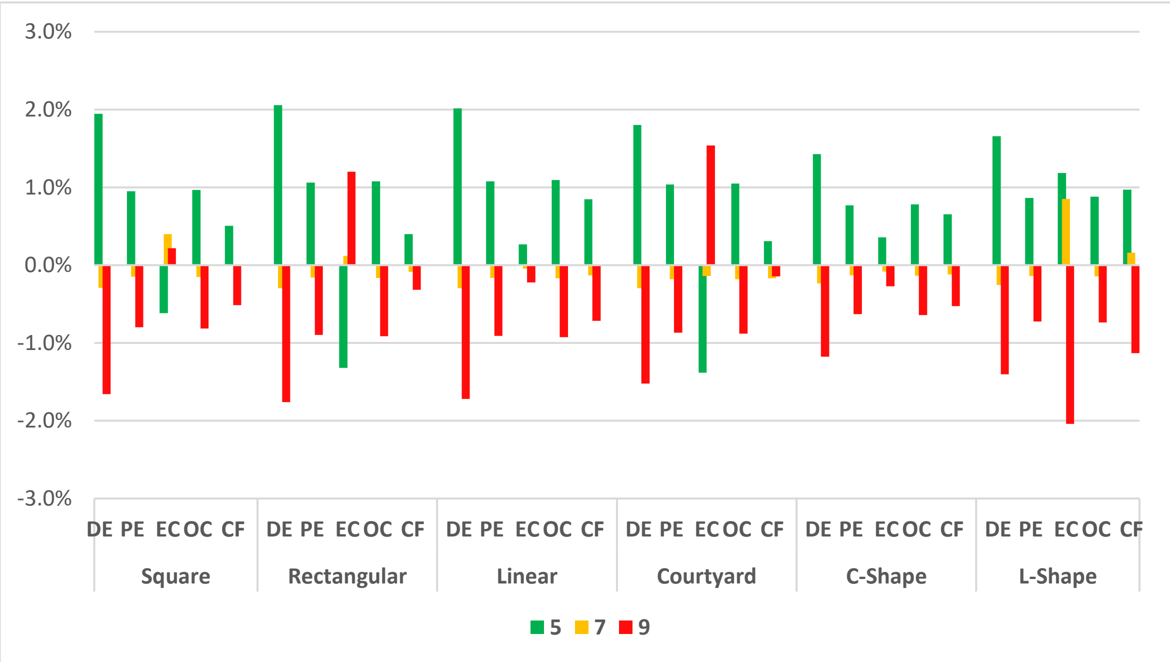


Figure 5.21. Comparison of the effect of number of floors on each shape in Urban Context

At first glance, it is apparent that the level of variance in metrics within an urban setting is greater in comparison to a non-urban environment. The aforementioned indicates that the performance of buildings exhibits a greater disparity when subjected to a simultaneous alteration in both the number of floors and the surrounding conditions.
A noteworthy observation is that the impact of the number of floors on EC exhibits a diametrically opposed pattern in comparison to the remaining metrics across all configurations. As an illustration, it can be observed that in structures comprising of five floors, there is an escalation in all metrics of building performance, while the EC exhibits a decline. The reduction in various metrics, specifically those related to energy performance, results in a decline in the ultimate CF of buildings, except for those with a rectangular shape. This phenomenon can be attributed to the fact that the reduction in EC outweighs the impact of energy-related indicators that contribute to an increase. Conversely, in buildings with nine floors, the trend is diametrically opposed. This implies that as the EC increases, there is a decrease in all energy-related performance metrics. Buildings with a rectangular shape and a courtyard with 9 floors exhibit distinct performance characteristics compared to structures with other shapes. This phenomenon arises due to a disproportionate rise in their EC relative to the decline in other performance metrics, ultimately leading to a higher overall CF.
Buildings comprising of 7 floors exhibit comparable characteristics to those with 9 floors, except for structures that are square or L-shaped. Based on the data presented in the chart, the cause appears to be consistent.
Overall, it can be inferred that taller buildings tend to exhibit superior performance in square, linear, C-shaped, and L-shaped configurations. However, caution should be exercised when considering square buildings, as their performance could vary depending on their having average height. Conversely, buildings with a rectangular shape exhibit optimal functionality when their height is reduced, while courtyard buildings tend to perform more effectively when constructed at an average height.
It is noteworthy that the impact of the number of floors on the performance metrics of L-shaped structures is significantly greater than that of other shapes.

5.9.5. The effect of Envelope-to-Volume Ratio (Env/Vol)

The ratio between the envelope and volume of a building can be utilized as a metric for assessing the degree of compactness of the building. Due to differences in building shape, this metric offers valuable insights into the impact of building compactness on their ultimate carbon footprint. Each geometric figure exhibits three distinct dimensions and three distinct heights, resulting in a total of nine distinct values for the Env/Vol. To facilitate a comprehensible comparison, the minimum, mean, and maximum Env/Vol values of each building were considered during the overall comparison of their shapes. The comparison across all building shapes in two distinct surrounding conditions is illustrated in Figures (5.22) and (5.23).

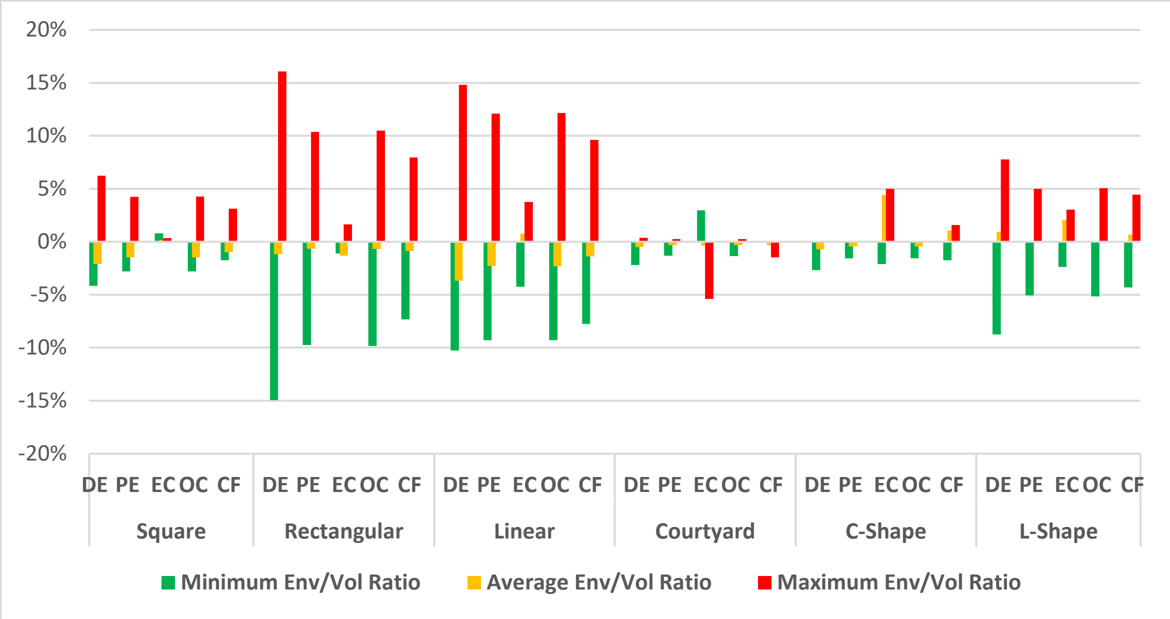


Figure 5.22. Comparison of the effect of Env/Vol on each shape in No Surrounding Condition

