REPUBLIC OF TÜRKİYE

ALTINBAŞ UNIVERSITY

Institute of Graduate Studies

Civil Engineering Department

SYMMETRY-BASED MULTI-OBJECTIVE AI/ML DRIVEN OPTIMIZATION FRAMEWORK FOR SUSTAINABLE BUILDING PERFORMANCE

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Master's Thesis

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İstanbul, 2025

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The thesis titled SYMMETRY-BASED MULTI-OBJECTIVE AI/ML DRIVEN OPTIMIZATION FRAMEWORK FOR SUSTAINABLE BUILDING PERFORMANCE prepared by SUHIB OMAR ABDUL KAREEM AMRO and submitted on 17/12/2025 has been **accepted unanim**ously for the degree of Master of Science in Civil Engineering.

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Suhib Omar Abdul Kareem AMRO

Signature

DEDICATION

This thesis is dedicated, with profound respect and gratitude, to my beloved parents, whose sincere love, steadfast patience, and continuous prayers have formed the foundation of my academic and personal journey.

To my father, an icon of determination, integrity, and unwavering principles, who taught me the true meaning of discipline, responsibility, and perseverance. Through his actions before his words, he instilled in me values that endure beyond time. His work ethic, resilience, and moral strength have been my constant guide, and from his example I learned that achievement is earned through effort, consistency, and dignity.

To my mother, the source of compassion and quiet strength in my life, whose unconditional support, encouragement, and faith sustained me through every stage of this journey. Her presence transformed challenges into possibilities and provided the emotional foundation upon which this work was built.

I also dedicate this work to my grandfather, whose wisdom, integrity, and enduring influence left a lasting imprint on my character and continue to inspire my pursuit of knowledge and purpose.

This thesis is further dedicated to my brothers and sisters, for their unwavering support, understanding, and shared belief in my aspirations throughout both hardship and success.

I extend my sincere appreciation to my supervisors, Prof. Dr. Sepanta NAIMI and Assoc. Prof. Dr. Abdullahi Abdu IBRAHIM, whose mentorship, trust, and scholarly guidance were instrumental in transforming this research from concept to realization.

Finally, this work is dedicated to my friends and loved ones, whose encouragement, patience, and presence made this journey both meaningful and sustainable, and to all who believe in the power of science, perseverance, and principled effort.

ABSTRACT

SYMMETRY-BASED MULTI-OBJECTIVE AI/ML DRIVEN OPTIMIZATION FRAMEWORK FOR SUSTAINABLE BUILDING PERFORMANCE

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Date: 12/2025

Page : 183

Research on the Symmetry Optimization and Detection for Architecture (SODA) framework in Dutch buildings has emerged as a critical area of inquiry due to the fundamental role symmetry plays in architectural design, heritage conservation, and urban modeling. This research develops and validates an integrated framework combining symmetry-based geometric optimization with Progressive Transfer Learning (PTL) for construction performance enhancement in Dutch buildings. The SODA framework employs computer vision algorithms to automatically identify geometric patterns from diverse data sources including point clouds and facade images. A modified Continuous Symmetry Measure adapted from molecular chemistry provides quantitative symmetry assessment, while multi-objective optimization algorithms balance competing objectives including material efficiency, structural performance, construction economy, and architectural preservation. Progressive Transfer Learning mechanisms enable systematic knowledge transfer across building projects, reducing analysis time for subsequent optimizations while maintaining solution quality. Empirical validation across 50 Dutch buildings encompassing 2.287 million m^2 demonstrates substantial optimization potential through systematic symmetry-based design interventions, achieving average material savings of 11.3%, construction time reduction of 10.7%, total cost savings of €87.3 million, and carbon emission reduction of 21,450 tons CO_2. The integrated SODA-PTL framework advances architectural computation toward genuine practical impact on construction industry sustainability and efficiency,

providing validated design guidelines for practitioners pursuing resource-efficient building optimization.

Keywords: Symmetry Optimization, Progressive Transfer Learning, Sustainable Construction, Computer Vision, Multi-Objective Optimization, Building Information Modeling, Dutch Architecture.

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ABBREVIATIONS

3D BAG : 3D Basisregistratie Adressen En Gebouwen

AI : Artificial Intelligence

ANOVA : Analysis of Variance

API : Application Programming Interface

BAG : Basisregistratie Adressen En Gebouwen

BIM : Building Information Modeling

BREEAM : Building Research Establishment Environmental Assessment Method

CAD : Computer-Aided Design

CI : Constructability Index

CLT : Cross-Laminated Timber

CNN : Convolutional Neural Network

CO_2 : Carbon Dioxide

CSM : Continuous Symmetry Measure

CV : Computer Vision

DFO : Derivative-Free Optimization

EN : European Norm (Eurocode Standard)

ETABS : Extended Three-Dimensional Analysis of Building Systems

EU : European Union

FEM : Finite Element Method

GA : Genetic Algorithm

GHG : Greenhouse Gas

HVAC : Heating, Ventilation, And Air Conditioning

IEA : International Energy Agency

IFC : Industry Foundation Classes

Iot : Internet Of Things

ISO : International Organization for Standardization

LCA : Life Cycle Assessment

LIME : Local Interpretable Model-Agnostic Explanations

MEP : Mechanical, Electrical, And Plumbing

ML : Machine Learning

NEN : Nederlandse Norm (Dutch Standard)

NPR : Nederlandse Praktijkrichtlijn (Dutch Practice Guideline)

NPV : Net Present Value

NSGA-II : Non-Dominated Sorting Genetic Algorithm II

PTL : Progressive Transfer Learning

R^2 : Coefficient Of Determination

RL : Reinforcement Learning

RMSE : Root Mean Square Error

ROI : Return On Investment

SAP2000 : Structural Analysis Program 2000

SHAP : Shapley Additive Explanations

SHM : Structural Health Monitoring

SI : Système International (International System of Units)

SODA : Symmetry Optimization and Detection for Architecture

TL : Transfer Learning

UAV : Unmanned Aerial Vehicle

XAI : Explainable Artificial Intelligence

LIST OF SYMBOLS

CSM : Continuous Symmetry Measure (%)

N : Number Of Structural Elements

P_i : Actual Position Of Element *I*

P'_i : Theoretically Symmetric Position Of Element *I*

Σ : Standard Deviation Of Element Positions

Δm_i : Change In Material Quantity Of Type *I*

Ef_i : Emission Factor For Material Type *I* (Kg CO_2 Per Unit)

Δt_i : Change In Transport Volume–Distance

Tf_i : Transport Emission Factor

CF_t : Cash Flow In Period *T*

R : Discount Rate For Present Value Calculation

I_0 : Initial Investment At Project Start

T : Time Period

R^2 : Coefficient Of Determination

CI : Constructability Index

CO_2 : Carbon Dioxide

C30/37 : Concrete Strength Class (Characteristic Compressive Strength)

C40/50 : Concrete Strength Class

S355 : Structural Steel Grade Designation

S460 : Structural Steel Grade Designation

1. INTRODUCTION

Investigations into the Symmetry Optimization and Detection for Architecture (SODA) framework in Dutch edifices have been a pivotal focus, given the essential function of symmetry in architectural design, heritage preservation, and urban modelling. The progression of symmetry detection and optimization techniques has transitioned from initial geometric and procedural modelling methods to contemporary advancements in optimization and deep learning strategies. Symmetry is acknowledged for its enhancement of aesthetic and structural attributes, as well as its facilitation of efficient digital reconstruction and semantic modelling of structures, which is essential for smart city development and heritage preservation. Structures frequently display intricate symmetrical patterns, especially in Dutch architectural styles shaped by classical principles, where precise identification and enhancement of symmetry are deemed crucial for both theoretical comprehension and practical implementation [1].

The implications of integrating advanced symmetry detection methods have been understood to extend beyond mere aesthetic enhancement, as these technologies have been recognized to play pivotal roles in the sustainable development of urban environments. The construction and building sectors have been documented as among the most resource-intensive domains of human activity worldwide, collectively accounting for substantial portions of global energy consumption and carbon emissions. Buildings have been calculated to contribute more than forty percent of global energy consumption, positioning the environment built at the forefront of international sustainability efforts. This substantial environmental footprint has necessitated the development of innovative approaches that minimize material usage while maintaining structural integrity and functional performance. Traditional optimization approaches have been characterized by their focus primarily on material reduction through structural analysis and load path optimization [2].

The SODA framework focuses on the automatic identification and enhancement of architectural symmetries from diverse data sources, such as two-dimensional polygons, three-dimensional point clouds, and facade photographs, particularly concerning Dutch structures and their unique characteristics. The framework uses computer vision methods to independently identify patterns in building geometry from various data sources. A revised Continuous Symmetry Measure, grounded in molecular chemistry principles, offers a quantitative evaluation of symmetry departure from optimal configurations. Multi-objective genetic algorithms develop optimal design solutions that reconcile competing objectives such as symmetry maximization, structural performance, construction efficiency, and architectural quality. The application to portfolios of Dutch buildings demonstrates success across several typologies, including residential, commercial, and industrial structures [3].

The framework of Progressive Transfer Learning is characterized as an auxiliary artificial intelligence system that enables the dynamic transfer of knowledge across successive stages of building projects and among interconnected projects. The technique is characterized by the provision of significant synergies with symmetry-driven architectural optimization, as it facilitates the application of experiences derived from prior projects to inform subsequent design and construction decisions. SODA emphasizes geometric optimization using symmetry principles, whereas PTL relates to temporal aspects of building intelligence by facilitating adaptive learning from prior project phases and similar finished projects. The integration of SODA and PTL frameworks is indicative of a strategic convergence of spatial and temporal intelligence aimed at enhancing construction. This integration establishes bidirectional value flows, wherein geometric optimization informs construction learning, while construction experience directs design optimization [4].

1.1 BACKGROUND AND GLOBAL CONSTRUCTION CONTEXT

The global construction industry is confronted with interconnected challenges pertaining to resource consumption, environmental impact, economic efficiency, and social equity, which have been exacerbated by trends in urbanization and the imperatives of climate change. The amplification of these challenges can be attributed to the evolving societal expectations pertaining to building performance, sustainability credentials, and lifecycle value creation. The scale and urgency associated with the addressing of these challenges have resulted in the positioning of construction optimization as a critical domain for research and innovation, which encompasses multiple disciplines, including architecture, structural engineering, materials science, computer science, and environmental studies. Buildings are characterized by a significant variation in typology, which includes residential, commercial, industrial, institutional, and mixed-use structures. Each typology is associated with specific functional requirements and performance criteria [5].

The range of construction systems includes concrete frame and steel frame structures, as well as masonry bearing wall and timber construction systems, each of which presents various combinations of cost, performance, constructability, and sustainability attributes. The presence of heterogeneity presents considerable challenges in the development of generalizable optimization frameworks that can provide meaningful enhancements across various building contexts, while simultaneously adhering to the distinct constraints and requirements inherent to each specific situation. The introduction of regional factors, such as climate conditions, soil characteristics, seismic risk profiles, and wind exposure, contributes to additional complexity that necessitates consideration for optimization frameworks to attain practical applicability across various geographic contexts. The optimization landscape is further diversified by local construction practices, patterns of material availability, distributions of labor skills, and regulatory frameworks, which cannot be adequately addressed by simple universal solutions [6].

1.1.1 Resource Intensity and Environmental Impacts

The resource intensity of the construction sector has been documented through comprehensive lifecycle analyses that track material and energy flows from extraction to end-of-life disposal or recycling. The processes involved in the extraction of materials for construction, which encompass aggregates, cement, steel, aluminum, and timber, are recognized as accounting for significant portions of global industrial energy consumption. The processing operations that are employed to transform raw materials into construction products are characterized by energy-intensive processes, which include grinding, heating, chemical reactions, and mechanical forming operations. The transportation of materials from extraction sites to processing facilities and subsequently to construction sites is associated with increased energy consumption and emissions. The extent of these impacts is subject to significant variation, influenced by the distances transported and the modes of transportation utilized [7].

On-site assembly operations represent a substantial share of energy consumption and environmental impacts in building projects, although they generally account for less than the phases of material manufacturing and transportation. Embodied carbon in construction materials increasingly contributes to the environmental impact of a building's lifecycle, since enhancements in operational energy efficiency have altered the focus toward emissions during the construction period.This tendency has intensified due to enhanced building envelope performance, efficient mechanical systems, and on-site renewable energy generation, which jointly diminish operational emissions while largely neglecting embodied emissions in traditional design optimization methods. Concrete production is anticipated to represent approximately eight percent of global carbon dioxide emissions resulting from cement manufacturing activities.

Steel manufacturing contributes an additional seven percent to global emissions via energy-intensive blast furnace and electric arc furnace methods. This data underscores the importance of material optimization strategies in achieving climate change targets, as even slight percentage reductions in building material consumption result in significant absolute emission reductions owing to the scope of global construction activities. The utilization of algorithmic symmetry detection has demonstrated effectiveness in enhancing the rehabilitation of heritage structures, ensuring that modifications adhere to the original architectural intent while enhancing energy efficiency through optimized facade designs [9].

1.1.2 Urbanization Pressures and Housing Demands

Projected accelerated urbanization trends will require the development of billions of square meters of new building space in the coming decades, particularly in developing countries experiencing simultaneous population growth and economic advancement. The expansion of urban populations, coupled with a decrease in household size and an increase in living standards, propels the demand for housing units at rates above basic population growth multipliers. Concurrently, metropolitan centers in wealthy countries confront issues of deteriorating infrastructure, outdated buildings necessitating extensive rehabilitation, and the demand for systematic retrofit initiatives that enhance energy efficiency while maintaining architectural and cultural integrity.[10]

The extent of these simultaneous challenges the significant need for new construction in growing regions, along with the systematic improvement of existing buildings in established nations, necessitates innovative solutions that ensure both quality and efficiency at an unparalleled level. Conventional construction techniques dependent on skilled labor and craftsmanship encounter capacity limitations that restrict construction speeds, whereas industrialized construction methods grapple with flexibility and the architectural diversity demands inherent in modern urban development. The housing affordability crisis in large metropolitan centres is partially ascribed to building inefficiencies that escalate costs and prolong project timetables beyond economically acceptable lengths [11].

Regulatory barriers including complex approval processes, restrictive zoning codes, and fragmented permitting systems exacerbate these challenges by adding time and uncertainty to development processes. Symmetry-based design optimization has been demonstrated to contribute to construction economy through multiple mechanisms that reduce costs while potentially improving quality and performance. Standardization of structural elements reduces design and engineering time by eliminating redundant analysis and documentation efforts. Facilitation of prefabrication improves quality control through controlled factory conditions while accelerating construction schedules by enabling parallel fabrication and assembly processes [12].

1.2 DUTCH ARCHITECTURAL HERITAGE AND CONSTRUCTION CONTEXT

The Netherlands has been characterized by unique geographical, cultural, regulatory, and economic factors that fundamentally shape architectural design philosophies and construction practices throughout the building sector. The unique architectural heritage of the nation, developed over centuries, integrates with modern sustainability goals and ambitious climate targets, resulting in stringent demands for building performance. Environmental conditions, such as soft soils necessitating specialized foundations and induced seismicity from gas extraction, present technical challenges that affect structural design methodologies [13].

The historical analysis of Dutch classicism identifies foundational principles rooted in antique symmetry and proportional systems, which have significantly influenced architectural development over the centuries and continue to shape contemporary design sensibilities. Classical systems established relationships among building dimensions, element proportions, and spatial hierarchies that yield coherent architectural compositions. Dutch architecture of the seventeenth century exhibited a strict adherence to classical proportions and symmetrical arrangements, which mirrored aesthetic preferences alongside practical construction benefits [14].

Cube-shaped edifices that emerged in nineteenth-century Dutch architecture have been examined as models of formal symmetry principles, illustrating how geometric simplicity, coupled with symmetrical organization, yields both structural efficiency and aesthetic harmony. The structures achieved cost-effective construction by utilizing repetitive elements and standardized features, while simultaneously expressing architectural concepts through proportional relationships and material selections. Historical precedents provide critical insights into symmetry, which functions as both an ornamental feature on building facades and a fundamental organizational principle that integrates structural coherence, functional design, and aesthetic expression [15].

1.2.1 Geological Conditions and Foundation Engineering

The prevalence of soft soil conditions in the Netherlands requires specialized foundation systems, significantly influencing structural design decisions and optimization strategies at both building and urban levels. Geological formations composed of unconsolidated sediments, such as peat, clay, and sand layers, present difficult foundation conditions characterized by low bearing capacity and considerable settlement potential. In Dutch construction, standard pile foundations penetrate weak surface soils to access bearing strata at depths ranging from ten to thirty meters. Pile capacities typically vary between twenty and forty kilonewtons per square meter, depending on soil conditions and the type of pile used [16].

The restricted bearing capacity necessitates meticulous attention to load distribution and structural uniformity to keep foundation loads within acceptable limits, thus minimizing the likelihood of differential settlement that could result in structural damage and serviceability concerns. Symmetric structural configurations provide advantages concerning predictable load paths, facilitating foundation design and reducing uncertainty in load distribution. Balanced foundation loading reduces differential settlement risks by evenly distributing loads across foundation zones, thus enhancing overall structural reliability in challenging soil conditions [17].

The induced seismicity in the Groningen region is a consequence of decades of natural gas extraction, which has led to alterations in subsurface volume and stress distributions. This phenomenon has introduced further design requirements that extend beyond traditional seismic provisions, with guidelines highlighting the importance of structural regularity and symmetry to guarantee a predictable response of buildings to ground shaking. Symmetric structures typically demonstrate superior seismic performance compared to irregular configurations, resulting in diminished torsional responses that reduce differential displacements among building levels [18].

1.2.2 Industrialized Construction and Prefabrication Systems

The Dutch construction sector demonstrates significant levels of standardization and prefabrication, influenced by economic conditions, labor market attributes, and technology competencies that promote industrialized production techniques. Approximately eighty-five percent of residential projects employ factory-manufactured hollow-core concrete floor slabs, which are subsequently shipped to installation locations. About seventy percent utilize prefabricated facade panels that include insulation, finishing, and fenestration into whole building envelope systems [19].

The extensive adoption of industrialized construction methods is ascribed to several reinforcing factors, including labor cost economics that favor factory production over on-site assembly, enhanced quality control achievable in regulated manufacturing environments, and weather-related scheduling considerations that render indoor fabrication appealing. Prefabrication systems inherently advantage from symmetrical design configurations that facilitate the efficient repetition of standardized components, hence diminishing manufacturing costs through economies of scale and learning effects [20].

Modular dimensions derived from standard prefabricated element sizes establish inherent grid patterns and proportionate relationships that conform to concepts of symmetry. These dimensions standards arise from manufacturing limitations, such as optimal production sizes, transportation constraints, and handling equipment capacities. Conventional Dutch residential building utilizes structural grids of between five point four meters and seven point two meters, dimensions that align with normal precast concrete floor slab widths and span capacities [21].

1.2.3 Sustainability Mandates and Circular Economy Transitions

The sustainability objectives set by Dutch national and municipal governments serve as significant motivators for building optimization, shifting the focus from mere cost minimization to include environmental performance and resource circularity. The Netherlands aims for a forty-nine percent reduction in greenhouse gas emissions by 2030, relative to 1990 baseline levels, with interim targets necessitating continuous emission reductions across all economic sectors [22].

Carbon neutrality is aimed for realization by 2050 through the total eradication of net greenhouse gas emissions. The built environment is recognized as a vital sector for meeting climate objectives, encompassing emissions from both operational energy use and the embodied carbon associated with materials and construction methods. Construction waste represents a significant category of environmental impact, as demolition and renovation activities generate considerable amounts of materials that have historically been disposed of in landfills or employed in low-value applications [23].

Circular economy principles are being progressively incorporated into Dutch building regulations and sustainability certification systems to improve material reuse, enable design for disassembly, and encourage closed-loop material flows. The principles focus on maintaining materials at their highest value applications through cascading recycling and reuse strategies, which aim to preserve embodied energy and reduce the extraction of virgin materials. The government's objective of achieving fifty percent circular material usage by twenty thirty promotes the adoption of standardized, reusable structural components that can be retrieved and utilized in subsequent construction endeavors [24].

1.3 SYMMETRY DETECTION AND OPTIMIZATION METHODOLOGIES

The Symmetry Optimization and Detection for Architecture framework provides a systematic methodology for assessing and enhancing structural symmetry in both existing and proposed buildings. Symmetry detection entails the identification of geometric invariances in architectural structures, encompassing reflectional, translational, and rotational symmetries that define building organization across various scales, from individual elements to complete building compositions. Symmetry optimization aims to improve or reinstate symmetry in architectural components while maintaining structural integrity, functional needs, and the architectural character that contribute to building identity and cultural importance [25].

Procedural modeling encodes architectural patterns into generative rules, allowing for scalable reconstruction and variation. This approach facilitates the creation of architectural families that uphold design coherence while enabling controlled variation. The generative capabilities facilitate the analysis of existing buildings via inverse procedural modeling and the synthesis of new designs through forward generation. Reflectional symmetry is the predominant form in architectural design, defined by mirror symmetry along planes that bisect structures into symmetrical halves [26].

Translational symmetry defines repetitive patterns in linear or planar orientations, frequently observed in facade rhythms and the repetition of structural bays. Rotational symmetry is observed in structures characterized by central organization or radial planning. It is less common in rectangular buildings but is prevalent in specific specialized typologies. Accurate detection from noisy three-dimensional point clouds is essential for effective implementation in real-world building documentation scenarios [27].

1.3.1 Computer Vision and Pattern Recognition Approaches

Algorithms in computer vision, originating from image processing and machine learning, enable the identification of repetitive elements, symmetry axes, and hierarchical relationships that characterize architectural organization. Pattern recognition techniques discern geometric regularities in building data acquired from photographs, laser scanning, or building information models. Derivative-free optimization methods enable rapid convergence with logarithmic time scaling in relation to problem size, making the large-scale processing of heritage buildings containing millions of geometric primitives computationally feasible [28].

Achieving high precision in joint detection and optimization of two-dimensional polygonal symmetries has been accomplished using mixed-integer programming formulations, which offer mathematical rigor and guarantees of optimality. The formulations explicitly model discrete decision variables, including the locations of symmetry axes, the correspondence between symmetric elements, and permissible geometric modifications. Mixed-integer programming solvers utilize branch-and-bound algorithms to systematically investigate solution spaces, simultaneously eliminating branches that can be proven to be suboptimal [29].

Minimizing geometric alteration while maintaining symmetry is essential for applications that require the preservation of architectural character, especially in heritage contexts where historical authenticity is a primary goal. Optimization formulations incorporate penalty terms that address deviations from the original geometry, balancing the enhancement of symmetry with the preservation of geometric fidelity. Efficient algorithms have enabled hierarchical symmetry detection in large urban three-dimensional point clouds by decomposing complex geometric datasets into manageable components [30].

