The Pennsylvania State University

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DEVELOPING A TOOL TO EXPLORE THE INFLUENCE OF COLUMN GRID PARAMETERS ON BUILDING VOLUME AND CARBON EMISSION IN A TWO-WAY CONCRETE SLAB STRUCTURAL SYSTEM.

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Parinaz Mansourimajoumerd

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The thesis of Parinaz Mansourimajoumerd was reviewed and approved by the following:

Orsolya Gaspar
Assistant Professor of Architecture
Thesis Co-Advisor

Corey Gracie-Griffin
Associate Professor of Architecture
Associate Director for Sustainability Research
Thesis Co-Advisor

Iulo Lisa Domenica
Associate Professor of Architecture

Nathan Brown
Assistant Professor of Architecture Engineering

Ute Poerschke
Professor of Architecture
Associate Dean for Research, Creative Activity, and Graduate Studies

Carlos Cerezo Davila
Environmental Performance Director at KPF New York

ABSTRACT

The construction industries increasingly focus on mitigating carbon emissions associated with buildings. There has been a notable shift in research interest towards embodied carbon (EC) over operational carbon (OP). Embodied carbon depends on the materials used and their mass in the building. It has been shown that conceptual design decisions have the greatest impact on EC. While heating, ventilation, air conditioning (HVAC), and building management systems can effectively reduce OP emissions, there is a pressing need to improve current tools for estimating EC emissions, especially in the early design stages. Furthermore, the significance of building structures influencing the EC emissions of a building cannot be overstated.

This thesis focuses on developing a parametric tool for architects to evaluate the structural volume of their early-stage designs and its impact on EC emissions. It proposes a methodology employing the parametric calculation of structural building elements. The tool's potential is showcased by the case study of two-way concrete slab structures supported by beams. While earlier studies focused on optimizing the horizontal loadbearing elements to reduce EC, more research needs to be done to quantify the effect of vertical loadbearing elements. In this thesis, the effect of changing the grid layout and changing the shape of the building is investigated and compared to traditional engineering approaches, such as optimizing mass by sizing the elements and changing the material. For simplification, only gravity load is considered.

The tool aims to support the early stages of design explorations through four primary tasks. Task 01: Optimize material efficiency through the column grid layout. Task 02: Optimize material efficiency through member sizing. Task 03: Optimize material efficiency by changing the shape of the building. Task 04: Comparing the performance of different optimizing strategies. The tool can help the designer to play with different options and give them an understanding of efficient building design and its effects on EC emissions. This study offers a qualitative comparison of how varying column layouts, member sizing, and building shapes affect EC in the selected case study. It underpins the importance of such a tool for the parametric design of building structural volume.

This research introduces a tool that includes more parameters than existing software: these are meaningful and available in the early design phase. This platform gives the designer greater control (and a more detailed understanding of the sustainability implications of their design) over their conceptual ideas. Hence, it contributes to more sustainable, responsible construction practices.

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Table 1_1 List of Abbreviations

Abbreviations	Description
EC	Embodied carbon
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
OP	Operational carbon

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Chapter 1

Introduction

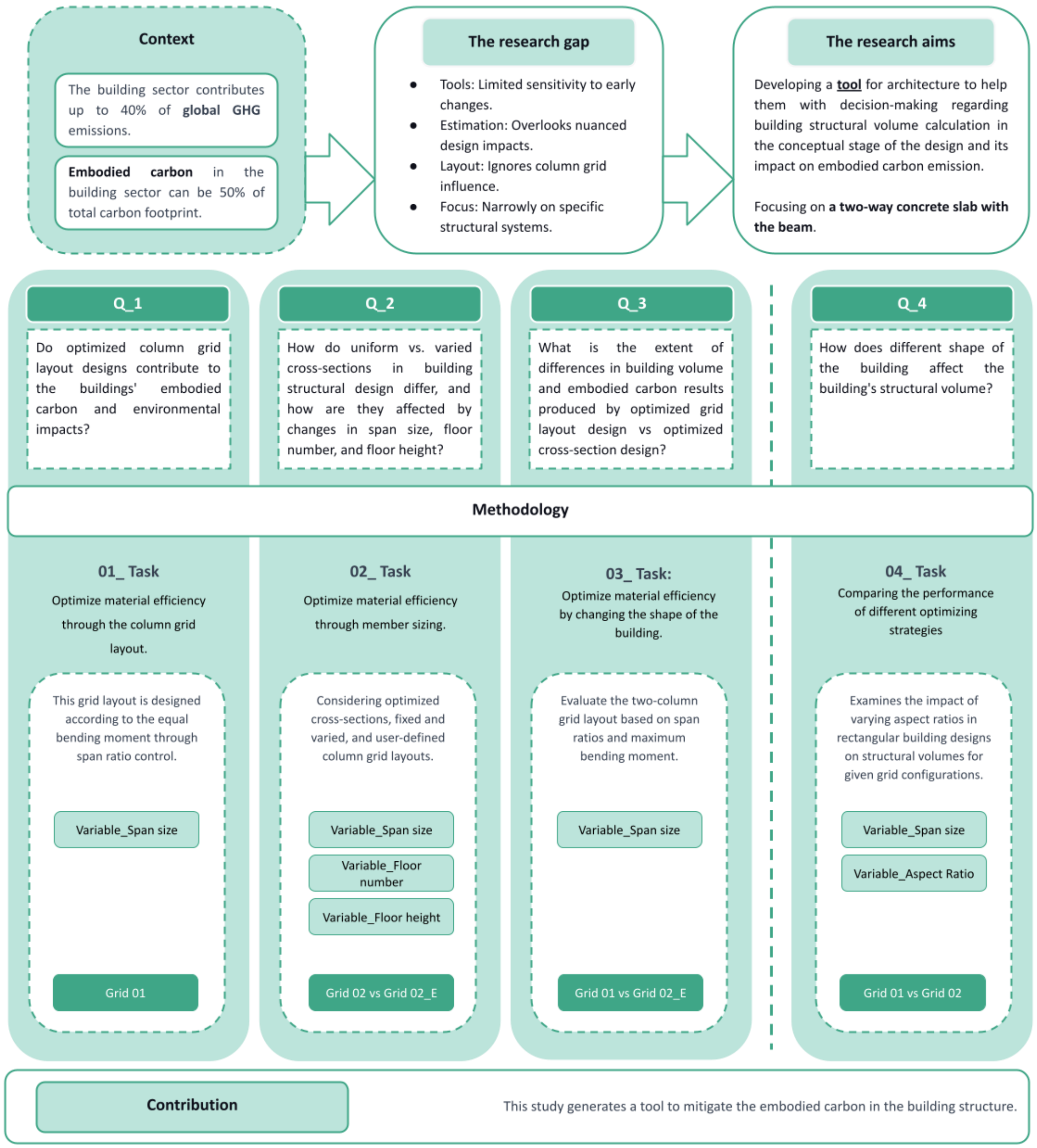

Figure 1_1 Research flow chart.

International agreements such as the Paris Agreement [1] [2] and the Kyoto Protocol [3], [4] aim to limit global warming and reduce greenhouse gas (GHG) emissions. These agreements provide a framework for concerted global action on climate change. Initiatives like the UNFCCC [5] and the Montreal Protocol [6] further bolster these efforts by facilitating international cooperation and regulating harmful emissions. Complementing these agreements, the Sustainable Development Goals (SDGs), notably Goal 13 [7], specifically target climate action, emphasizing the importance of mitigating environmental impact. Organizations like the Global Covenant of Mayors [8] and the Carbon Disclosure Project (CDP) [9] play a crucial role in translating these agreements and goals into actionable steps. They work to engage governments, businesses, and individuals in implementing sustainable practices and reducing carbon emissions [10]. By adopting sustainable strategies in the building sector, we can significantly mitigate the effects of climate change.

The Importance of GHG and GWP in Mitigating Climate Change

Reducing GHG emissions is crucial for mitigating climate change impacts like rising temperatures and extreme weather events [11], [12], [13]. Global Warming Potential (GWP) assesses the relative warming effect of different GHGs compared to carbon dioxide over 100 years, aiding in policymaking for emissions reduction [14] [15]. GHGs, including carbon dioxide, methane, and nitrous oxide, contribute to global warming, with carbon dioxide responsible for around three-quarters of emissions [11]. Efforts to reduce emissions focus on both operational emissions and embodied emissions [16], [17], [18], [19]. Operational emissions can be addressed through energy efficiency and renewable energy, while embodied emissions require decarbonizing materials and embracing regenerative alternatives.

Operational Carbon (OP)

OP refers to a building's energy-related emissions during occupancy, primarily from HVAC systems, lighting, and appliances. Reducing OP includes efficient equipment, zero-energy strategies, and cleaner energy sources [20]. Furthermore, passive design and energy-efficient systems lower energy demand [21]. Innovative building envelopes can reduce heating and cooling needs by up to 40%, leading to significant energy savings [22]. However, improved living conditions have increased EC emissions, exacerbating economic inequalities [23]. A more in-depth understanding of EC emissions in building design is crucial to address this issue.

Embodied Carbon (EC)

EC refers to the cumulative carbon emissions throughout a building's life cycle, including material extraction, processing, component fabrication, construction, assembly, and end-of-life emissions, with potential material reuse or recycling post-demolition [24], [25], [26]. Mitigating the construction-related carbon footprint, especially EC emissions, is crucial for climate change mitigation [20]. Research indicates a considerable variation in embodied emissions, typically ranging from 10% to 50% in conventional LCAs [27], [28].

Research shows that cutting OP can increase EC [29], [30]. Typically, OP garners more attention due to its perceived long-term impact on energy consumption. However, EC, though a one-time expense during construction, is crucial for overall sustainability. Current building codes and standards often overlook EC due to its perceived complexity and one-time nature [31]. However, neglecting it can lead to substantial environmental consequences, with estimates suggesting it could contribute up to 50% of a building's carbon footprint [30]. Thus, there is a pressing need to integrate EC considerations into building design and assessments to ensure sustainable resource use and mitigate environmental impact.

Research Gap

Current tools available for calculating EC emissions in buildings, such as Tally and OneClick LCA, are primarily suited for later design stages when architectural concepts are nearly finalized [32], [33]. These tools help optimize material selection but lack sensitivity to early-stage design changes that could significantly reduce material usage through efficient building design. On the other hand, tools like CARE and EPIC provide rough estimates of EC emissions based on simplistic parameters like building area and number of floors [34], [35]. However, they should account for the more nuanced impact of design decisions on EC emissions, readily available in the early design phases.

Current tools such as Peroptmia, Cove.tool and Athena offer functionalities for evaluating the environmental impact of architectural designs, particularly on carbon emissions. However, they exhibit certain limitations. Peroptmia is constrained by its inability to accommodate diverse building shapes and floor configurations, thus limiting its practicality [36]. Cove.Tool needs more flexibility in building design options, restricting its ability to assess building volume and carbon footprint [37]. Athena requires users to possess some technical proficiency but does not mandate structural engineering or architecture expertise for building modeling [38]. However, these studies need to consider how the column grid layout affects the overall volume of the building's structure and its resulting carbon emissions. Additionally, each study focuses solely on one type of structural system determined by the chosen material.

Research Goal

The research aims to develop a tool to support architects during the initial phases of building design. This tool will facilitate the estimation of material volumes necessary for structural elements like slabs, beams, and columns. Architects can adjust various parameters within the tool, such as building program, floor size, span size, number of floors, and building height. By doing so, they can obtain estimates of structural element volumes tailored to their specific design requirements.

Furthermore, the research investigates the impact of design choices on buildings' GWP. This will be achieved by analyzing the EC emissions of different design alternatives. By providing architects with insights into the environmental consequences of their design decisions, the research aims to encourage adopting more sustainable building practices.

Ultimately, the objective is to empower architects to make informed decisions early in the design process to optimize resource utilization and minimize environmental impact. By considering factors such as grid layout and structural specifications from the outset, architects can efficiently tailor their designs to meet practical and sustainable objectives. Through developing and implementing this tool, the research aims to streamline the design process and promote the creation of more sustainable and effective buildings.

Hypothesis

- The structural volume of buildings may fluctuate depending on the arrangement of the column grid, indicating a potential correlation between grid layout and overall volume variations.

- Building design variations could lead to structural volume fluctuations, suggesting a potential relationship between architectural choices and overall volumetric considerations.

Selected Structural System

The analysis will focus on a two-way concrete slab system with beams. This system is chosen because it simplifies the calculation of volumes for different structural components. Considering all three key elements - slabs, beams, and columns - we can understand how each affects the overall structural volume based on specified parameters and column grid layout.

Chapter 2

Literature Review

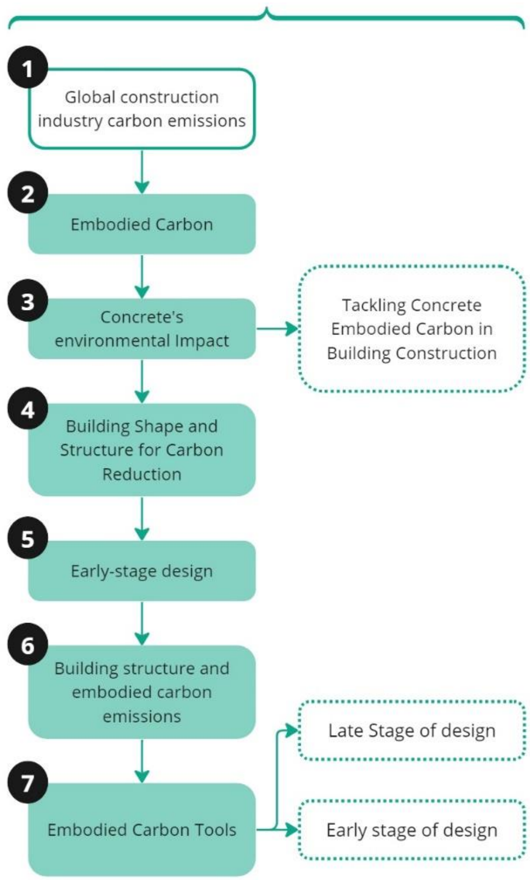

Figure 2_2 Literature review flow chart

Global construction industry carbon emissions

Erlandsson and Borg (2003) emphasize the importance of prioritizing the building industry to achieve sustainability within a reasonable timeframe [39]. This is because the sector's use of building materials, energy, water, and land has a significant impact on the environment. The sector consumes a large portion of natural resources, both renewable and non-renewable, that harm the environment. Heisel et al. developed a building stock and energy model to assess whole-life carbon emissions and saving potential in the built environment [40]. The model focuses on reactivating EC in existing buildings, a factor often overlooked in carbon neutrality policies. The study uses Ithaca, NY, as a case study, utilizing construction archetypes and geospatial data to create a detailed 3D geometry. The approach offers a new way to inform carbon neutrality policies through holistic renewal efforts. To reduce energy consumption in the building sector, it is essential to analyze and change current construction procedures, including design and engineering approaches, construction methods, and manufacturing technology. Dixit et al. (2010) emphasize the importance of such changes to achieve sustainable development [41].