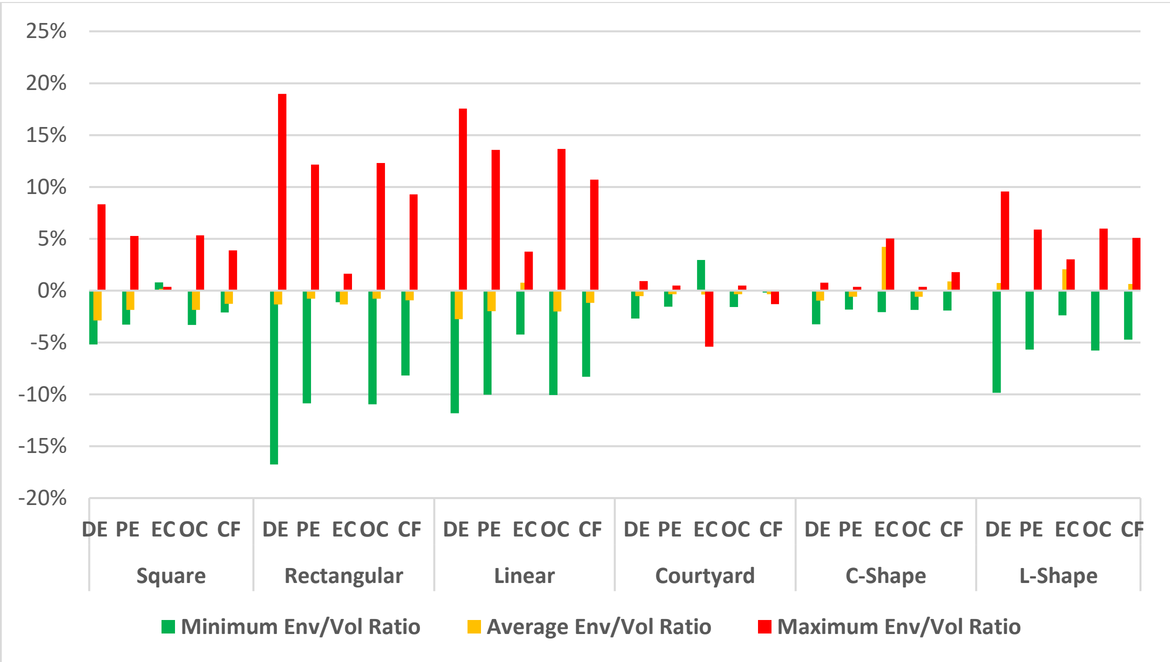


Figure 5.23. Comparison of the effect of Env/Vol on each shape in an Urban Context

In general, geometric shapes exhibiting symmetrical dimensions possess a smaller Env/Vol. However, as the extension of each side occurs, the aforementioned ratio experiences an increase. Additionally, shapes that are geometrically simpler exhibit lower Env/Vol. Upon initial observation, it is evident that the chart's scale magnitude highlights the noteworthy impact of Env/Vol on building performance metrics. Furthermore, the influence of Env/Vol in an urban setting is marginally greater than that of a no surrounding condition. The rectangular and linear shapes exhibit a significantly greater influence of Env/Vol in comparison to the remaining shapes. Conversely, buildings with courtyard and C-shape designs exhibited the lowest degree of deviation in response to alterations in the Env/Vol ratio. Furthermore, it is evident that minimum the Env/Vol ratio results in improved performance metrics across all building configurations. The outcome is diametrically opposed when the Env/Vol is at its maximum, except in the case of the courtyard building. It is noteworthy that the Env/Vol to EC relation exhibits an upward trend in all types of buildings, whereas in courtyard buildings, the trend is reversed. This may also account for the varying behavior of courtyard buildings in this respect.

A noteworthy observation is that the impact of Env/Vol is considerably more substantial on performance metrics related to energy, which serves as the primary determinant of the outcomes in the ultimate CF.

The mean value of Env/Vol exhibits a decline in the measured metrics for performance. Nevertheless, the reduction observed is notably lesser in comparison to the minimum Env/Vol. Overall, it can be inferred that the most favorable outcome for building performance is achieved by selecting the minimum Env/Vol ratio across all building shapes, with the exception of courtyard buildings where the maximum Env/Vol ratio is more advantageous.

6. DISCUSSION

The necessity to optimize the thermal performance of the building envelope, which encompasses windows and insulation materials, in order to curtail energy consumption and carbon emissions in buildings for residential use is axiomatic. Nevertheless, in pursuit of this goal, prioritizing the energy efficiency of buildings can result in a phenomenon known as problem shifting. The rationale behind this problem shifting is that although thicker insulations and windows lead to a reduction in operational carbon, they also entail a higher utilization of materials in constructions, thereby elevating the embodied carbon and ultimately contributes to a greater overall carbon footprint throughout the entire life cycle of the building. Hence, possessing the ability to contemplate the complete life cycle of a building starting from the initial phases of its design would enable decision-makers to select the most advantageous alternatives at each stage of the process and prevent the transfer of issues to subsequent stages.

The research involved performing a total of 3888 simulations that encompassed diverse building shapes characterized by varying dimensions, heights, WWRs, orientations, and external wall constructions.

The present study has indicated that square-shaped buildings exhibit optimal performance when their longer dimension is oriented in the North-South direction. Conversely, rectangular, linear, and courtyard-shaped buildings demonstrate optimal performance when their longer lengths are extended in the East-West direction, with their faces oriented towards the North-South direction. This observation aligns with Abanda and Buyers' (2016) finding, which asserts that the optimal orientation for their case study is the South direction [141]. It also supports Littlefair (2001) statement that buildings are frequently situated in a manner that aligns with the architectural principle that living spaces should face South which is done to ensure that the rooms that are utilized most frequently can take advantage of the heat provided by the sun [142]. These findings also align with the conclusions of Soufiane et al. (2019), who observed that increasing the length to width ratio in the East-West orientation can reduce the energy demands placed on a building's energy providers [143]. Additionally, the present study has indicated that optimal orientation for C-shaped structures is achieved by extending their extrusions towards the East, while for L-shaped buildings, extending their extrusions towards the North is most favorable. Furthermore, the research determined that WWR of 30% yielded the most favorable results among three distinct WWRs across all shapes and specifications. This encompasses the research by Thalfeldt et al. (2013) in which the authors concluded that for triple-glazed windows, which are the type of windows that is used for the present study, the optimal energy performance of buildings occurs when WWR is around 30% [144]. Moreover, it has been observed

that an increase in WWR is associated with a decrease in building performance. The present discovery aligns with the outcome of Troup et al.'s (2019) study, which affirms that the descriptive statistics pertaining to energy use intensity (EUI) indicate a rise in median total EUI with an increase in glazing, primarily due to the escalation in cooling loads [145]. Regarding the construction of external walls, current research has determined that buildings featuring cross-laminated timber (CLT) external walls exhibit superior performance with respect to their ultimate carbon footprint. This aligns with the findings of Liang et al. (2021) which acknowledges timber as a material possessing low carbon content, owing to its comparatively lower embodied carbon in contrast to conventional construction materials such as concrete and steel. According to the findings of Węglarz and Pierzchalski (2018), wooden walls are considered to be one of the most favorable choices for building envelopes [146]. The findings of this study are also consistent with Monteiro and Freire's (2012) research, which concluded that the timber wall was identified as the preferred solution across all three methods employed in their extensive study [147]. However, this discovery contradicts Maoduš et al.'s findings, which indicated that the aerated autoclaved concrete wall model exhibited superior environmental performance while optimizing thermal mass utilization could enhance the energy performance of timber-frame walls [148].
Furthermore, the results suggest that an increased number of floors is associated with a reduction in the overall carbon footprint. Finally, the study suggests that there is a correlation between the compactness of a building and its carbon footprint, whereby a more compact building which means lower envelope to volume ratio tends to have a lower carbon footprint. The aforementioned observation aligns with the outcomes of a research conducted by Rezaee et al. (2021), wherein it was reported that one of the case studies with a greater envelope to volume ratio exhibited a wider spectrum and greater magnitudes of energy consumption in comparison to the other prototypes [149].

An intriguing topic for discussion pertains to the primary energy demand threshold of 120 kWh/m^2y as stipulated in Estonian regulations. Specifically, an examination of the potential impact on the range of carbon footprint and identification of the buildings that would be most and least affected is warranted.