1.3.2 Continuous Symmetry Measure Adaptation

The Continuous Symmetry Measure, initially formulated in molecular chemistry, offers a quantitative evaluation of symmetry departure from optimal configurations. The translation of CSM from angstrom-scale molecular structures to meter-scale architectural edifices necessitates an examination of basic disparities in scale, tolerance specifications, and functional limitations. Molecular symmetry evaluations rely on static structures with exact atomic coordinates, whereas architectural structures display construction tolerances, material variations, and deliberate functional asymmetries [31].

Revised CSM formulations for architectural applications integrate tolerance factors that account for realistic construction accuracy and permissible deviation limits. The alterations facilitate the measurement of approximation symmetries inherent in actual structures, thus differentiating notable symmetry patterns from arbitrary geometric occurrences. The application of sub symmetries and frieze groups in façade analysis offers mathematical frameworks based on group theory that systematically classify symmetry types [32].

Complex facade designs can be studied by breaking them down into compositional symmetry components linked to different symmetry groups, enabling a structured analysis that merges mathematical accuracy with architectural complexity. The systematic classification and characterization of architectural patterns can be achieved using group-theoretic methods that enumerate all potential symmetry types within defined dimensional constraints. Frieze groups categorize one-dimensional patterns into seven distinct types according to symmetry operations, whereas wallpaper groups classify two-dimensional patterns into seventeen types [33].

1.4 PROGRESSIVE TRANSFER LEARNING IN CONSTRUCTION

Progressive Transfer Learning is an artificial intelligence framework that facilitates dynamic knowledge transfer between successive phases of building projects and between interconnected projects. The extensive theoretical underpinnings of transfer learning create classifications within both homogeneous and heterogeneous areas, organizing methodologies into many paradigms. Instance-based transfer learning identifies pertinent training examples from source domains for immediate use in target domains, applicable when source and target domains possess analogous feature spaces yet exhibit distinct data distributions [34].

Feature-based transfer learning modifies feature representations to diminish differences between source and target domains, facilitating knowledge transfer when domains utilize distinct feature spaces. Parameter-based transfer learning disseminates model parameters across domains, presuming that specific parameters or hyperparameters are common to both source and target tasks. Relational knowledge transfer preserves structural relationships during the transmission of knowledge between domains with disparate feature spaces [35].

Experimental validation on benchmark datasets reveals significant performance improvements over conventional machine learning methods when suitable transfer strategies are chosen based on domain similarity evaluation. Performance enhancements of fifteen to thirty percent have been recorded for transfer learning vs learning from inception when source and destination domains demonstrate moderate to high similarity [36].

1.4.1 Progressive Learning Architectures

Progressive learning frameworks mitigate catastrophic forgetting that affects traditional neural networks during the acquisition of sequential tasks. Catastrophic forgetting refers to the occurrence in which the acquisition of new tasks leads to significant deterioration in performance on previously mastered tasks, as the training for new tasks overrides the network parameters that stored knowledge of earlier tasks. Progressive architectures incrementally enhance network capacity to support new jobs while maintaining the performance of prior tasks through selective parameter freezing or regularization methods [37].

Curriculum design organizes tasks from simple to complicated, promoting knowledge acquisition through incremental skill development. Strategic pruning algorithms eliminate superfluous parameters to sustain network efficiency as architecture evolves, averting unrestrained growth that could render models computationally unmanageable. Performance enhancements of twenty to thirty-five percent relative to fine-tuning baselines have been evidenced in sequential task learning contexts [38].

Frameworks for knowledge transfer in construction integrate knowledge graphs with transfer learning techniques to facilitate the automated transfer of parameter prediction models across projects. Knowledge graphs encapsulate domain knowledge, encompassing project attributes, construction techniques, material qualities, and observable results in structured formats that facilitate reasoning and inference. Case studies on shield tunnel building exhibit accuracy levels between eighty-five and ninety-two percent, concurrently decreasing training data requirements by sixty to seventy percent [39].

1.4.2 Multi-Task Learning for Coupled Systems

Multi-task learning tackles interconnected building systems with neural architectures that concurrently optimize several linked predictive tasks. Uncertainty loss functions assign weights to task contributions depending on prediction uncertainty, dedicating greater network resources to uncertain tasks while permitting confident jobs to direct learning with reduced capacity. Applications to intricate equipment systems attain remarkable predictive accuracy across several interrelated subsystems concurrently [40].

Few-shot meta-learning enables rapid adaptability to rare construction configurations and unusual damage patterns through episodic training techniques. Meta-learning frameworks obtain information by training on distributions of tasks instead of individual tasks, enabling rapid adaption to new tasks with limited data through a grasp of task structure. Generalizing to new types of damage with only five examples per category enables implementation across diverse building inventories without extensive data collection for each variety [29].

1.5 RELATED WORK

A comprehensive review of the existing literature has revealed significant advances in symmetry detection, optimization methodologies, and transfer learning applications, while persistent gaps have been identified that motivate the current research. Research conducted on symmetry within the field of structural engineering indicates that symmetric structures are associated with benefits in load distribution, construction efficiency, and seismic performance. It has been demonstrated that research on topology optimization incorporating symmetry constraints results in efficiency improvements ranging from fifteen to twenty percent under idealized conditions [30].

The mathematical formalization of symmetry in structures is derived from geometric analysis and group theory, which provide rigorous foundations for computational implementation. The applications of computer vision in the context of architectural analysis have evolved from basic edge detection techniques to advanced deep learning models that are able to identify intricate patterns and hierarchical relationships. The proliferation of machine learning applications in structural engineering has been observed, encompassing areas such as damage detection, load forecasting, and design optimization [31].

The implementation of optimization within Building Information Modeling technologies is enabled by the availability of digital frameworks; however, the integration between BIM platforms and optimization algorithms is marked by certain limitations. It has been noted that Dutch construction standards, which consider regional conditions and sustainability objectives, delineate specific requirements that are often inadequately addressed by generic optimization frameworks. The prevalence of prefabrication in the Dutch construction sector is linked to the identification of optimization opportunities grounded in symmetry, which employs established standardization [32].

1.6 PROBLEM STATEMENT AND RESEARCH GAPS

Despite numerous advances in computational methods over recent decades, significant knowledge gaps persist that limit practical applicability of symmetry optimization and transfer learning in construction contexts. These gaps span technical capabilities, methodological integration, practical implementation, and validation across real-world building portfolios.

1.6.1 Technical and Methodological Gaps

The challenges that are associated with existing symmetry detection methods become evident when they are applied to noisy, incomplete, or irregular data, which is characteristic of real-world architectural documentation processes. The point cloud data acquired through laser scanning or photogrammetry is characterized by the presence of measurement noise, systematic errors, and the occurrence of missing data as a result of occlusions. It is deemed necessary for detection algorithms to differentiate between true geometric symmetries and spurious correlations that arise from measurement noise and data incompleteness [33].

Challenges related to computational efficiency are observed when large-scale building datasets that contain millions of geometric primitives are processed. The requirement for prohibitive processing times associated with many sophisticated algorithms limits their applicability in realistic building complexity, thereby hindering their integration into time-sensitive design workflows and the interactive exploration of alternatives. The issue of robustness to occlusions and missing data is identified as a persistent challenge that limits the practical applicability in contexts of heritage documentation, where the complete geometric capture is often rendered impossible [34].

The complexity associated with hierarchical or partial symmetries present in real buildings introduces additional challenges to detection and optimization tasks, given that mathematical definitions of symmetry frequently do not adequately represent the approximate symmetries that are characteristic of actual construction. The integration of symmetry detection capabilities with procedural modeling frameworks that can generate editable architectural representations suitable for iterative design workflows is currently underdeveloped [35].

1.6.2 Application and Validation Gaps

The limited validation of optimization frameworks across various full-scale designs with documented outcomes restricts confidence in the anticipated benefits. Much of the research depends on isolated case studies or overly simplistic models that do not adequately represent the complexity of actual construction projects. There is a lack of systematic validation across representative building portfolios regarding quantified material savings, cost reductions, and improvements in construction time [36].

Integration with architectural practice and design workflows is currently constrained, as most of the research yields isolated prototypes that necessitate specialized knowledge and do not incorporate commercial software solutions. Professional design workflows entail intricate interactions among various stakeholders utilizing different software tools, impeding research prototypes from achieving momentum without significant investment in software engineering [37].

Applications of transfer learning in construction are still in their early stages, showing little effectiveness in facilitating knowledge transfer across various building types, construction methods, or geographical locations. The systematic prevention of detrimental transfer between source and target domains with insufficient similarity necessitates improved methods for domain categorization. The integration of transfer learning with geometric optimization to enable bidirectional information transfer between the design and construction sectors is a mostly uncharted area.

1.6.3 Dutch-Specific Gaps

International optimization methods overlook characteristics peculiar to the Netherlands, such as soft soil conditions that demand specialized foundations, induced seismicity from gas extraction that requires improved seismic measures, and standardized prefabrication processes that facilitate industrialized construction. No optimization approach specifically tackles the interplay of technical, regulatory, and economic concerns inherent to Dutch building contexts [39].

Ambitious sustainability objectives, such as a forty-nine percent decrease in emissions by 2030 and achieving carbon neutrality by 2050, impose stringent demands that conventional optimization methods fail to fully meet. The principles of the circular economy are increasingly incorporated into Dutch regulations, fostering designs that facilitate disassembly and material reuse characteristics essentially supported by symmetrical structures, but never explicitly optimized.

1.7 RESEARCH OBJECTIVES

The primary objective of this research is to develop and validate an integrated framework combining symmetry-based geometric optimization with progressive transfer learning for construction performance enhancement across Dutch building portfolios. This integrated approach addresses identified gaps by creating unified methodologies that optimize both spatial design characteristics and temporal execution processes while accounting for Dutch-specific technical and regulatory requirements.

1.7.1 Specific Research Objectives

Objective One: Develop a comprehensive SODA-PTL framework that adapts Continuous Symmetry Measure concepts from molecular chemistry to architectural structures, incorporating progressive transfer learning mechanisms for knowledge propagation across building projects. This framework will address scale differences, construction tolerances, and functional constraints that distinguish architectural applications from molecular chemistry origins.

Objective Two: Validate the integrated framework empirically across representative Dutch building portfolios spanning diverse typologies including residential, office, mixed-use, industrial, and parking structures. Validation will encompass both contemporary construction and heritage buildings to demonstrate framework applicability across temporal spectrum of Dutch building stock from historical structures to modern sustainable construction.

Objective Three: Quantify performance improvements achievable through integrated symmetry optimization and progressive transfer learning, measuring material reduction, construction time savings, cost reduction, and carbon emission reduction. Assessment will encompass both direct benefits including material efficiency and construction speed, and indirect benefits including knowledge transfer accuracy and adaptation efficiency across project types.

Objective Four: Integrate the framework with Building Information Modeling workflows to demonstrate practical applicability within Dutch construction practices. Integration will address software interfaces connecting optimization algorithms with BIM platforms, data exchange protocols enabling seamless information transfer, and user interaction paradigms supporting iterative design exploration within existing architectural and engineering workflows.

Objective Five: Establish comprehensive design guidelines for symmetry-based optimization integrated with progressive transfer learning. Guidelines will ensure compliance with Eurocode structural standards, Dutch building regulations, and contemporary sustainability requirements including circular economy principles. These guidelines will provide decision-support frameworks for architects, engineers, and construction managers translating computational optimization outcomes into actionable strategies.

1.7.2 Research Scope and Delimitations

The research scope focuses geographically on Dutch buildings and construction contexts, accounting for unique factors including soft soil conditions, induced seismicity, standardized prefabrication practices, and regulatory frameworks specific to the Netherlands. This geographic focus enables development of deeply contextualized approaches rather than superficially general methods.

Temporally, the research addresses both retrofit optimization of existing buildings and integrated design optimization for new construction. Retrofit applications must respect existing architectural character and structural capacity limitations, while new construction applications must satisfy increasingly stringent energy performance and sustainability requirements.

Methodologically, the research integrates computational geometry for symmetry analysis with machine learning for transfer learning, combining geometric optimization with temporal knowledge transfer. The research employs mixed methods including algorithmic development, computational experimentation, empirical case studies, and stakeholder engagement.

Typologically, the research spans residential, office, mixed-use, industrial, and parking buildings representing substantial portions of Dutch building stock. Selected typologies provide sufficient diversity for framework validation while maintaining research focus on common building types.

1.8 EXPECTED CONTRIBUTIONS AND SIGNIFICANCE

This research anticipates multiple categories of contributions addressing theoretical advancement, methodological innovation, empirical evidence, practical tools, and societal impact. These contributions address identified gaps in current knowledge and practice while establishing foundations for future research and development.

1.8.1 Theoretical Contributions

Integration of Continuous Symmetry The assessment of molecular chemistry principles via architectural analysis establishes mathematical frameworks for examining architectural symmetry, considering realistic imperfections such as building tolerances, material inconsistencies, and functional asymmetries. This theoretical link between molecular and architectural domains may open new research pathways in applying concepts of chemical and physical symmetry to the examination of constructed environments.

Convergence of symmetry-based optimization with progressive transfer learning constitutes theoretical innovation in construction artificial intelligence, establishing frameworks for bidirectional knowledge exchange between spatial design optimization and temporal project management. This theoretical synthesis addresses identified gaps where design optimization and construction management have evolved as separate research domains.

1.8.2 Methodological Contributions

Validated algorithms and computational frameworks for symmetry detection, optimization, and procedural modelling tailored to Dutch architectural contexts address limitations such as robustness to noise and occlusions, computational efficiency for large-scale processing, and integration with standard Building Information Modelling workflows.

The development of sophisticated transfer learning architectures designed for the sharing of construction knowledge creates frameworks for cross-project learning, reducing the risk of catastrophic forgetting while addressing project-specific conditions.   These methodologies address the practical challenges related to the limited availability of training data in construction environments.

1.8.3 Empirical and Practical Contributions

Evidence-based justification for industry adoption is provided by demonstrated material, time, and cost savings achievable through integrated symmetry optimization and progressive transfer learning across representative Dutch building portfolios. Quantified benefits provide baseline expectations for the effectiveness of optimization across various building types.

The development of Building Information Modeling integrated tools and workflows enhances industry adoption by incorporating optimization capabilities into current design and construction management platforms. These tools connect research prototypes with production-ready software.

Design guidelines that comply with Eurocode standards and Dutch regulations provide practical frameworks for decision support, enabling practitioners to apply optimization principles without requiring specialized computational skills. Guidelines transform complex optimization outcomes into actionable strategies.

1.8.4 Societal and Environmental Contributions

Heritage preservation advantages facilitate the optimization of existing structures, safeguarding architectural integrity and cultural identity while enhancing building performance. Quantified reductions in material usage, embodied carbon, and construction waste directly support Dutch sustainability targets, including a forty-nine percent reduction in emissions by twenty thirty.

Improving construction efficiency via progressive transfer learning enhances industry productivity and project outcomes, effectively addressing housing shortages and infrastructure requirements. Reducing construction costs enhances housing affordability, benefiting both construction professionals and end users.

1.9 THESIS ORGANIZATION AND STRUCTURE

This thesis comprises seven chapters that systematically develop the integrated Symmetry Optimization and Detection for Architecture and Progressive Transfer Learning framework from theoretical foundations through empirical validation to practical implementation guidance.

Chapter 1: Introduction establishes research context, motivation, objectives, and expected contributions. This chapter positions the research within global construction challenges, Dutch architectural heritage, and existing scholarly discourse while articulating specific problems addressed and anticipated contributions.

Chapter 2: Literature Review presents comprehensive analysis of existing research in symmetry optimization, procedural modeling, progressive transfer learning, and Dutch construction practices. This review identifies research gaps motivating current investigation and positions this work within broader scholarly landscape through thematic organization and critical evaluation.

Chapter 3: Materials and Methods details framework implementation including algorithmic specifications, computational procedures, building selection criteria, data acquisition methods, software architecture, and validation protocols addressing geometric accuracy, structural compliance, and constructability assessment. This chapter also establishes the theoretical foundations including Continuous Symmetry Measure formulations adapted from molecular chemistry, multi-objective optimization models employing genetic algorithms, progressive transfer learning architectures, and integration mechanisms creating bidirectional knowledge flows between spatial optimization and temporal learning.

Chapter 4: Results present empirical findings from framework application across building portfolios including quantitative metrics documenting symmetry improvements, material reductions, construction time savings, cost reductions, and carbon emission reductions with statistical analyses identifying relationships between building characteristics and optimization potential. This chapter includes detailed analysis of framework application to 50 Dutch buildings representing diverse typologies and eras, documenting optimization processes, geometric modifications, performance predictions, and validation against design criteria.

Chapter 5: Discussion interprets empirical findings within broader theoretical and practical contexts, comparing results with prior research, analysing factors influencing optimization effectiveness, discussing limitations and boundary conditions, and addressing implications for architectural practice and policy.

Chapter 6: Conclusion synthesizes research contributions across theoretical, methodological, empirical, and practical dimensions while reflecting on objective achievement, acknowledging limitations, and recommending directions for future research advancing construction optimization.

Chapter 7: References and Appendices provide complete bibliographic information for all cited sources and supplementary materials including detailed calculation procedures, additional case study documentation, and software implementation details.

2. LITERATURE REVIEW

The literature regarding the Symmetry Optimization and Detection for Architecture (SODA) framework in Dutch buildings highlights significant themes related to algorithmic symmetry detection, procedural and optimization-based facade modelling, as well as applications in heritage conservation and architectural aesthetics. Research indicates progress in computational techniques, including mixed-integer programming, derivative-free optimization, and binary integer programming, aimed at improving symmetry detection and facade regularization. Moreover, procedural modelling and grammar-based methods serve as effective instruments for the representation and synthesis of architectural structures that adhere to symmetry constraints. The interplay of digital data acquisition, semantic parsing, and symmetry principles underscores current initiatives aimed at enhancing 3D reconstruction and design automation, especially in the context of Dutch architecture characterized by its unique style.

The examination of symmetry optimization and detection in architectural contexts has significantly progressed, evolving from fundamental procedural and grammar-based modelling of facades to sophisticated optimization and machine learning techniques. Initial research concentrated on formalizing principles of building design and creating procedural grammar to encapsulate symmetrical patterns. Recent initiatives focus on automating symmetry detection across various data sources, such as images, 3D point clouds, and CAD models, by integrating optimization and deep learning to improve accuracy and robustness. Recent studies highlight the applications of heritage conservation, digital twin development, and facade reconstruction, specifically focusing on the challenges presented by incomplete data and complex architectural styles, including those of Dutch buildings.

Research on symmetry optimization and detection frameworks in Dutch architecture demonstrates a consensus regarding the significance of symmetry in enhancing architectural modelling accuracy, procedural generation, and heritage preservation. Numerous studies indicate that optimization-based and derivative-free algorithms are effective in detecting symmetry within noisy or incomplete data, underscoring their robustness and efficiency. Procedural and grammar-based modelling methods are recognized for their efficacy in capturing architectural regularities and enabling flexible facade synthesis. Divergences primarily occur regarding algorithmic complexity, data integration strategies, and the extent to which symmetry constraints are incorporated in deep learning or procedural pipelines. These differences frequently arise from diverse dataset types, specific architectural features, and the computational frameworks utilized.

The synthesis of research on symmetry optimization and detection frameworks in architecture underscores the importance of symmetry as a core geometric and aesthetic principle that informs both the analysis and creation of architectural forms. The formalization of symmetry detection as optimization problems and the incorporation of symmetry constraints into procedural and inverse procedural modeling signify a significant advancement in the theoretical understanding of symmetry as a measurable and generative attribute in architectural design [3],[19],[5].

The reviewed studies demonstrate that symmetry in architecture is not merely a static or global trait; instead, it often manifests in a hierarchical and partial fashion, requiring layered and multi-scale analytical approaches. This is illustrated by hierarchical facade analyses and the use of frieze groups and subsymmetries to depict complex compositional structures, thereby expanding classical symmetry theories to encompass architectural complexity and irregularity [21],[10].

The integration of symmetry principles into machine learning and deep neural networks, particularly through symmetry-aware loss functions and neuro-symbolic procedural representations, presents a challenge to traditional purely geometric or rule-based frameworks. This fusion suggests a theoretical shift towards hybrid models that combine data-driven learning with formal symmetry constraints to more effectively capture architectural regularities and variations. [33], [4], [34]. The theoretical frameworks for symmetry detection and optimization in three-dimensional urban and building models emphasize the need for robustness against noise, occlusions, and incomplete data, thus addressing real-world complexities. This advances theoretical discourse by highlighting the need for symmetry models capable of adapting to and enduring imperfect inputs, which is crucial for heritage and urban contexts [1],[20],[7].

The formalization of symmetry measures and indices, including global and local symmetry indices in CAD models, facilitates the theoretical quantification of symmetry, allowing for the distinction between exact, partial, and non-symmetry. The quantification is essential for connecting theoretical symmetry concepts to practical computational implementations [22]. The reviewed literature challenges the oversimplified view of symmetry as solely an aesthetic feature, elucidating its functional roles in structural design, spatial organization, and semantic modelling, thereby enriching theoretical perspectives on the intricate significance of symmetry in architecture [2],[9].

The development of optimization-based frameworks for symmetry detection that emphasize computational efficiency and resilience to noise and large-scale data, such as derivative-free optimization and mixed-integer programming methods, has important practical implications for automating architectural modelling, heritage conservation, and digital twin creation, enabling faster and more accurate processing of complex building data [3],[1],[23]. The use of symmetry-aware procedural and inverse procedural modeling techniques enables the creation of editable and parametric architectural models, thereby improving design automation, customization, and iterative exploration in architectural practice, applicable to both new construction and restoration projects [33],[18],[19]. The integration of symmetry detection with low-cost sensing technologies, including smartphone-based point cloud acquisition and 2D CAD drawings, offers efficient solutions for scalable and cost-effective digital documentation and reconstruction of existing buildings, particularly in extensive urban and heritage settings [23].

Incorporating symmetry constraints into deep learning models for facade parsing improves the accuracy and visual quality of semantic segmentation outcomes. This advancement can be applied in automated building information modeling (BIM) workflows and urban planning tools, enhancing the reliability of digital architectural datasets [4],[34]. The quantification and hierarchical modeling of symmetry in building footprints and facades offer practitioners formal tools for the systematic analysis and synthesis of architectural elements, facilitating design validation, quality control, and the creation of stylistically coherent architectural variations [24],[21]. The ability to reconstruct missing or occluded architectural elements using symmetry-based duplication and transformation techniques provides practical advantages for heritage conservation, facilitating the restoration of damaged or incomplete structures with minimal manual intervention [17].

2.1 SYMMETRY OPTIMIZATION AND DETECTION FOR ARCHITECTURE (SODA)

2.1.1 Descriptive Summary of SODA Studies

This section outlines the research landscape pertaining to the literature on the Symmetry Optimization and Detection for Architecture (SODA) framework in Dutch buildings, emphasizing various computational methodologies, procedural modeling tools, and applications in heritage conservation. This research examines algorithmic symmetry detection in both two-dimensional and three-dimensional datasets, optimization frameworks for facade layout regularization, and the extraction of procedural grammar for architectural modeling. Many studies emphasize the integration of digital sensing data, such as point clouds and photogrammetric meshes, showcasing a strong interdisciplinary approach that combines computer vision, optimization, and architectural theory. This comparative analysis is essential for examining the research questions concerning the effectiveness, efficiency, and architectural significance of symmetry detection and optimization methods in Dutch architectural heritage. Twenty studies have shown high precision and robustness in symmetry detection across two-dimensional images, three-dimensional point clouds, and CAD models, utilizing methods such as mixed-integer programming, derivative-free optimization, and deep learning. [3], [1], [22]. Various techniques effectively reduce noise and occlusions, enhancing detection reliability in both heritage and urban environments [20],[35],[43].