Embodied carbon

A study on used steel portal frames for single-story buildings focuses on minimizing EC [42]. It was reduced (14.34% to 26.47%) through increased member divisions and incorporating non-prismatic segments. Design charts illustrate these variations, emphasizing the potential for optimizing steel portal frames to align with global net-zero emission goals. Structural design decisions are crucial in minimizing carbon intensity and aligning with sustainability goals and regulatory standards [43]. Despite decreased operational CO2 emissions, a study highlights a notable rise in EC dioxide in building structures. The need for a global standard assessment method is underscored, proposing a uniform approach for quantifying material weights and calculating embodied CO2. Structural engineers, facing challenges such as data standardization issues, emphasize the necessity for a unified and transparent methodology.

Concrete's Environmental Impact

The materials chosen for construction significantly influence a building or product's carbon emissions throughout its lifecycle [44]. Although energy-efficient buildings can lower operational emissions, they may inadvertently contribute to increased emissions in other stages related to materials, owing to the energy-intensive manufacturing and disposal of construction materials like insulation, windows, and renewable energy technologies [26]. Prioritizing low-carbon materials and setting explicit EC targets in the project's early phases are crucial [45], [46], [47]. Material selection during design is particularly impactful in reducing a building's overall carbon footprint [48], [49], [50], [51].

Concrete production significantly contributes to global carbon emissions, prompting the development of low-carbon solutions. These include using Supplementary Cementing Materials (SCMs) like fly ash, slag cement, and silica fume, which enhance concrete properties while reducing costs and permeability [52]. These materials enhance concrete properties, lower expenses, decrease permeability, and boost strength. COPact incorporates Pozzotive, a ground glass pozzolan made from recycled glass, replacing up to 50% of cement and significantly reducing CO_2 emissions [53]. CarbonCure injects recycled CO_2 into fresh concrete to decrease its carbon footprint [54]. These innovations offer promising solutions to mitigate the environmental impact of concrete production.

Cement production alone accounts for 6% of global emissions, with concrete production adding another 8%. EC in reinforced concrete is primarily from cementitious content, comprising 70% of total EC. Strategies to mitigate carbon footprint include leaner designs, low-GWP alternatives for cement and steel, and specifying low-carbon pre-manufactured concrete products [55]. Research highlights the environmental impact of overdesign in concrete, revealing that only

15% of surveyed projects met requirements in Pennsylvania in 2020, with overdesign-induced cement consumption contributing up to 6.7% of total US cement use [55]. Prefabricated concrete (PC) buildings exhibit lower carbon footprints during the materialization phase, with production contributing over 90% of emissions. Cement, steel, concrete, and wire rank highest in carbon emissions among building materials [150]. The developed tool allows users to choose different GWP regarding the concrete and rebar they choose for their design.

Nevertheless, reducing EC emissions is not solely reliant on selecting materials with low carbon footprints. Another approach under consideration in this research involves regulating the EC emissions concerning the volume of the building's structure. **The following section analyzes previous studies that have explored concrete structural systems.**

Tackling Concrete EC in Building Construction

Gregory.J. et al. research focuses on concrete in construction and aims to reduce the structural volume of buildings, particularly those using reinforcing materials. The study targets a 49% reduction in building emissions by 2050, with ambitious efforts aiming for 57%. In pavements, projections aim for a 14% reduction, while ambitious measures target 65% by 2050. The study highlights the dominant role of building energy in life cycle emissions, proposes using low-carbon cement for mitigation, and emphasizes the need for comprehensive life cycle analysis [58]. Griffin et al. examine how different structural systems (one-way concrete slab and beam or one-way joist slab) affect sustainability, mainly focusing on EC. They compare long-span systems using steel, concrete, and wood and evaluate factors. The study emphasizes the cost impacts of meeting criteria for acoustics, fire ratings, and thermal efficiency. It advocates for the early involvement of integrated design teams and stresses the need to reduce construction's environmental impact [54].

Overall, although there was an improvement in having low carbon emission concrete per volume, a critical issue arises from the substantial volume required to achieve structural functionality [59]. Consequently, it becomes imperative to explore strategies to minimize the utilization of concrete in specific structural elements. This approach addresses environmental concerns associated with excessive concrete usage and promotes resource efficiency and sustainability within construction practices. **Our research is also centered on developing a tool for optimizing the volume of building structures while focusing exclusively on reducing concrete's average GWP.**

Building Shape and Structure for Carbon Reduction

Understanding the impact of building geometry design on structural systems is essential for reducing carbon emissions. Architects can optimize designs by understanding how the structural elements impact the overall volume of the building.

Zargar et al. [60] utilize machine learning to predict EC in early tall timber structural designs, showing that basic massing data suffices for accuracy. They stress the influence of geometric parameters, especially in tall timber structures, aiming to enhance sustainability and urging broader datasets. Their automated simulation-based approach identifies design improvements, emphasizing caution in automated workflows and the importance of multidirectional design exploration. Kim et al. [61] find the IsoTruss® grid comparable to diagrid systems in exterior column strength, with potential wind load reduction benefits. Hou et al. [62] present a novel architectural growth model inspired by plant development, offering insights into space evolution but acknowledging context-specific limitations.

Early-stage design

By strategically engaging in an analysis of diverse design alternatives early in the process, architects can substantially impact the structural volume of the building. During conceptual design, Sory proposes Physics-based structural quantities for estimating EC in buildings [63]. Using a combination of engineering calculations and data-driven modeling, case studies, including a Lisbon urban simulation. The approach aims to inform early-stage planning and policy decisions for decarbonizing the built environment, focusing on reinforced concrete structures. The paper acknowledges data limitations and the challenge of estimating EC in early design stages but highlights the potential for informed decision-making in retrofitting and building design. Another study introduces a parametric framework for early-stage tall timber design, focusing on EC in post-beam panels and post-and-platform systems [64]. Emphasizing the role of floors as contributors to EC, the framework allows simultaneous decisions on system and geometry. Results reveal higher EC in the post-beam-panel system, increasing with building height. The study identifies critical timber elements for potential material alternatives. Utilizing Grasshopper and Karamba3D, it aims to promote timber application in large-scale construction. Limitations include a narrow focus on tall timber design and reliance on EC coefficients from the Inventory of Carbon and Energy (ICE) database. Xiang et al. focus on early-stage EC emissions in a Chinese educational building design [65]. Steel and concrete emerge as primary contributors, with local and reused materials identified as effective low-carbon options. Results emphasize prioritizing reused and recycled materials for reduced carbon impact. The study employs a process-based LCA, highlighting the significance of considering sustainability factors in the design stage.

Building structure and EC emissions

Engineers are urged to prioritize EC to achieve an emission-free building sector by 2050, despite challenges such as limited data on EC equivalents and time constraints in LCAs [66]. Fang et al. rigorously examined thirteen strategies to reduce EC in building structures [67]. These strategies cover various aspects, including the adoption of parametric design space, using less material, incorporating low-carbon materials, reusing structural elements, designing for longevity, estimating EC, statistically predicting it, reducing load demands, implementing active structures, considering regional and cultural factors, addressing trade-offs, and evaluating compatibility and implementation. Through a synthesis of academic research and practical insights, the study provided actionable guidance for sustainable structural design practices. Results indicated a noticeable trend towards adopting parametric design space while highlighting the longstanding efficacy of strategies such as reusing structural elements and incorporating low-carbon materials. Additionally, emerging approaches like statistically predicting EC and reducing load demands were identified as promising but requiring further research.

In terms of tall buildings, Choi. et al. introduced a sustainable design model for steel-reinforced concrete (SRC) composite structures, emphasizing CO2 emissions reduction [68]. The model optimizes material combinations and demonstrates positive environmental performance and space utilization results, especially in high-rise buildings. Examining tall buildings globally focuses on sustainable design strategies to achieve net-zero carbon emissions by 2030 [69]. Notable examples such as the China Resources Building, the Stadthaus, and the Bank of America Tower demonstrate advancements in construction waste management, embodied energy reduction, and operational efficiency improvement. The study emphasizes the necessity for widespread adoption of new construction methodologies and policies to effectively combat climate change in rapidly expanding urban areas. Key factors considered include the reuse of structures, optimization of wall-to-floor area ratios, and the importance of the building form.

Considerable studies focus on assessing slabs and their impact on the buildings' EC emissions, emphasizing their significant volumetric contribution to the overall structure [70]. Optimizing this component is considered highly impactful for enhancing overall effectiveness. Structural engineers' influence on sustainable design is constrained. The study by Trinh et al. identifies optimum designs using a parametric design algorithm to minimize EC in reinforced concrete flat slabs. Factors like allowable thickness, column spacing, and lower-grade concrete significantly influence EC. The column grid initially assumed to be rectangular with equal span lengths in both directions, is considered.

Trinh. et al. study was a motivation for the following thesis regarding the importance of building structure specification and the importance of slabs and columns in structural volume [71]. They studied flat plate buildings and found that shorter spans, thinner depths, and pre-stressed tendons could decrease environmental impacts. Columns contributed approximately 10-11% to the total floor weight. Implementing an innovative algorithm resulted in a significant 31% reduction in embodied emissions. Concrete consistently accounted for 82.8-84.1% of the carbon in the slab system. The study achieved significant reductions in emissions ranging from 5.3-17.7%, highlighting the need for further optimization. Park et al. highlight the significance of addressing all structural elements despite the notable efficacy of slab improvements in mitigating EC emissions owing to their substantial volume [72]. Only a few studies have focused on building structural components beyond slabs, emphasizing elements such as columns. As an exception, an optimal design model for green building construction analyzes circular and square concrete-filled steel tube columns. Circular columns prove more effective in reducing CO_2 emissions and costs, while the square section is advantageous for space utilization. They recommend a holistic approach to EC reduction in building structures. **Hence, the following thesis aims to evaluate the environmental implications of all structural elements, slab, beam, and column.**

Some contemplate utilizing Building Information Modeling (BIM) to optimize building structures and mitigate the impact of GWP [73]. A paper examines the impact of optimized structural designs on building carbon performance using a Building Information Modeling (BIM) embedded approach. Structural floors significantly contribute to EC and emissions. The study identifies the two most carbon-efficient options, emphasizing the need to integrate structural optimization models in LCAs: 1. structural alternative (bay dimensions) and 2. building elements (material types). A BIM-based optimization method for reinforced concrete structures targets cost and EC reduction [74]. The study employs Finite Element Method (FEM) and a multi-objective genetic algorithm, highlighting the importance of structural layout for optimal solutions.

Temizel-Sekeryan et al. center on the structural design aspects of buildings and integration with critical factors such as fire protection, as well as their correlation with the EC emissions of the structure. They assess long-span structural systems' environmental impact and performance (steel, concrete, wood), focusing on embodied energy and fundamental properties (acoustics, fire protection, thermal). The research aims to inform design teams about sustainability and cost considerations. It emphasizes the need for more research on alternative long-span systems, pointing out existing neglect in understanding the role of structural systems in building performance [75].

Table 2_2 Literature review based on building structure and EC emissions.

R	Aim	Gap	Method	Output	Grid Layout
[71]	Methodology introduced for optimizing carbon in concrete building design.	Studies isolate slab and column systems, limiting structural engineers' applicability.	Genetic algorithm ------ Two-way slab	1. Minimize CO_2 emissions 2. Reduce slab-to-column area ratio for optimal designs	Rectangular grid with equal spans.

[70]	identifying the viable design space and relevant limiting criteria	Uncertainty of EC estimations	Parametric design algorithm ------ Flat slabs	1. Optimum slab thickness 2. Column size impact 3. Span increase 4. Lower concrete grades 5. Deflection checks 6. Larger deflections 7. Reinforcement increases 8. Reduction methods.	Square-shaped grids are considered in this scope (4 m–10 m with 0.25 m intervals)
[76]	Understand how design variables affect embodied emissions.	Design optimization involves many variables and requires extensive computation.	A sustainable design parametric ------ Flat slabs	1. Different column spacings 2. Concrete strengths 3. Structural component sizes 4. Detailed reinforcements	A square grid of different column layouts.
[68]	Minimize CO_2 emissions through optimized SRC construction.	Sustainable CO_2 strategies favored reinforced concrete over steel reinforced concrete, overlooking SRC's eco-design potential.	Design Parameter Optimization ------ Case study ------ SRC composite structures	1. Emissions Relationships 2. Optimal Material Combinations 3. CO_2 Comparison 4. Design Parameters 5. Space Efficiency Analysis 6. Design Recommendations	Designed regarding the case study
[72]	Propose an optimal design model for analyzing CO_2, cost, and CFT columns.	Relationship among CO_2, cost, & structural parameters in CFT columns not explored.	Design Parameter Optimization ------ Case study ------ Concrete-filled steel tube (CFT) column	CO_2 emissions ------ 1. Comparison of types. 2. Material cost determination. 3. Advantages of variations. 4. Design results. 5. Comparative analysis.	Designed regarding the case study
[73]	Integrate sustainable structural analysis via BIM and heuristic optimization.	Underestimation of optimized structural designs' impact on building carbon performance.	BIM ------ NSGA-II ------ Case study ------ Flat slabs	1. Structural Optimization Impact 2. EC Proportion 3. Floor Design Importance	Rectangular Bay 9 alternative
[74]	Optimize reinforced concrete structures for cost and carbon efficiency early.	Existing methods lack integrated cost-carbon optimization for concrete structures.	BIM ------ NSGA-II ------ Case study ------ Flat slabs	1. Cost and EC optimization. 2. BIM-based optimization approach. 3. Utilizes Finite Element Modeling (FEM). 4. Structural layout optimization. 5. Slab and columns sizing. 6. Slab and columns reinforcement.	Designed by user

EC Tools

Various tools have been developed to calculate the EC emissions of buildings, each serving specific purposes. These tools assess the benefits of material reuse, different structural systems, building designs, and design stages. In the subsequent section, I will discuss and compare the EC tools pertinent to my thesis while also conducting an evaluation to identify areas for potential improvement.

Tools For Late Stage of Design

OneClick LCA

OneClick LCA is an advanced software solution designed to streamline and automate LCAs for construction projects, products, and portfolios. It offers a platform for evaluating the environmental impacts throughout the entire life cycle of buildings and infrastructure [77]. Users input various data points related to building design, materials, and construction methods into the software. One Click LCA then processes this input, leveraging its extensive database and algorithms to produce reports outlining the environmental impacts across different stages of the project life cycle. These reports are valuable resources for certification, design optimization, and sustainability planning.

Limitations: Despite its robust capabilities, One Click LCA may encounter limitations in accurately accounting for certain complex scenarios or dynamic factors within LCAs. Additionally, the software's effectiveness may be contingent upon users' availability and accuracy of input data. The most important limitation is that it is for the late design stage [78].