The study's results indicate that the carbon footprint range is estimated to be between 820,05 to 1254,56 kgCO_2e/m^2 in non-urban settings and 822,39 to 1246,2 kgCO_2e/m^2 in urban environments. The morphology that exhibits superior carbon performance is a courtyard building spanning 25606,18 m^2 of gross floor area, comprising seven floors, featuring CLT external walls, possessing a WWR of 30%, and facing the North direction. Conversely, the building that exhibits the least desirable characteristics in this context is a square-shaped building spanning 3829,27 m^2 of gross floor area, comprising nine floors, featuring external walls made of autoclaved aerated concrete, possessing a WWR of 70%, and facing the northern direction. The building, which possesses an average value of 1056,02 $kgCO_2e/m^2$ is L-shaped. It spans a gross floor area of 6689,84 m^2, is comprised of nine floors, features AAC external walls, boasts a WWR of 50%, and is oriented in a northerly direction. In an urban setting, the circumstances vary for buildings that possess maximum and average CF. The least favorable option is a nine-story square building with a GFA of 4755,41 m^2, featuring AAC external walls, a WWR of 70%, and an east-facing orientation. The average value belongs to a square building that encompasses a gross floor area of 2641,89 m^2, consisting of five levels, with external walls made of AAC material, a WWR of 30%, and an orientation towards the East. As depicted in Figure (6.1), the imposition of a 120 kWh/m2y limit on the primary energy demand of buildings results in a reduction of the carbon footprint associated with them. Nonetheless, the reduction observed in cases featuring the highest and mean CF values is deemed unfavorable. This highlights the importance of adopting a holistic approach that encompasses the complete life cycle of buildings.

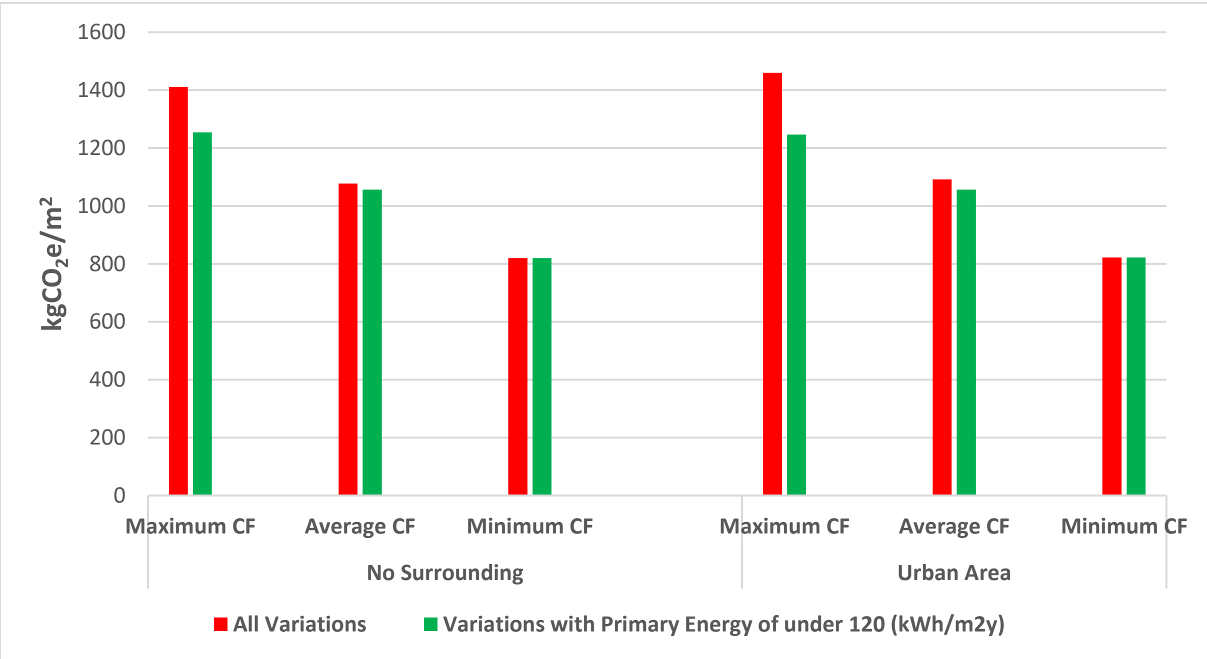


Figure 6.1. A comparison between maximums, averages, and minimum CF performance of buildings between all variations and the ones with primary energy of under 120 kWh/m^2y

The graphical representation depicted in Figure (6.2) illustrates the percentages of reduction in the maximum, average, and minimum of CF subsequent to the implementation of the threshold in both surrounding conditions.

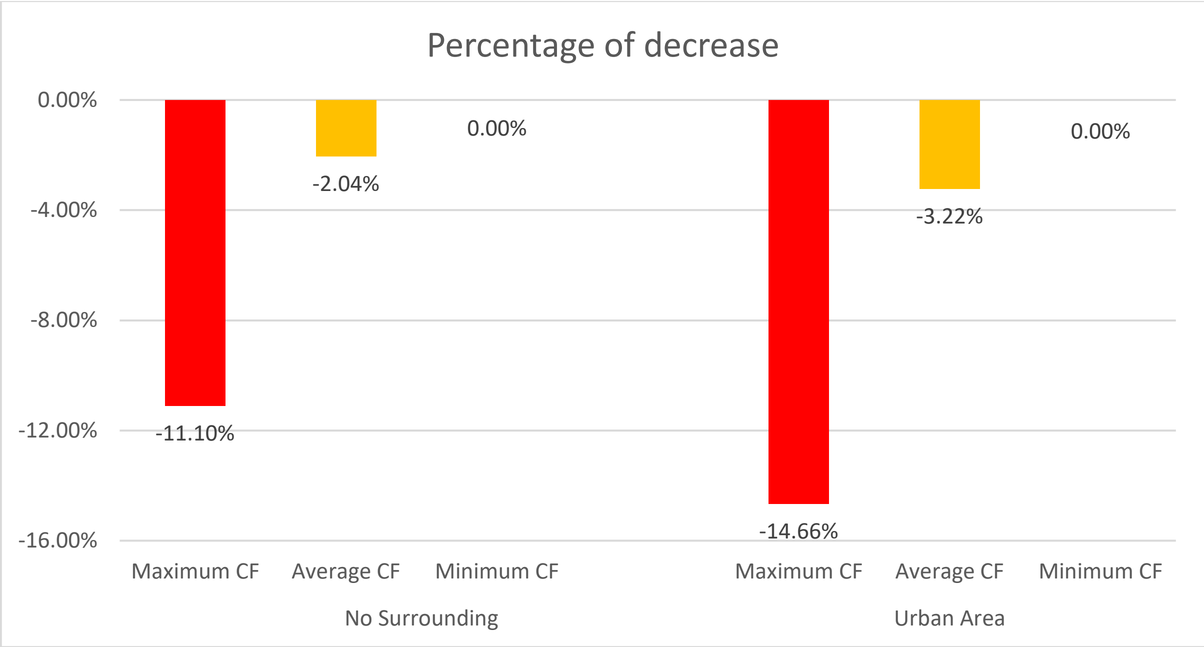


Figure 6.2. Percentage of decrease in maximum, average, and minimum CF performance of buildings by limiting their primary energy demand to under 120 kWh/m^{2}y

7. LIMITATIONS OF THE STUDY

Conducting research across diverse disciplines can be a complex and arduous endeavor. Parametric design, specifically, highlights the precision of this statement. Undoubtedly, several hindrances and limitations have emerged during the phases of model development and formulating consistent research outcomes. There were various limitations encountered during the course of the research. The limitations encountered were either due to inadequate data or were outside the scope of the study. For instance, it is conceivable that specific data could have been unattainable or unsuitable for utilization in the study. Additionally, there were certain variables that fell beyond the author's jurisdiction and had the potential to impact the research findings.

Despite the aforementioned constraints, the research provides noteworthy insights into the utilization of parametric design in the early stages of residential construction design, along with the necessary assessments that need to be made during this period. The transparency of the author's account of the research process is enhanced by their acknowledgement of the limitations that were incorporated into the workflow.

Table (7.1) presents an overview of the constraints and restrictions encountered in each particular aspect of the study and further developments that can be implemented in each section.