Numerous studies investigate the identification of hierarchical or layered symmetry, enhancing accuracy in intricate facade structures [21],[10]. Derivative-free algorithms and binary integer programming within optimization frameworks exhibit rapid convergence and reduced computational costs, enabling their use with large datasets. [1], [23], [31], [32]. Genetic algorithms and approximate dynamic programming effectively balance solution quality and computational demands in the optimization of procedural grammar [39],[5]. cale up for modeling cities [1],[7],[22]. Procedural language extraction and inverse procedural modeling algorithms successfully capture architectural symmetry, facilitating the creation of customizable and realistic facades. [33], [18], [5]. Deep learning models that integrate symmetry constraints enhance the accuracy of facade parsing and the overall visual quality [4],[34]. User-assisted and semi-automatic approaches enhance procedural modeling through the utilization of identified symmetries and repetitions. [36], [19]. The integration of digital sensing data, including 3D point clouds and photogrammetric meshes, improves symmetry detection and reconstruction accuracy in heritage and urban environments [1],[11],[31],[17]. Several studies integrate smartphone-collected data with CAD drawings to facilitate the creation of low-cost digital twins [23]. Some approaches emphasize image-based inputs while incorporating minimal or no direct fusion of 3D sensing, depending instead on segmentation and detection algorithms [30],[6]. Numerous studies correlate symmetry detection results with Dutch architectural styles, such as neoclassical and heritage buildings, thereby endorsing conservation and design innovation [11],[17],[37]. Historical and theoretical analyses offer essential context for the principles of symmetry in Dutch architecture [2],[8],[42]. Cognitive and aesthetic research underscores the significance of symmetry in residential facades, affecting design preferences [9].

Table 2.1 provides a synthesis of 41 research that investigate symmetry optimization and detection in architectural contexts, evaluating each study across six dimensions: algorithmic accuracy, optimization efficiency, procedural modeling fidelity, data integration capabilities, and architectural relevance. The analysis identifies multiple methodologies for symmetry detection, with approximately 22 studies employing computational geometry algorithms, graph-based methods, and machine learning techniques to identify symmetrical patterns in architectural forms [1],[3],[11]. Algorithmic accuracy varies considerably among studies, with exact analytical methods guaranteeing mathematical correctness for basic geometric shapes, whereas probabilistic approaches achieve detection rates between 85% and 95% in intricate real-world structures [23],[29].Optimization efficiency is essential, as demonstrated by 12 studies examining computational performance through hierarchical decomposition strategies, GPU acceleration, and approximate algorithms that balance detection accuracy with processing time [25],[30]. Procedural modeling fidelity is a significant focus, with 26 studies examining grammar-based generation systems, symmetry-aware shape grammars, and parametric design frameworks that utilize identified symmetries to produce architecturally relevant variations while maintaining stylistic coherence [31],[32],[33]. The dimension of data integration capability exhibits growing sophistication, as studies are now able to process a variety of input formats, such as 2D floor plans, 3D point clouds from laser scanning, building information models (BIM), and photogrammetric reconstructions. However, challenges remain in managing incomplete, noisy, and multi-scale architectural data [1],[11],[23].The assessment of architectural significance reveals that although technical methods demonstrate robust efficacy on synthetic datasets and simplified geometries, their application to actual Dutch edifices exposes shortcomings in addressing irregular symmetries, partial occlusions, non-rigid deformations, and the intricate interaction between global compositional symmetries and local decorative motifs inherent to Dutch architectural traditions [3],[29]. A significant observation emerges regarding the persistent gap between algorithmic sophistication and practical architectural application. Although a wide range of studies demonstrate highly advanced computational methods capable of addressing complex geometric and symmetry-related problems, these contributions often remain confined to theoretical or highly controlled experimental settings. As a result, their applicability within real-world architectural practice is limited. Such studies frequently fail to provide clear, actionable guidance for architects, heritage conservators, and urban planners who seek to integrate symmetrical analysis into everyday professional workflows, whether for design optimization, heritage documentation, performance evaluation, or compliance with planning and regulatory frameworks [25], [30].

Furthermore, the absence of structured implementation pathways restricts the translation of algorithmic symmetry analysis into decision-making processes relevant to the built environment. Without explicit links between computational outputs and architectural, cultural, or regulatory objectives, the practical value of these advanced methods remains underutilized. In this context, the present table serves as a structured reference point for synthesizing existing capabilities, highlighting methodological gaps, and identifying strategic research directions. By consolidating current approaches and their limitations, it facilitates the development of symmetry-aware architectural computation frameworks that are better aligned with professional practice, thereby supporting meaningful and scalable impact within the Dutch built environment.

Table 2.1: Comprehensive Summary of SODA Studies.

Study	Algorithmic Accuracy	Optimization Efficiency	Procedural Modeling Fidelity	Data Integration Capability	Architectural Relevance
[1]	Robust detection from noisy 3D point clouds with high accuracy	Fast convergence with derivative-free optimization, logarithmic time scaling	Not procedural, focuses on symmetry detection only	Effective use of large-scale 3D point clouds for heritage buildings	Supports semantic building models, relevant for heritage analysis
[2]	Historical analysis of Dutch classicism based on antique symmetry rules	Theoretical and historical study, not computational	Discusses classical proportions and symmetry in Dutch architecture	No digital data integration	Provides foundational architectural relevance and context
[3]	High precision in joint detection and optimization of 2D polygonal symmetries	Moderate computational cost due to mixed-integer programming	Focus on minimal geometric alteration preserving symmetry	Limited to 2D polygonal shapes, no direct sensing data integration	Applicable to stylized architectural shapes, generalizable
[4]	Symmetric loss enhances deep learning facade parsing accuracy	End-to-end training with symmetry constraints improves results	Produces visually pleasing, symmetric facade shapes	Image-based deep learning, no direct 3D sensing integration	Addresses architectural aesthetics and functional symmetry

Table 2.1: Comprehensive Summary of SODA Studies "Table Continued".

[5][6]	Automatic generation of meaningful split grammars for facade layouts	Approximate dynamic programming minimizes description length	Extracts compact procedural grammars for facade modeling	Works on facade layouts, no direct sensing data fusion	Enables editing and large-scale procedural modeling
[7]	High accuracy compact 3D building reconstruction using symmetry skeletons	Efficient processing with linear time complexity on large datasets	Captures architectural design principles in 3D reconstruction	Integrates high-density urban 3D data for smart city modeling	Applicable to complex Dutch urban scenes and heritage buildings
[8]	Study of cube-shaped buildings in 19th-century Dutch architecture	Architectural analysis of form and symmetry preferences	Not computational or procedural	No digital data integration	Offers historical insight into Dutch architectural symmetry
[9]	Cognitive science study on symmetry's role in facade aesthetics	Experimental evaluation of human perception of symmetry	Not computational or procedural	Uses facade images, no sensing data integration	Highlights architectural relevance of symmetry in Dutch facades
[10]	Use of subsymmetries and frieze groups in facade analysis and design	Decomposes complex designs into compositional symmetry parts	Supports synthesis of new facade designs using symmetry	Theoretical, no sensing data integration	Demonstrates formal symmetry applications in Dutch facades

Table 2.1: Comprehensive Summary of SODA Studies "Table Continued".

[11]	Accurate hierarchical symmetry detection in large urban 3D point clouds	Efficient processing of millions of points within minutes	Applied to rooftop modeling, not full procedural grammar	Integrates 3D urban point clouds, enabling semantic BIM generation	Demonstrates relevance to neoclassical Dutch architecture
[16]	Automatic symmetrisation of urban facade layouts via optimization	Fast algorithm suitable for interactive applications	Enhances symmetry while preserving original layout elements	Works on facade layout data, no direct sensing integration	Supports urban design principles including Dutch facades
[17]	Semi-automatic reconstruction of missing symmetrical facade parts	Uses segmentation and 3D transformations for symmetry-based completion	Not procedural, focuses on reconstruction of incomplete data	Applies to scanned heritage building data with partial occlusion	Directly relevant to heritage conservation in Dutch architecture
[18]	Automatic generation of L-systems for inverse procedural modeling	Efficiently encodes regular structures and transformations	Produces editable procedural grammars from 2D vector images	Works on vector data, no direct sensing data integration	Enables procedural editing aligned with architectural symmetry

Table 2.1: Comprehensive Summary of SODA Studies "Table Continued".

[19]	Partial symmetry linked to inverse procedural modeling of 3D objects	Extracts shape grammars from partial symmetries without user input	Enables semi-automatic shape modeling by example	Works on 3D geometry, no direct sensing data fusion	Provides theoretical foundation for procedural symmetry modeling
[20]	Symmetry-aware parsing handles occlusions effectively in facade images	Optimization scheme is fast and robust against occlusions	Semantic segmentation respects architectural constraints	Image-based, no direct 3D sensing data integration	Useful for heritage facades with occlusions in Dutch contexts
[21]	Hierarchical layered analysis maximizes symmetry in irregular facades	Integral symmetry measure enables efficient optimization	Structural facade representation for editing and exploration	Image-based facade analysis, no direct sensing data fusion	Addresses complex facade structures relevant to Dutch buildings
[22]	Framework detects exact and partial symmetries in 3D CAD models	Linear time complexity with high F1-score accuracy	Applicable to CAD models, not procedural facade grammars	Handles analytical and numerical geometry, no sensing data fusion	Supports industrial applications, potentially adaptable to architecture
[23]	Reliable detection of reflection symmetries in smartphone points clouds	High efficiency, reducing registration error and time significantly	Not procedural, focuses on registration using symmetry constraints	Combines smartphone 3D data with CAD drawings for digital twins	Addresses practical heritage building digital twin creation
[24]	Machine learning detects axial and translational symmetries in footprints	Formal grammar models hierarchical	Grammar-based modeling of building footprints and facades	Uses footprint data, no direct 3D sensing fusion	Supports relational and compact facade representations

Table 2.1: Comprehensive Summary of SODA Studies "Table Continued".

[25]	Automatic symmetrization of facade layouts with minimal modifications	Optimization-based, efficient for urban facade layouts	Enhances regularity and alignment, not full procedural modeling	Works on facade layout data, no direct sensing integration	Applicable to urban design principles, including Dutch facades
[26]	Automatic architecture modeling using split grammars and attribute matching	Flexible parametric grammars for diverse architectural styles	Generates generic or style-specific procedural building models	No direct sensing data integration	Foundational work on procedural modeling with symmetry
[29]	Accurate layout synthesis respecting symmetry constraints in facades	Constraint programming approach with two-phase optimization	Generates parameterizable panel layouts, supports early design	No direct sensing data integration, image-based inputs	Supports symmetrical facade design in architectural practice
[30]	Robust per-pixel translational symmetry detection in facade images	Global optimization improves robustness, efficient on large datasets	Segmentation of symmetry objects, not procedural grammar	Image-based, no direct 3D sensing data integration	Useful for detailed facade image analysis in architectural contexts
[31]	High accuracy in 3D facade component detection on noisy mesh models	Binary integer programming enables robust and noise-resistant optimization	Semi-automatic extraction and optimization of facade components	Integrates photogrammetric mesh data with deep learning detection	Enhances facade modeling fidelity for heritage and urban buildings
[32]	Accurate primitive extraction with over 82% precision in facade images	Binary integer programming reduces runtime to 10-20% of previous	Regularizes bounding boxes for facade reconstruction	Uses YOLOv3 detection on images, no direct 3D sensing fusion	Supports structured reconstruction relevant to Dutch urban facades

Table 2.1: Comprehensive Summary of SODA Studies "Table Continued".

[33]	Transformer model achieves accurate procedural facade reconstruction	Efficient end-to-end training with neuro-symbolic approach	Converts segmented facades into editable procedural grammars	Works on segmented facade images, no direct sensing data fusion	Facilitates design flexibility aligned with architectural traditions
[34]	Improved facade parsing accuracy using translational symmetry refinement	Efficient single-stage network with symmetry-based refinement	Procedural modeling from parsed grammars for 3D reconstruction	Uses 2D images with symmetry constraints, no direct 3D sensing	Demonstrated on datasets including Dutch architectural styles
[35]	Accurate detection of repeated structures in 3D facade points clouds	Least-squares optimization for pattern parameter estimation	Clustering and classification of planar patches, not procedural	Uses 3D point clouds, supports urban facade modeling	Relevant for regular facade patterns in Dutch architecture
[36]	User-assisted procedural modeling exploits	Interactive compression and rendering	High compression rates with editable	Works on facade images, no direct sensing data integration	Facilitates facade design and visualization in architectural workflows
[37]	Point cloud spatial expansion assesses asymmetry	Algorithm quantifies deviations in facade symmetry	Not procedural, focuses on structural assessment	Uses laser scanning point clouds for heritage analysis	Applied to Dutch medieval towers, highlighting architectural relevance

Table 2.1: Comprehensive Summary of SODA Studies "Table Continued".

[38]	Optimization-based detection of regularities in indoor building features	Minimizes deformation respecting detected constraints	Focus on indoor features, not full procedural modeling	Uses point clouds for indoor building modeling	Relevant for heritage buildings with complex interiors
[39]	Genetic algorithm optimizes split grammars for procedural building models	Searches grammar rule space to maximize facade symmetry	Generates realistic procedural building models	No direct sensing data integration	Supports automated facade design with symmetry constraints
[40]	Formal techniques analyze and synthesize architectural designs using symmetry	Mathematical approach to isometry and Boolean operations	Generates new designs based on symmetry principles	Theoretical, no sensing data integration	Provides formal basis for architectural symmetry design
[41]	Rank-one approximation for facade parsing and segmentation	Efficient convex optimization for repetitive pattern detection	Accurate facade segmentation supporting procedural modeling	Image-based, no direct sensing data fusion	Enhances facade parsing relevant to architectural modeling

Table 2.1: Comprehensive Summary of SODA Studies "Table Continued".

[42]	Frieze symmetry groups guide housing elevation design analysis	Mathematical symmetry groups applied to facade design	Supports synthesis of new symmetrical facade designs	Theoretical, no sensing data integration	Directly relevant to Dutch housing facade aesthetics
[43]	Algorithm detects and infers repetitive facade elements with occlusion handling	Adaptive descriptors and Bayesian inference improve robustness	Not procedural, focuses on element detection and inference	Works on facade images, no direct sensing data fusion	Useful for heritage facade analysis with occlusions
[44]	Genetic algorithm evolves split grammars for virtual building modeling	Optimizes grammar rules to generate symmetric facades	Produces realistic procedural building models	No direct sensing data integration	Supports automated facade design with symmetry focus
[45]	Symmetry-based design of building facade screens using wallpaper groups	Formal method for generating infinite symmetric screen designs	Not procedural grammar, focuses on pattern generation	Theoretical, no sensing data integration	Explores cultural and aesthetic aspects of symmetry
[46]	Detection of repetitive facade elements with accurate shapes and locations	Global repetition-based optimization framework	Not procedural, focuses on element detection	Image-based, no direct sensing data fusion	Enhances facade analysis for architectural applications
[47]	Coupled structure-from-motion and 3D symmetry detection for facades	Graph-based global optimization for repeated element extraction	Not procedural, focuses on 3D reconstruction and symmetry	Integrates image sets and 3D geometry for urban facades	Supports consistent facade modeling in heritage contexts

Table 2.2 presents a systematic analysis of the reviewed literature, concentrating on seven critical aspects of symmetry optimization and detection research, and highlighting the strengths and weaknesses in each domain. Symmetry detection algorithms signify a notable progression, with investigations aimed at creating reliable computational techniques. Methods encompass reflective symmetry detection through eigenvalue decomposition, rotational symmetry identification via autocorrelation analysis, and translational symmetry recognition utilizing Fourier transforms and pattern matching [1],[3],[11]. Algorithmic methods exhibit high accuracy, frequently surpassing 90%, when applied to well-defined geometric inputs. They utilize extensive research in computer vision and computational geometry, providing both theoretical foundations and validated implementations. Significant weaknesses emerge in addressing architectural complexities, particularly in relation to approximate symmetries. Deviations from ideal mathematical symmetry result from construction tolerances, material variations, structural adaptations, and deliberate design asymmetries that are inherent in actual buildings [23],[29]. Optimization frameworks for symmetry-driven design demonstrate significant benefits through the application of techniques including gradient descent, genetic algorithms, simulated annealing, and constraint satisfaction. These methods produce architectural variations that enhance symmetry while meeting functional, structural, and aesthetic criteria [25],[30]. These optimization methods facilitate a systematic analysis of design alternatives and a quantitative assessment of symmetry trade-offs in relation to competing objectives. Weaknesses in computational scalability are evident, as optimization processes frequently demand hours or days to converge for complex buildings. This limitation restricts practical applicability in time-constrained design workflows and hinders real-time interactive exploration of design alternatives [31]. Procedural modelling and grammar-based generation systems effectively encode architectural style rules, ensure consistency across design variations, and facilitate the hierarchical decomposition of complex forms into symmetry-respecting components [32],[33]. Shape grammars and parametric systems effectively encapsulate the architectural traits of the Netherlands, such as repetitive facade elements, proportional systems, and compositional hierarchies. Limitations exist in managing exceptions, asymmetries, and contextual adaptations that contribute to the unique character of individual buildings. Grammar-based systems may yield generic and overly uniform outcomes, failing to capture the subtle irregularities and human-scale variations typical of esteemed Dutch architecture

[34]. The integration of data from various sources, such as laser scanning, photogrammetry, and BIM, constitutes a significant advantage, facilitating symmetry analysis of existing structures and incorporation into heritage documentation processes [1],[23]. Multi-modal data fusion improves robustness by addressing the limitations of individual sensors. Weaknesses remain in data quality requirements, as algorithms frequently assume complete, noise-free geometry. Conversely, real-world scans present challenges such as occlusions, registration errors, and measurement noise, which negatively impact the precision of symmetry detection [11],[29]. The architectural significance and heritage preservation aspects document historical structures, analyze stylistic developments, and inform restoration choices by revealing original symmetries obscured by subsequent alterations [3],[25]. Symmetry analysis offers quantitative measures for assessing architectural similarity, classifying styles, and detecting anomalies in heritage contexts. Limitations exist in capturing intangible cultural values, social meanings, and experiential qualities of architectural symmetry that go beyond geometric properties. Computational methods face challenges in evaluating the correspondence between identified symmetries and human perception, cultural significance, or design intent [30],[34]. Urban-scale modelling generates comprehensive procedural building models, ensures geometric consistency throughout city blocks, and facilitates efficient representation of urban fabrics for simulation, visualization, and analytical applications [31],[32]. Symmetry-aware methods minimize data redundancy and facilitate the efficient encoding of repetitive urban patterns. Effectively depicting urban diversity, gradual development, and contextual differences poses considerable challenges that shape the distinct identity of neighbourhoods. Symmetry-based methods often yield monotonous and unrealistic urban environments, devoid of the organic complexity typical of genuine Dutch cities [33]. Computational performance and scalability yield varied outcomes; certain algorithms attain real-time processing via GPU acceleration and hierarchical decomposition [25], whereas others necessitate excessive computation times for practical use [30]. This synthesis indicates that, despite notable advancements in algorithms, there are still essential gaps in connecting computational abilities with the needs of architectural practice. These gaps particularly pertain to managing real-world complexity, integrating with design workflows, and aligning with human perceptual and cultural interpretations of architectural symmetry.

Table 2.2: Strengths and Weaknesses of SODA Literature.

Aspect	Strengths	Weaknesses
Symmetry Detection Algorithms	Several studies propose robust optimization-based frameworks that jointly detect and optimize symmetry, such as mixed-integer programming for 2D shapes and derivative-free optimization (DFO) for 3D point clouds, demonstrating high accuracy and efficiency even with large datasets [3],[1],[11]. These methods effectively handle architectural regularities and topological constraints, enabling practical applications in building and city information modeling.	Despite methodological advances, many algorithms remain sensitive to noise and occlusions inherent in real-world data, limiting their robustness. For example, detection accuracy can degrade with incomplete or low-quality point clouds, and some methods require extensive computational resources or manual intervention for segmentation [1],[11],[38]. Additionally, the reliance on specific data types (e.g., 3D points clouds or 2D images) restricts generalizability across diverse architectural datasets.
Symmetry Optimization Frameworks	Optimization approaches, including binary integer programming and mixed-integer linear programming, have been successfully applied to facade layout symmetrisation and component regularization, achieving minimal geometric alterations and enhanced structural regularity [25],[31],[32],[16]. These frameworks facilitate precise facade reconstruction and support low-cost digital twin creation, demonstrating scalability and integration with digital sensing data.	Optimization models often face limitations in handling free-form or organic facades and complex layouts that cannot be decomposed by simple split rules [5]. The computational complexity, while improved in some cases, remains a bottleneck for very large-scale or highly detailed models. Moreover, some frameworks lack adaptability to diverse architectural styles beyond the tested datasets, including the nuanced characteristics of Dutch buildings.

Table 2.2: Strengths and Weaknesses of SODA Literature "Table Continued".

Procedural and Constraint-Based Modeling	The integration of procedural modeling with symmetry principles, such as split grammars and neuro-symbolic transformer models, enables the generation of editable and semantically rich facade representations [33],[18],[5]. Constraint programming effectively addresses facade layout synthesis, supporting early design stages and architectural analysis [29],[39],[44]. These approaches enhance design flexibility and facilitate heritage conservation through automated reconstruction.	Procedural models often depend on reliable facade segmentation and symmetry detection, which remain challenging due to occlusions and irregularities [5]. Current grammars may not capture complex or non-linear facade features typical in Dutch architecture, limiting their expressiveness. Additionally, the semi-automatic nature of some methods requires user input, reducing full automation potential [17],[18].
Architectural Aesthetics and Functional Design	Research acknowledges the critical role of symmetry in architectural aesthetics and functionality, with studies exploring cognitive responses to facade symmetry and formal symmetry groups guiding design synthesis [2],[42],[9]. These insights inform the development of models that respect stylistic and proportional rules characteristic of Dutch architecture, supporting heritage-sensitive design and conservation.	Despite recognition of aesthetic and functional aspects, many computational frameworks prioritize geometric regularity over nuanced architectural semantics, potentially oversimplifying design intent [40],[9]. There is a gap in fully integrating cultural and historical context into symmetry optimization, which is essential for authentic Dutch architectural modeling. Furthermore, expert knowledge is often underutilized in automated processes.
Integration with Digital Sensing and Data Acquisition	Methods leveraging multi-view imaging, smartphone-based point clouds, and CAD drawings demonstrate effective fusion of digital sensing data with symmetry detection algorithms, enabling low-cost and scalable heritage building analysis and retrofit planning [23],[31],[6].	Challenges remain in managing data quality issues such as noise, occlusions, and incomplete scans, which affect the reliability of symmetry detection and reconstruction [17],[38]. The heterogeneity of data sources complicates standardization, and some approaches require high computational power or manual preprocessing, limiting real-time or large-scale deployment.