Tally

Tally is an LCA software plugin for Autodesk Revit, tailored for architects and builders to assess the environmental impacts of building materials and systems, providing real-time feedback and aiding in sustainable material selection. Tally integrates with Revit to generate data and feedback at every design phase, answering questions like cross-country lumber transportation's environmental impact, major contributors to GWP, carbon emissions savings by altering concrete mix components, and comparison of insulation materials [79].

Limitations: While Tally offers real-time feedback and aids in sustainable material selection, its integration with Revit limits its usage to Revit users. It is not for the early stage of design. Additionally, it may not address all environmental impact categories comprehensively, and alternative tools like EC3 and tallyCAT may offer additional features for EPD-based procurement and more comprehensive LCA [79].

Tools For Early Stage of Design

EPIC

The Early Phase Integrated Carbon (EPIC) assessment tool, developed by EHDD, facilitates climate-positive design decisions during early project stages by addressing the challenge of limited data availability. Leveraging machine learning algorithms and data collection methods, EPIC aims to investigate carbon emissions effectively. However, it exhibits certain limitations. Notably, its accuracy is compromised when predicting the carbon footprint of buildings with varying shapes but identical geometric areas. Additionally, EPIC cannot differentiate between the carbon emissions associated with different structural elements of a building. Its functionalities primarily focus on assessing EC, OP, carbon storage, Energy Use Intensity (EUI), and EC intensity. It is essential to recognize that EPIC is not designed to provide high-resolution whole-building Life Cycle Assessment (wbLCA), generate reports, or predict future outcomes. Ultimately, EPIC aims to balance embodied and OP to support sustainable design decisions [80].

Table 3_2 Baseline detail of EPIC

Parameter	Project Base Case	Project Name *
		Year of Project Completion *
		Location *
		Baseline Structural System *
		Primary Building Use *
		Number of Above Ground Floors *
		Area per Above Ground Floor *
	Type of Structural Material	Light Wood Frame
		Mass Timber
		Reinforcement Concrete
		Composite Steel Frame
		Hybrid Concrete_Steel (High Rise)
	Output	OP
		EC
		Carbon Storage
		Energy Use Intensity (EUI)
		EC Intensity (ECI)

CARE

The CARE Tool facilitates the comparison of carbon footprints between renovating an existing building and constructing a new one. It relies on a heuristic approach, incorporating the proportions of various building components. However, the result presents the GWP of the total building elements. Like Epic, it does not account for alterations in building configuration, focusing solely on factors like Window-to-Wall Ratio, Total Floor Area, Floors Above Grade, Floors Below

Grade, and Average Floor Area. Its primary objective is to assess the environmental advantages of retrofitting buildings and to inform decisions regarding reusing existing structures, particularly during the initial design stages [81].

Table 4_2 Baseline detail of CARE

Parameter	Project Base Case	Project name
		Location
		Window-to-Wall Ratio
		Total Floor Area
		Floors Above Grade
		Floors Below Grade
		Square Feet | Average floor area
	Type of Structural Material	Wood
		Hybrid
		Steel and/ or Concrete
	Output	Embodied Emissions
		Operational Emissions
		Total Emissions
		Total Emissions Intensity

Cove.tool

The EC estimation tool is provided by Cove.tool employs recognized industry standards and methodologies, such as ACI 318-19 and ANSI/AISC 360-16, to evaluate the carbon emissions of structural materials in construction projects. It aims to accurately estimate the carbon footprint of elements like concrete and steel, utilizing conservative approaches for comprehensive assessment. This tool considers factors such as material quantities, load profiles, and industry guidelines to facilitate informed decision-making and minimize construction carbon emissions [82]. **This tool has been selected to evaluate the developed tool for this thesis.**

Input and Output: The "Project Information" section collects essential data such as project name, location, construction type, building lifespan, and design phase. This information provides context for assessing emissions accurately and effectively. The "Project Total Carbon Emissions" tool comprehensively evaluates the carbon footprint throughout various construction phases, considering different structural material types. It offers a holistic view to assess environmental impact [37].

Limitations: The approach adopts conservative techniques and industry norms, possibly oversimplifying particular design situations. It could face inaccuracies from regional disparities in material supplies, energy origins, and construction methodologies, especially globally. Its main emphasis lies in evaluating structural materials, disregarding crucial phases like transportation, upkeep, and dismantling, which are vital for a thorough carbon footprint assessment [82].

Table 5_2 Baseline detail of Cove.Tool

Parameter	**Project Base Case**	**Project Name**
		Program
		Location
		Height
		Roof Area
		Floor Area
		Skylight Area
		Rotate Building
		Wall Area
		Glazing Area
		New Construction
		Renovation
	Design	Concept
		Schematic
		Design development
		Construction Documents
		Construction Documents
		Complete

	Type of Structural Material	Steel
		Concrete
		Mass Timber
	Output	Project Total Carbon Emissions
		Project Carbon Emissions Breakdown
		System Carbon Emissions Breakdown
		Mechanical, Electrical, Plumbing system reuse
		Modifiers

Preoptima

Preoptima streamlines building design by integrating AI and generative design, allowing stakeholders to analyze and optimize designs for low whole-life carbon (WLC) impact. Their platform facilitates informed decision-making throughout the project lifecycle, ensuring alignment with sustainability goals and regulatory requirements. The primary focus is delivering environmentally friendly buildings while meeting client needs and minimizing construction-related environmental impacts [83].

Inputs and Outputs: The system takes in project details like name, location, architect, client, budget, and carbon price, along with building specifications such as use type and floor heights. It also considers the dataset selection, methodology, reporting requirements, assessment boundary for carbon calculations, and the drawing of the building site with specified vertices. Outputs include real-time whole-life carbon assessments, comparative analysis of design choices regarding carbon impact, exportable design details, material quantities, carbon data, and geometry data. Additionally, it provides high-quality reports with standardized LCA formatting and detailed breakdowns, integrating with MEP data for comprehensive analysis [84].

Limitations: The platform's effectiveness depends on accurate data input and expertise in sustainability and construction. Carbon assessments rely on reliable data availability, but accuracy may vary by region. Users need training to use the platform effectively, especially for drawing building sites. They must exercise judgment to interpret results and make informed decisions on design optimization and carbon mitigation strategies, minimizing interpretation bias [84].

Table 6_2 Baseline detail of Preoptima

Parameter	**Project Base Case**	**Project Name**
		Location Address
		Building use type
		Assessment Boundaries
		Draw the site one the map
	Design	L-shape
		Court
		Block
		Tower
		C-shape
		H-shape
		Target Floor area
		max number of Storeys_15
		storey height_6m
		Underground storeys_3m
		UG storey height_5m
	Type of Structural Material	Concrete
		Steel
		Timber
		Hybrid
		LWTimber
	Output	Project Total Carbon Emissions

The ATHENA

The ATHENA EcoCalculator is a software tool developed by the ATHENA Sustainable Materials Institute, aimed at assessing the EC of structural assemblies in building construction projects [85].

Inputs and Outputs: The EcoCalculator offers users options for Residential or Commercial versions, city selection, and assembly categories. Users input specific assembly details and square footage, with optional adjustments. Instant LCA results include environmental impact measurements like Fossil Fuel Consumption and GWP [86]. Results are presented in real-time tables, enabling fair comparisons based on preset assumptions, covering the entire building lifecycle [87].

Limitations: a) the scope may not comprehensively address all sustainability concerns. b) reliability relies on data quality and assumptions made during assessment. c) Precision may be limited due to the complexity of factors involved. d) Lack of standardized protocols for certain aspects of assessment. d) Uncertainty in predicting future waste management practices may impact accuracy [88].

Table 7_2 Baseline detail of Athena

Parameter	Project Base Case	Project Name	_
		Location Address	_
		Building use type	_
		Assembly selection sheet category	Columns and Beams
			Intermediate Floors
			Exterior Walls
			Windows
			Interior Walls
			Roofs
		Selecting Assemblies and Generating Building Scale Results	GWP
			Fossil fuel depletion
			Pollution to air and water
			Weighted resource use
	Design	square footage	_

	Type of Structural Material	Diverse	_
	Output	Global Warming Potential	_
		Acidification Potential	_
		Human Health Respiratory Effects Potential	_
		Ozone Depletion Potential	_
		Photochemical Smog Potential	_
		Eutrophication Potential	_
		Fossil Fuel Consumption	_

The thesis addresses the pressing need for GHG emissions in construction, a major contributor to global emissions. Emphasizing the importance of considering downstream industries like construction for carbon emissions, the research advocates for low-carbon technologies and policies. Strategies for reducing EC in materials, particularly concrete, are explored, including supplementary materials and innovative production methods. LCA methods and tools are highlighted for evaluating environmental impacts across building stages. Studies on building shape, structural design, and optimization using BIM are reviewed, emphasizing the need to minimize structural volume and choose low-carbon materials. The evaluation compares various EC tools, focusing on their suitability for different design stages. Tools like OneClick LCA and Tally are for late-stage design, while EPIC and CARE target early-stage decisions. Cove.tool, and Preoptima offer AI-driven solutions, and the ATHENA EcoCalculator specializes in assessing EC for structural assemblies.

This thesis aims to build a tool that assists architects in evaluating the environmental impact of structural elements during the initial design stages. By focusing on calculating the volume of concrete components such as slabs and beams, designers can gain insight into the emissions associated with their designs early in the process.

Chapter 3

Methodology

I developed a tool that determines and optimizes the column grid layout and the volume of the structural skeleton of a mid-rise building with a rectangular plan. Meanwhile, it addresses the associated EC emissions, focusing on two-way concrete slabs with beams. In the context of this study, an algorithm is formulated within Grasshopper, a plugin for Rhino.

In early-stage design, a parametric model is a highly effective approach for estimating EC. This method facilitates a systematic analysis by considering various parameters influencing EC, such as span size, column grid layout, and building geometry. By employing this technique, designers can evaluate the EC impact of different design options early on, aligning with sustainable design practices and contributing to the broader objective of reducing buildings' environmental footprint.

This methodology, with its aim to guide early-stage design, heavily relies on the ‘rule of thumb’ both in determining acceptable span ranges and in sizing the members as a starting place. However, the optimized grid layout relies on basic calculations from the strength of materials in determining the maximal bending moments to derive the optimized span sizes.

Simplifications

- To keep the research manageable, it was assumed that only vertical loads affect the columns. I acknowledge the relevance of the other vertical structural elements, like stiffening cores, which handle lateral loads and contribute to the overall structural volume of a building. I consider their integration one of my first steps in the future.

- The study has focused solely on rectangular plans featuring square bays to streamline the analysis process. This deliberate simplification enables a more focused examination of key factors without the complications that other configurations might introduce.
- The slabs and the beams are assumed to be continuous (i.e., multi-span).
- Moments were calculated without accounting for moment redistribution in the plastic state (i.e., the ultimate load theory was not applied).

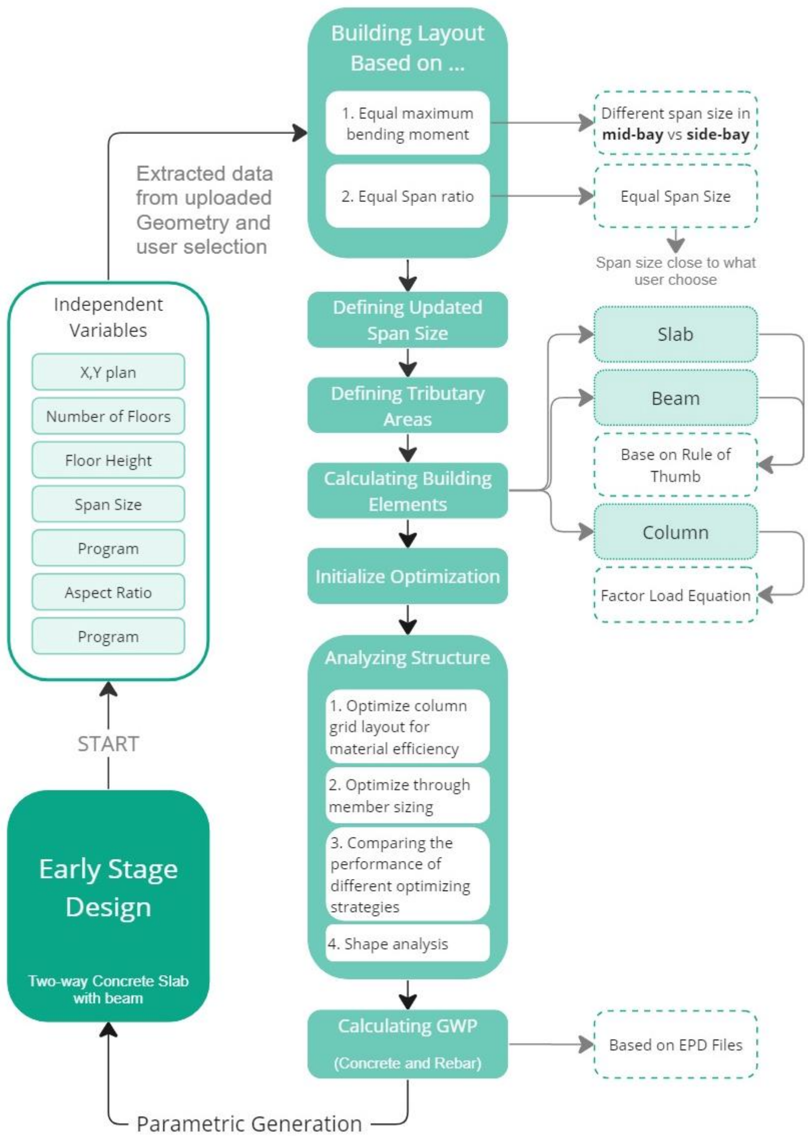

Figure 3_3 Methodology flow chart

User-Defined Geometry Variables

Users can input their design parameters through Grasshopper or upload their designs to the algorithm. Key geometry variables include Aspect Ratio, Floor Area, Floor Height, and Number of Floors. The algorithm autonomously defines these variables based on the user's design input.

Area of Each Floor for Live and Dead Load Calculation: The initial step involves the determination of the floor area, a pivotal factor in ascertaining the live and dead load borne by the building. This is achieved through precise measurement and calculation of the horizontal space on each floor.

X and Y Coordinates for Updated Span Size: To accommodate the user-specified span size within the chosen grid system, it is imperative to ascertain the X and Y coordinates for each floor. These coordinates play a crucial role in recalculating the span size and ensuring alignment with the user's preferences.

Floor Height for Column Volume Calculation: The vertical dimension of each floor, commonly referred to as the floor height, is integral for computing the volume of columns on every level. This calculation aids in understanding the distribution of structural elements throughout the building.

Floor Number for Dead Load on Columns: The numerical designation of each floor is indispensable for evaluating the dead load exerted on the columns. This information is pivotal in determining the vertical load distribution and ensuring structural integrity.