Table 7.1. A summary of the limitations of the study

Building parameter	Sub-Category	Limitations	Further development
Shape		Subjective definitions Basic architectural shapes	More complicated and real-life geometries can be evaluated in further studies.
	Dimensions	Limited to the boundary of studied buildings in Tallinn	A diverse range of dimensions and varying relation between dimensions can be considered.
Structure		Only reinforced concrete structure	Other structural materials such as Steel and Timber structures also can be evaluated.
	Design	The design calculations employed in the present workflow are estimations that rely on basic mechanics and manual computations, and thus, are advantageous for preliminary design phases. It is advisable to utilize a sophisticated software for structural analysis and design in subsequent phases, until the design techniques employed in the workflow are enhanced to match the capabilities of such software.	Major improvement is required in this section. This can be facilitated by evaluation of various structural systems.

Building parameter	Sub-Category	Limitations	Further development
			Table 7.1 continued
	Structural elements	Foundation is not considered in the structural elements.	-
Envelope			
	Internal walls	The length of internal walls was generally assumed in this study while there are several different types of internal walls, i.e., walls between apartments, walls of bathrooms, etc. The thickness and specifications of different aforementioned walls can differ diversly. However, to reduce the complexity of the study, this facet has not been considered.	Enhancing the workflow to anticipate the arrangement of apartments or staircases can involve the consideration of various wall specifications.

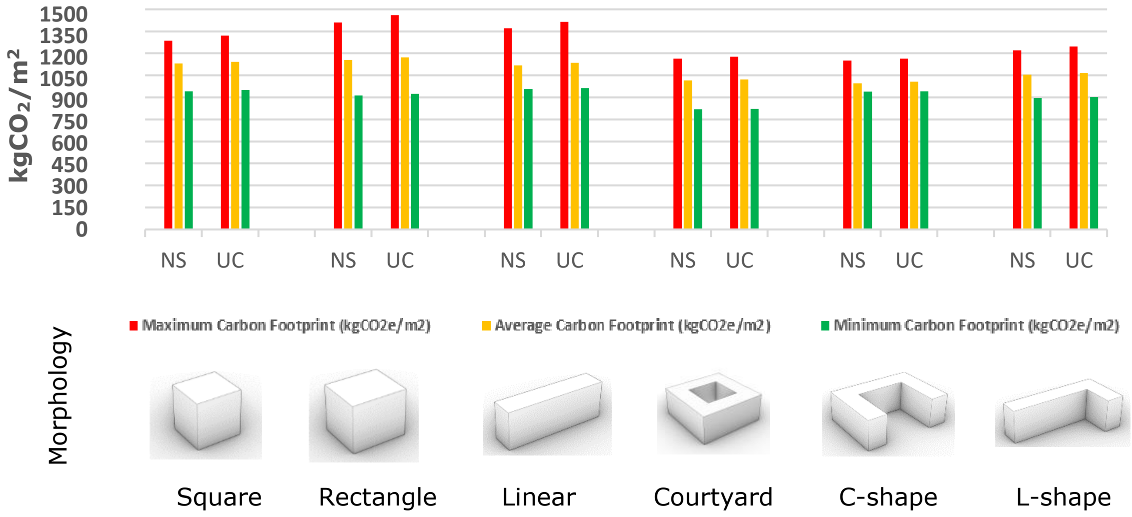
8. CONCLUSION

The objective of the study was to establish a framework that serves architects and engineers by providing pertinent data regarding the consequences of their choices on building morphology, elements, and material selection during the initial phases of design. The study examined the influence of various building characteristics, including orientation, number of floors, envelope-to-volume ratio, window-to-wall ratio, and external wall construction, on the energy used and carbon footprint of buildings. The investigation also analyzed the influence of adjacent structures on the energy performance and carbon emissions of buildings. The research is innovative due to the shortage of literature on the impact of building morphology on carbon footprint in tandem with material selection in Estonia. The study aimed to fill the gap in the existing body of literature and offer valuable perspectives on sustainable building design within the Estonian context. This study utilized parametric design and simulations to examine the initial impacts of architects' choices on the carbon footprint of buildings, with the aim of making a valuable contribution towards the mitigation of buildings' carbon footprint. This is a crucial step towards the attainment of climate objectives.

A Grasshopper-based parametric methodology has been devised to examine the correlation between the morphology of a building and its energy consumption and carbon footprint, both in terms of embodied and operational carbon. The workflow comprises six distinct stages, namely Shape Definition, Structure Generator, Mass Generator, Envelope Generator, LCA Workflow, and Energy Workflow. The buildings were defined by a multitude of parameters at each stage, whereby certain parameters remain fixed while others are subject to variation. This research centers on various architectural configurations, encompassing linear, rectangular, square, C-shaped, L-shaped, and courtyard buildings. The study involved an analysis of the dimensions and characteristics of the aforementioned shapes. Based on the length and width of the primary rectangle, certain assumptions were made to establish distinct categories for each shape. A study was conducted to collect data on building attributes in Tallinn, utilizing statistical analyses on a sample of 154 existing residential buildings. The obtained analysis outcomes offered significant insights for the development of different architectural typologies. The statistical analysis imposed limitations on the dimensions of the shapes, and subsequently, three significant alternatives were chosen for subsequent investigation. The floor-to-floor height of buildings was pre-established. The study assessed each variation in shape across four distinct orientations. The original orientation of the shape was towards the north, after which it underwent a rotation around the center point to align with the primary cardinal directions. The utilization of Python programming has been implemented in Grasshopper for the purpose of designing and analyzing building structures in the present investigation. The subject of interest pertained to structures made of reinforced concrete. The study employed simplifications, including the assumption of a uniform bay width and the utilization of simplified design methods based on common practice. Python scripts were utilized for the purpose of designing slabs, encompassing aspects such as thickness, reinforcement, and shear reinforcement. Furthermore, supplementary scripts were employed to verify the compliance of the slabs with the stipulations outlined in Eurocode 2. The design of columns was carried out utilizing a Python component, which considered load combinations and Eurocode 2 criteria. The scripts were utilized to adapt the columns by implementing appropriate dimensions and reinforcement. During the course of the procedure, various parameters were considered. The utilization of Python programming has enabled the streamlining of the design process within the parametric workflow in Grasshopper. The study uses a parametric cluster in Grasshopper to design a flexible and adaptable building envelope. The chosen roof construction is ROCKWOOL 7.1.1. The selected window profile is the NTech triple-glazed passive window from NorDan. Three wall constructions are considered: Reinforced Concrete-V1, CLT-V2, and Aerated concrete-V3. Internal walls are based on a structure from Paroc. The floor structure is a modified version of a detail offered by PAROC. Detailed specifications of each element are provided in the Methodology section.

The Embodied Carbon workflow employed the One Click LCA software tool for evaluating the carbon emissions linked to construction materials and systems. The process entailed the integration of the building geometry into Grasshopper, specification of the construction materials and systems, assignment of the materials and systems to the building geometry, and implementation of the One Click LCA analysis for the computation of the embodied carbon. The Operational Carbon workflow employed the Climate Studio software tool to forecast the energy usage of a structure throughout its operational stage. The methodology entails the creation of a parametric model of the buildings utilizing Grasshopper, followed by the simulation of energy consumption through EnergyPlus, and culminating in the analysis of the resulting outcomes. The workflow considered various factors, including but not limited to building geometry, and envelope, external obstructions, orientation, systems, occupancy, and internal loads. The EnergyPlus model inputs, such as building zones, loads, conditioning parameters, and envelope details, are determined in accordance with the Estonian regulations. The workflow computed the rate of air flow due to infiltration and the Air Change Per Hour (ACH) in accordance with regulatory standards. The quantification of energy requirements for heating, cooling, and electricity is accomplished through the utilization of coefficients and underlying assumptions. Subsequently, the energy demand that has been computed is subjected to multiplication by CO_2 emission factors used in Estonia, thereby leading to the determination of the CO_2 emissions for every building variation.