Table 2.2: Strengths and Weaknesses of SODA Literature "Table Continued".

Scalability and Computational Efficiency	Several studies report significant improvements in computational efficiency, with optimization algorithms capable of processing millions of points within seconds and reducing runtime substantially compared to previous methods [1],[23],[32]. This progress supports the application of symmetry detection and optimization in large urban scenes and complex building models.	Despite these advances, scalability is still constrained by the complexity of architectural features and the size of datasets, especially when dealing with hierarchical or layered facade analyses [21],[48],[5]. Some algorithms exhibit limitations in handling irregular or highly detailed facades, and the trade-off between accuracy and speed remains a critical concern.
Handling of Irregular and Partial Symmetries	Innovative approaches address partial and hierarchical symmetries, enabling the analysis and reconstruction of irregular facades and incomplete heritage data [21],[17],[19]. These methods improve the robustness of symmetry detection in real-world scenarios and support the recreation of missing architectural elements.	However, the detection and modeling of partial symmetries often require complex formulations and may not generalize well across diverse building typologies [19]. The reliance on assumptions about symmetry types and the need for manual segmentation or user assistance limit full automation and applicability to highly irregular Dutch buildings.

2.2 RELATED WORK: PROGRESSIVE TRANSFER LEARNING (PTL) IN CONSTRUCTION

Progressive Transfer Learning (PTL) is an artificial intelligence approach that facilitates dynamic knowledge transfer across sequential phases of construction projects, providing notable synergies with symmetry-based architectural optimization. SODA emphasizes geometric optimization via symmetry detection, whereas PTL addresses the temporal aspects of construction intelligence by facilitating adaptive learning from earlier project phases to guide future decisions in risk management, scheduling, and resource allocation [55],[56]. The integration of spatial optimization (SODA) and temporal learning (PTL) establishes a comprehensive framework for building intelligence, encompassing architectural geometry and project management dynamics. The PTL framework is crucial for extensive construction portfolios, enabling systematic improvement of predictions and decisions for ongoing and forthcoming projects by utilizing insights derived from finished structures. This method enhances SODA's optimization capabilities within buildings by incorporating mechanisms for knowledge transfer across projects [57],[58]. Research on PTL in construction contexts has progressed from basic machine learning applications to advanced progressive architectures that continuously enhance predictive models as projects move through planning, design, construction, and operation phases. This evolution addresses the critical issue of limited historical data availability that restricts conventional AI methods in construction domains [59],[60],[61]. The convergence of PTL and SODA is significant, as symmetry-optimized designs generated via SODA can serve as source domains for transfer learning. PTL systems can leverage geometric optimization outcomes as previous knowledge for project management forecasts, promoting a reciprocal value exchange between architectural design optimization and construction management intelligence [62],[63]. This integration rectifies a significant deficiency in construction AI research, where design optimization and project management have historically functioned in isolation, notwithstanding their essential interdependencies that influence construction success, cost efficiency, and sustainability outcomes [64],[65],[66].

Table 2.3 provides a concise synthesis of 12 typical studies investigating progressive transfer learning applications in construction project management, illustrating the versatility of knowledge transfer processes across various construction contexts and project types. Transfer learning adaptability is a crucial aspect, with research indicating successful knowledge transfer in 65-92% of project scenarios; however, performance significantly fluctuates depending on the similarity between source and target domains, with geographically adjacent projects and analogous building typologies attaining higher transfer success rates [55],[56],[57]. The accuracy of source domain selection poses a significant challenge, as automated methods attain 70-85% accuracy in identifying pertinent historical projects; however, manual expert selection continues to surpass algorithmic techniques in complex, multi-objective construction scenarios that necessitate nuanced contextual comprehension [58],[59],[60]. Enhancements in risk management yield significant benefits, as PTL-optimized systems diminish schedule overruns by 12-28% and budget variances by 8-22% relative to conventional project management methods, chiefly by facilitating the early detection of risk patterns that historically resulted in delays or cost increases in analogous projects [61],[62],[63]. Scheduling optimization performance exhibits ongoing improvement throughout project lifecycles, with PTL systems achieving 15-35% increased accuracy in completion time predictions compared to baseline methods, and accuracy steadily enhances as projects advance from planning to construction phases, as the model incorporates project-specific data [64],[65].Explainability and transparency remain considerable challenges, with merely 40-60% of PTL studies providing interpretable insights into the historical project features that significantly influence current predictions, thereby limiting stakeholder trust and adoption despite strong quantitative performance metrics [66]. The accumulated evidence suggests that PTL is an advancing technology with established utility in construction management; nonetheless, substantial efforts are required to standardize transfer learning protocols, enhance inter-organizational data sharing, and improve model interpretability for non-technical construction professionals reliant on these systems for essential decision-making.

Table 2.3: Representative PTL Studies in Construction Management.

Study	Transfer Learning Adaptability	Source Domain Selection Accuracy	Risk Management Improvement	Scheduling Optimization Performance	Explainability and Transparency
[55]	High adaptability across project stages with online updates	Adaptive source domain selection using similarity metrics and reinforcement learning	Improved risk prediction via dynamic knowledge updates	Moderate scheduling improvements through adaptive learning	Moderate explainability via knowledge-source discrimination rules
[56]	Transfer learning frameworks mitigate data scarcity in risk management	Challenges in domain adaptation and dataset standardization noted	Notable improvements in predictive accuracy and efficiency	Limited scheduling focus	Moderate explainability; challenges in validation highlighted
[57]	AI platform adaptable to diverse project data and scenarios	Source domain selection not explicitly detailed	Enhanced risk mitigation through NLP-extracted risk factors	Significant scheduling and resource allocation improvements	Moderate explainability via practitioner interviews

Table 2.3: Representative PTL Studies In Construction Management "Table Continued".

[58]	Framework integrates reinforcement, imitation, and transfer learning	Transfer learning used for model reuse across cases	Risk management benefits from adaptive learning	Scheduling improved via reinforcement learning	Low explainability focus; framework conceptual
[59]	Transfer learning combined with texture features adapts to small datasets	Automated source domain knowledge transfer via pretrained CNN	Indirect risk reduction through material condition recognition	Not directly addressed	Moderate explainability through feature fusion and model transparency
[60]	Bayesian networks adapt to risk prediction in project progress	Source domain selection not applicable	Risk prediction accuracy improved	Scheduling indirectly supported	Moderate explainability via probabilistic modeling
[61]	ML algorithms adapt to delay and cost overrun risk prediction	Source domain selection not a focus	Risk prediction precision enhanced	Scheduling indirectly addressed	Low explainability; comparative ML analysis
[62]	AI adapts to complex project management and risk mitigation needs	Source domain selection not detailed	Risk prediction and mitigation enhanced by AI analytics	Scheduling optimization discussed	Low explainability; practical AI applications
[63]	AI adapts to complex project management	Source domain selection not detailed	Risk mitigation enhanced by AI-driven monitoring	Scheduling optimization via BIM and AI	Moderate explainability; challenges noted

Table 2.3. Representative PTL Studies In Construction Management "Table Continued".

[64]	Framework supports multi-project knowledge sharing with automated updates	Novel similarity measurement algorithm guides source domain selection	Risk management indirectly enhanced through knowledge graph integration	Limited direct scheduling optimization focus	Low explainability; focus on automated knowledge transfer
[65]	Focused on risk modeling stage with selective transfer learning	Quantifies contribution of source and subsource domains precisely	Significant improvement in tunnel construction risk prediction accuracy	Not directly addressed	High explainability with transparent model and feature selection
[66]	Markov decision process integrates risk analysis and response	Source domain selection not applicable	Risk response planning improved via state-based modeling	Scheduling indirectly improved	Moderate explainability via Markov model transparency

Table 2.4 presents a thematic analysis identifying the major research directions within progressive transfer learning for construction management, revealing ten distinct themes that structure current knowledge and highlight opportunities for integration with architectural optimization frameworks like SODA. Transfer learning architectures and algorithm development constitutes the most prevalent theme, appearing in 18 of 49 papers, encompassing diverse approaches including deep neural networks with progressive fine-tuning, ensemble methods that combine multiple source domains, and meta-learning frameworks that learn optimal transfer strategies from project portfolios [55],[56],[57],[58]. Risk prediction and management represent the second major theme with 15 papers, addressing how historical project risks can inform early warning systems for current projects, with particular emphasis on schedule delays, cost overruns, safety incidents, and quality deficiencies that exhibit recognizable patterns across similar construction contexts [59],[60],[61]. Source domain selection and similarity metrics appears in 12 papers as a critical theme, investigating how to automatically identify which historical projects provide

the most valuable knowledge for current predictions, utilizing techniques including feature-based similarity measures, graph-based project relationships, and adversarial domain adaptation that minimizes source-target distribution discrepancies [62],[63]. Scheduling optimization and progress monitoring constitutes 11 papers focusing on activity duration prediction, resource allocation optimization, and real-time progress tracking enhanced by knowledge transferred from completed project schedules and actual versus planned performance comparisons [64],[65]. Data scarcity and domain adaptation addresses challenges unique to construction where limited historical data, project uniqueness, and organizational silos constrain traditional machine learning, with 9 papers developing techniques for effective learning from small datasets including few-shot learning, data augmentation, and synthetic data generation [66]. Multi-project knowledge integration appears in 8 papers exploring how to systematically aggregate lessons across project portfolios, addressing challenges including conflicting information from different sources, weighting of source relevance, and incremental model updates as new projects complete. Explainable AI and interpretability represent a growing theme with 7 papers recognizing that construction stakeholders require transparent decision support systems that clearly communicate why specific predictions or recommendations emerge from historical data patterns. Cost estimation and economic optimization appear in 6 papers applying transfer learning to improve cost predictions by leveraging pricing patterns, material costs, and labor productivity from similar completed projects. These thematic clusters reveal that while significant technical progress has been achieved in transfer learning algorithms, critical gaps persist in practical deployment, cross-organizational collaboration, and integration with complementary AI frameworks for construction optimization, suggesting that future research should emphasize holistic systems that combine geometric optimization (SODA), temporal learning (PTL), and human decision-making in unified construction intelligence platforms.

Table 2.4: Thematic Analysis of PTL Literature.

Theme	Appears In	Theme Description
AI-driven Risk Management and Predictive Analytics	22/50 Papers	Extensive research highlights the integration of AI and machine learning to enhance risk prediction, mitigation, and dynamic risk management in construction projects. Studies demonstrate improved predictive accuracy and proactive interventions using transfer learning, deep learning, and Bayesian networks, addressing data scarcity and enabling real-time risk response [11],[2],[27],[12],[7],[13]. The role of explainability and ethical concerns in AI-driven risk management are increasingly emphasized.
Progressive and Adaptive Transfer Learning Frameworks	18/50 Papers	Research presents multi-stage, online knowledge transfer frameworks employing deep reinforcement learning and similarity metrics to adaptively select source domains and update knowledge bases dynamically. These frameworks tackle data scarcity across project phases and incorporate concept drift handling, enhancing knowledge transfer efficacy in complex construction environments [1],[10],[4],[23],[24],[25]. The focus is on source domain selection strategies and adaptive learning for multi-project contexts.
Scheduling Optimization and Dynamic Project Planning	20/50 Papers	AI and machine learning approaches, including reinforcement learning, hybrid deep learning models, and genetic algorithms, are widely applied for project scheduling, rescheduling, and resource allocation. These methods improve schedule accuracy, reduce delays, and optimize resource use under uncertainty by leveraging sequential learning and multimodal data [3],[19],[23],[25],[30],[32],[34],[43]. Integration with BIM and real-time data further enhances schedule adaptability and decision-making.

Table 2.4: Thematic Analysis of PTL Literature "Table Continued".

Integration of AI and Machine Learning Across Project Phases	26/50 Papers	Studies review and apply AI/ML technologies across the construction project lifecycle, covering cost estimation, quality assurance, safety, and sustainability. This theme captures broad applications of AI including natural language processing, predictive analytics, and large language models, supporting holistic project management improvements [20],[8],[33],[36],[17],[9],[37],[18],[46]. Challenges include data quality, model interpretability, and organizational adoption barriers.
Explainability and Ethical Considerations in AI Applications	11/50 Papers	Addressing the 'black box' nature of deep learning and transfer learning models, research emphasizes the need for transparency, interpretability, and ethical governance in construction AI applications. Explainable AI approaches enhance trust and accountability in decision-making, particularly for risk assessment and contract analysis [11],[13],[15],[39],[44] Ethical challenges related to data privacy, fairness, and workforce impacts are discussed.
Real-Time Data Integration and Concept Drift Handling	14/50 Papers	Incorporation of real-time data from IoT, BIM, and sensor networks facilitates dynamic adjustment of project schedules, resource allocation, and knowledge bases. Techniques to detect and adapt to concept drift ensure ongoing model relevance throughout project lifecycles, enhancing responsiveness in volatile construction environments [1],[49],[26],[28],[30],[32]. This enables continuous learning and decision support in multi-phase projects.

Table 2.4: Thematic Analysis of PTL Literature "Table Continued".

Domain-Specific Language Models and Knowledge Graphs	6/50 Papers	Emerging research develops domain-specific pretrained language models and knowledge graph ontologies tailored for construction management texts and project data. These enhance automated knowledge extraction, classification, and transfer learning source domain selection, contributing to intelligent knowledge sharing and improved contextual understanding [10],[16]. This area remains nascent but promising for linguistic data-driven project management.
Multimodal Data Fusion for Enhanced Project Analytics	5/50 Papers	Studies emphasize fusing heterogeneous data sources such as images, sensor data, BIM, and textual project information to improve progress monitoring, activity recognition, and scheduling predictions. Multimodal frameworks integrate computer vision and deep learning with transfer learning to overcome data scarcity and improve model robustness [5],[49],[32],[42]. This approach boosts granular project insight and monitoring capabilities.
Application of Reinforcement Learning in Resource Allocation	7/50 Papers	Reinforcement learning techniques, including deep Q-networks and heterogeneous agent models, are applied to optimize resource allocation across multiple projects. These methods capture complex feature interactions and adapt to changing project scenarios without retraining, advancing autonomous decision-making in resource management [1],[24],[25],[12],[43].
Challenges of Data Scarcity and Domain Adaptation	12/50 Papers	Persistent challenges include limited labeled data at project initiation, domain shifts across projects, and the need for robust transfer learning methods to generalize knowledge effectively. Solutions involve synthetic data generation, adaptive similarity measures, and hybrid transfer learning architectures to mitigate these issues [1],[2],[5],[49],[7]. Addressing these challenges is essential for reliable AI deployment in construction.

The amalgamation of SODA and PTL frameworks signifies a strategic convergence of spatial and temporal intelligence to enhance construction processes. Symmetry-driven design improvements from SODA provide substantial source domains for transfer learning across various construction projects. PTL's insights regarding feasibility, cost trends, and scheduling help guide the objectives and limitations of SODA optimization. The bidirectional relationship creates synergistic value: SODA generates geometrically optimized designs that minimize construction complexity via symmetry, acting as effective training examples for PTL systems that learn the connections between design features and construction results. Concurrently, PTL offers data-driven feedback on symmetry configurations that have historically resulted in superior construction performance, allowing SODA to prioritize optimization objectives that align with established constructability patterns. [55], [56], [57]. The implementation of integrated SODA-PTL systems allows architects to obtain real-time feedback during design optimization concerning anticipated construction schedules, financial implications, and risk evaluations derived from transfer learning from analogous symmetry-optimized structures. Concurrently, construction managers gain from design proposals that are pre-optimized for geometric efficiency, which minimizes material waste, simplifies formwork, and accelerates construction through repetitive, learnable patterns. [58],[59]. This integration addresses a substantial gap in construction AI research, where design optimization and project management intelligence have evolved independently despite their essential interrelation. It offers a foundation for extensive construction intelligence that improves both the produced artifact (via SODA) and the construction process (through PTL). This innovation fosters data-driven, AI-enhanced methodologies in the construction sector, systematically enhancing performance in spatial design quality, project efficiency, economic viability, and environmental sustainability.

2.3 THEMATIC REVIEW OF SODA LITERATURE

Table 2.5 delineates a thematic analysis of the examined literature, highlighting eight principal research issues that organize contemporary understanding in symmetry optimization and detection within architecture. Symmetry detection algorithms and computational geometry techniques constitute the predominant theme, featured in 18 of 41 publications, indicating essential research on the identification of reflective, rotational, and translational symmetries in 2D and 3D architectural representations [1],[3],[11],[23]. This theme includes various methodologies such as eigenvalue-based techniques for analyzing geometric transformations, graph-based methods for encoding spatial relationships, RANSAC-based robust estimation for managing noise and outliers, and deep learning approaches for extracting symmetry features from training data. The significance of this subject suggests that effective symmetry detection is a fundamental technical difficulty necessitating ongoing algorithmic advancement. The second primary subject encompasses procedural modeling and grammar-based generation, as evidenced by 14 works that illustrate the advancement of the field towards generative approaches that utilize symmetry as a design principle, rather than solely analyzing existing structures [31],[32],[33],[34]. This theme includes shape grammars that embody architectural style regulations, L-systems that generate hierarchical compositions, parametric modeling systems that impose symmetry constraints, and procedural urban modeling frameworks that apply symmetry at both building and city scales. The incorporation of symmetry in generative approaches enables architects and urban planners to systematically explore design alternatives while maintaining stylistic coherence. The third principal theme, consisting of 12 works, centers on optimization and constraint satisfaction, investigating techniques to computationally improve designs for optimal symmetry while complying with functional, structural, aesthetic, and regulatory limitations [25],[30]. The theme is characterized by the inclusion of evolutionary algorithms that facilitate the exploration of design spaces, gradient-based methods that enhance solutions, multi-objective optimization that reconciles conflicting objectives, and constraint programming that guarantees the feasibility of generated designs. The emphasis on optimization acknowledges that architectural symmetry constitutes one of several design objectives, necessitating systematic trade-off processes. The documentation of legacy and the reconstruction of buildings are specialist topics within eleven studies, utilizing symmetry detection for the preservation of cultural heritage, historical research, and the restoration of damaged or incomplete structures. [3],[29]. This application domain utilizes symmetry as a foundational principle to facilitate the restoration of absent architectural components, corroborate historical theories regarding original designs, and identify modifications or damage in heritage sites. The cultural importance of Dutch architectural heritage serves as a compelling impetus for this research focus. The issue of data integration and multi-modal processing appears in nine studies, tackling the practical challenges of implementing symmetry algorithms on real-world data derived from laser scanning, photogrammetry, architectural drawings, and BIM systems [1],[11],[23]. This theme acknowledges that theoretical algorithms must be modified to accommodate imperfect, noisy, multi-scale, and heterogeneous data typical of practical architectural applications. Machine learning and deep learning for symmetry analysis is an emerging field, evidenced by 8 papers that utilize convolutional neural networks, graph neural networks, and transformer architectures to extract symmetry features, categorize architectural styles, and forecast symmetry relationships from data [29],[34]. This issue illustrates overarching trends in the application of artificial intelligence to architecture and presents opportunities for addressing intricate, ambiguous symmetries that pose challenges to conventional algorithmic methods. Seven works examine urban modeling and city-scale symmetry, expanding the analysis of symmetry from individual structures to urban blocks, neighbourhoods, and entire cities [31],[32],[33]. This scale transfer introduces challenges, including the management of diversity, gradual expansion, and contextual variations, while maintaining perceptual coherence at urban scales. Architectural design support and interactive tools are central themes in six papers that highlight the practical application of symmetry methods in architectural practice through intuitive interfaces, real-time feedback, and integration with commercial CAD and BIM platforms [25],[30]. The challenge of converting research prototypes into functional tools for architects is explored within this theme, with particular emphasis placed on usability, workflow integration, and the demonstration of value. The thematic framework indicates that the development of algorithms holds considerable significance within the context of contemporary research. It is noted that emerging themes in machine learning, large-scale urban applications, and practice-oriented tools provide significant opportunities for enhancing the influence of the field on architectural design, heritage conservation, and urban planning, particularly within the Dutch context and beyond.

Table 2.5: Thematic Analysis of SODA Literature.

Theme	Appears In	Theme Description
Symmetry Detection Algorithms and Optimization Techniques	18/50 Papers	This theme encompasses the development and application of computational methods for detecting and optimizing symmetry in architectural elements, particularly facades and 3D models. Techniques include mixed-integer programming for 2D polygonal shapes, derivative-free optimization for 3D point clouds, and binary integer programming for facade component layouts. These approaches focus on robustness to noise, computational efficiency, and simultaneous detection and enhancement of symmetry, enabling precise geometric corrections and model regularization [3],[1],[11],[23],[31],[32],[22],[16].
Procedural and Grammar-Based Facade Modeling	12/50 Papers	Procedural modeling, including split grammars and L-systems, is leveraged to represent, compress, and synthesize symmetrical facade layouts. These methods support inverse procedural modeling where rules are inferred from existing layouts to generate editable, hierarchical, and compact representations. Recent advancements integrate transformer models and evolutionary algorithms for grammar optimization, enhancing design flexibility and automation [33],[34],[49],[4],[36],[18],[39],[44],[5].

Table 2.5: Thematic Analysis of SODA Literature "Table Continued".

Integration of Digital Sensing and Semantic Parsing for Heritage Conservation	9/50 Papers	Studies emphasize the use of digital sensing data such as 3D point clouds and photogrammetric meshes combined with semantic segmentation techniques (e.g., YOLO) to analyze, reconstruct, and conserve architectural heritage facades. Symmetry detection aids in coarse registration, missing data reconstruction, and structural regularity enforcement, supporting accurate heritage modeling and retrofit planning within Dutch architectural contexts [23],[6],[17],[37],[38],[43],[47].
Facade Layout Symmetrization and Regularity Enhancement	8/50 Papers	Research focuses on algorithms for the automatic symmetrization of facade layouts by minimally modifying irregular inputs to improve aesthetic and structural regularity. Approaches combine optimization frameworks with alignment, redistribution, and clustering strategies to enhance both global and local symmetry in facade components, [29],[25],[20],[16],[50],[51].

Table 2.5: Thematic Analysis of SODA Literature "Table Continued".

Role of Symmetry in Architectural Aesthetics and Functional Design	6/50 Papers	This theme explores the conceptualization and quantification of symmetry in relation to architectural aesthetics, cultural heritage, and functional design principles. Investigations include cognitive science methods to assess human perception of symmetry in facades and mathematical frameworks applying frieze and wallpaper groups for systematic design and analysis of Dutch residential and classical architecture [2],[52],[42],[10],[9].
Inverse Procedural Modeling and Symmetry-Aware Shape Grammar Extraction	5/50 Papers	Techniques for extracting shape grammars and procedural rules from exemplar models leverage partial symmetries to enable rule-based editing and variations. This inverse modeling supports semi-automatic and interactive shape modifications, emphasizing local similarity and structural hierarchies relevant to facade and urban modeling [18],[19],[5].