Grid layout-optimization Strategies

Understanding column grid layout is crucial for accurate volume assessment across architectural designs. The column grid's layout may vary based on function or other design parameters. One of the hypotheses of this thesis is that it significantly influences the necessary concrete volume associated with columns. Accordingly, this thesis takes the user input and (a) suggests the closest match where the maximal bending moments are equal in each span. The methodology considers the importance of bending moments and internal forces induced by loads on structural elements like beams and columns. However, it is important to know that it is a random choice to have an equal bending moment, and it is only to show the concept of the tool. (b) Non-equal beam bending moment and closest match to user input with an equal cross-section of an entire floor. (c) Non-equal beam bending moment and closest match to user input with various cross-sections (slab and beam depth) in the entire floor.

Optimization Strategies

a) Grid 01: Equal beam bending moment and optimized column layout (Non-uniform column grid)
b) Grid 02: Non-equal beam bending moment - Equal cross-sections. (Uniform column grid)
c) Grid 02 + E: Non-equal beam bending moment - Optimized via member sizing. (Uniform column grid)

a) Gird_01: Equal beam bending moment and optimized column layout

1. Initialization: Overall Dimension vs. User Input in Determining Number of Bays

One way of optimizing a column grid layout is to ensure that the maximal bending moments are the same across all spans with consideration of having square bays. This results in a similar utilization ratio in the horizontal load-bearing elements.

Problem statement: Achieving equal maximum bending moments across all spans can be achieved for the beams and the slabs by adjusting the spans on the perimeter vs. in the center of the grid. Users are allowed to select spans within the predefined ranges. For example, the range is between 4m to 12m for a two-way slab with a beam. The ranges were determined based on loading requirements, material properties, structural configuration, design codes, and standards [89].

This research will illustrate the guiding equations to achieve equal moments along one axis, and the other follows accordingly.

2. Refinement of the grid: user input vs suggested result from optimization.

Moment Calculation: Based on the engineering ToolBox [90], the beam maximum bending moment in side-bay and mid-bay follows the below equations:

Side-bay Beam: A side-bay beam is positioned between two adjacent supports within a structure in structural engineering. When analyzing side-bay beams, the maximum bending moment typically occurs near the supports due to the concentration of loads or the effect of support reactions. The bending moment decreases towards the center of the span, reflecting the varying distribution of bending stresses along its length.

$$M1 = M\,max = \frac{qL1^2}{12} \qquad 1)$$

Where:

M_{max} = maximum moment (Nm, lb in)

q = uniform load per length unit of beam (N/m, N/mm, lb/in)

L1 = length of side-bay beam (m, mm, in)

Mid-bay Beam: In contrast, a mid-bay beam is situated at the midpoint of the span, equidistant from adjacent supports. The bending moment diagram for a mid-bay beam displays a single maximum value at the center of the span, diminishing towards the supports on either side, illustrating the uniform distribution of bending stresses.

$$M2 = \ M\,max\ = \frac{qL1^2}{24} \qquad 2)$$

Where:

M_{max} = maximum moment (Nm, lb in)

q = uniform load per length unit of beam (N/m, N/mm, lb/in)

L2 = length of mid-bay beam (m, mm, in)

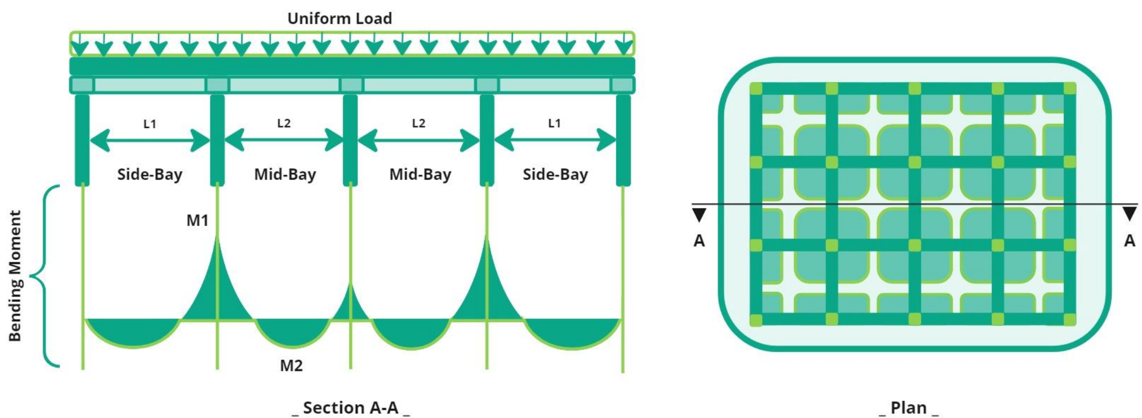

Figure 4_3 Two-way slab concrete with beams

How the requirement of Equal Moments affects Span Sizes: In the preliminary stage, equilibrium in moments is attained, leading to the determination of two span sizes, designated as L1 and L2. These span sizes are configured to ensure parity in bending moments within the structural design. To achieve equivalence in moments, the subsequent equation is formulated and solved to establish the correlation between L1 and L2.

$$\boldsymbol{M1} = \boldsymbol{M2} \tag{3}$$

$L1$:

$$L1 = \frac{L2}{\sqrt{2}} \tag{4}$$

$And\ L2$:

$$L2 = \sqrt{2} * L1 \tag{5}$$

Regarding L1 and L2 results, to have an equal maximum bending moment in the beam, if a user chooses a span size, for example, 6m, this span size will be updated to L1 and L2 according to the location of the beam to the bay (side-bay, mid-bay). However, having to update the L1 and L2 lengths, there is a need to use the total dimension of the building plan length of width.

$$y = (n-2)(L2) + 2L1 \tag{6}$$

Where:

y = total dimension of building plan length of width; the building length must be a minimum of 2 times the span length, ensuring the results will be null.

x = user-defined span size

n = y/x: number of bays, rounded

n-2 = number of mid-bays

L1 = length of side-bay beam = span size in the side-bay (m, mm, in)

L2 = length of mid-bay beam = span size in the mid-bay (m, mm, in)

$And\ L2$:

$$L2 = \frac{y\sqrt{2}}{\sqrt{2}(\mathrm{n}-2)+2} \quad 7)$$

$And\ L1$:

$$L1 = \frac{y}{\sqrt{2}(\mathrm{n}-2)+2} \quad 8)$$

By having L1 and L2, the algorithm defines the different designs' column grid layouts and calculates the building structural elements' volume parametrically. The methodology extends to user-defined geometry, allowing customization based on individual preferences. The algorithm can suggest an optimized layout with equal bending moments with different span sizes closer to the spans defined by the user. However, it is important to know that achieving equal bending moments depends on specific load configurations or beam support conditions. While it simplifies analysis and design, it may only sometimes be achievable in real-world scenarios. Engineers strive to efficiently distribute loads and moments to ensure safety and stability in structural designs.

b) Grid 02: Non-equal beam bending moment - Equal cross-sections.

In our case, non-equal bending moments are attributed to a one-end continuous slab with a consistent span size. The asymmetry in the support conditions of the slab contributes to the unequal distribution of bending moments along the structure. This scenario allows users to stick with their original (desired) spans.

For further calculation of different building structural elements' volume, there is a need to determine n (number of bays) and update the span size in the total dimension of the building plan's length of width (y).

$$n = \frac{y}{x} \qquad 9)$$

Where:

y = total dimension of building plan length of width; the building length must be a minimum of 2 times the span length, ensuring the results will be null.

x = user-defined span size

n = number of bays

n must be an integer. Thus, the updated span size is:

$$Updated\ x = x + \frac{\text{n decimal number}}{\text{rounded n}} \qquad 10)$$

For clarification, let's use an example: Suppose *y*=40 and *x*=6. In this scenario, *n* will be approximately 6.6. Now, having six spans, each with a length of 6m, makes sense. But what do we do with the remaining 0.6 of the 6m span, which equals 3.6 meters?

In this case, instead of having different span sizes because of the decimal part of n (6 spans = 6m, one span = 6*0.6m). We consider having six spans, but their length will be slightly bigger than what the user chooses regarding the above equation. The spans are adjusted to remain closest to the one the user defined. The grid layout considers all the span sizes to be equal.

c) Grid 02 + E: Non-equal beam bending moment - optimized via member sizing.

In this scenario, the column grid is the same as Grid 02; the differences between them are in their cross-section, which I will explain in the second part of the methodology.

Structure volume calculation (member sizing)

Two distinct parametric calculation methods are applied for volume calculations in this research. a) rule of thumb: This method determines volumes associated with slabs and beams. b) factor loads for column volume calculation: This approach uses equations to calculate column volumes. Future iterations aim to substitute the heuristic "rule of thumb" approach with precise equations tailored to the structural element calculations of the building.

1) Slab Based on Rule of Thumb:

The key load-bearing component in a two-way concrete slab with a beam structural system is the concrete slab, which has equal cross, and a flat and horizontal surface positioned between beams and columns. This study has considered slabs with solid structures, with thickness variations tailored to specific design criteria and load considerations. In the case of a two-way slab system, the load is efficiently distributed in both longitudinal and transverse directions, forming a grid-like pattern that enhances structural integrity.

The building slab volume is calculated by multiplying the slab thickness by the sum of each floor's total tributary area, which equals each floor area. The slab thickness is determined using the rule of thumb [91]:

$$T = 0.04 \times L \qquad 11)$$

Where:

T = Slab thickness

L = The characteristic length of the span, which is defined regarding the chosen column grid layout.

2) Beams Based on Rule of Thumb:

In a two-way system, beams are designed to support the slab in longitudinal and transverse directions. Beam volume is calculated as the product of a) beam depth, b) beam width, c) beam length, and d) the number of beams. The rule of thumb guides [91]:

a) $\textbf{Beam depth} = \text{updated span size}/18.5$

b) $\textbf{Beam width} = 1/3 \text{ of the beam depth}$[91]

c) **Beam length** = Span size and can vary according to the chosen grid layout.

Grid 01: The first location of the beam will be defined (side-bay or mid-bay), and then the length of the beam will be calculated, as mentioned in the grid section, to have an equal maximum bending moment in the beams in all floor areas. Two different lengths, L1 and L2, will be calculated for side-bay beams and mid-bay.

Grid 02: Beam length equals the updated span size and is close to the target value (user input) user.

Calculate the number of beams in plans through parametric calculations based on tributary area location. To clarify how parametric calculation happens in the written algorithm, which is not only related to the calculation of beam number and beam length in this section but is also needed in the following part in finding column size and defining various cross-sections.

Three groups of tributary areas regarding their location in the plan are identified: corners, edges, and central. Each can have a different area, span length, number of beams, column size, etc. Like the below example, each tributary group has varying sizes based on the chosen span (according to the chosen grid layout) and the length of the rectangular plan. Referencing the provided documents allows for determining all the mentioned variables regarding different design considerations.

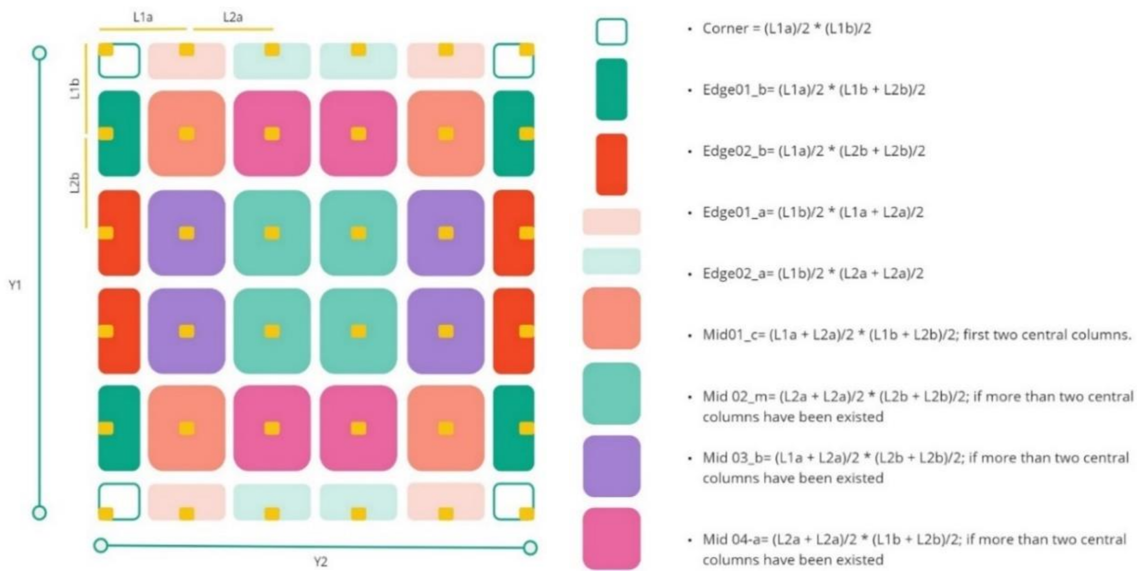

Figure 5_3: Tributary areas distribution regarding their location in the plan.

Calculating Beam number based on tributary area: In the context of parametric calculations for beam numbers in various building designs, the beam distribution is as follows:

- **Corner Beams:** Each corner is associated with two beams, with half of these beam's volume contributing to the corner tributary area.
- **Edge Beams:** Every edge is equipped with three beams, and half of these beam volumes are attributed to the corner tributary area.
- **Central Beams:** Each central location is supported by four beams, and half of these beam volumes are allocated to the corner tributary area.

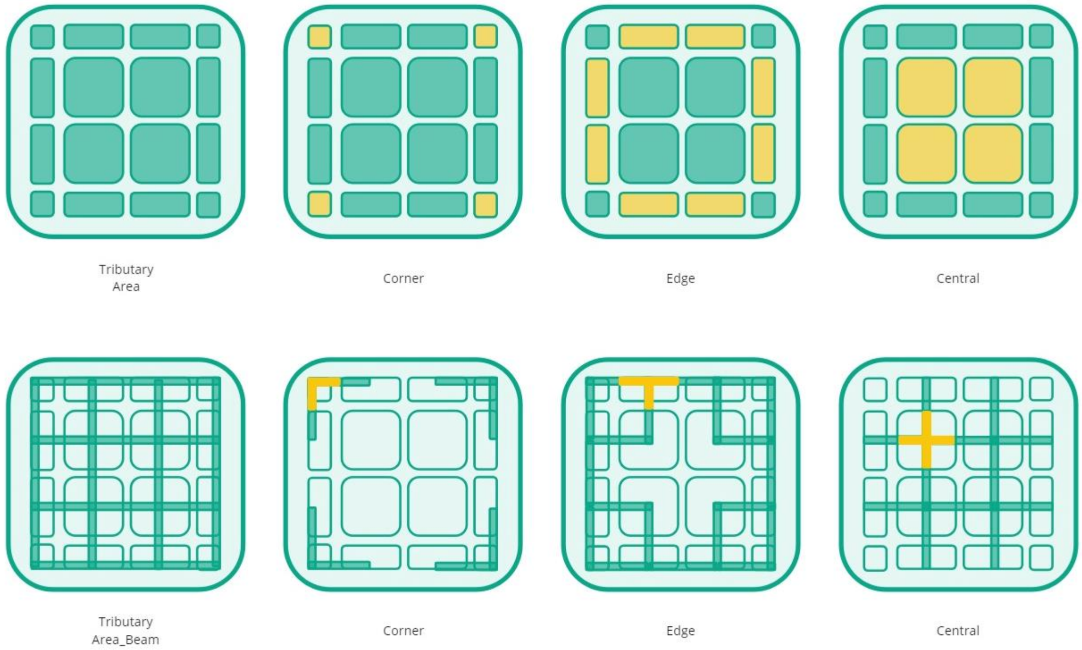

Figure 6_3: Beam distribution regarding their location to the plan and tributary area.