Addressing the first research question regarding the optimal architectural form to return the least carbon footprint, the findings of the study revealed that among the 3888 variations of diverse configurations in both no surrounding and urban context conditions, a seven-story courtyard building facing the North direction, featuring Cross-Laminated Timber (CLT) external walls and a Window-to-wall Ratio (WWR) of 30%, and height of 7 floors demonstrated the least amount of carbon footprint. In no surrounding condition the amount was 820,05 $kgCO_2e/m^2$ and in an urban context it demonstrated 822,39 $kgCO_2e/m^2$. The study also found that the mean carbon footprint was recorded in a five-story rectangular building with a CF of 1077,98 $kgCO_2e/m^2$, which was oriented towards the East and had external walls made of Autoclaved Aerated Concrete (AAC) in no surrounding condition while the mean value in an urban context belonged to a square shaped building with 5 floors, CLT walls , WWR of 30% and oriented towards the North. The building with the most unfavorable characteristics in terms of carbon footprint in both surrounding conditions was a five-story rectangular structure, positioned towards the East, encompassing a gross floor area of 1062,77 m^2, featuring an expansive window-to-wall ratio of 70%, and external walls constructed from autoclaved aerated concrete. Furthermore, the study indicates that urban areas exhibit marginally higher metrics than their non-urban counterparts. Additionally, buildings with elevated energy demands and carbon footprint are more influenced by surrounding built environment than those with optimal energy consumption and emissions. Figure (8.1) summarizes the maximum, average and minimum values of carbon footprint for different shapes separately in no surrounding condition and urban context.



Guide:
NS: No Surrounding, UC: Urban Context

Figure 8.1. A summary of carbon performance of each building morphology in no surrounding condition and urban context

A noteworthy discovery in this context pertains to the number of variations, amounting to 648, for each shape that satisfy the criterion of possessing a primary energy demand below 120 kWh/m^{2}y. Table (8.1) presents a summary of the quantity of variations that meet the specified criteria in both surrounding conditions.

Table 8.1. The number of shapes which satisfy the threshold of primary energy demand

Shape	No Surrounding	Urban Context
Square	274	234
Rectangular	216	198
Linear	252	204
Courtyard	324	320
C-shape	324	324
L-shape	324	288

Furthermore, the numbers in table (8.1) provide a reliable means of assessing the responsiveness and versatility of each geometric form within an urban setting. Regarding this matter, the C-shaped buildings exhibited the highest degree of success while the Linear buildings demonstrated the lowest level of success.

In an endeavor to answer the question regarding the balance between embodied and operational carbon to achieve the optimal carbon footprint, the study found that the optimal carbon footprint can be achieved by balancing the trade-off between embodied carbon and operational carbon at a ratio of 80% for OC and 20% for EC. The present study reveals that this equilibrium yields the minimum CF across diverse building configurations, regardless of whether they are situated in urban or non-urban settings.

Regarding the effect of building attributes on carbon footprint, the study concludes that orientation of a building has a negligible effect on its metrics. The impact of orientation is more prominent in an urban environment. Orientation has a significant impact on delivered energy. Buildings that are square in shape exhibit superior performance when oriented in a North-South direction and the extended dimension faces East-West orientation. Conversely, structures that are rectangular, linear, or courtyard in shape demonstrate an opposite outcome. Buildings with a C-shaped configuration exhibit optimal performance when oriented in an East-West direction and feature extrusions that face South. Conversely, L-shaped buildings demonstrate superior performance when their extrusions face North.

Furthermore, the research emphasizes the notable influence of Window-to-Wall Ratio on building performance indicators. The level of variance observed in metrics is marginally higher in urban environments. The WWR and surroundings have a significant impact on delivered energy, primary energy, and operational carbon. The impact of

WWR on EC is significant. The study reveals that a WWR of 70% is linked with poor performance across all shapes, whereas a WWR of 30% is associated with a converse effect. A WWR of 50% exhibits varying impacts on diverse metrics and variations. The most favorable WWR is rated at 30%, succeeded by 50% and 70% in both surrounding conditions. Optimal building performance is achieved with a WWR of 30%, whereas a WWR of 70% results in suboptimal performance. The aforementioned trends exhibit a greater degree of prominence within urban settings.

An additional significant discovery of the research is that the construction of external walls has a comparatively lesser influence than the window-to-wall ratio, yet a more substantial influence than the orientation in terms of building metrics. The construction of external walls has a significant impact on both the embodied carbon and the overall carbon footprint when compared to other metrics. Cross-laminated timber is deemed as the most suitable option for external walls in various shapes, with the exception of rectangular structures where reinforced concrete is found to exhibit superior performance. The utilization of AAC external walls is associated with unfavorable effects on energy-related metrics, resulting in an increase in EC and subsequently leading to elevated CF. The consideration of AAC may not be considered as the most optimal course of action.

The influence of the number of floors on metrics varies depending on the configurations, whereby a rise in the number of floors typically results in elevated metrics in both surrounding conditions, except for embodied carbon, which experiences a decline. Buildings that consist of five floors exhibit decreased energy-related metrics and a lower carbon footprint, with the exception of those with a rectangular shape, where the reduction in energy consumption is offset by the impact on environmental carbon. Conversely, buildings comprising of nine levels demonstrate a contrasting pattern. Structures comprising of seven floors exhibit comparable features to those of nine-story buildings, with the exception of square and L-shaped buildings. In general, it has been observed that taller structures tend to exhibit superior performance in square, linear, C-shaped, and L-shaped configurations. However, it is important to exercise prudence when considering square buildings with moderate elevation. Rectangular structures exhibit optimal performance when their height is decreased, whereas courtyard structures tend to perform well when constructed at an average height. The influence of the number of floors is notably more pronounced for L-shaped buildings in contrast to other configurations.

The research findings indicate that the Envelope-to-Volume Ratio has a noteworthy influence on the metrics related to the performance of buildings. Urban environments exert a marginally more pronounced impact compared to their non-urban counterparts. Rectangular and linear shapes are observed to be more susceptible to external influences, whereas designs featuring courtyard and C-shape configurations display a relatively lower degree of sensitivity. In most cases, a decrease in the ratio of Env/Vol results in enhanced performance metrics, with the exception of courtyards. The influence of Env/Vol is significantly greater on energy-related parameters, which have a bearing on the overall carbon footprint. The minimum Env/Vol has a more pronounced impact in comparison to the mean Env/Vol value. Typically, opting for the minimum Env/Vol ratio is advantageous in terms of enhancing building performance, with the exception of courtyard buildings where the optimal ratio is the maximum.

Overall, the research findings suggest that the morphology of a building is a significant factor in determining the energy performance and carbon footprint of buildings, particularly in regions with extended heating seasons and low temperatures. The significance of enhancing the energy efficiency of buildings is acknowledged by policymakers across the globe. The Envelope-to-Volume ratio and Window-to-Wall ratio are the predominant factors affecting various aspects of building performance, particularly the ultimate carbon footprint.

The study's results are valuable for architects and engineers during the initial phases of design, when critical determinations regarding the primary characteristics of the building are established. Moreover, the methodology and reasoning can be applied to assess the efficacy of a majority of structures regardless of their configuration, as the methodology is compatible with diverse geometries. This facilitates decision-making for stakeholders and streamlines the transition towards nearly Zero Energy Buildings (nZEBs) which is widely regarded as a crucial trajectory of the present era.

SUMMARY

Buildings account for 27% of energy usage and approximately one-third of worldwide greenhouse gas emissions, resulting in significant environmental degradation and contributing to climate change on a global scale. Life Cycle Assessment is essential to effectively tackle the issue of embodied carbon, minimize operational carbon, and establish circularity techniques. Low-energy devices, renewable energy sources, and consideration of building life cycles are key measures in mitigating carbon emissions.

The process of Life Cycle Assessment is intricate which necessitates a comprehensive understanding of the components of a building. The objective of this research is to examine the initial impacts of architects' choices on the carbon footprint of buildings through the utilization of parametric design. The study aims to address inquiries pertaining to the most efficient architectural forms in terms of carbon footprint, the point of equilibrium between embodied and operational carbon, and the impact of neighboring structures on carbon footprint employing a streamlined LCA procedure by removing stages that have a smaller influence on energy performance and carbon footprint. It uses a parametric design process to investigate the relationship between morphology and carbon.