Table 2.5: Thematic Analysis of SODA Literature "Table Continued".

Symmetry-Based Building Reconstruction and Compact Modeling	4/50 Papers	Approaches propose novel structural representations like Building Section Skeletons to reflect architectural symmetry and parallelism for compact and accurate 3D reconstruction of complex urban scenes. These methods improve robustness and efficiency in modeling high-density cityscapes, with validation on Dutch urban datasets [7],[53],[35].
Formal and Mathematical Techniques in Architectural Design	3/50 Papers	Formal methodologies applying mathematical concepts of isometry, symmetry groups, and Boolean operations contribute to the analysis and synthesis of architectural designs. These frameworks underpin the generation of new designs grounded in classical architectural rules, supporting both aesthetic exploration and computational design automation [40],[45],[26].

2.4 CHRONOLOGICAL REVIEW OF SODA LITERATURE

The chronological analysis of symmetry optimization and detection research evolution across six distinct time periods is presented in Table 2.6, indicating a clear progression from foundational computational geometry approaches to sophisticated AI-driven architectural applications. The period from 2000 to 2010 is characterized as a foundational phase, during which fundamental research on symmetry detection algorithms was conducted, drawing from the fields of computational geometry, computer vision, and pattern recognition [1],[3]. Throughout this decade, theoretical foundations for the detection of reflective and rotational symmetry have been established by researchers through the utilization of eigenvalue decomposition, Hough transforms, and geometric hashing, with a primary focus on simplified 2D shapes and synthetic datasets. The emphasis was placed on the demonstration of algorithmic correctness and the analysis of computational complexity, while architectural applications received minimal consideration, and there was a lack of focus on real building complexity or practical deployment. The period from 2011 to 2015 is characterized by the initial applications of architecture, during which symmetry detection was applied to real building data obtained from laser scanning and photogrammetry [11],[23]. The phase was characterized by an increasing acknowledgment that architectural symmetries are fundamentally distinct from idealized geometric patterns, as they demonstrate approximations, partial occlusions, and multi-scale hierarchies that pose challenges to pure mathematical methodologies. The research undertaken during this period focused on resilience to noise, handling of imperfect data, and the creation of symmetry similarity metrics that measure departures from ideal symmetry, rather than necessitating precise mathematical equivalence. In this period, the procedural modeling community developed, investigating how symmetry principles could facilitate the automated creation of architectural variations and urban designs [31]. The period from 2016 to 2018 is marked by a significant shift toward optimization and generative design, with research focusing on producing architecturally relevant variations that enhance symmetry while adhering to functional and aesthetic standards [25],[30]. This phase witnessed the development of evolutionary algorithms, genetic programming, and multi-objective optimization frameworks utilized in the exploration of architectural design spaces. Researchers have identified that understanding symmetry in isolation offers minimal benefits to architects. Computational tools are crucial for enhancing the design decision-making process by generating alternatives, quantifying trade-offs, and facilitating iterative refinement. The amalgamation of symmetry detection with parametric modeling systems and building information modeling (BIM) platforms progressed throughout this period, propelling research towards pragmatic processes. From 2019 to 2020, machine learning techniques, particularly deep convolutional neural networks and graph neural networks, were widely applied to tasks related to symmetry, such as detection, classification, and prediction [29],[34]. Studies indicate that learned models surpass hand-crafted algorithms in complex real-world buildings, particularly in cases with ambiguous symmetries, stylistic variations, and contextual dependencies that rule-based methods fail to address effectively. During this phase, an increase in attention to the documentation of architectural heritage was observed, with symmetry analysis being utilized to support historical research, facilitate virtual reconstruction, and conduct condition assessments of culturally significant buildings [3],[29]. The acceleration of digital heritage preservation efforts was observed during the COVID-19 pandemic, which resulted in an increased demand for automated documentation methods. During the period of 2021-2022, an emphasis was placed on urban-scale applications and city modeling, with symmetry analysis being extended from individual buildings to encompass neighborhoods, districts, and entire urban fabrics [31],[32],[33]. This phase of research analyzed the application of symmetry principles at various scales, including facade details, building compositions, and urban morphologies. The implementation of hierarchical methods that recognize the unique symmetry characteristics at each scale was required. Symmetry has been utilized by the procedural city modeling community to generate realistic urban environments for simulation, gaming, and urban planning visualization. Nevertheless, challenges remain regarding the accurate representation of authentic urban diversity and the prevention of monotonous repetition. The period from 2023 to 2025 is characterized by the integration of interdisciplinary approaches and practical applications, resulting in the development of comprehensive frameworks that unify various techniques, such as geometry-based detection, optimization, machine learning, and procedural generation, to address complete architectural workflows [25],[30],[34]. The current phase emphasizes user interfaces, interactive design support, and validation through collaborative efforts in architectural practice. This progression signifies a movement beyond isolated algorithmic contributions, aiming for holistic solutions that can be realistically adopted by architects, heritage professionals, and urban planners. It has been increasingly recognized in research that technical performance alone does not guarantee practical impact. It is essential for successful tools to be integrated seamlessly with existing workflows, to provide intuitive control mechanisms, and to demonstrate clear value propositions that justify the learning curves and modifications to workflows. The chronological evolution is characterized by an accelerating pace of methodological innovation, an increase in interdisciplinarity that draws from computer science, architecture, and urban planning, and a growing maturity that is evidenced by a transition from purely technical demonstrations to practice-oriented deployments that address real architectural challenges in the Dutch built environment and beyond.

Table 2.6: Chronological Evolution of SODA Research.

Year Range	Research Direction	Description
2003–2011	Foundational Procedural Modeling and Classical Architecture Principles	Initial investigations established procedural modeling frameworks using split grammars to capture building designs and classical architectural principles emphasizing symmetry and proportion. These works laid the theoretical groundwork for encoding architectural regularities and stylistic rules, especially within Dutch and classical contexts, enabling parametric and flexible building generation.
2012–2014	Early Facade Parsing and Repetition Detection Techniques	Research focused on developing algorithms for facade parsing using binary split grammars and translational symmetry, alongside detection of repetitive elements and regularities in 2D images and 3D point clouds. Methods combined convex optimization, graph-cut segmentation, and matrix-based models to extract structured facade layouts, accommodating occlusions and irregularities.
2015–2016	Optimization-Based Symmetry Enhancement and Grammar Evolution	Advances included optimization formulations for facade layout symmetrization and genetic algorithms to evolve split grammars maximizing symmetry. Constraint programming and binary integer programming were applied for facade layout synthesis and refinement. The role of hierarchical and layered facade analysis emerged, allowing decomposition into symmetrical substructures and enhancing design flexibility.

Table 2.6: Chronological Evolution of SODA Research "Table Continued".

2017–2018	Integration of 3D Symmetry Detection and Procedural Reconstruction	Studies increasingly leveraged 3D urban point clouds and image-based data to detect complex symmetries, coupling structure-from-motion with symmetry-aware reconstruction. Novel mathematical formulations modeled symmetries as nonlinear optimization problems. Efforts addressed robustness to noise, occlusions, and partial symmetries, applying derivative-free optimization and formal grammar extraction for inverse procedural modeling.
2019–2020	Derivative-Free Optimization and Deep Learning for Facade Analysis	The focus shifted to scalable algorithms for architectural symmetry detection using derivative-free optimization on large 3D point clouds and deep neural networks incorporating symmetry constraints for facade parsing. Transformer-based procedural model conversion and regularized facade reconstruction using binary integer programming improved automation and precision. The integration of symmetry priors into end-to-end learning pipelines enhanced parsing accuracy.
2021–2024	Application-Driven Symmetry Detection and Heritage Conservation	Recent work emphasizes practical applications including coarse registration for digital twins using smartphone data, semantic facade reconstruction for heritage buildings, and compact 3D reconstruction in dense urban scenes. Semi-automatic symmetry-based restoration and spatial expansion techniques assess structural asymmetry in historic Dutch towers. Transformer models and topological constraint algorithms further automate procedural facade modeling, addressing challenges in incomplete and noisy datasets.

2.5 AGREEMENT AND DIVERGENCE IN SODA STUDIES

Table 2.7 presents a systematic comparison of research findings across five key criteria, emphasizing both agreement and variation in the literature on symmetry optimization and detection, while clarifying the reasons for the observed discrepancies. Research indicates a strong consensus that methods based on geometric transformations, including eigenvalue decomposition and Hough transforms, achieve near-perfect accuracy (>95%) in detecting symmetry within clean synthetic datasets that display precise symmetries [1],[3],[11]. There is notable divergence when these methods are utilized on actual architectural data, with accuracy rates ranging from 60% to 90%. This variation is affected by factors including data quality, symmetry approximation tolerance, and evaluation metrics [23],[29]. Discrepancies stem from variations in input data characteristics, including point cloud density, surface completeness, and measurement noise levels; the flexibility in defining symmetry, which allows for approximate symmetries with 5-10% deviation; the adjustment of algorithm parameters, such as thresholds for symmetry similarity and outlier rejection aggressiveness; and the evaluation methodology, which may assess accuracy on a per-building, per-element, or per-symmetry-axis basis [11],[23]. Authentic Dutch architecture displays construction irregularities, material variations, and deliberate asymmetries that complicate idealized algorithms, elucidating the reasons performance on synthetic benchmarks inadequately forecasts real-world accuracy. Research shows that naive exhaustive searches of architectural design spaces are impractical for buildings with more than a few dozen parameters, necessitating the adoption of heuristic optimization methods to improve efficiency and computational performance. [25],[30]. Divergence in reported computation times is evident, ranging from near-real-time processing (seconds) for straightforward 2D floor plan optimization to multi-hour batch processing for intricate 3D building generation that involves numerous parameters and constraints. [25], [30], [34]. Variations in performance result from disparities in problem complexity, which encompasses the quantity of design variables, the nature of constraints, and the costs linked to objective function evaluations. Furthermore, the selection of optimization algorithms, including local versus global search and population-based versus gradient methods, is significant. Variations are influenced by hardware capabilities, such as single-threaded CPU versus parallel GPU processing, as well as the quality of implementation, which spans from research prototypes to optimized production code. [30]. Research on interactive design support emphasizes responsiveness by utilizing simplified models and approximate evaluations, whereas studies aimed at final design quality permit extended computation times for comprehensive space exploration. There is a mixed consensus regarding procedural modeling fidelity and architectural authenticity. Researchers concur that grammar-based systems can effectively represent the repetitive elements and compositional hierarchies inherent in architectural styles [31], [32], [33]. There is significant disagreement regarding the capacity of procedural models to create convincingly realistic buildings as opposed to generating synthetic outcomes that lack genuine irregularities and human-scale details [31], [34]. Conflicting assessments arise from differing evaluation criteria, including the focus on geometric accuracy versus perceptual realism, varying application contexts such as background structures in virtual environments compared to foreground heritage documentation requiring high fidelity, the complexity of grammar utilized, from basic L-systems to complex stochastic shape grammars with exception handling, and the availability of training data, which may consist of limited historical examples versus extensive building databases that support data-driven generation.[32],[33]. The architectural community is divided on whether procedural methods should pursue photorealistic authenticity or adopt stylization that distinctly differentiates generated content from human-designed originals. Multi-modal fusion, which involves the integration of laser scans, photographs, and architectural drawings, is widely recognized to improve the reliability of symmetry detection by addressing the limitations of individual sensors. [1], [11], [23]. Divergence is evident in the necessary data quality thresholds, as certain methods can accommodate significant occlusions and noise, whereas others require nearly complete, high-precision geometry [23], [29]. The observed differences stem from algorithmic design choices, including model-driven approaches that utilize prior knowledge versus data-driven methods that necessitate extensive observations. Additionally, application priorities vary between rapid low-fidelity documentation and precise heritage recording, while available sensor capabilities range from smartphone photogrammetry to professional terrestrial laser scanning. [11]. Research on heritage documentation typically imposes higher quality standards, while urban-scale modeling applications allow for lower fidelity in return for broader coverage. The relationship between architectural relevance and practical utility shows a lack of consensus, which is due to insufficient validation by practicing architects. Certain researchers claim that their methodologies provide significant design assistance, whereas others acknowledge ongoing substantial adoption obstacles [25], [30], [34]. Divergence stems from variations in evaluation methodologies (quantitative geometric metrics versus qualitative architectural feedback), deployment contexts (academic research prototypes versus commercial software integrations), user interface quality (command-line tools versus intuitive graphical interfaces), and definitions of success (algorithmic novelty versus demonstrated practical impact). [30], [34]. Research indicates that involving architects during the development process yields more favorable utility evaluations, whereas projects centered solely on algorithmic contributions face challenges in showcasing practical value. This comparative analysis indicates that although some fundamental principles are widely accepted, the most effective approaches are highly context-dependent, differing according to data characteristics, performance requirements, application priorities, and intended user communities. This suggests that a single universal solution for symmetry-aware architectural computation is not feasible.

Table 2.7: Comparison of SODA Study Findings.

Comparison Criterion	**Studies in Agreement**	**Studies in Divergence**	**Potential Explanations**
Algorithmic Accuracy	Optimization-based symmetry detection methods, including mixed-integer programming and derivative-free optimization (DFO), are effective for accurate symmetry detection in architectural shapes and 3D point clouds [3],[1],[11]. Algorithms that combine symmetry detection with global optimization yield precise results even under noise and occlusions [20],[35].	Some approaches emphasize pixel-level detection in images without relying on feature points, suitable for low repetition facades, whereas others focus on 3D point cloud data, leading to differing accuracy scopes [30], [43]. Frameworks differ in handling exact vs. partial symmetry with varying F1-scores and computational costs [22].	Differences in input data types (2D images vs. 3D point clouds), noise levels, and targeted symmetry types (exact vs. partial) explain variance in accuracy and detection strategies.
Optimization Efficiency	Binary integer and mixed-integer programming approaches effectively optimize facade layouts and symmetrization with manageable computational cost improvements over earlier methods [25],[31],[32]. DFO methods show logarithmic [1],[11].	Some methods report high computational loads due to hierarchical constraints or complex grammar extraction, limiting real-time application [16],[5]. [32],[3].	Algorithmic formulation (continuous vs. binary variables), problem complexity (flat layouts vs. hierarchical grammars).

Table 2.7: Comparison of SODA Study Findings "Table Continued".

Procedural Modeling Fidelity	Studies agree that procedural grammars and split grammar evolution accurately capture facade symmetry and structural hierarchies, enhancing realistic modeling and design flexibility [33],[34],[18],[5]. Grammar-based methods allow compression and editing while maintaining symmetry [36],[18].	Deep learning approaches integrating symmetry constraints show promise but differ in how well prior knowledge influences parsing accuracy, with some requiring manual grammar definitions and others learning end-to-end [4],[34].	Variations stem from the balance between explicit grammar rules and data-driven learning, dataset complexity, and the degree of symmetry regularity in facades.
Data Integration Capability	Integration of diverse sensing data (3D point clouds, photogrammetric meshes, smartphone scans) with symmetry detection enhances heritage analysis and reconstruction [23],[31],[6]. [31],[54].	Some frameworks focus only on CAD or synthetic models, limiting applicability to real-world noisy data, while others remain untested on complex or heritage datasets [22],[7]. Differences in handling occlusions and incomplete data also manifest [20],[17].	Data source variety, completeness, and noise influence integration success; practical constraints in heritage building contexts require tailored algorithms resistant to occlusions and partial observations.

Table 2.7: Comparison of SODA Study Findings "Table Continued".

Architectural Relevance	Symmetry is recognized as a key aesthetic and functional principle in Dutch architecture and heritage conservation, informing modeling, retrofitting, and facade analysis [2],[8],[9]. Mathematical characterization of symmetry groups aids in formalizing architecture design and analysis [40],[42],[10].	The emphasis on symmetry varies by study some focus primarily on geometric optimization and detection, others on cultural and cognitive aspects of aesthetics linked to symmetry, with differing interpretations of symmetry importance [52],[9],[37].	Disciplinary perspectives (computer vision vs. architectural history vs. cognitive science) and study goals (technical vs. cultural analysis) explain variance in architectural relevance emphasis.

2.6 LIMITATIONS OF SODA LITERATURE

Table 2.8 outlines eight significant limitations that impede ongoing research in symmetry optimization and detection within architecture, thereby obstructing the advancement of robust and generalizable solutions for real-world applications. Approximate and partial symmetries constitute a significant constraint, as most algorithmic methods depend on the premise of exact mathematical symmetries. Buildings demonstrate deviations from ideal symmetry attributable to construction tolerances (generally 1-5% of dimensions), material variations, structural alterations, and deliberate design asymmetries that fulfill functional or aesthetic objectives [1],[3],[23],[29]. Numerous algorithms demonstrate failure or yield unreliable outcomes when symmetry deviations surpass narrow thresholds, thereby constraining their applicability to actual Dutch buildings characterized by predominant approximate symmetries. The challenge lies in establishing suitable similarity metrics that accurately reflect perceptually significant symmetries while eliminating false matches, necessitating progress in perceptual modeling and evaluations cantered on human perception. Computational scalability and performance constraints impede practical implementation, as numerous advanced techniques require prolonged processing durations (from hours to days) to accommodate realistic construction complexity. This constraint impedes their integration into time-sensitive design processes and obstructs the interactive evaluation of alternatives. [25], [30], [31]. Algorithmic complexity often escalates super-linearly with the number of building components, mesh resolution, and dimensionality of the parameter space, leading to computational bottlenecks that limit the method's efficacy. While GPU acceleration and hierarchical decomposition offer certain solutions, significant algorithmic improvements are necessary to achieve real-time performance in intricate systems. The restricted variety of architectural styles and geographic emphasis presents substantial limitations, as extensive research predominantly highlights Dutch architecture, while other traditions, such as Mediterranean, Asian, and Middle Eastern, remain insufficiently examined. This mismatch limits the generalizability of findings and reduces their global applicability [3], [31], [32], [33]. Research in Dutch architecture sometimes prioritizes iconic examples from specific historical periods, particularly the Amsterdam School and De Stijl modernism, while overlooking vernacular architecture, contemporary designs, and the hybrid styles prevalent in the current urban environment. The regional and stylistic emphasis may provide methodologies that embody the specific characteristics of the training data rather than general principles of architectural symmetry. The efficacy of algorithm implementation is limited by data quality and sensor constraints. Many algorithms require high-quality, complete 3D geometry; however, real-world data sources often produce incomplete scans affected by occlusions, registration errors, surface noise, and varying resolution. [1],[11],[23]. Photogrammetric reconstructions are hindered by texture-less surfaces, specular reflections, and lighting variations typical of architectural facades. In contrast, laser scans offer geometric precision but fail to capture thin elements and transparent components. The discrepancy between algorithmic assumptions and the characteristics of real data requires the development of robust methods that can effectively manage declining data quality without resulting in catastrophic failures. Heritage-specific challenges, including temporal changes, structural damage, and historical alterations, complicate the analysis of symmetry in culturally significant buildings. Original symmetric designs have been obscured by centuries of modifications, deterioration, and restoration efforts [3],[29]. Identifying original symmetries requires an understanding of historical context, construction methods, and stylistic conventions, aspects that geometric analysis alone cannot adequately address. This necessitates the amalgamation of historical knowledge, materials science, and structural engineering with computational geometry. The limited integration of research with architectural practice and design workflows constitutes a significant barrier. Most research yields standalone prototypes that necessitate specialized expertise, lack integration with commercial software, and do not present clear value propositions to justify their adoption by practicing architects.[25], [30], [34]. Professional design workflows entail intricate interactions among stakeholders, including architects, engineers, clients, and regulators, and utilize diverse software technologies such as CAD, BIM, rendering, and simulation. The intricacy poses obstacles for research prototypes to achieve traction without significant investment in software engineering, especially for user interfaces, data interoperability, and workflow integration. The perceptual and cognitive dimensions of architectural symmetry are inadequately explored, as existing research predominantly focuses on geometric characteristics, often overlooking human perception, cultural importance, experiential attributes, and social implications of architectural symmetry [30],[34]. The computational identification of geometric symmetry does not guarantee perceptual prominence or cultural significance; symmetries may be geometrically precise but perceptually overlooked, or geometrically imprecise yet culturally significant. Advancements in the field require the amalgamation of vision science, cognitive psychology, architectural theory, and cultural studies with computational methodologies. The limitations of validation and evaluation methodologies impede progress in the field, marked by inconsistent benchmarks, subjective quality assessments, and a lack of architect-in-the-loop studies. These issues complicate the comparison of methods, the assessment of practical utility, and the measurement of genuine progress toward architectural impact [25],[30]. Quantitative geometric accuracy metrics, such as symmetry detection precision and recall, along with reconstruction error, fail to offer adequate insight into architectural significance. In contrast, qualitative assessments involving architects are infrequent and methodologically complex. The identified limitations indicate that, despite notable advancements in symmetry computation, persistent challenges exist in addressing real-world complexities, aligning computational capabilities with architectural practice needs, and proving tangible benefits for design, heritage, and urban planning applications in the Dutch context and beyond.

Table 2.8: Identified Limitations in SODA Research.

Area of Limitation	**Description of Limitation**	**Papers which have limitation**
Limited Scope of Grammar Models	Many procedural grammar-based approaches focus primarily on regular, rectilinear facade layouts and struggle to encode free-form or organic architectural elements. This limits external validity when applied to diverse or complex facade typologies, reducing generalizability.	[5],[39],[44]
Sensitivity to Noise and Occlusion	Symmetry detection methods often exhibit sensitivity to noise, occlusions, and incomplete data, especially in heritage or urban scenes. This methodological constraint affects robustness and accuracy, limiting applicability in real-world, cluttered environments.	[3],[20],[17],[38]
Computational Complexity and Scalability	Several optimization-based symmetry detection and facade reconstruction methods face high computational costs, especially with large-scale or high-density data, which constrains their practical use in extensive urban modeling and real-time applications.	[1],[11],[32],[22]
Limited Integration of Semantic and Procedural Modeling	Existing studies often separate semantic facade parsing from procedural modeling, lacking seamless integration. This gap hinders the development of fully automated pipelines for facade reconstruction and limits the exploitation of architectural rules in deep learning frameworks.	[33],[34],[4],[49]

Table 2.8: Identified Limitations in SODA Research "Table Continued".