3) Parametric Column Volume Calculation based on tributary area

Utilizing a parametric approach, the calculation of column volume involves a systematic algorithm that considers specific parameters within the structural framework. Column volume calculation involves a) column height and b) column area.

a) **Column height:** The height of each floor will be extracted from the uploaded geometry, and it will be considered a column height.

b) **Column area:** Factor load equations will calculate each column area.

Factor Load Equations in Column Volume Calculation:

Factor loads play a role in determining the optimal column dimensions. The factor load is calculated using two equations: 1) factor load based on live and dead load. 2) factor load based on the chosen material on the column.

1) **Factor load based on live and dead load** [149]:

$$Factor\ Load\ =\ 1.2\ \times\ D\ +\ 1.6\ \times\ L \qquad 12)$$

Where:

D = Dead Load

L = Live Load

Live Load: To calculate this equation, the live load has been considered to be between 20 and 250 psf. This range is optimum for a two-way concrete slab with a beam [89]. As mentioned in the literature review chapter for two-way slabs, categorize loads into light (20-60 psf), medium (60-100 psf), heavy (100-150 psf), and very heavy (150-250 psf). The chosen live load for our baseline design in this research is 80 psf.

Dead Load Calculation: The following steps have been considered to calculate the dead load for each column.

- Column Location Identification: The position of each column is determined based on the area it supports, known as the tributary area.
- Volume of Slab and Beam within the Tributary Area: The volume of slab and beam components falling within the defined tributary area is calculated.
- Counting Floors above Each Column: Determining the number of floors atop each column begins by initially considering one floor at the topmost position. Subsequently, as one descends

to the first floor, the count of floors is incrementally added based on the upward progression through the structure.

- Calculation of Total Tributary Area: The total tributary area is computed by considering the cumulative loads of slabs, columns, and beams above the column, accounting for the load progression downwards.

These steps are essential in parametrically calculating the dead load on each column.

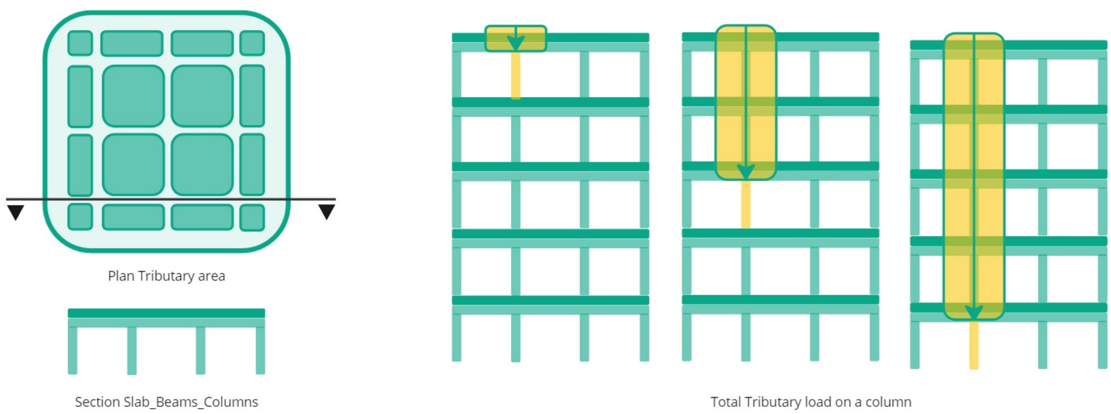

Figure 7_3: Total tributary area Dead load on a column.

2) **Factor load based on chosen material on column** [91], [93]:

$$Pu = 0.4\, fck * Ac + 0.67\, fy * Asc \quad 13)$$

Where:

Pu = axial load on the member,

fck = characteristic compressive strength of the concrete,

Ac = area of concrete,

fy = characteristic strength of the compression reinforcement,

Asc = area of longitudinal reinforcement for columns.

In this study, Pu will be equal to what we found as a rule of thumb is employed to establish the concrete compressive strength chosen to be, denoted as fck, which is set at 20 MPa for the purposes of structural calculations within this thesis (it is a safe (low) estimation of industry standard) Additionally, steel yield strength, denoted as fy, is chosen to be at 344.73786 units MPa [91]. The column's cross-sectional area (Ac) is determined by the percentage of reinforcement bars (rebar) within the concrete column [94]. The column's area can be calculated with these parameters identified, facilitating further analysis and design considerations within the study's structural framework. Also, a minimum allowable column area of 200 cm^2 is enforced (according to code) [91] if the area of the calculated column is less than 200 cm^2.

This systematic approach, driven by user-input material properties, facilitates accurately determining factor loads and optimal column dimensions based on specified structural characteristics. It enhances our understanding of column behavior within the overall structural context, particularly in high-rise buildings where minimizing structural volume is crucial.

In this scenario, to optimize the volume of the structural skeleton, the cross-section of the horizontal structural members is equal from bay to bay. The following part will explain the rule of thumbs when cross-section varies from bay to bay.

Determining different cross sections -Rule of thumb

Variations are introduced in the slab's thickness and the beam's depth in the side bays vs. mid-bays algorithm. These variations directly impact the dead load transmitted by the column to the ground and the dimensions of the associated structural components.

Slab Thickness [91], [95], [96]**:**

- Slab thickness on mid-bay = 0.04 × updated span size (grid 02)
- Slab thickness on side-bay = 0.035 × updated span size (grid 02)

Beam Depths [91], [95]**:**

- One End continuous slab = updated span size (grid 02)/18.5
- Two End continuous slab = updated span size (grid 02)/21

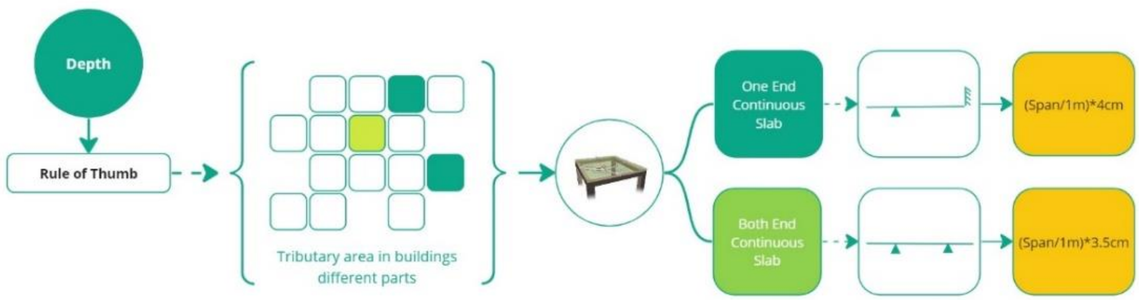

Figure 8_3: Depth of the beam and slab regarding one or two end continuous slab

Material specifications

Material percentage (rebar) in reinforcement concrete:

To calculate the environmental impact of a building, we need to consider carbon emissions from reinforced concrete and steel components. This involves assessing the GWP related to the production of concrete mix and steel, including the carbon footprint of mining, processing, and transporting raw materials. In this research, fixed percentages of steel reinforcement in beams (2.5%), columns (3.2%), and slabs (0.9%) are used for analysis. However, the algorithm is designed to give variation in the percentage rebar in the concrete, beam (3.2 - 4.5 %), column (2.5 - 5.7 %), and slab(0.9 - 1.7 %) [94].

GWP Calculation

The GWP associated with using reinforcement concrete in building structures is a critical consideration, with an average value of 270.69 $kgCO_2e$ per cubic meter determined from an analysis of 42 EPD files covering a spectrum of 20 mpa concrete strengths compared to our baseline design. However, these averages mask a significant range, with GWP values spanning from 145.4 $kgCO_2e$ to 595.18 $kgCO_2e$. This variability is primarily attributed to incorporating supplementary materials, such as slag cement and fly ash, in concrete production, which can serve as partial substitutes for cement. Varying the proportions of these supplementary materials allows for reductions in concrete's GWP. In this section, we opted to utilize 366 kgCO2e, which lies at the upper end of the range we identified. **This decision was influenced by Cove.tool's adoption of this value, allowing for evaluation of the outcomes yielded by the developed tool.**

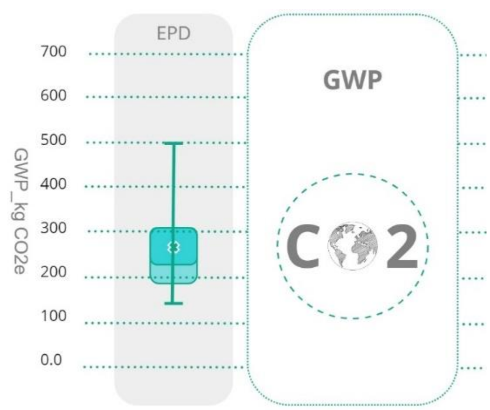

Figure 9_3 GWP average based on EPD files

Chapter 4

Results and Discussion

After writing the algorithm for the parametric calculation of building structure volume in the previous chapter, we are discussing the importance of different factors for improving the efficiency of the building industry in controlling EC emissions by choosing the optimum building structural volume in a case study.

Guideline for users of the tool:

This guideline explains how to use the of the developed tool which aimed to calculate building structural components volume, focusing on two-way concrete slab systems with beams in the preliminary design phase. The tool facilitates the manipulation of various independent variables to assess their influence on the EC emissions of the building. Its purpose is to assist architects in making informed decisions during the early stages of design and their impact on building GWP.

Selection of Independent Variables:

1. **X, Y Plan:** Users can specify the plan dimensions (X and Y) without restriction on length.
2. **Number of Floors:** The tool is tailored for mid-rise buildings due to its focus on the vertical load-bearing capacity of columns.
3. **Floor Height:** Users can adjust floor heights up to 5m. For larger floor heights, column buckling becomes a primary structural concern which lays outside the scope of present study. It represents a potential area for future tool development.
4. **Span Size:** Users have the flexibility to choose span sizes ranging from 4m to 12m. This parameter influences the selection of the column grid layout.

5. **Live Load:** The tool accounts for a range of building live loads, varying from 20psf to 250psf.
6. **Aspect Ratio:** Users can maintain the same floor area while altering the aspect ratio of the building's plan. This feature allows exploration of how changes in plan geometry affect the building's volume and Global Warming Potential (GWP).

Integration of Conceptual Design models:

Alternatively, users have the option to upload their conceptual designs, varying parameters such as floor heights, floor numbers, and plan areas. These design attributes will be extracted and processed by the tool accordingly. The accepted format is based on all of the factors that have been mentioned, like floor height, floor number, rectangular plan, and separate floors.

Column Grid Layout:

Upon selecting independent variables, users can define the column grid layout. Two options are available: a uniform grid layout where all span sizes are equal, and a non-uniform grid layout based on equal beam maximum bending moment, providing different span sizes for mid-bay versus side-bay.

Member sizing

For uniform-column grid layout, users can choose between equal or varied slab and beam thickness for mid-bay versus side-bay configurations. The latter, referred to as the optimized strategy, is considered for this thesis.

Reinforcement Selection:

Users can specify the percentage of reinforcement in beam (3.2 - 4.5 %), slab (0.9 - 1.7 %) and column (2.5 - 5.7 %) within predefined ranges. Accordingly, the GWPs of the composite will be calculated assuming concrete with 20Mpa strength and Rebar Density 7870 kg/m^3 are considered.

Output:

1. **Updated Span Size**: The tool provides information on the adjusted span size based on user inputs and design parameters. (see methodology)
2. Volume Calculation: The tool computes the volumes of columns, beams, and slabs, as well as the total volume, measured in cubic meters (m^3).
3. Normalized Volume: Normalized volume values for columns, beams, slabs, and the total volume are provided per cubic meter (m^3). Normalization involves dividing the volume by the building's floor area, floor height, and number of floors in this thesis. While previous research typically calculates building volume by dividing it solely by the building area, our study adopts a more precise approach. We divide the building volume by its area and factor in variations in floor heights. This ensures greater accuracy in our results and accounts for the influence of different floor heights on the overall building volume.
4. GWP: The tool calculates the GWP for columns, beams, slabs, and the total GWP, expressed in kgCO_2e.
5. Normalized GWP: Normalized GWP values for columns, beams, slabs, and the total GWP are presented kgCO_2e. Similar to normalized volume, normalization involves dividing the GWP by the building's floor area, floor height, and number of floors. The utilization of normalized volume facilitates the computation of normalized GWP, ensuring a comprehensive assessment of environmental impact relative to the building's design parameters.

In this discussion, four different sections have been considered:

- **Task 01 Optimize material efficiency through the column grid layout.**
- **Task 02 Optimize material efficiency through member sizing.**
- **Task 03 Optimize material efficiency by changing the shape of the building.**
- **Task 04: Comparing the performance of different optimizing strategies.**

In this research, the utilization of normalized volume is imperative. Normalized volume, indicating the quantity of reinforced concrete within one cubic meter, is a valuable metric for facilitating a clearer comprehension of distinctions among various variables. This is particularly advantageous when dealing with diverse design considerations, as it enhances the interpretability of differences in a straightforward manner. For example, when incorporating the number of floors, it is logical to expect a higher volume for buildings with more floors. However, expressing this difference in volume per cubic meter allows for a more precise assessment of the impact of adding floors to the building.

A baseline design has been chosen regarding the different variables considered for the design in this section. For the baseline design, the span length is 6m, the number of floors is 15, aspect ratio is one, the building area is 1600 m_2, the concrete strength is 20 MPa, and the live load is 80 psf.

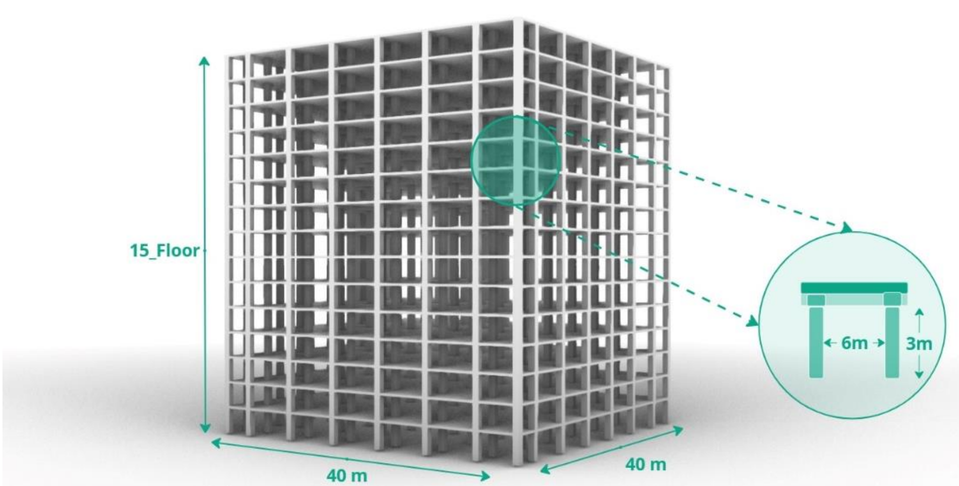

Figure 10_4 Baseline Design

Task 01 Optimize material efficiency through the column grid layout.