The parametric workflow is composed of six steps. The definitions of shapes are based on subjective interpretation, and the dimensions are derived from a statistical analysis of 154 existing residential apartment buildings in Tallinn.

The study involves an examination of 54 distinct shapes across four primary cardinal directions. The composition of all variants is considered to be of reinforced concrete, which is formulated by four separate Python coding components within Grasshopper. These elements undertake manual calculations in accordance with Eurocode 1 and 2 for Estonia. The components comprising the envelope of variations include the roof, floors, external walls, internal walls, and windows. While the specifications of the roof, floors, internal walls, and windows are predetermined, the external walls offer three distinct variations, namely reinforced concrete (RC), cross-laminated timber (CLT), and autoclaved aerated concrete (AAC). The current research employs the OneClick LCA plugin, as well as the Climate Studio and EnergyPlus plugin integrated in grasshopper, to assess the embodied carbon and operational carbon of the aforementioned samples, respectively. The specifications and considerations utilized in this study are derived from the regulations governing residential apartment buildings in Estonia. The calculations were conducted in accordance with the established methodology for residential buildings in Estonia.

The results section primarily presents the maximums, averages, and minimums of all performances of the building variations, along with the parameters that contributed to

these outcomes. The study findings indicate that a seven-story courtyard building, featuring a 30% Window-to-wall Ratio, North-facing orientation, and Cross-Laminated Timber external walls, demonstrated the lowest carbon footprint of 820.05 kgCO2e/m2. In contrast, a rectangular building with a 30% WWR, East-facing orientation, and Autoclaved Aerated Concrete external walls, standing at five stories high, exhibited an average carbon footprint of 1077.98 kgCO2e/m2. Notably, the highest carbon footprint among all variations was observed in a rectangular building with a 70% WWR, East-facing orientation, and AAC external walls, standing at five stories high. Additionally, the carbon performances' minimum, average, and maximum values for each shape were individually documented. The analyses conducted indicate that the optimal solutions for each shape exhibit a trade-off of 80% for OC and 20% for EC in the ultimate CF, regardless of the surrounding conditions. Furthermore, it was observed that buildings that exhibit subpar performance in no surrounding condition are more prone to displaying even worse performance in urban settings.

In addition, an analysis was conducted on the impact of various building parameters, including orientation, window to wall ratio, external wall constructions, number of floors, and envelope to volume ratio. Research has indicated that varying shapes demonstrate optimal performance in distinct orientations, and that a reduced WWR correlates with enhanced building performance. Research has indicated that CLT is the optimal choice for external wall construction, and that improved performance observed in taller buildings. Moreover, a reduced ratio of envelope to volume, thereby resulting in a more compact building, yields superior building efficiency.

Additionally, the study highlights the significant impact of the WWR on various building performance metrics. The degree of variability detected in metrics is slightly elevated in urban settings. Another notable finding of the study is that the impact of external wall construction on building metrics is relatively minor compared to the WWR, but still more significant than building orientation. The impact of the number of floors on metrics is contingent upon the configurations, with an increase in the number of floors generally leading to heightened metrics in the surrounding conditions, with the exception of embodied carbon, which undergoes a decrease. The empirical evidence suggests that the Envelope-to-Volume Ratio exerts a significant impact on the performance-related metrics of buildings.

The findings of this study are important for professionals in the fields of architecture and engineering, as they can be applied to evaluate the effectiveness of a range of structures. This process enables stakeholders to make informed decisions and optimizes the progression towards the implementation of nearly Zero Energy Buildings (nZEBs), a significant trajectory in the current era.

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APPENDICES

Appendix 1. Comparison of carbon footprint ranges between different building morphologies

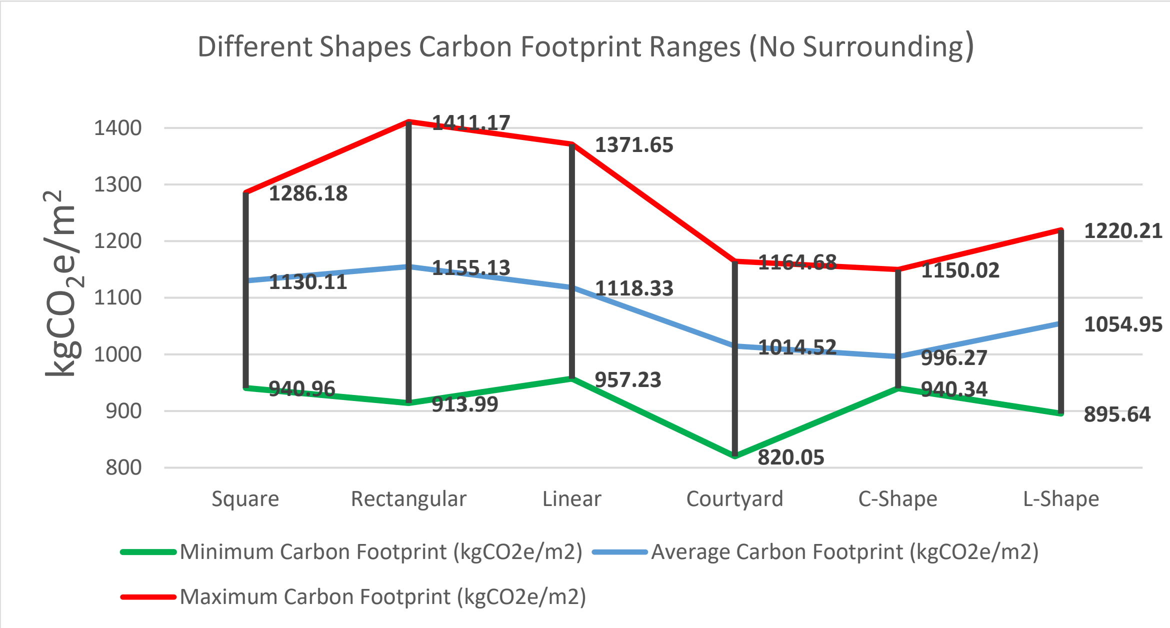

Figure A1. 1. Comparison of ranges of carbon footprint based on shapes in no surrounding condition

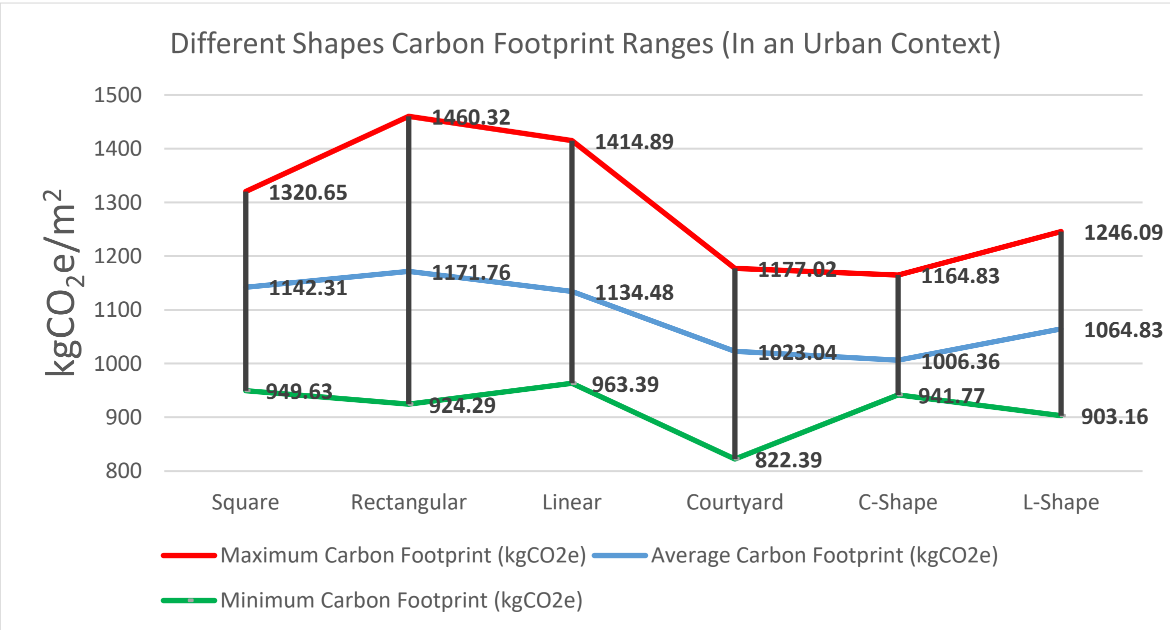

Figure A1. 2. Comparison of ranges of carbon footprint based on shapes in an urban context