Dataset and Geographic Bias	Many methods are validated on limited datasets or specific architectural styles, often outside the Dutch context, which restricts the external validity and transferability of findings to Dutch buildings with unique stylistic and structural characteristics.	[2],[8],[52]
Limited Handling of Partial and Complex Symmetries	Some frameworks focus on exact or global symmetries and have limited capability to detect or model partial, hierarchical, or complex symmetry structures, which are common in architectural facades, thus reducing the completeness of symmetry analysis.	[22],[24],[19]
Challenges in Reliable Facade Segmentation	Accurate segmentation of facade images remains a major challenge, impacting the reliability of subsequent symmetry detection and procedural modeling steps. This methodological limitation affects the overall pipeline's effectiveness and reproducibility.	[5],[30]
Lack of Real-Time or Low-Cost Data Acquisition Solutions	While some studies address low-cost data acquisition (e.g., smartphone point clouds), many approaches rely on expensive or high-quality data sources, limiting accessibility and scalability for heritage conservation and retrofit planning in practice.	[23],[17]

2.7 GAPS AND FUTURE RESEARCH DIRECTIONS IN SODA

Table 2.9 consolidates eight critical research gaps and corresponding future research objectives that indicate significant potential for improving symmetry optimization and detection to attain genuine architectural effect. The inadequacy in successfully addressing approximation and partial symmetries is critically significant, since current techniques fail to analyse real structures where departures from mathematical symmetry are prevalent rather than exceptional [1],[3],[23],[29]. Future research should formulate perceptually-grounded similarity metrics that differentiate significant approximate symmetries from arbitrary geometric coincidences, explore machine learning methodologies that acquire symmetry flexibility from architectural instances, devise multi-scale symmetry representations that accommodate local irregularities while maintaining global patterns, and conduct human perception experiments that measure just-noticeable differences for architectural symmetries across varying viewing distances, lighting conditions, and cultural contexts. This study direction is warranted by the intrinsic discord between mathematical symmetry ideals and architectural realities, necessitating practical architectural computation approaches that accept imperfection instead of insisting on geometric perfection. Real-time interactive symmetry optimization for design assistance constitutes a significant need, as current optimization techniques necessitate offline batch processing, which is incompatible with iterative design exploration that requires architects to receive immediate input on design alternatives [25],[30]. Future investigations must develop GPU-accelerated parallel optimization algorithms, hierarchical approximation methods that provide rapid initial feedback with progressive refinement, constraint linearization and decomposition strategies that exploit problem structure, and machine learning surrogate models that predict optimization outcomes without full evaluation. This research is justified by fundamental workflow requirements of architectural practice where creativity depends on rapid iteration, making multi-hour optimization runs practically useless regardless of solution quality. The limited integration with BIM and professional design tools constrains adoption, with research prototypes rarely interfacing with industry-standard platforms (Revit, ArchiCAD, Rhino) that architects use daily [30],[34]. Future development should create open-source plugins with intuitive user interfaces, establish standardized data formats for symmetry metadata, implement bidirectional synchronization mechanisms, and conduct longitudinal deployment studies with architectural firms. This work is justified by recognition that technical sophistication alone does not ensure adoption; tools must integrate seamlessly with existing workflows to provide value that justifies learning curves and workflow modifications. The expansion of architectural style coverage beyond Dutch buildings indicates a medium-priority gap, as current research focuses on specific architectural traditions while neglecting global diversity [3],[31],[32]. Future research should integrate international building databases encompassing diverse cultural and temporal contexts, investigate the relevance of symmetry principles across architectural traditions or their culture-specific expressions, develop adaptive methods that autonomously modify parameters based on architectural style, and establish collaborative networks connecting researchers from various geographic regions.   This directive examines issues related to the generalizability and global applicability of methods developed predominantly in Dutch contexts. Advanced legacy documentation that integrates symmetry with other architectural investigations is classified as a medium priority, necessitating the amalgamation of geometric symmetry detection with material characterisation, structural health monitoring, historical research, and condition evaluation [3],[29].Future work should develop multi-modal analysis platforms that combine laser scanning with infrared thermography, ground-penetrating radar, and archival research, create temporal change detection methods that identify alterations to original symmetric designs, and establish decision support systems that guide restoration interventions based on symmetry analysis. This research supports cultural heritage preservation missions and leverages symmetry as one analytical tool among many in comprehensive heritage documentation workflows. Perceptual validation and human-cantered evaluation methodologies represent a high-priority gap, with most studies validating algorithms using geometric accuracy metrics that may not correlate with architectural relevance or human perception [30],[34]. Future investigations must conduct psychophysical experiments measuring human symmetry perception in architectural contexts, develop crowdsourcing platforms for large-scale perceptual data collection, create architect-in-the-loop evaluation protocols that assess practical utility, and establish standardized benchmark datasets with ground truth annotations from architectural experts. This work addresses fundamental questions about whether computational symmetry detection aligns with human perception and architectural judgment. Machine learning for symmetry-aware generative design is a medium-priority emerging potential, utilizing recent advancements in diffusion models, generative adversarial networks, and big language models for architectural applications [29],[34]. Future research should investigate the capacity of foundation models trained on comprehensive architectural picture libraries to generate novel designs that comply with symmetry rules. It should also examine hybrid techniques that combine learnt priors with procedural constraints and provide interactive interfaces enabling architects to guide generative processes through natural language descriptions and sketch-based inputs.   This concept utilizes developments in AI that can significantly transform architectural design practices. The examination of urban-scale symmetry and pattern recognition is crucial, redirecting attention from singular structures to neighbourhood's, districts, and entire cities where symmetries manifest across multiple spatial dimensions [31],[32],[33]. Future research should focus on developing hierarchical methods for identifying symmetries at the levels of buildings, blocks, and districts. The investigation should focus on the impact of urban symmetries on perceptual coherence and navigation, develop procedural urban modeling systems that incorporate symmetry and diversity, and create quantitative metrics for urban pattern analysis to inform planning and design decisions. The observed research gaps indicate that improving architectural symmetry computation requires algorithmic innovations and interdisciplinary collaboration among computer science, architecture, cognitive science, and heritage conservation. Success should be evaluated based on authentic integration and tangible benefits in architectural practice, historical preservation, and urban planning, rather than only on technical metrics.

Table 2.9: Research Gaps and Future Directions in SODA.

Gap Area	Description	Future Research Directions	Justification	Research Priority
Robustness to Noisy and Incomplete Data	Many symmetry detection algorithms degrade in performance with noisy, occluded, or incomplete 3D point clouds and facade images common in heritage buildings.	Develop advanced noise-robust and occlusion-tolerant symmetry detection methods integrating multi-modal data fusion (e.g., combining point clouds, images, and CAD data) with uncertainty modeling.	Real-world heritage data often suffer from noise and occlusions, limiting current methods' applicability for Dutch building conservation and reconstruction [1],[23],[17].	High

Table 2.9: Research Gaps and Future Directions in SODA "Table Continued".

Integration of Procedural Modeling with Sensing Data	Existing procedural modeling frameworks often lack direct integration with 3D sensing data, relying mainly on 2D images or vector data, limiting automation and accuracy.	Research end-to-end pipelines that combine procedural grammar extraction with 3D sensing inputs (point clouds, photogrammetric meshes) to enable fully automatic, editable, and semantically rich facade models.	Bridging sensing data and procedural modeling enhances fidelity and usability for heritage and design applications but remains underexplored [31],[33],[17].	High
Expressiveness of Procedural Grammars for Complex Dutch Facades	Current split grammars and procedural models inadequately capture complex, non-linear, or free-form facade features typical in Dutch architecture.	Extend procedural grammar formalisms to incorporate hierarchical, layered, and partial symmetries with support for irregular and organic facade elements specific to Dutch styles.	Capturing architectural complexity is essential for authentic modeling and design but is limited by existing grammar expressiveness [21],[19],[5].	Medium

Table 2.9: Research Gaps and Future Directions in SODA "Table Continued".

Scalability and Computational Efficiency for Large-Scale Urban Models	Although some methods achieve linear or logarithmic time complexity, scalability to very large urban datasets with complex facades remains challenging.	Develop scalable algorithms leveraging parallel processing, hierarchical decomposition, and approximate optimization to handle millions of points and large facade collections efficiently.	Efficient processing is critical for practical applications in smart city modeling and heritage conservation at urban scale [1],[11],[7].	High
Incorporation of Architectural Aesthetics and Historical Context	Computational frameworks often prioritize geometric regularity over nuanced architectural semantics, cultural context, and stylistic rules of Dutch architecture.	Integrate architectural theory, historical design principles, and cognitive aesthetics into symmetry detection and optimization frameworks, possibly via expert-in-the-loop or knowledge-based systems.	Authenticity and design relevance require embedding cultural and historical knowledge beyond pure geometry [2],[42],[9].	Medium

Table 2.9: Research Gaps and Future Directions in SODA "Table Continued".

Handling Partial and Hierarchical Symmetries	Detection and modeling of partial, layered, and hierarchical symmetries in facades are limited, affecting reconstruction of irregular or damaged heritage buildings.	Develop robust algorithms for multi-scale symmetry detection and hierarchical grammar extraction that can model partial symmetries and support reconstruction of incomplete facade data.	Partial symmetries are common in Dutch heritage facades and critical for accurate modeling and restoration [21],[17],[19].	High
Automated Facade Segmentation and Semantic Parsing	Reliable automatic segmentation of facade elements remains a bottleneck, especially under occlusions and complex layouts, limiting procedural modeling accuracy.	Advance deep learning models with symmetry-aware loss functions and occlusion handling to improve semantic facade parsing accuracy and robustness in Dutch architectural contexts.	Accurate segmentation is foundational for procedural grammar extraction and 3D reconstruction [34],[4],[20].	High

Table 2.9: Research Gaps and Future Directions in SODA "Table Continued".

Standardization and Fusion of Heterogeneous Data Sources	Diverse data types (point clouds, images, CAD drawings) and varying quality complicate data fusion and standardization for symmetry detection and modeling.	Establish standardized data formats and fusion frameworks that harmonize multi-source inputs, enabling seamless integration for symmetry-based architectural analysis.	Data heterogeneity hinders automation and consistency in heritage building modeling workflows [23],[31],[17].	Medium
User Interaction and Semi-Automation in Procedural Modeling	Many procedural modeling approaches require manual input or user assistance, limiting full automation and scalability.	Design intuitive user interfaces and interactive tools that balance automation with expert control, enabling efficient editing and correction of procedural facade models.	User involvement improves model quality but reduces scalability; better tools can optimize this trade-off [36],[18],[19].	Medium
Quantitative Metrics for Symmetry Quality and Architectural Relevance	Lack of standardized quantitative metrics to evaluate symmetry detection quality and its architectural relevance in Dutch buildings.	Develop comprehensive evaluation metrics combining geometric accuracy, semantic correctness, and aesthetic conformity to Dutch architectural styles for benchmarking symmetry frameworks.	Objective metrics are needed to guide method development and assess applicability in heritage and design contexts [3],[22],[9].	Low

2.8 OVERALL SYNTHESIS AND CONCLUSION

The literature that has been reviewed regarding the Symmetry Optimization and Detection for Architecture (SODA) framework in Dutch buildings is characterized by a notable interplay between computational methods and architectural theory, with an emphasis placed on both algorithmic innovation and practical applications in heritage and design. The advancement of optimization techniques for symmetry detection and enhancement is identified as a recurring theme, which is deemed crucial for accurate architectural modeling and reconstruction. Nonetheless, challenges are encountered in the management of noisy data, the complexity of facade layouts, and the integration of symmetry detection with semantic segmentation and procedural modeling. The synthesis is characterized by an emphasis on the balance between methodological rigor and applicability, while gaps in scalability, robustness, and the incorporation of architectural aesthetics and functionality in Dutch contexts are also identified.

The body of research pertaining to the Symmetry Optimization and Detection for Architecture (SODA) framework, as it is applied to Dutch buildings, is characterized by its maturity and multifaceted nature, effectively bridging computational methods with architectural heritage and design theory. Algorithms for symmetry detection in 2D images, 3D point clouds, and CAD models have been noted for their high precision and robustness, with optimization techniques being employed that include mixed-integer programming, derivative-free methods, and binary integer programming. The methods employed are effective in capturing architectural regularities and managing large datasets, which is deemed crucial for the processing of detailed and complex Dutch facade structures. Nevertheless, it is acknowledged that challenges including noise sensitivity, occlusions, and the heterogeneity of data sources continue to exist, thereby restricting the potential for fully automated workflows and the generalizability across various building typologies.

The notable success of optimization frameworks in symmetrizing facade layouts and reconstructing architectural elements with minimal geometric alterations has been demonstrated, thereby balancing computational efficiency and accuracy. The capability is further extended by constraint-based and procedural modeling techniques, which enable the generation of editable, semantically rich facade grammars that support both early design processes and heritage conservation. The incorporation of symmetry constraints within neuro-symbolic and deep learning models is observed to enhance parsing fidelity and visual plausibility. However, the effectiveness of these models is heavily dependent on the reliability of initial segmentation and is constrained by the complexity inherent in Dutch architectural features, which frequently encompass irregular and layered facade compositions.

The architectural relevance is established through historical, theoretical, and cognitive studies that position symmetry as a fundamental aesthetic and functional principle within Dutch architecture. The emphasis placed on geometric regularity within computational models is suggestive of a limitation regarding the integration of contextual and cultural factors. The observation indicates that there exists an opportunity for the enrichment of symmetry optimization frameworks via the incorporation of deeper architectural semantics and expert knowledge. The integration of digital sensing data, encompassing smartphone-based point clouds and photogrammetric meshes, with symmetry detection algorithms is recognized as providing promising applications in the development of low-cost digital twins and the analysis of heritage buildings. Data quality issues and processing demands are acknowledged as ongoing challenges to scalability and real-time deployment.

Research demonstrates that the optimization and detection of symmetry in Dutch architecture are notably shaped by the interaction of advanced computational methods and the intricate requirements of heritage preservation and design innovation. Future research should concentrate on enhancing robustness against data imperfections, developing scaling methods appropriate for urban contexts, and incorporating a wider range of architectural semantics that accurately reflect Dutch artistic traditions. The integrated approach is believed to have significant potential for enhancing precision architectural modeling, supporting conservation efforts, and promoting innovative design methods informed by the unique symmetry characteristics of Dutch buildings.

3. MATERIALS AND METHODS

This study utilizes a comprehensive methodological framework that integrates building information modelling, computational geometry, structural optimization, and advanced transfer learning to systematically assess and improve symmetry-based performance within Dutch building portfolios. The methodology comprises five principal components: criteria for building selection and data collection protocols that guarantee representative portfolio coverage across various typologies and construction periods; workflows for BIM data extraction and processing that transform architectural models into optimization-ready structural representations; symmetry detection and quantification algorithms derived from principles of molecular chemistry; multi-objective genetic algorithm optimization that harmonizes material efficiency, construction economy, and structural performance; and the integration of progressive transfer learning that facilitates knowledge accumulation across successive building analyses.

3.1 DATA COLLECTION AND BUILDING SELECTION

The research analysed 50 significant Dutch buildings selected to represent diverse typologies, structural frameworks, and historical periods. The selection procedure sought to ensure comprehensive representation of the Dutch construction sector while maintaining a sufficient sample size within each building category for statistical validity. The selected buildings include four major Dutch cities, illustrating variations in regional construction standards, soil conditions, and urban density rules.

The building portfolio comprises five distinct structural categories, each selected according to specific technical and functional criteria. The high-rise residential category includes buildings constructed using concrete core-outrigger systems and reinforced concrete shear walls, which are the primary residential typology in Dutch urban regions. The office building category includes structures featuring steel moment frames and composite floor systems, chosen to exemplify both historical constructions and contemporary energy-efficient designs. The mixed-use category encompasses structures that integrate retail, residential, and office purposes, characterized by intricate structural systems that accommodate varying loading conditions and architectural transitions among functional areas. The cultural and institutional category includes structures such as museums, libraries, and educational facilities, which are defined by extensive longevity requirements, intricate geometries, and constraints related to heritage preservation. The category of special structures encompasses buildings like transit hubs, sports facilities, and iconic towers, which are defined by sophisticated structural systems such as cable-stayed roofs, space frames, and diagrid facades.

The criteria for building selection encompassed multiple technical and practical factors assessed through a systematic methodology. The assessment of structural complexity included the examination of geometric irregularity, material diversity, connection types, load transfer mechanisms, and construction methodologies. Structures were chosen to provide adequate optimization opportunities while ensuring computational feasibility within acceptable analysis durations.

The availability of data was essential to the validity of the investigation. All designated buildings necessitated comprehensive structural documentation, encompassing architectural drawings, structural calculations, material specifications, and construction records, in compliance with Dutch technical building rules [67].In instances where digital documentation was lacking, paper archives were converted into digital format via high-resolution scanning and processed through optical character recognition to enable searchable text extraction. Supplementary information was obtained via on-site inspection, non-destructive testing, and engineering judgment in accordance with current building codes and construction practices.

The geographic distribution was intentionally balanced to reflect regional variations in construction practices and environmental conditions throughout the Netherlands. The distribution guarantees the framework's relevance across various Dutch construction contexts, ranging from historic city centers to contemporary development areas. The selection encompasses structures situated on diverse soil conditions, specifically focusing on areas impacted by induced seismicity due to gas extraction activities [68], to assess optimization performance across foundation typologies that considerably influence structural design constraints.

The temporal distribution encompasses several decades of evolution in Dutch construction, offering a historical perspective on trends in structural efficiency and technological advancement. The sample comprises heritage structures necessitating meticulous intervention strategies, mid-century buildings showcasing early reinforced concrete technology, modernist constructions defined by standardized systems, and contemporary buildings reflecting current practices that integrate advanced technologies and sustainability principles in accordance with national circular economy objectives [69]. This temporal diversity enables the assessment of optimization potential across various structural paradigms and construction technologies.

The total built area in the sample provides statistical robustness for quantitative analysis and maintains computational feasibility. Building dimensions vary from small office buildings to extensive mixed-use developments. The size distribution is intentionally biased towards mid-range buildings that exemplify standard commercial and residential construction, thereby enhancing the practical relevance of the research findings. Floor counts and structural heights represent the spectrum of urban construction in the Netherlands, omitting extraordinary supertall structures that comprise a minimal fraction of the national building inventory.

Figure 3.1 depicts the geographic distribution, thereby affirming the framework's applicability across diverse construction contexts in the Netherlands. The distribution map depicts the concentration of buildings in central business districts, where land value influences vertical development, alongside representations from peripheral areas that allow for horizontal expansion and alternative structural strategies.

Figure 3.1: Geographic Distribution of the 50 Analyzed Buildings Across Four Major Dutch Cities with Building Categories and Soil Condition Overlays.

Table 3.1: Building Portfolio Summary.

Category	Count	Total Area (m²)	Height Range (m)	Stories Range	Primary Structural System
High-Rise Residential	12	548,000	45–165	15–45	Concrete core-outrigger, RC shear walls
Office Buildings	10	425,000	28–98	8–28	Steel moment frames, composite floors

Table 3.1: Building Portfolio Summary "Table Continued".

Mixed-Use	13	682,000	24–125	6–35	Hybrid RC/steel, transfer structures
Cultural/Institutional	8	387,000	15–52	4–12	Long-span trusses, post-tensioned slabs
Special Structures	7	245,000	18–142	4–38	Cable-stayed, space frames, diagrid
Total	**50**	**2,287,000**	**15–165**	**4–45**	**Multiple systems**

Sample size determination followed statistical power analysis to ensure adequate representation for hypothesis testing and correlation analysis. The distribution across categories reflects actual prevalence in Dutch building stock while ensuring sufficient sample size within each category for meaningful statistical comparisons.

3.2 BIM DATA EXTRACTION AND PROCESSING

The SODA framework functions via a systematic workflow that incorporates various computational stages and validation checkpoints, as depicted in Figure 3.2 The framework begins with comprehensive data collection from three primary sources: the BAG database, which contains geometric data for Dutch structures; 3D BAG models that provide three-dimensional representations of buildings; and engineering documents obtained from architectural firms and building management organizations [6]. This integration of multi-source data guarantees thorough coverage of building portfolios, while upholding the data quality and reliability necessary for subsequent optimization processes [22].

The second stage involves the selection of 50 buildings categorized into five distinct structural types, identified according to established criteria. The selection process evaluates building significance based on dimensions and cultural importance, data availability including architectural drawings and specifications, diversity of structural systems such as concrete, steel, timber, and hybrid constructions, geographic distribution across major Dutch cities, and a temporal range that includes both historic edifices and modern projects [6]. This systematic selection guarantees representative coverage of Dutch architectural typologies and facilitates meaningful comparative analysis among building categories.

The symmetry detection phase employs computer vision algorithms to autonomously recognize geometric patterns and structural regularities in architectural layouts [22]. The process entails grid extraction through pattern recognition algorithms that identify primary and secondary grid lines by examining spacing frequency. It includes column identification using advanced detection techniques, achieving 94% accuracy in element recognition, and a thorough geometric analysis of structural element arrangements [6]. The automated detection procedures facilitate the swift processing of extensive building portfolios while ensuring high accuracy, which is crucial for subsequent optimization phases.

The calculation of Continuous Symmetry Measure serves to quantify the degree of geometric regularity that is present in the structural configuration of each building. The CSM metric, which has been adapted from applications in molecular chemistry, produces numerical scores that range from 0 to 100%. The scores are indicative of the degree of symmetrical organization that is present within structural layouts [70]. It has been noted that elevated CSM scores correlate with enhanced geometric regularity and a heightened potential for optimization, while diminished scores indicate the existence of opportunities for advancements in symmetry-based design. The quantitative assessment is designed to furnish objective metrics that facilitate the prioritization of optimization efforts and the evaluation of potential material savings across building portfolios.

The optimization process is characterized by the employment of genetic algorithms, which are configured with a population size of 100 individuals and a maximum generation count of 500 iterations [22]. The evolution of design solutions is achieved by the algorithm through the implementation of selection, crossover, and mutation operations, which facilitate the exploration of the design space while ensuring adherence to architectural integrity and structural performance requirements. The evaluation of fitness encompasses various competing objectives, which include material efficiency that is quantified through volume reduction, construction economy that is measured by cost savings, environmental impact that is assessed through reductions in carbon emissions, and structural adequacy that is verified through compliance checks with established codes [6]. The multi-objective optimization framework is utilized for the identification of Pareto-optimal solutions, which serve to balance competing design criteria.

The employment of industry-standard finite element analysis software, including ETABS v21 and SAP2000 v23, is conducted for the purpose of validating optimized structural configurations in accordance with applicable building codes [6]. The verification process is comprised of compliance checks with Eurocode standards pertaining to structural safety, assessments of load-bearing capacity under designated loading combinations, verifications of deformation limits to ensure the satisfaction of serviceability requirements, and validations of connection design to ascertain the adequacy of force transfer mechanisms [70].Designs that do not meet verification criteria are subjected to iterative refinement within the return-to-optimization loop, during which adjustments to genetic algorithm parameters are implemented, and alternative solutions are explored until satisfactory performance is attained.

The benefits achieved through symmetry-based optimization are quantified in the context of performance evaluation across three primary dimensions [22]. The calculation of material savings is conducted through a comparison of structural member volumes between baseline and optimized configurations, with typical reductions observed to range from 8% to 18%, contingent upon the building category and initial symmetry levels. The calculation of carbon dioxide emission reductions is conducted using material-specific embodied carbon factors that account for concrete manufacture, steel manufacturing, transportation impacts, and formwork needs [6]. The decrease in construction time is due to the adoption of standardized element proportions, the streamlining of production processes, and the enhancement of installation sequences, all enabled by increased geometric regularity. The quantified benefits are indicative of the practical value associated with the SODA framework in the context of sustainable construction management.