This section's grid layout uses equal maximum bending moment through span ratio control. In this approach, two different span sizes (L1 and L2) are calculated based on user-selected input from the existing range of span size (4m to 12m). In our case, a square plan with a 40m width length has been analyzed.

The table illustrates the relationship between the selected span sizes and the resulting dimensions of L1 in the side-bay and L2 in the mid-bay. Increasing the span size from 4.40m to 8.28m in the side-bay and from 6.23m to 11.72m in the mid-bay correlates with a proportional increase in the normalized total building structural volume, approximately by 0.06. This underscores the significance of considering span sizes when determining the structural volume of a building.

Notably, no results are shown for a user-selected span size of 12m, as the updated mid-bay span length exceeds 12m (L2= 16.57m). This limitation is due to the structural constraints imposed by the chosen system, a two-way concrete slab, which cannot accommodate span sizes beyond a certain range (4m to 12m). Consequently, the outlined algorithm excludes updated span lengths outside this prescribed range.

The variations in span size underscore the necessity for parametric calculations to streamline the design process. Such tools provide designers insights into optimizing structural volume efficiency while maintaining uniform maximum beam bending moments.

Table 8_4 Updated span size and building normalized structural volume based on span size in Grid_01

	L1 (m)	L2 (m)	User selected Span Size (m)	Normalized Total Structure Volume (**per** m^3)	Differences from baseline design (**per** m^3)
Grid 01	4.40	6.23	6	0.10	0

	5.22	7.39	7	0.11	0.01
	6.41	9.06	8	0.13	0.03
	8.28	11.72	9	0.17	0.06
	8.28	11.72	10	0.17	0.06
	8.28	11.72	11	0.17	0.06
	11.72	16.57	12	null	null

The diagram below studies the impact of span lengths on the normalized building volume elements in a structural system with a consistent cross-section slab. The legend on the left side of the diagram displays the normalized volume per cubic meter for different building span sizes. The legend on the right side of the diagram displays the normalized GWP per kg Co_2e for different building span sizes. Blue bars show the baseline, while green bars represent various span sizes. White bars indicate the total building volume per span size. In the rest of the diagrams, all the legends for simplicity present the same data.

Span Characteristics: The spans range from 6m to 12m, each comprising 15 floors with a uniform floor height of 3m. The aspect ratio is consistently 1:1 in all span sizes.

Building Properties: Key properties, including the building area (1600 m_2), live load (80 psf), and remain constant across all spans.

GWP Data: GWP is 366 per kg CO_2e, rebar density is 7870 kg/m^3, and concrete strength (20 MPa). Also, the percentage of rebar in each element is slab (1.7%), beam (4.5%), and column (5.7%).

In various structural configurations characterized by spans ranging from 6m to 11m, distinct proportions for each structural element, expressed as normalized volumes, have been identified. For slabs, the proportions exhibit a progression of 0.083 per m^3 to 0.156 per m^3, corresponding to span lengths of 6m through 11m. For beams, the associated values are between 0.007 per m^3 and 0.006 per m^3 for the respective span lengths, while columns manifest varying proportions from 0.012 m^3 to 0.003 per m^3 across the same span range. In total, with an increase in the span size in this case study, the total volume of buildings can rise by 6% which is 28.83 kg CO_2e.

The analysis uncovers trends where the normalized volume of slabs generally increases with longer span sizes while the normalized volume of beam and columns decreases. However, although the reduction of beam and column size has positive results on the reduction of building structural volume when the span size increases, the total volume of the structural building trend rises.

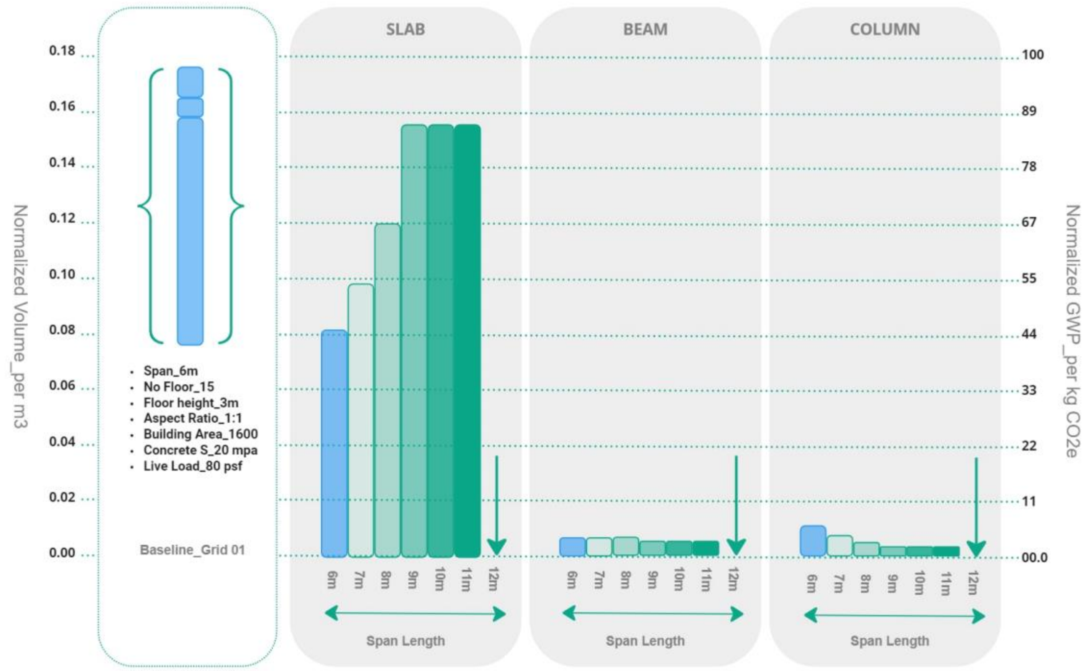

Figure 11_4 Impact of span size on building structure volume in grid 01

Task 02 Optimize material efficiency through member sizing.

Considering optimized cross-sections with span size closer to what the user selects as tools input. The design grid layout in this study has the same span size in the entire plan with an aspect ratio of 1:1 (square) in both side-bay and mid-bay. This part will compare optimized cross-sections with equal cross-sections to investigate the impact on the structural building volume.

Grid_02 exhibits consistent cross-sectional characteristics across its entire floor area, whereas Grid_02_E displays variations in cross-section between its side-bay and mid-bay regions. This discrepancy in cross-section extends to differences in slab thickness and the depths of side-bay and mid-bay beams. Notably, variations in beam depth directly impact beam width and subsequently influence the dead load exerted on columns, necessitating adjustments in column area dimensions.

The table below shows the user's selected and updated span sizes, which are equal for Grid_02 and Grid_02_E based on the building square plan's width length. The plan's width length equals 40m, and the chosen span size is between 6m and 12m. If the span size is less than 4m and more than 12m, like the updated span size (12.11m), when the user selects span size 12m, the results will be null, as mentioned before. Selected floor number (15), floor height (3m), live load (80psf), and concrete strength (20 MPa) are the same as the baseline design.

A positive linear regression correlation exists between increasing span size and building total structural volume in Grid_02 and Grid_02_E. However, increasing total normalized structural volume is higher when the cross-section is equal in the entire floor area vs. when it varies. Furthermore, differences between span sizes 6 to 7, 7 to 8, etc., show an increasing amount of growth when span size increases. Nevertheless, as mentioned in the previous part, the results of spans 9m, 10m, and 11m are equal because the number of bays is rounded.

Table 9_4 Updated span size and building normalized structural volume based on span size in Grid 02 and Grid 02_E

L (m)	User selected Span Size (m)	Normalized Total Structure Volume _ Gride 02 (**per** m^3)	Differences from baseline design_ Gride 02 (**per** m^3)	Normalized Total Structure Volume _ Gride 02_E (**per** m^3)	Differences from baseline design_ Gride 02_E (**per** m^3)
6.09	6	0.11	0	0.10	0
7.12	7	0.12	0.01	0.11	0.01
8	8	0.14	0.03	0.13	0.03
9.11	9	0.17	0.06	0.16	0.05
10	10	0.17	0.06	0.16	0.05
11.16	11	0.17	0.06	0.16	0.05
12.11	12	0	null	null	null

The whisker diagram below shows the differences between having equal (Grid_02) and varied (Grid_02_E) cross-section normalized building structural volume per m^3 (On the left) when the span size increases from 6m to 12m. The diagram illustrates the range of differences between the minimum and maximum normalized volumes for two grids, focusing on structural building elements like slabs, beams, and columns.

The maximum difference in the normalized total building volume between Grid_02 and Grid_02_E is 1%, which happens in the 9m, 10m, and 11m span. Also, the importance of different structural elements is shown in this diagram. Differences between the maximum and minimum elements show the level of slab effectiveness when spanning size changes in both options (0.05 per m^3 for Grid_02_E vs. 0.06 per m^3 for Grid_02). In total, we can have approximately a 1.0 percent (6.93 kg CO_2e) improvement when various cross-sections are considered in the building's structure design.

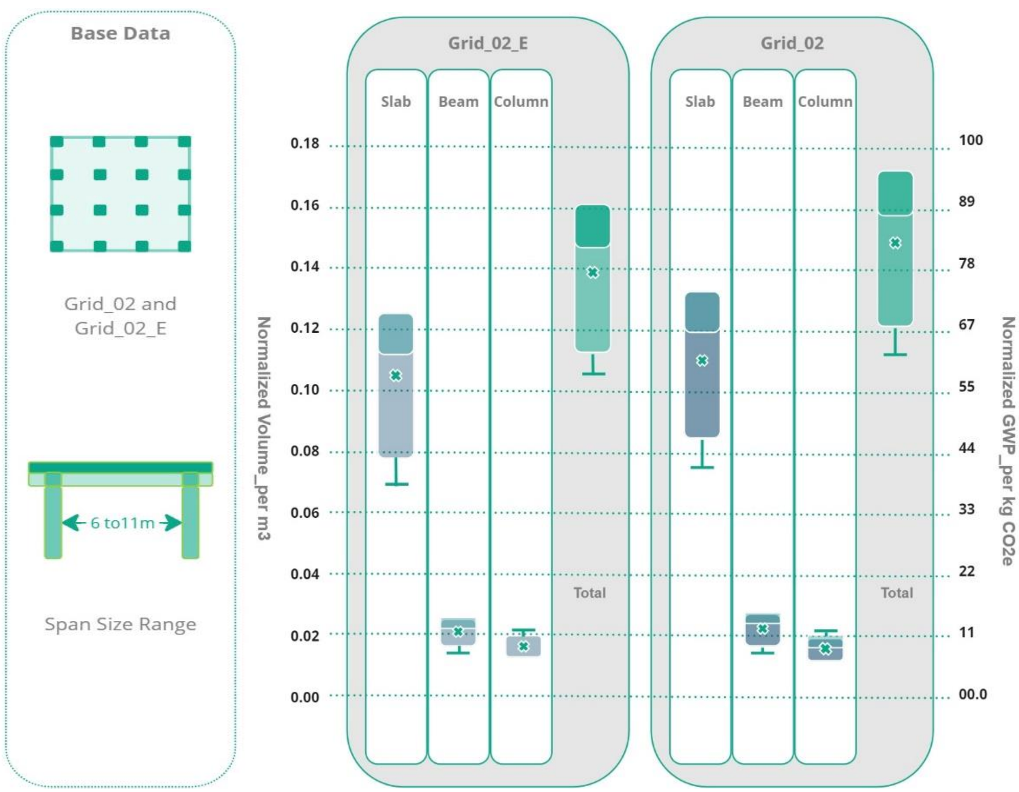

Figure 12_4 Impact of span size on building structure volume grid 02 vs grid 02_E

In the next step, two changeable variables were considered to evaluate the importance of considering various cross-sections. a) Number of floors impact on normalized building volume, b) Floor height impact on normalized building volume

a) Number of floors impact on normalized building volume

This study delves into the ramifications of a 6-meter span length and varying floor numbers on mid-rise structures ranging from 15 to 40 (in increments of five). This approach is particularly pertinent as the number of floors increases.

When the cross-section varies, changing the floor number from 15 to 40 can have a minimum and maximum of 0.11 to 0.12 normalized building total volume (per m^3). Moreover, 0.10 per m^3 to 0.11 per m^3 minimum and maximum when the cross-section is equal in the building. These results depict around 0.01 per m^3 changes when comparing minimum and maximum results. Therefore, using various cross-sections on floors can decrease the building's structural volume by around 1%.

Also, increasing the floor number changes the column volume size by around 1% (3.35 kg CO_2e) when the cross-section varies and 1% (4.78 kg CO_2e) when it is equal. Also, it is necessary to mention in this part that the slab and beam are not affected by the number of floors when we consider the normalized volume, as depicted in this diagram.

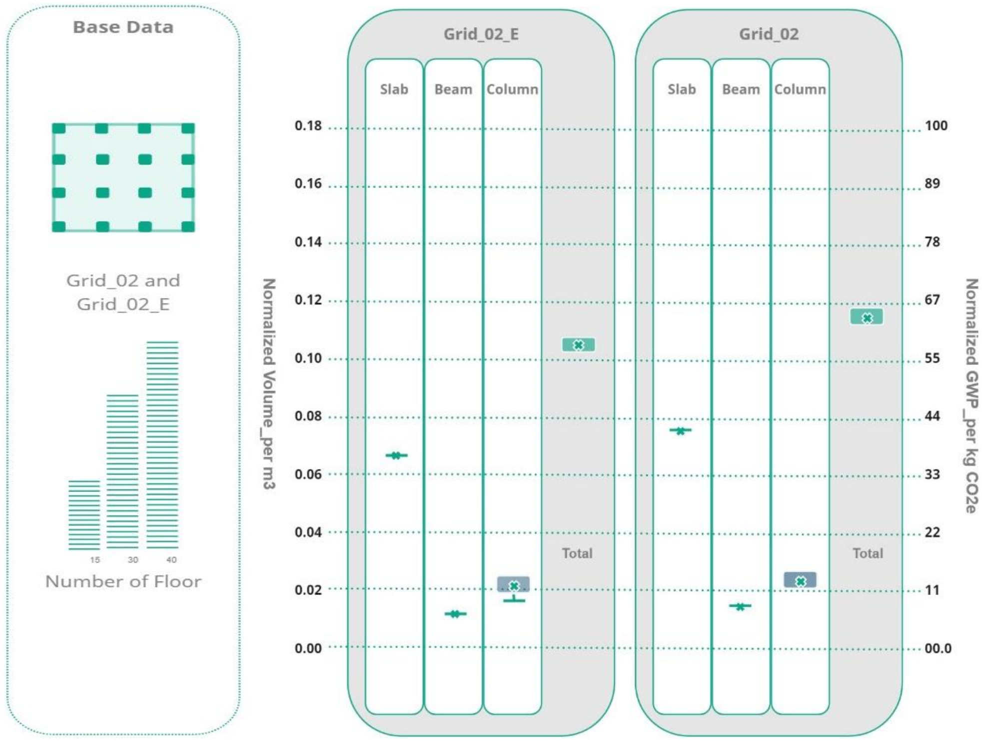

Figure 13_4 Impact of number of floors on building structure volume grid 02 vs grid 02_E

b) Floor height impact on normalized building volume

This study explores the ramifications of a uniform 4-meter span length while varying floor heights (ranging from 3.0m to 5.0m at 0.4m intervals) within a 15-story building (Baseline design parameters). The key focus lies in the parametric calculation of column sizes, considering both live and dead loads within the total tributary area. This approach gains significance as floor heights increase.