Appendix 2. Comparison of operational carbon ranges between different building morphologies

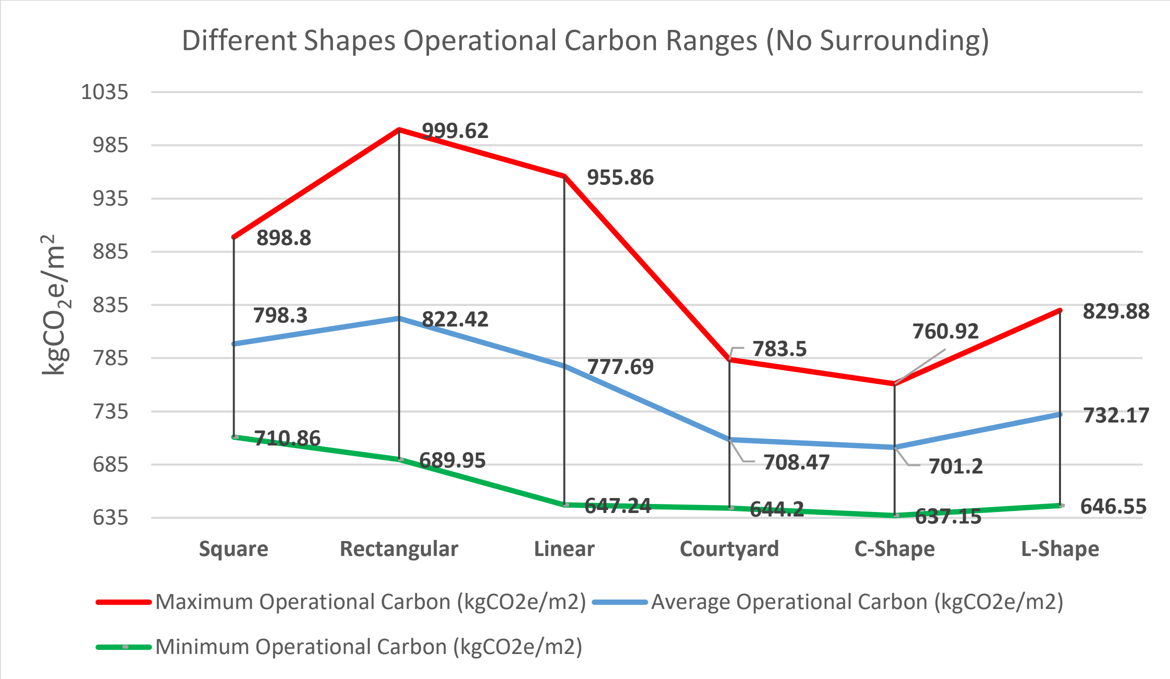

Figure A2. 1. Comparison of ranges of operational carbon based on shapes in no surrounding condition

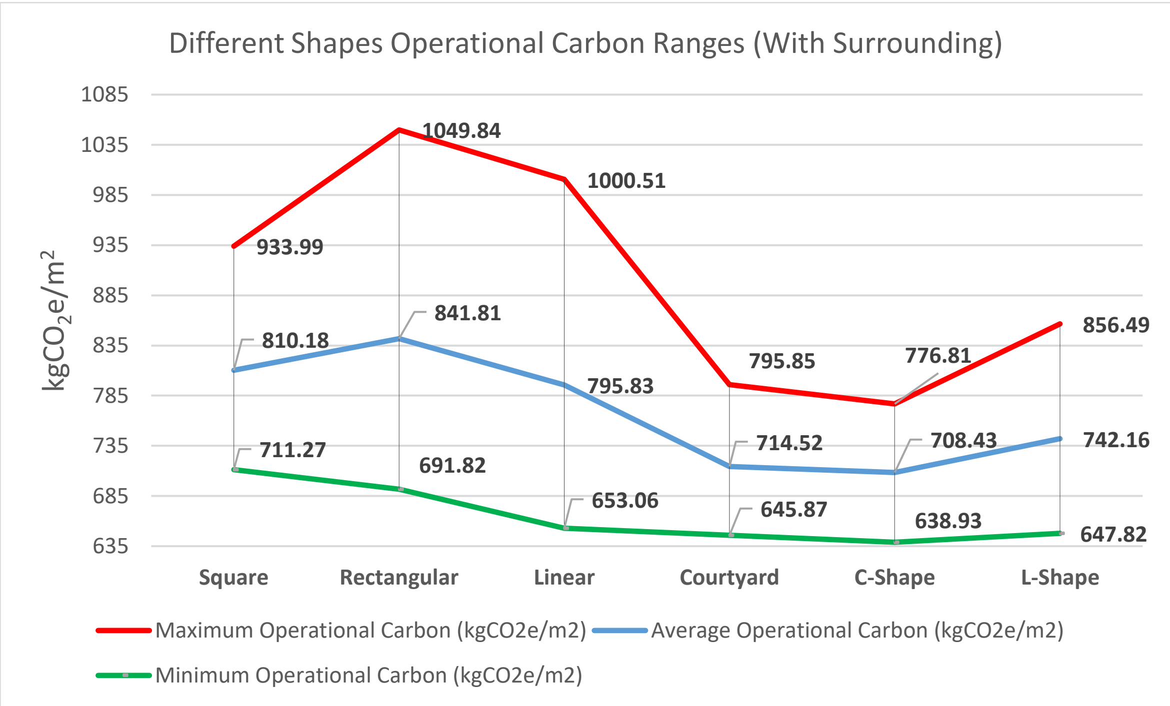

Figure A2. 2. Comparison of ranges of operational carbon based on shapes in an urban context

Appendix 3. Comparison of embodied carbon ranges between different building morphologies