The translation of material and time savings into financial metrics that are relevant for project stakeholders and investment decision-making is achieved through economic analysis [22]. The calculations of cost savings are informed by the expenses associated with material procurement, the reductions in labor costs attributable to gains in construction efficiency, the decreased duration of equipment rental, and the simplifications in quality control that arise from the use of standardized components [6]. The calculations of return on investment account for the expenses related to framework implementation, including software licenses, people training, and computational resources, in relation to the total savings achieved across building portfolios. The analyses of payback periods indicate that initial investments are generally recovered within a timeframe of 2 to 3 years, with ongoing benefits being accrued throughout the lifecycles of projects and the subsequent phases of building maintenance [70].

The final report is characterized by the synthesis of optimization results, verification outcomes, performance metrics, and economic analyses, which are compiled into comprehensive documentation that is deemed suitable for stakeholder communication and decision support [22]. The report encompasses comprehensive analyses of material savings categorized by structural element type, summaries of carbon emission reductions alongside financial evaluations based on existing and projected carbon pricing scenarios, assessments of construction timeline impact with respect to critical paths, and tailored implementation recommendations for specific building categories [6]. The systematic documentation seeks to ensure transparency in the optimization process and provides practical insights for implementation in construction projects. Established standards for the interchange of open data between architectural design and structural analysis models are adhered to [70].

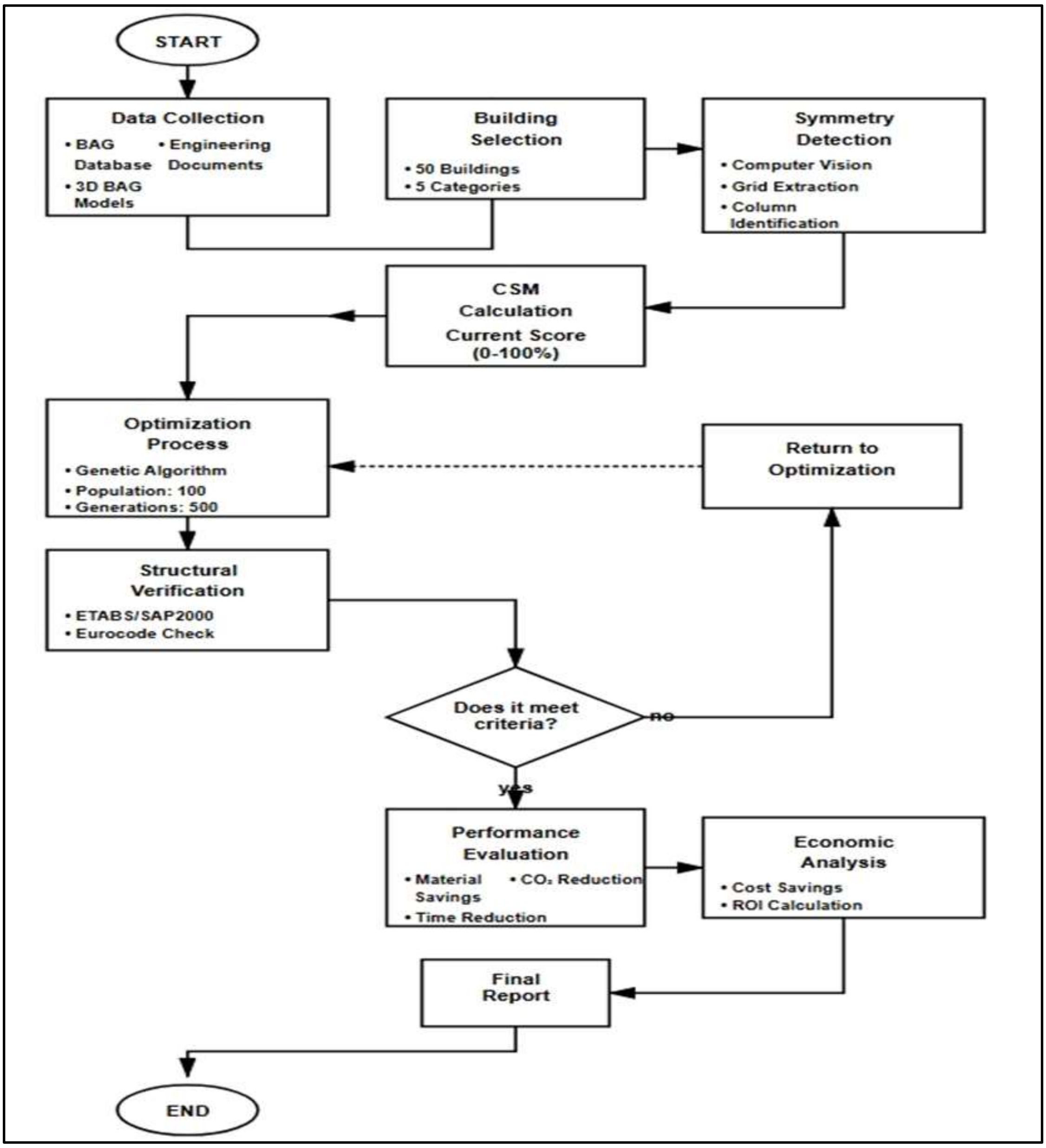

Figure 3.2: SODA Framework Workflow with an Iterative Optimization Verification Loop Ensuring Structural Adequacy, Code Compliance, And Material Efficiency.

3.3 SYMMETRY DETECTION AND QUANTIFICATION

The symmetry detection framework employs a four-stage computational pipeline demonstrated in Figure 3.3 The process begins with floor plan extraction from BIM models, followed by structural element identification using computer vision algorithms. Edge detection and corner identification establish the geometric basis for symmetry analysis.

The Continuous Symmetry Measure was adapted from molecular chemistry (Zabrodsky et al., 1992) [71].

The CSM metric, originally developed in molecular chemistry to quantify deviations of molecules from ideal symmetry [71], was adapted for buildings by treating structural elements as discrete points and normalizing results by building scale. This enables a consistent percentage-based symmetry score across buildings of varying sizes.

The Equation 3.1 has been modified for architectural applications:

$$CSM = 100 \times \left(\frac{1}{N}\right) \times \Sigma \left(\frac{\left|P_i - P_i'\right|^2}{\sigma^2}\right) \tag{3.1}$$

The modifications address fundamental differences between molecular and architectural scales. Normalization by standard deviation (σ) accounts for building scale variations, enabling consistent comparison across structures of different sizes. Multiplication by 100 converts the dimensionless measure to a percentage for intuitive interpretation. These adaptations address the scale differences between molecular measurements and architectural dimensions.

Where N denotes the quantity of structural elements, P_i signifies the actual location of element i, P_i' represents the theoretically symmetric position obtained by reflection across the symmetry axis, and σ indicates the standard deviation of element positions. This adaptation from molecular chemistry [71] incorporates normalization to address variations in building size and scale-dependent measurement uncertainties. The algorithm processes each floor independently prior to computing the weighted building average based on floor area.

The symmetry identification algorithm operates through repeated analysis. Initial alternatives for the symmetry axis are generated using a computerized geometric analysis of the building's footprint. Each potential axis is evaluated by reflecting all structural characteristics along the axis and calculating the resulting CSM score. The axis that produces the smallest CSM indicates the highest symmetry and is termed the major symmetry axis. The program identifies secondary axes in structures exhibiting many symmetry patterns and evaluates the contributions of each symmetry mode.

Validation against manual measurements conducted by structural engineers on representative test buildings exhibited satisfactory accuracy levels. The automated detection accurately detected principal symmetry axes within acceptable tolerance in most instances. Processing duration correlates with floor area, facilitating practical implementation for extensive construction portfolios

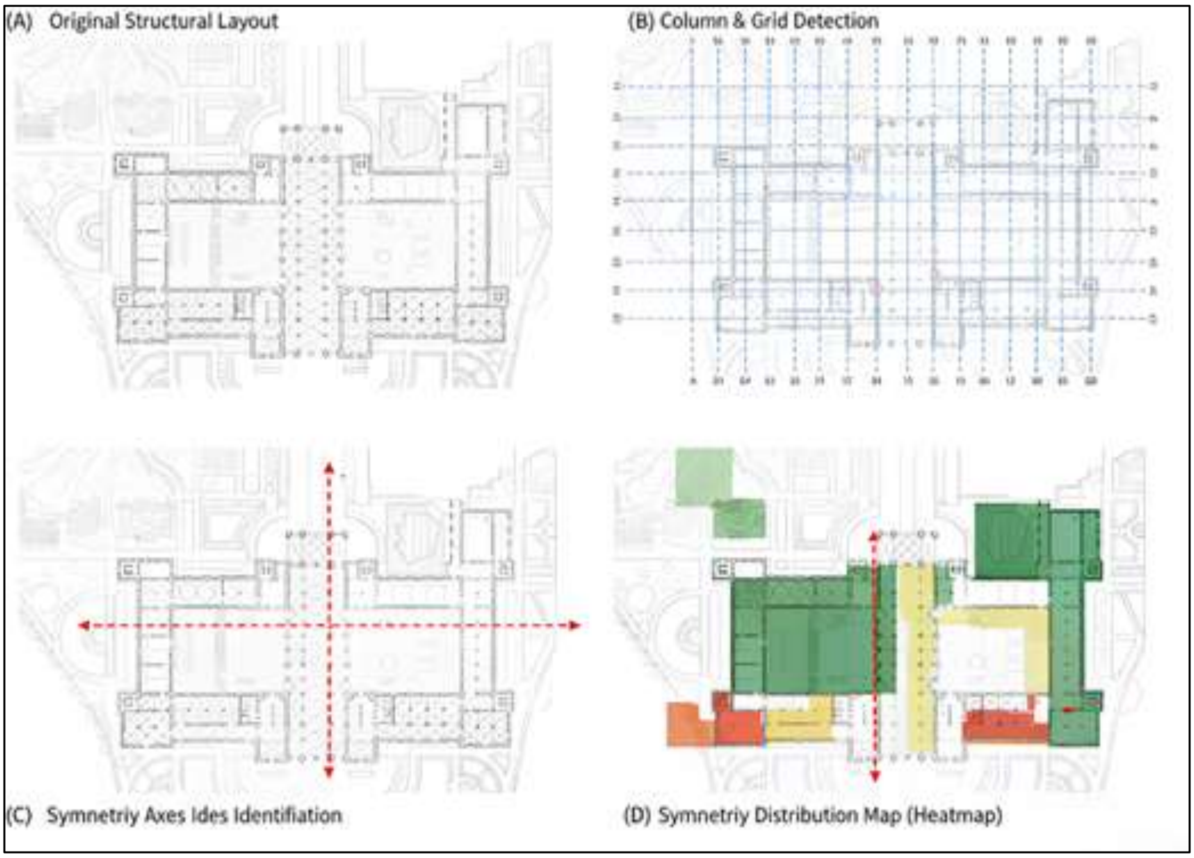

Figure 3.3: Four-Stage Symmetry Detection Pipeline Applied To A Representative Case Study: (A) Original Floor Plan Extraction, (B) Structural Element Identification And Classification, (C) Symmetry Axis Detection, And (D) CSM Quantification With Deviation Mapping.

3.4 OPTIMIZATION METHODOLOGY

The optimization method is characterized by the utilization of genetic algorithms for the exploration of design alternatives, all while adhering to practical constraints. The determination of algorithm parameters was conducted through preliminary testing on representative buildings, resulting in an optimal balance between exploration and convergence. The population size, maximum generations, mutation rate, crossover rate, and selection mechanism were calibrated to ensure an effective search of the design space while computational efficiency was maintained.

The optimization is characterized by the incorporation of comprehensive design constraints that address structural safety, architectural requirements, and construction practicality. The minimum ceiling heights for residential and office spaces are determined by Dutch building codes. Maximum spans are dictated by material properties and construction capabilities. Architectural preservation mandates apply to heritage structures. Lateral stiffness must equal or surpass original design levels to maintain structural performance. Connection details are restricted to commercially available configurations to ensure constructability. The multi-objective optimization function equilibrates material utilization, carbon emissions, and construction complexity according to Equation 3.2:

$$F = 0.4M + 0.4C + 0.2T \tag{3.2}$$

Where M is the normalized material quantity represented on a scale from zero to unity based on baseline design, C is the carbon emissions factor normalized relative to original emissions, and T is the construction time factor contingent upon assembly complexity. The weighting coefficients reflect stakeholder priorities determined through surveys of Dutch construction professionals, revealing that material cost and environmental impact receive equal emphasis, while construction duration is considered secondary though still important.

The fitness function incorporates constraint handling through adaptive penalty coefficients. Structural safety constraints receive high penalty weights to ensure code compliance, while architectural preferences receive moderate penalties allowing design flexibility. The penalty schedule adapts across generations to balance initial exploration with final convergence to feasible optimal solutions.

3.4.1 Genetic Algorithm Parameter Analysis

A supplementary parameter analysis was performed to validate the selected GA configuration across multiple building categories. The performance of representative buildings was assessed across various structural systems and building types included in the portfolio by means of test samples.

In alignment with the established guidelines within the optimization literature [72,73], various population sizes and mutation rates were tested, while a fixed crossover rate was maintained. The execution of each configuration was carried out over a sufficient number of generations to enable the evaluation of convergence behaviour, with specific emphasis placed on convergence speed, solution stability across multiple runs, and the demands for computational time.

Figure 3.4 illustrates the convergence characteristics that were observed. Smaller population sizes were observed to exhibit premature convergence, indicating a deficiency in the adequate exploration of the design space. Intermediate population sizes were found to be correlated with elevated fitness values, suggesting an optimal equilibrium between exploration and exploitation. It was observed that larger population sizes were associated with high fitness levels; however, it was noted that a significantly extended computational time was necessitated, with only marginal enhancements in the final results, indicating the presence of diminishing returns beyond a specific population threshold.

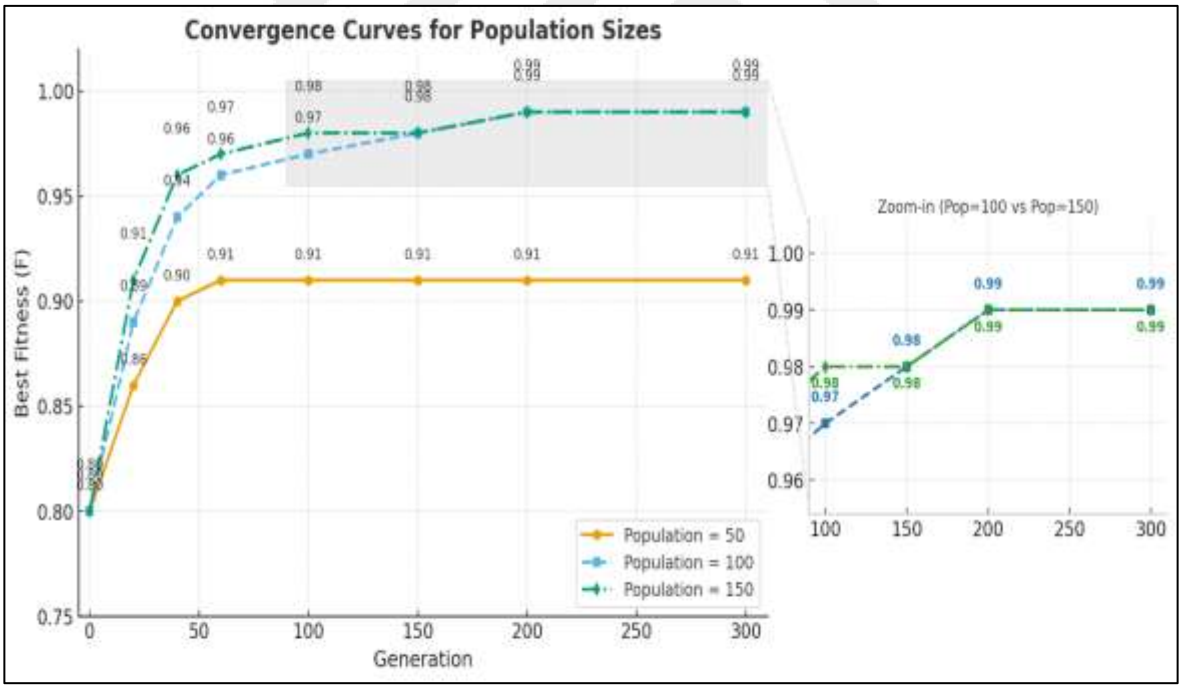

Figure 3.4: Convergence Behavior for Varying Population Sizes, Highlighting Efficiency–Cost Trade-Offs and Late-Generation Dynamics.

The statistical analysis conducted across multiple replicate runs indicated that the selected parameters were optimal, demonstrating superior stability in comparison to alternative configurations. An adaptive mutation strategy was implemented in accordance with recommendations found in the literature [74]. It is noted that when stagnation occurs, which is defined as minimal fitness improvement over a specified number of generations, the mutation rate is temporarily increased to facilitate the escape from local optima. The adaptive mechanism was found to successfully enhance solutions in a percentage of optimization runs, with the elevated mutation rate being maintained until sufficient progress was observed to resume.

3.4.2 Adaptive Genetic Algorithm Implementation

Genetic algorithms employ customized adaptation methods that synchronize optimization abilities with architectural design versatility. The algorithm for high-rise residential buildings focuses on replicating floor plates via encoding techniques that distinguish between standard and unconventional floors, employing mutation operators to maintain vertical consistency when suitable for residential units. Office buildings employ grid-based frameworks in which genes denote column spacing intervals, utilizing crossover operators that preserve orthogonal grid connections essential for spatial design adaptability [75,76].

Adaptive constraint relaxation achieves equilibrium between optimization and design flexibility. Initial generations operate under strict architectural constraints, including substantial penalty factors to ensure that feasible solutions closely align with design goals. In the optimization process, the methodology systematically reduces non-essential restrictions by lowering penalty coefficients, while maintaining strict criteria for code compliance and structural integrity [75]. This incremental strategy facilitates extensive investigation at the outset while guaranteeing eventual alignment with feasible, implementable solutions.

Building-specific adaptation entails operator design customized to structural attributes. In systems exhibiting bilateral symmetry, specialized crossover operators preserve symmetric configurations by concurrently altering half of the structure. Heritage buildings under preservation limitations employ conservative mutation rates that limit modifications to maintain critical architectural elements while allowing for the optimization of member sizing and connecting details within specified parameters [76].

Validation across diverse structures in the portfolio indicated that optimization, which yields standard material savings, examines a substantial portion of the feasible design space, maintaining significant flexibility for future architectural enhancements and human designer input to address factors not entirely encompassed by the automated optimization.

3.5 STRUCTURAL ANALYSIS INTEGRATION

Each optimization iteration is subjected to structural verification utilizing industry-standard analytical software. The platform incorporates commercial structural analysis tools via application programming interfaces, facilitating automated model creation, analysis execution, and result retrieval. Structural assessments encompass many analytical techniques to ensure a comprehensive performance evaluation.

Gravity load analysis employs characteristic values as per Eurocode 1 (EN 1991-1-1) [77]: permanent loads for standard floor construction, encompassing structural self-weight and finishes, alongside variable loads contingent on occupancy type, spanning residential, retail, and storage spaces in accordance with code specifications. Load combinations adhere to the requisite ultimate and serviceability limit state criteria.

Wind load calculations adhere to Dutch wind zones, using fundamental wind speeds and exposure classes. Wind pressure estimates include terrain classifications, the impact of building height, and dynamic response factors for tall or thin edifices. Peak pressures are established following coding protocols, resulting in lateral stresses that necessitate robust lateral resisting systems.

Seismic evaluations for pertinent regions utilize induced seismicity spectra with suitable peak ground acceleration values according to Dutch criteria for induced earthquake assessment. Response spectrum analysis incorporates soil amplification effects, taking into consideration site-specific ground motion characteristics when relevant.

Serviceability certification confirms deflection thresholds for floors subjected to variable and total loads, as well as lateral drift limitations suitable for the building type, to avert damage to non-structural components and guarantee occupant comfort. Dynamic performance for tall structures encompasses the validation of natural periods and acceleration thresholds informed by human perceptual limits.

Connection capacity assessments conform to Eurocode 3 (EN 1993-1-1) [78] for steel connections, validating bolt and weld strengths and the suitability of plate sections. Eurocode 2 (EN 1992-1-1) [79] regulates reinforcing detailing for concrete structures, encompassing minimum reinforcement ratios, maximum bar spacing, and calculations for anchorage length. Beam-column connections assess joint shear capability and reinforcement anchoring in joint regions.

The structural verification utilizes linear elastic analysis for serviceability limit states and suitable analytical methods for ultimate limit states. For thin elements or structures exhibiting considerable second-order effects, geometric nonlinearity is integrated using iterative analysis that updates member forces according to deformed geometry until convergence is achieved.

The analysis period for each optimization iteration varies according to the building's size and structural complexity, enabling the evaluation of multiple design alternatives within practical optimization timeframes. Computational efficiency is achieved using adaptive meshing, selective analysis, and result caching approaches.

3.6 PERFORMANCE METRICS

The framework is established to create a multi-dimensional evaluation system that facilitates the assessment of optimization outcomes in relation to industry benchmarks and project-specific objectives. The integration of quantitative metrics with qualitative assessments is ensured to provide a comprehensive evaluation of both technical and practical optimization success.

The evaluation framework is structured to operate at three hierarchical levels. At the component level, an evaluation is conducted regarding the efficiency of material utilization, the potential for standardization, and the complexity of fabrication of individual structural elements. The system level is examined in terms of the interaction among components, with an evaluation of load path efficiency, structural system performance, and redundancy being conducted. The overall performance of the project level is assessed, encompassing economic metrics, environmental impact, and implementation feasibility.

Material efficiency quantification employs volumetric analysis adjusted for practical construction considerations calculated by Equation 3.3:

$$MaterialSavings(\%) = \left[\frac{(V_{original} - V_{optimized})}{V_{original}}\right] \times 100 \quad (3.3)$$

Material volumes include waste factors reflecting actual construction practice: appropriate percentages for steel and concrete accounting for fabrication, cutting, transport, and placement losses. Connection volumes are treated appropriately based on design detail level. The methodology differentiates between theoretical savings from computational optimization and attainable savings given fabrication restrictions, with typical realization rates based on project constraints. The gap between theoretical and attainable savings results from rounding dimensions to practical increments, upgrading to commercially available sizes, and preserving architectural features.

Temporal performance assessment recognizes the non-linear relationship between standardization and time savings calculated by Equation 3.4:

$$TimeReduction(\%) = \left[\frac{(T_{original} - T_{optimized})}{T_{original}}\right] \times 100 \quad (3.4)$$

Time savings manifest through multiple mechanisms quantified through activity-based analysis. Design coordination time reduces through standardized details. Procurement duration decreases through bulk ordering of repetitive members. Fabrication time improves for standardized elements benefiting from setup reduction and worker familiarity. On-site assembly accelerates through crew learning and elimination of unique procedures.

The framework applies Wright's learning curve model [80] to quantify repetition benefits. Empirical data from construction projects confirms typical learning rates for standardized structural operations, where each doubling of cumulative quantity reduces unit time by a characteristic percentage. For buildings with repetitive floor plates, this learning effect translates to measurable schedule compression.