Increasing the floor height from 3.0m to 5.0m results in a minimum and maximum normalized building total volume range of -0.01 per m^3 to -0.04 per m^3 when the cross-section varies and -0.01 per m^3 to -0.03 per m^3 when the cross-section is uniform. Consequently, a 3% (12.25 kg CO_2e) reduction in the total building structural volume when height of the building change from 3.0m to 5.0m. When there's variation in the cross-section instead of uniformity, a mere 1% (2.73 kg CO_2e) difference arises.

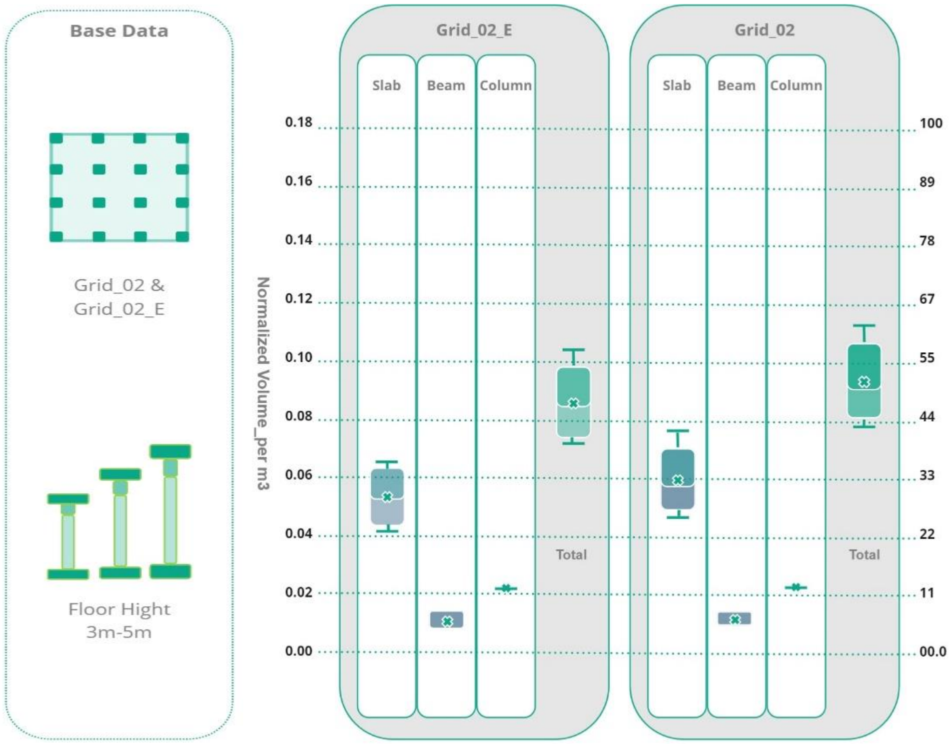

Figure 14_4 Impact of floor high on building structure volume grid 02 vs grid 02_E

In summary, alterations to building specifications can significantly affect total structural volume, such as span size (6%), floor height (1%), and number of floors (1%). Moreover, optimizing the cross-section can lead to a 1% reduction in the total normalized building structural volume. However, it is noteworthy that implementing Building Grid 02_E may pose challenges due to its cost and complexity.

Task 03: Optimize material efficiency by changing the shape of the building.

Examines the impact of varying aspect ratios in rectangular building designs on structural volumes for given grid configurations. This study aims to improve understanding of efficient building design and its effects on EC emissions.

The building area is $1600m_2$ in all the selected aspect ratios; the rectangular plan width (a) and length (b) are the ones that change regarding the selected aspect ratio between 1:1 to 1:7.84. For this part analysis, a 6-meter span size, 15 floors, concrete strength of 20 MPa, and a live load of 80 pounds per square foot are considered.

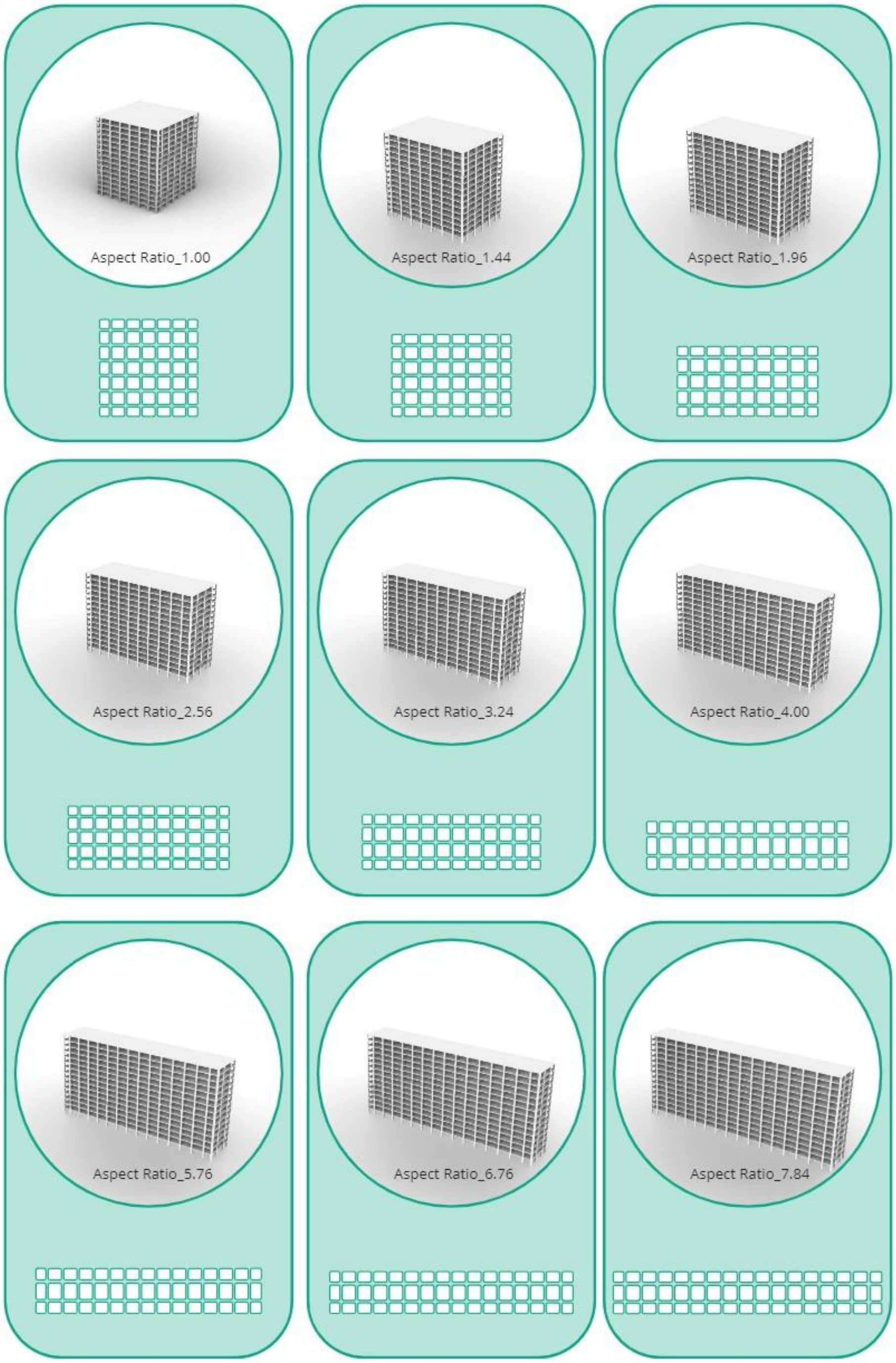

Figure 15 _4: Buildings' structure regarding grid1 with different rectangular plan aspect ratio.

The table below depicts the updated span size based on the user's chosen span size, grid layout, and aspect ratio. Therefore, Grid 01, with equal maximum bending moment in side-bay and mid-bay, will have two different grid sizes on two sides of the rectangular plan (L1_a, L2_a, L1_b, and L2_b). While Grid 02 has an equal span size on each side of the rectangular plan (L_a and L_b), the results show a diverse number of changes regarding the selected aspect ratio, which shows the need for a tool to help the designer understand their design impact on building structural volume.

Table 10 _4 Updated span size based on span size in Grid 01 and Grid 02

Grid_01				**Grid_02**		**Aspect Ratio**	Grid 01 and Grid 02 volume differences (m^3)
L1_a (m)	L2_a (m)	L1_b (m)	L2_b (m)	L_a (m)	L_b (m)		
4.40	6.23	4.40	6.23	5.71	5.71	1	0.011
4.58	6.47	4.35	6.16	5.55	5.56	1.44	0.013
4.71	6.65	4.58	6.47	6.22	5.7	1.96	0.015
4.34	6.14	5.18	7.32	5.82	6.25	2.56	0.008
4.46	6.31	4.60	6.51	6	5.56	3.24	0.016
4.56	**6.44**	**5.86**	**8.28**	**6.15**	**6.67**	**4**	**0.004**
4.32	6.10	5.32	7.53	5.87	6.06	4.84	0.005
4.40	6.23	4.88	6.90	6	5.56	5.76	0.014

The diagram below shows the importance of grid layout; having an optimized layout vs. grid layout with equal span size can reduce the building volume in the range of 1.6% in span size 6m to 0.4% in span size 11m. However, regarding the rebar's different percentage in the structural elements, this amount is lower when the span size is 6m (10.40 $kgCO_2e$), and it increases when the span size is 11m (13.60 $kgCO_2e$).

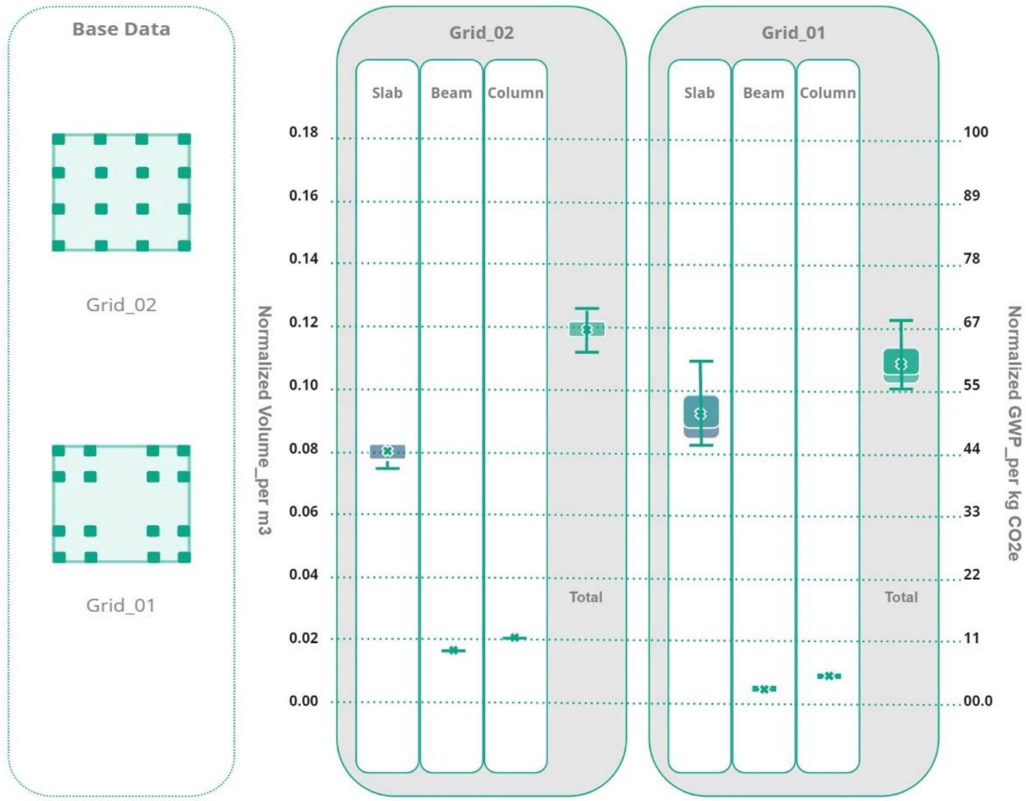

Figure 16_4 Impact of aspect ratio on building structure volume Grid 01 vs Grid 02

Task 04: Comparing the performance of different optimizing strategies.

Evaluate the two-column grid layout (Grid 01 vs Grid 02_E) based on span ratios and maximum bending moment. In this case, the Plan is square with a width length of 40m, an area of $1600m_2$, a floor Height of 3.0m, a Live load of 80 psf, and a concrete strength of 20 MPa.

The table below shows the differences between the span lengths of grid layouts and the total normalized building volume differences in each one of the span sizes but two different grid designs. Grid 01 is based on one maximum equal bending moment in both the side-bay and mid-bay beam, which causes us to have different span sizes for the side-bay (L1) vs the mid-bay (L2) area. Grid 02_E is based on various span sizes in the entire floor area.

Noticeably, all the span sizes users chose in both grid layouts have been updated regarding the chosen grid. Moreover, since in designed grid layouts, the 12m span size changed to be over 12m when it is updated, there will be no results for this span size.

Furthermore, the differences between the two grid layout is 0 per m^3 when the span size is minimum (Grid 01: L1=4.40m, L2 = 6.23m; Grid 02_E: L = 5.71m), and it increases to $0.01m^3$ when span size is maximum (Grid 01: L1=8.28m, L2 = 11.71m; Grid 02_E: L = 10m).