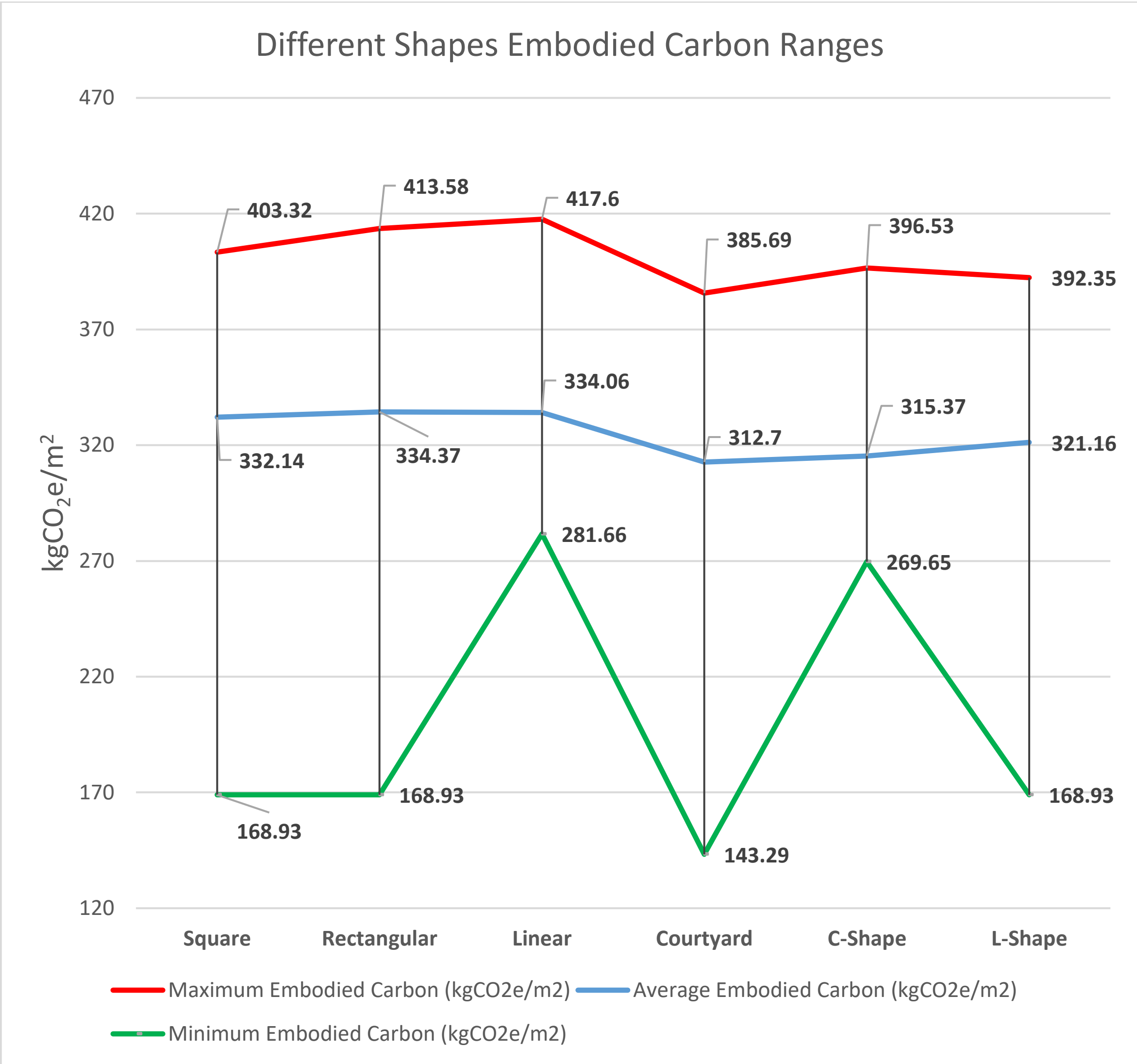

Figure A3. 1. Comparison of the ranges of embodied carbon based on shapes

Appendix 4. Comparison of delivered energy ranges between different building morphologies

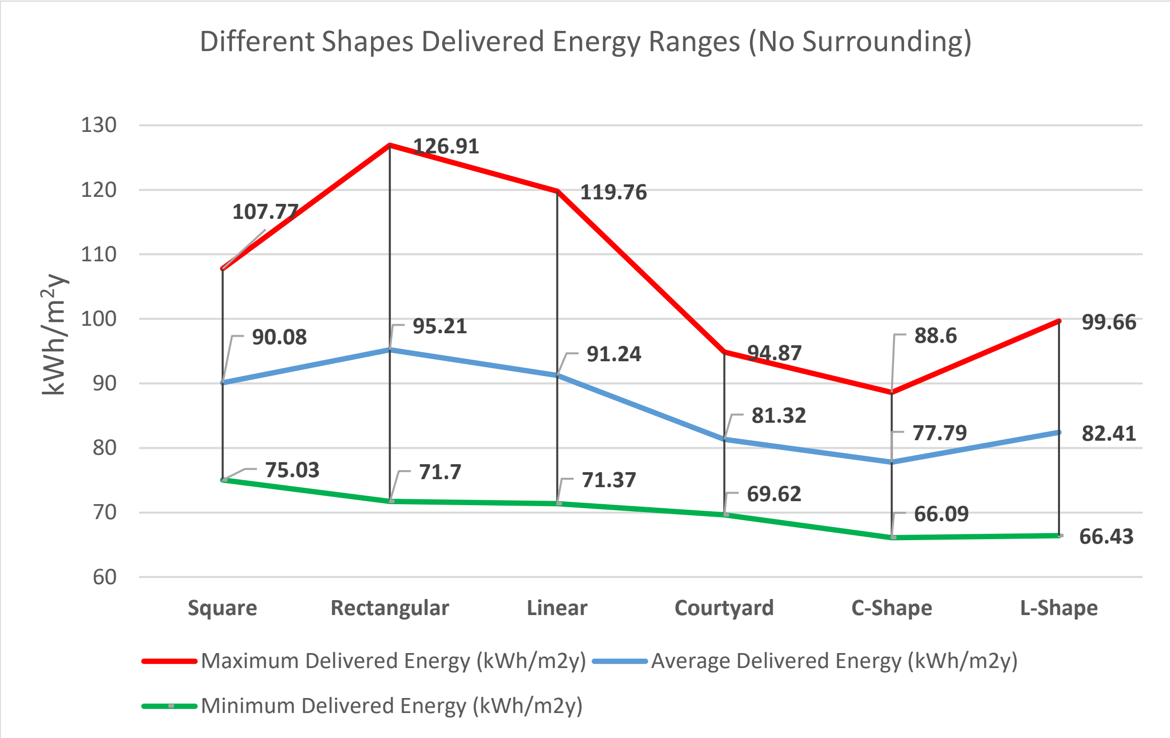

Figure A4. 1. Comparison of ranges of delivered energy based on shapes in no surrounding condition

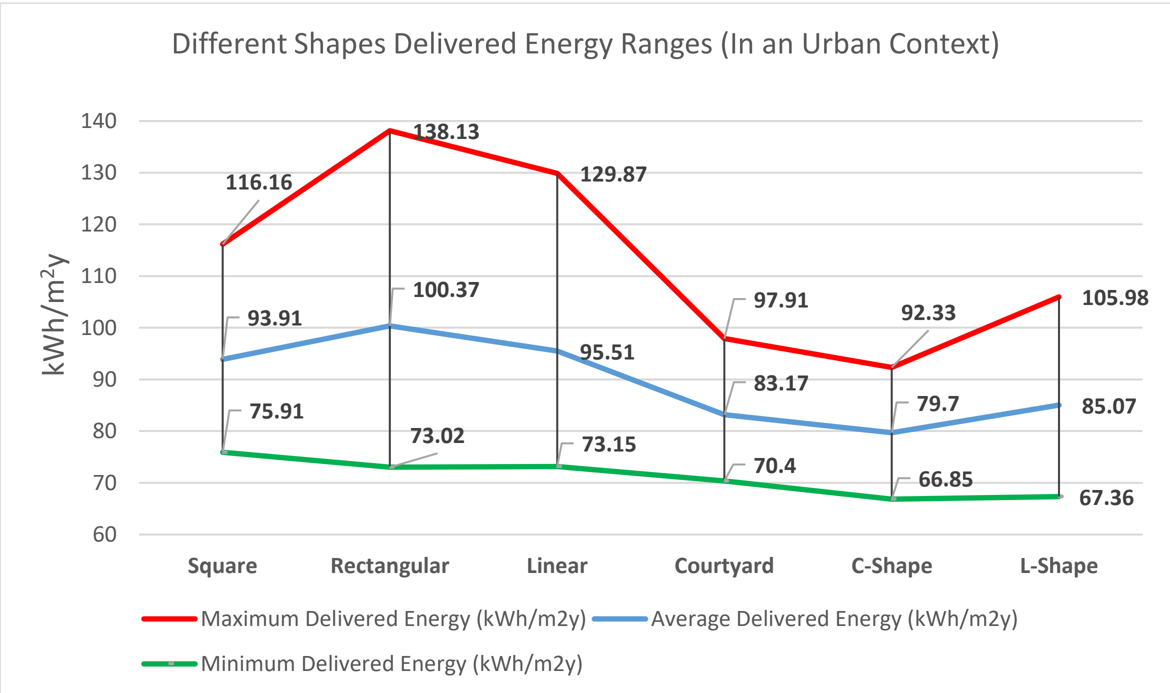

Figure A4. 2. Comparison of ranges of delivered energy based on shapes in an urban context

Appendix 5. Data and Analysis Excel File

Entire Data and Analysis Excel File