Table 11_4 Updated span size and building normalized structural volume based on span size in Grid 01 and Grid 02_E

Grid 01		Grid 02_E	User selected Span Size (m)	Grid 01 (m^3)	Grid 02_E (m^3)	Grid 02_E & Grid 01 Differences
L1 (m)	L2 (m)	L (m)				
4.40	6.23	5.71	6	0.10	0.10	11.12083
5.22	7.39	6.67	7	0.11	0.11	10.25139
6.41	9.06	8	8	0.13	0.13	9.763889
8.28	11.71	10	9	0.17	0.16	9.956944
8.28	11.71	10	10	0.17	0.16	9.956944
8.28	11.71	10	11	0.17	0.16	9.956944
11.72	16.57	12.11	12	null	null	null

To better understand the above table, the diagram below shows the differences between the grid layouts' impact on building normalized structural elements volume, slab, beam, and column. Choosing the uniform grid layout (Grid 02_E) vs the optimized grid layout (Grid 01) can reduce the building's total structural volume from 1% in span size 6m to 3 % in span size 11m. Also, each one of the grids can reduce the building's slab structural volume by choosing a smaller span size. For example, choosing a span size of 6m vs. 11m can reduce building structural volume by 7% in Grid 01 and 6% in Grid 02_E.

The volume of structural elements has different trends when span size increases; slab and beam normalized volume in both grid layouts raises as well. However, the column has a reverse trend by increasing the span size column normalized volume decrease. The effectiveness of span size changes from 6m to 11m is more on beam (Grid 01= 0.00 per m^3; Grid 02_E = 0.01 per m^3) and column (Grid 01= -0.01 per m^3; Grid 02_E = -0.01 per m^3), respectively. In summary, choosing an optimized grid layout vs. an optimized cross-section with equal span size in the grid layout can affect total structural volume; however, the differences between these two optimizations were minor in the selected case study.

While the overall outcomes of Grid_02_E closely approximate those of Grid_01, disparities arise in the volume distribution of individual elements contingent upon the chosen layout and building cross-sections. Specifically, Grid_01 exhibits a greater proportion of slab volume compared to Grid_02_E, whereas Grid_02_E demonstrates higher volumes attributed to beams and columns compared to Grid_01.

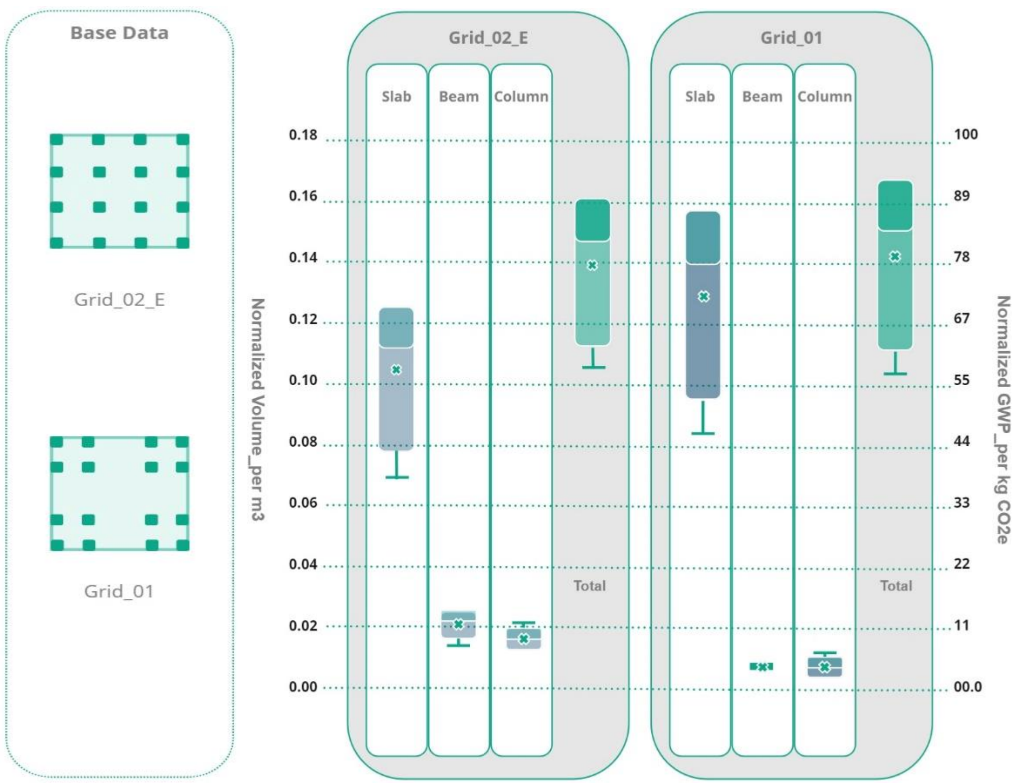

Figure 17_4 Impact of span size on building structure volume grid 01 vs grid 02_E

However, differences in structural volume across building components can lead to divergent GWP outcomes, driven by variations in the quantities of reinforcing bars (rebar) employed. Specifically, equivalent adjustments in rebar composition within columns versus slabs can engender increased carbon emissions due to the comparatively higher percentage of rebar in columns.

Table 12_4 GWP ($kgCO_2e$) in Grid 02_E vs. Grid 01 in different span size

Span	**G2_E**	**G1**	**G2_E**	**G1**	**G2_E**	**G1**	**G2_E**	**G1**
m	slab	slab	beam	beam	column	column	Total	Total
6	34.15	41.04	10.07	4.99	17.02	9.20	61.24	55.23
7	40.06	48.62	11.68	5.18	13.89	6.63	65.63	60.43
8	48.42	59.63	13.89	5.11	11.38	4.49	73.71	69.23
9	61.18	77.10	17.15	5.81	9.61	2.68	87.94	85.59
10	61.18	77.10	17.15	5.81	9.61	2.68	87.94	85.59
11	61.18	77.10	17.15	5.81	9.61	2.68	87.94	85.59

The presented table illustrates a trend where increasing the span size in both grid layouts results in an increase in the GWP of slabs and beams, alongside a decrease in the GWP of columns. Notably, the total GWP increases when the span size escalates from 6m to 11m (evidenced by GWP values of 30.36 $kgCO_2e$ for Grid_01 and 26.70 $kgCO_2e$ for Grid_2_E). Furthermore, the comparison between Grid_01 and Grid_2_E highlights that while the GWP of slabs and beams is lower in Grid_2_E, the GWP of columns is lower in Grid_01. This underscores the necessity for streamlined tools to facilitate the analysis process.

Summary and Discussion

The discourse surrounding environmental sustainability within the construction industry necessitates a concerted effort to mitigate EC emissions. This study responds to this imperative by introducing a tool to optimize the structural volume of a two-way concrete slab with a beam, emphasizing minimizing environmental impact through material efficiency.

Analysis of varying span sizes in the case study revealed larger spans increase building volume while reducing beam and column volumes, stressing design parameter analysis. Results show a 6% increase in total volume with spans from 6m to 11m, emphasizing the importance of smaller spans in the case study. Optimizing column grid layout impacts structural volume metrics, advocating for thorough design analysis. Maintaining smaller spans minimizes material usage, aligning with sustainability principles but may limit spatial flexibility. Balancing design aspirations with practical considerations is crucial for optimal material utilization. Understanding span-size relationships informs efficient and sustainable building design decision-making, highlighting the importance of design parameter analysis.

The study examines the influence of optimizing member sizes on the efficiency of structural materials. It finds that optimizing cross-sections leads to a notable 1% reduction in total structural volume, suggesting potential material savings important for economic and environmental considerations. However, varying cross-sections may not be advantageous during implementation. Furthermore, analyzing design factors like floor count and height reveals that increasing floors from 15 to 40 results in a comparable volume increase of about 1%, underscoring the significance of verticality. The increase in building volume with added floors is expected, but the normalized volume only rises by 1%, which aligns logically with the larger column sizes required for lower floors.

Additionally, floor height significantly impacts column volume, consistent with stability expectations, with a 3% change observed between 3.0m and 5.0m. While it is intuitive that taller columns necessitate greater bulk, the available range of optimal sizing could be better. Moreover, increasing floor height could decrease the normalized volume of the building's slabs.

While optimizing member sizes is crucial, its impact is limited compared to adjustments in other design parameters. A approach that considers various parameters is essential for maximizing material efficiency and sustainability in structural design, providing valuable stakeholder insights.

The efficacy of various optimization strategies can lead the designer to different results. This thesis focuses on two-column grid layouts characterized by span ratios and maximum bending moment. The study indicates small disparities in total structural volume (Less than 1%) between optimized grid layouts and those employing equal span sizes. However, there are differences between each building element's volumes relative to the selected grid. This can change the structure's GWP based on the rebar percentage to concrete in the elements.

The investigation examines the importance of diverse designs in guiding designers toward informed decisions. It assesses the impact of varying aspect ratios in rectangular building designs on structural volumes. Emphasizing the role of grid layout optimization in reducing structural volume and associated environmental carbon (EC) emissions, the study underscores how design choices influence structural efficiency and environmental sustainability. Through the analysis of various aspect ratios, the research offers insights into potential reductions in structural volume ranging from 0.4% to 1.6%, contingent upon the aspect ratio employed. While the observed alterations in the chosen case study may seem slight, they highlight the ramifications of design choices, especially when comparing buildings with similar characteristics such as height, floor count, program, and area but varying shapes. This underscores the importance of design considerations in attaining intended objectives.

This tool helps designers understand and choose sustainable options by reducing emissions and promoting eco-friendly design practices within the selected structural system (Tow-way concrete slab with beam). Additionally, it emphasizes the necessity of parametric calculation tools for assessing the impact of building structural volume on emissions early in the design phase.

Evaluation

To assess the performance of the developed tool, two methodologies were employed: manual evaluation and comparison with Cove.tool. A specific case study, which involves a square plan with dimensions of 1600m², comprising 15 floors with a floor height of 3.0m and a uniform span size of 6m (Grid 02), was selected as a baseline.

This evaluation observed discrepancies between the results obtained from Cove.tool and the developed tool. The primary variance stemmed from the disparate structural systems considered by each tool. Cove.tool analyzed structural components such as beams, columns, slabs, girders, and roof slabs independently, whereas the developed tool focused on a simplified system featuring beams, slabs, and columns. To facilitate a comparative analysis, the results for slabs and roof slabs were combined, as were those for beams and girders.

To comprehend the variations between Cove.Tool and the developed tool in this thesis, a manual calculation was executed to determine the dimensions of structural elements. This endeavor sought to unveil the foundational rationale behind the disparities between the two tools.

Table 13_4 Comparing Cove.tool vs. the developed tool

Superstructure	**Material Types**	**Cove.tool**	**Cove.tool (Update)**	**Developed Tool**
Beam	Concrete_m^3	876	3544	1066
	Rebar_kg	56070	248282	277343
Column	Concrete_m^3	564	564	2361
	Rebar_kg	110677	110677	476516
Slab	Concrete_m^3	44814	45092	5436
	Rebar_kg	635514	639450	388552
Girder	Concrete_m^3	2668	_	_
	Rebar_kg	192212	_	_
Roof Slab	Concrete_m^3	278	_	_
	Rebar_kg	3936	_	_

Total	Sum-Concrete_m^3	49200	49200	8863
	Sum-Rebar_kg	998409	998409	1142411

In this manual evaluation, only concrete volume is the main concern since the percentage of rebar in concrete for most selected elements is less than 2.5 percent.

- Beam area = beam volume/ (floor numbers* span size* beam number)
  Beam area_Cove.tool = 3544m^3/ (15* 6m*49) = √ 0.80m$_2$ = 0.89m
  Beam area_Developed Tool = 1066m$_3$/ (15* 6m* 49) = √ 0.24m$_2$ = 0.48m
- Column size = Column volume/ (floor numbers* floor height* column number)
  Column size_Cove.tool = 564m^3/ (15* 3m*68) = √ 0.18m$_2$ = 0.42m
  Column size_Developed Tool = 2361m^3/ (15* 3m* 68) = √ 0.77m$_2$ = 0.88m
- Slab Thickness = slab volume/ (floor numbers* slab area)
  Slab Thickness_Cove.tool = 45092m^3/ (15* 1600m$_2$) = 1.88m
  Slab Thickness_Developed Tool = 5436m^3/ (15* 1600m$_2$) = 0.26m

According to the guidelines outlined in the "Building Construction Illustrated" [91], a general rule of thumb for estimating the depth of a concrete beam is to divide the span of the beam by 16. This suggests that for the Cove.tool, the beam width should exceed 2.1 m, while for the Developed tool, it should be approximately 0.64 m.

In a two-way concrete slab with beams, the acceptable range for slab thickness typically falls between 0.12m and 0.38m. However, **the Cove. tool analysis yields a slab size result of 1.88m, which exceeds this range.** Conversely, the calculated slab thickness from the developed tool falls within the acceptable range at 0.26m, demonstrating alignment with industry standards [97].

Regarding column dimensions, the Cove.tool estimates a column size of 0.42 meters, which falls within the acceptable range of 0.30m to 0.81m. **However, the developed tool indicates a column size of 0.88 m, slightly surpassing the upper limit of the acceptable range.** This highlights a potential area for improvement or refinement in the column section of the developed tool.

Conclusion

This thesis presents a developed tool tailored to estimate the volume of structural components in two-way concrete slabs with beams, focusing on their impact on a building's environmental carbon (EC) emissions during initial design phases. By analyzing key factors such as span length, floor height, and structural elements, architects gain valuable insights into how design choices influence EC emissions, thereby promoting sustainable construction practices.

The methodology proposed in this study involves parametric calculations of structural building elements, with a detailed case study on two-way concrete slab structures supported by beams. Through this research, architects are equipped with a practical tool to evaluate and refine early-stage design decisions, integrating EC considerations into architectural design processes to encourage responsible construction practices and carbon emission mitigation.

The development of this tool marks a contribution to the field, as it assists architects in making informed decisions regarding EC optimization in the initial stage of design, thereby integrating sustainability considerations into architectural practices. Moreover, the provision of building component structural findings for the proof-of-concept enables practical implementation and validation of the proposed methodology, further enhancing its credibility and usability.

However, it's important to acknowledge certain limitations of this study. The focus on rectangular plans with square bays for simplicity may restrict the applicability of the tool to more complex building geometries. Additionally, the consideration of columns only for vertical loads, with integration of lateral elements pending, may limit the tool's accuracy in seismic-prone regions. Furthermore, assumptions of continuous slabs and beams and neglect of moment redistribution in the plastic state may lead to conservative estimates of structural performance and EC emissions.

Overall, despite these limitations, the introduction of this software tool with a broader range of parameters compared to existing software enhances architects' control and understanding of sustainability implications early in the design phase. This promotes the adoption of more sustainable and responsible construction practices, ultimately contributing to a positive impact on the future of the built environment.

Possible further research

- **Building Shape:** The research focuses on buildings with a rectangular plan. In the future, the algorithm will be expanded to accommodate different geometric shapes.
- **Structural system**: A two-way concrete slab was chosen as the structural system for this research analysis. Other systems can be considered for future tool development.
- **Bay shape:** Different aspect ratios of the bay can be one of the alternatives for further investigation.
- **Incorporating lateral elements**: Address seismic considerations to enhance predictive accuracy regarding structural performance and environmental carbon emissions.
- **Refining assumptions regarding slab and beam behavior**: Include moment redistribution in the plastic state for more realistic estimates of structural performance and environmental impact.

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