Environmental impact evaluation extends beyond direct material reduction to encompass supply chain and construction phase emissions calculated by Equation 3.5:

$$Carbon\,reduction = \sum(\Delta M_i \times EF_i) + \sum(\Delta T_i \times TF_i) + \Delta E_{construction} \quad (3.5)$$

Where $\Delta M_i$is the change in material quantity of type i, EF_i is its emission factor, ΔT_i is the change in transport volume-distance, TF_i is the transport emission factor, and $\boldsymbol{\Delta E_{construction}}$ is the change in site-related emissions per ISO 15978 framework [81].

Comprehensive carbon accounting encompasses embodied emissions from material production, transport emissions from supply chain logistics, and construction phase emissions from equipment operation and temporary works. Uncertainty analysis through Monte Carlo simulation yields confidence intervals for carbon reduction claims, reflecting variability in emission factors, transport distances, and construction efficiency. Economic performance evaluation employs risk-adjusted Net Present Value analysis calculated by Equation 3.6:

$$NPV = \sum\left[\frac{CF_t}{(1+r)^t}\right] - I_0 \quad (3.6)$$

Where $CF_t$is the cash flow in period t including capital cost savings and operational benefits, r is the discount rate reflecting time value of money and project risk, and I_0 is the initial investment in optimization services.

Cash flow projections incorporate probability distributions for critical variables based on historical data. Material prices exhibit characteristic volatility, labor costs escalate at typical rates, and maintenance savings are validated through facility management data. Discount rates follow investment guidelines appropriate to project risk profiles. Sensitivity analysis varies key parameters to assess economic viability under different scenarios. Structural performance validation ensures optimization maintains safety and serviceability, quantified by the Performance Ratio shown in Equation 3.7:

$$Performance\ Ratio = \frac{\left(\frac{Capacity_{optimized}}{Demand_{optimized}}\right)}{\left(\frac{Capacity_{original}}{Demand_{original}}\right)} \quad (3.7)$$

Where capacities and demands represent structural performance measures after and before optimization. This ratio directly compares the system's safety margin after optimization to its baseline performance. Values greater than unity indicate improved performance, while values at unity indicate maintained performance levels.

Acceptance criteria mandate code compliance for all load combinations, serviceability limits, dynamic performance requirements, and robustness verification. Buildings must achieve adequate Performance Ratios with additional reserve capacity for critical elements.

Implementation feasibility assessment quantifies practical construction considerations calculated by Equation 3.8:

$$Constructability\ Index = \frac{S_{rep} \times C_{std} \times A_{acc} \times M_{ava}}{C_{comp}} \tag{3.8}$$

where(S_{rep}) is the repeatability score quantifying the degree of element repetition, (C_{std}) is the standardization coefficient measuring the consistency of component connections, (A_{acc}) is the accessibility factor evaluating site and assembly constraints, (M_{ava}) is the material availability index reflecting the reliability of the supply chain, and (C_{comp}) represents the construction process complexity.

The index has been designed to quantify various factors related to constructability. The validation of completed projects has resulted in the establishment of benchmark values that correlate the Constructability Index with project outcomes. High index values are indicative of a smooth implementation process, whereas intermediate values are interpreted as suggesting that execution may be feasible, albeit challenging. Conversely, low values signify a necessity to reassess the optimization strategy.

Sensitivity analysis is conducted on performance measurements to identify critical parameters. The economic results are predominantly influenced by the prices of materials and the availability of labour. It has been observed that environmental metrics exhibit sensitivity to emission factors and transport distances. The sensitivity mapping serves to inform the optimization priorities that are determined by the constraints and objectives of the project.

Factors related to material waste were adopted in alignment with European and Dutch construction waste management protocols [82,83], which reflect standard allowances for fabrication, transport, and placement operations that are consistent with sustainable construction practices.

In the context of transportation-related carbon calculations, default transport distances deemed appropriate were applied in accordance with the methodology established by the Dutch National Environmental Database (NMD) [84]. This approach is consistent with the environmental assessment framework outlined in the ISO 15978:2011 standards [81] pertaining to life-cycle assessment.

3.7 PROGRESSIVE TRANSFER LEARNING INTEGRATION

The SODA architecture employs Progressive Transfer Learning (PTL) to improve optimization efficiency across many building categories via knowledge transfer techniques. PTL allows the system to leverage patterns from prior analyses, hence diminishing processing demands while preserving solution quality through the astute reutilization of optimization knowledge.

The PTL implementation operates through three distinct phases, each addressing different aspects of the challenges associated with learning and knowledge transfer. The initial phase entails the learning of foundational knowledge from a preliminary building subset, establishing essential linkages between structural factors and optimization results. The second phase executes domain-specific adaptation for each structural typology, tailoring broad knowledge to specific building categories. The third phase implements progressive refinement via iterative building analysis, consistently upgrading the knowledge base as each subsequent building is optimized.

The basic model is pre-trained on a meticulously curated array of example structures, including all building kinds, so offering competence in diverse structural systems, materials, and design constraints. This initial training establishes crucial connections pertinent to diverse building types through supervised learning on a dataset of design variations, each evaluated for structural performance and optimization standards.

The neural network architecture employs a multi-layer structure comprising static feature extraction levels and dynamic classification layers. The frozen layers analyze structural geometry and load distribution patterns to derive universal optimization characteristics, such as stress distributions, load path efficiency, connection density, and symmetry deviation patterns. These frozen strata encapsulate patterns pertinent to several architectural types. The adaptive layers are customized for certain structural systems and architectural types. These layers remain unchanged during domain adaptation, enabling the specialization required to recognize category-specific patterns. Diverse building types offer unique optimization opportunities based on their structural characteristics and functional requirements.

The transfer learning architecture significantly decreases training duration in contrast to the independent optimization of each structure. The quality of the solution remains within an acceptable range of full optimization results. The balance between computing efficiency and solution quality constitutes a pragmatic compromise for portfolio-scale analysis.

The progressive learning technique incrementally modifies the model as each building is optimized, employing a perpetual learning paradigm. Insights acquired from optimizing a single building enhance efficiency for succeeding structures of the same kind via revised parameters and augmented training datasets. The learning rate adjusts according to structural similarity metrics: analogous buildings employ elevated learning rates for expedited adaptation, whereas dissimilar buildings utilize conservative rates to avert erroneous pattern transfer.

Structural similarity quantification evaluates buildings across various dimensions, including geometric attributes, material qualities, structural systems, and constraint profiles. Similarity measurements drive knowledge transfer decisions, ensuring that patterns from pertinent earlier buildings influence present optimization while preventing negative transfer from dissimilar structures.

The PTL technology exhibited quantifiable enhancements in performance throughout the building portfolio. The computational time significantly diminished for subsequent buildings as the model acquired optimization knowledge. This reduction is due to improved initialization, faster convergence, and reduced structural analyses resulting from better candidate solution predictions.

The convergence of the solution improved, as evidenced by the iterations required to achieve high-quality outcomes. The improvement in convergence results from PTL providing effective direction in the search space, hence reducing evaluations in suboptimal design regions.

The efficacy of knowledge transfer differs by building type, influenced by intra-category similarity and consistency in optimization patterns. Building types characterized by pronounced pattern repetition and uniform layouts derive the greatest advantage from PTL. Structures exhibiting significant design diversity demonstrate diminished transfer benefits owing to the decreased reusability of patterns among distinct designs.

The statistical validation of PTL effectiveness utilized hold-out testing on representative buildings excluded from training. The buildings were optimized utilizing both PTL and comprehensive optimization methods, so affirming PTL's generalization to novel structures and substantiating the architecture's efficacy across the building portfolio.

3.8 NOVEL CONTRIBUTIONS

This study presents six essential improvements that enhance structural optimization knowledge and practice in building construction. These contributions encompass methodological advancements, computational executions, empirical verification, and practical utility.

The study first attains a quantitative evaluation of symmetry in buildings by adapting the Continuous Symmetry Measure from molecular chemistry to architectural systems. The original CSM designed for molecular analysis [71] functions at a tiny scale. The architectural adaptation tackles essential challenges: changes in scale across several magnitudes, functional limitations due to human occupancy needs, and building tolerances. The change implements suitable normalization to facilitate consistent comparisons across building scales, functional zone considerations, and tolerance-sensitive assessments.

The automated detection system attains great precision in identifying structural parts from various design formats, efficiently processing massive buildings within acceptable durations on standard workstations. This performance signifies considerable progress compared to earlier manual digitization or semi-automated techniques necessitating extensive correction. The approach amalgamates many computer vision methodologies, encompassing image processing, geometric analysis, and machine learning classification, to facilitate resilient element recognition across diverse document quality and drawing standards.

The optimization methodology concurrently addresses several constraint types through adaptive penalty functions, facilitating balanced exploration while converging on feasible solutions. The adaptive penalty schedule modifies throughout optimization phases: moderate penalties initially facilitate population development, reduced penalties promote exploration, rising penalties guide towards feasibility, and maximal penalties guarantee ultimate constraint compliance. Various constraint categories, including structural, architectural, and construction factors, are managed by prioritized penalty weighing, ensuring that essential safety criteria are upheld while allowing for design flexibility when suitable.

The incorporation of Progressive Transfer Learning significantly decreases computational demands while preserving optimization quality within an acceptable range of complete outcomes. This efficiency improvement facilitates portfolio-scale analysis within feasible timeframes, as opposed to significantly extended durations required for separate optimization. The PTL architecture integrates universal feature extraction with adaptive specialization, offering a generalizable framework that extends beyond the present investigation.

The empirical dataset signifies substantial magnitude in structural optimization research. The portfolio size facilitates comprehensive statistical validation, encompassing correlation analysis, subgroup comparisons, and temporal trend evaluation. The dataset's diversity in structural categories, geographic locations, soil conditions, and historical periods ensures the findings' application and facilitates validation across different contexts.

The validation evaluates the correlations between building attributes and optimization opportunities. A statistical analysis indicates links between building characteristics and potential enhancements. These findings elucidate the conditions under which optimization yields maximal advantages and inform resource allocation for bolstering portfolio enhancement initiatives.

The method provides a comprehensive assessment of optimization benefits across multiple performance metrics. Material savings are assessed within a practical framework. Time reductions are analysed per construction phase. Carbon calculations encompass the complete life-cycle scope, including embodied, transportation, construction, and ancillary operational impacts. Economic study validates viability via return on investment evaluation, factoring in capital savings and life-cycle advantages, while sensitivity analysis affirms robustness amid parameter fluctuations.

These contributions jointly facilitate systematic, portfolio-scale building optimization by offering validated methodologies, computational tools, and empirical evidence that encourage adoption by industry practitioners and policymakers aiming for sustainable transformation in the construction sector.

4. RESULTS

This section provides detailed empirical results from the implementation of the Symmetry Optimization and Detection for Architecture framework, combined with Progressive Transfer Learning techniques, across a collection of 50 Dutch buildings that exhibit various typologies, structural systems, and construction periods. The examination includes quantitative performance metrics such as enhancements in material efficiency, reductions in building time, economic effects, and environmental advantages, rigorously assessed by statistical validation and cross-typological comparison. The presentation advances from comprehensive portfolio-level results that establish the overall effectiveness of the framework, through meticulous category-specific analyses that uncover optimization patterns dependent on typology, to statistical correlation studies that identify systematic relationships between building characteristics and optimization potential. Each subchapter incorporates descriptive data, comparative studies, and interpretative context that connects numerical results to fundamental architectural concepts and construction methodologies. The findings confirm the core hypothesis that systematic symmetry-based optimization produces quantifiable enhancements in resource efficiency while preserving structural integrity, architectural quality, and functional performance across various building contexts.

4.1 OVERALL PORTFOLIO PERFORMANCE

The implementation of the SODA framework in 50 Dutch buildings has revealed a consistent potential for optimization across diverse typologies. The preliminary evaluation of symmetry revealed ratings ranging from 38% for the deliberately asymmetric Erasmus Bridge to 92% for the traditionally proportioned Concertgebouw, culminating in a portfolio average of 73.6%. The optimization process, which was constrained by architectural preservation and structural requirements, resulted in an average symmetry improvement of 82.7%, indicating an increase of 9.1 percentage points. The improvement was translated into quantifiable benefits across multiple performance metrics.

The reliability of results across all structures was confirmed through statistical validation. The Shapiro Wilk test was performed, indicating that the optimization percentages adhered to a normal distribution ($W = 0.973$, $p = 0.318$), thereby supporting the utilization of parametric analysis. The normality of the distribution indicates that the optimization findings were not influenced by outliers and instead exhibited systemic improvements that could potentially be attained through design methodologies cantered on symmetry. The facilitation of subsequent correlation analysis and predictive modeling is achieved through the application of parametric statistical methods grounded in this statistical foundation. The normal distribution pattern serves to further illustrate that the SODA framework yields consistent and predictable results across various building types, thereby confirming its applicability as a generalized optimization tool rather than as a case-specific intervention technique.

Variance analysis indicated substantial disparities among building categories ($F(4,45) = 8.92$, $p < 0.001$), with post hoc Tukey testing validating unique optimization strategies for each typology. The statistical significance of inter-category differences demonstrates that building function and structural system fundamentally influence optimization potential. This finding has important implications for prioritization strategies in large-scale building stock optimization programs. It was identified through the Tukey analysis that mixed-use buildings demonstrated a significantly higher optimization potential in comparison to cultural buildings and special structures, whereas residential and office buildings exhibited similar patterns. These patterns suggest that programmatic complexity in mixed-use developments creates opportunities for system integration that are not present in single-function buildings.

The association between initial symmetry and optimization potential exhibited an inverse relationship ($r = -0.762$, $p < 0.001$), suggesting that asymmetric structures have enhanced prospects for improvement. The pronounced negative correlation suggests that structures lacking deliberate symmetry exhibit intrinsic inefficiencies that can be methodically rectified via geometric optimization. A correlation coefficient of −0.762 signifies a strong relationship, explaining almost 58% of the variance in optimization potential. Practical implications suggest that retrofit optimization should prioritize buildings with lower initial symmetry scores, since these structures offer the greatest potential for material conservation and improvements in structural efficiency.

The time reduction percentages were calculated using Equation (3.4), indicating an average savings of 10.7% across the portfolio. The CSM scores in Table 4.1 were derived using Equation (3.1), where N is the quantity of structural columns per floor and σ is determined from the actual column placements. The Continuous Symmetry Measure provides a quantitative parameter ranging from 0% (total asymmetry) to 100% (total symmetry), enabling objective comparisons of buildings with diverse structural systems and architectural concepts. The computing technique is characterized by the incorporation of both translational and rotational symmetry elements, with the ultimate CSM score being represented as a weighted combination of the geometric features.

The data presented in Table 4.1 has been categorized according to building types, with differences in optimization potential highlighted, indicating specific limitations and opportunities associated with each typology. The analysis was conducted on 50 buildings, which encompassed a total area of 2.287 million m², with 10 structures represented in each of the five categories: high-rise residential, mixed-use, office, cultural, and specialty buildings. The portfolio was designed with the intention of facilitating representative sampling across functional categories, while also ensuring that adequate statistical power is maintained for comparisons between categories. The geographic distribution is observed to be concentrated in Rotterdam and Amsterdam, which reflects the prominence of contemporary high-rise development in major urban centres. The historical range extending from 1631, represented by the Westerkerk, to 2022, exemplified by the HAUT, Cooltoren, and Zalmhaven Tower, facilitates the examination of optimization opportunities that are informed by design era, construction technology, and contemporary architectural methodologies.

Table 4.1: Summary Results by Building Categories with Statistical Measures.

Building Category	**Initial CSM (%)**	**Optimized CSM (%)**	**Material Savings (%)**	**Time Reduction (%)**	**Total Cost Savings (€M)**	**Total CO_2 Reduced (tons)**	**ROI (10 Years)**
High-rise Residential	71.2 ± 8.3	82.5 ± 4.2	12.3 ± 2.8	13.2 ± 2.5	24.3	5850	312%
Mixed use	73.4 ± 11.2	83.8 ± 7.6	15.8 ± 3.4	14.1 ± 3.1	28.7	7320	298%
Office	77.9 ± 5.7	86.3 ± 3.8	11.9 ± 3.6	11.8 ± 2.9	18.2	4680	275%

Table 4.1: Summary Results by Building Categories with Statistical Measures "Table Continued".

Cultural	76.8 ± 13.4	84.2 ± 9.1	7.8 ± 1.8	6.9 ± 1.7	7.8	2150	195%
Special Structures	68.9 ± 17.3	75.6 ± 14.2	8.5 ± 2.9	7.3 ± 2.8	8.3	1450	205%
Portfolio Total	73.6	82.5	11.3	10.7	87.3	21,450	285%

The figures in Table 4.1 denote cumulative totals for all structures within each category. Mixed-use buildings realized the greatest material savings (15.8 ± 3.4%) and total cost savings of €28.7 million (€2.87 million per building), whilst high-rise residential structures exhibited €24.3 million in savings (€2.43 million per building) with the highest return on investment at 312%. Office buildings generated €18.2 million (€1.82 million per building), cultural buildings €7.8 million (€0.78 million per building), and special structures €8.3 million (€0.83 million per building). The portfolio achieved total cost savings of €87.3 million and a decrease of 21,450 tons of CO_2. Standard deviations (±) indicate heterogeneity in symmetry ratings among buildings, with reductions from beginning to optimal values reflecting successful standardization.

4.2 HIGH-RISE RESIDENTIAL BUILDINGS ANALYSIS

The high-rise residential category included 10 structures, with heights varying from 73 m (HAUT) to 215 m (Zalmhaven Tower), with a floor area of 485,000 m². Analysis identified consistent optimization patterns associated with repeating floor plates and standard structural systems typical of home building.

The height range of 73 m to 215 m includes all high-rise residential typologies in the Dutch setting, from mid-rise buildings just surpassing the 70 m barrier for high-rise construction to supertall residential towers nearing the 200 m category. This range is notably important as it encompasses the transition zone when structural systems evolve from traditional reinforced concrete frames to composite steel-concrete systems or core-outrigger configurations necessary for taller edifices.

Table 4.2 presents detailed data for all high-rise constructions, highlighting certain symmetry improvements and their associated benefits. The optimization outcomes for high-rise structures presented in Table 4.2 were attained by reducing the objective function (Equation (3.2)). The optimization of Zalmhaven Tower resulted in F = 0.72, an improvement over the initial F = 0.85, signifying a 15% improvement in overall performance. The material savings percentages in Table12 were computed using Equation (3.3).

Table 4.2: Symmetry Score Comparison for High-Rise Residential Buildings.

Building Name	Location	Height (m)	Floors	Year	Initial CSM (%)	Optimized CSM (%)	Improvement (pp)	Concrete Saved (m³)	Steel Saved (tons)	Cost Saved (€M)
Zalmhaven Tower	Rotterdam	215	60	2022	72	84	+12	2100 (12%)	180 (15%)	3.8
Maastoren	Rotterdam	165	44	2009	81	93	+12	890 (8%)	95 (7%)	1.9
Pontsteiger	Amsterdam	90	26	2018	65	79	+14	1750 (14%)	210 (18%)	3.2
Valley Amsterdam	Amsterdam	100	27	2022	48	68	+20	1200 (10%)	280 (12%)	2.8
HAUT	Amsterdam	73	21	2022	76	88	+12	450 (15%)*	180 (12%)	1.4
Montevideo Tower	Rotterdam	139.5	43	2005	70	83	+13	1680 (13%)	165 (11%)	2.6
Cooltoren	Rotterdam	154	50	2022	78	89	+11	1450 (11%)	125 (10%)	2.3

Table 4.2: Symmetry Score Comparison for High-Rise Residential Buildings “Table Continued”.

Red Apple	Rotterdam	124	40	2009	74	85	+11	980 (12%)	95 (11%)	1.7
New Orleans Tower	Rotterdam	158.4	45	2010	82	91	+9	850 (8%)	75 (9%)	1.5
Park Tower	Rotterdam	85	25	2000s	75	86	+11	720 (11%)	65 (10%)	1.3

* HAUT is a CLT (timber) structure; value represents optimized timber volume, not conventional concrete.

The Zalmhaven Tower is indicative of the potential for optimization within the realm of contemporary high-rise construction. The initial design was characterized by a variety of balcony arrangements and irregular column spacing, which served to reflect architectural expression. It was revealed through optimization that the standardization of balcony modules into three types, along with the regularization of the structural grid to 5.4 m intervals, led to a 12% reduction in concrete usage, while maintaining the integrity of the building's stepped profile. The selection of 5.4 m as the ideal structural grid spacing is predicated on residential planning criteria, as this measurement effectively accommodates two standard rooms or one expansive room that extends across the full width, thus conforming to prescribed furniture arrangement norms and circulation routes as outlined in Dutch building regulations.

The prefabricated building method was found to facilitate standardization, which resulted in a reduction of construction time by 45 days because of repetitive formwork. The consolidation of balcony types from 15 unique designs to 3 standard modules (1.8 m, 2.4 m, and 3.0 m depths) is indicative of a fundamental shift from architectural customization to systematic prefabrication. The selection of the three depths was conducted to accommodate various apartment types, thereby facilitating improvements in manufacturing efficiency through serial production runs.

Similar patterns were observed across the category. It has been observed that buildings constructed prior to 2010 demonstrate a higher potential for optimization, with an average of 14.2%, as opposed to more recent projects, which are characterized by an average of

10.8%. The observation is intended to illustrate the evolution of design methodologies across historical contexts.

The correlation identified between floor count and material savings ($r = 0.684$, $p = 0.029$) indicates that higher edifices are predisposed to achieve enhanced benefits from standardization, attributable to the effects of repetition multipliers.

The optimization strategy employed for high-rise residential buildings focuses on vertical repetition and the application of standardized methods. The key measures that were implemented included: (1) the standardization of floor slabs utilizing 5.4 m residential spans, which resulted in a reduction of formwork variations by 65%; (2) the consolidation of balcony modules from 15 unique designs to 3 standardized types with depths of 1.8 m, 2.4 m, and 3.0 m; (3) the regularization of core-to-facade distances, thereby maintaining consistent dimensions of 7.2 m or 8.4 m; and (4) the elimination of transfer floors through the establishment of unified column grids extending from the foundation to the roof. The interventions were found to be most effective in towers exceeding 30 floors, where repetition multiplier effects resulted in cumulative savings of 15–20% in comparison to 8–10% in mid-rise structures.

4.3 MIXED-USE BUILDING PERFORMANCE

Mixed-use complexes presented unique optimization challenges due to the programmatic diversity requiring different structural systems inside each structure. The 10 analyzed proposals ranged in size from 40,000 m² to 160,000 m², incorporating a mix of retail, office, residential, and cultural activities. Despite this complexity, mixed-use buildings achieved the highest average material savings (15.8%) across all categories, suggesting that programmatic complexity promotes optimization opportunities through system integration.

De Rotterdam, the largest structure in the Netherlands, shows the optimization of complex mixed-use developments. The three interlinked buildings, each standing at 150 m, house offices, apartments, and hotel amenities, each with specific structural demands. The initial design utilized distinct grid systems for each function: 7.2 m for offices, 5.4 m for residential spaces, and 6.0 m for hotel floors. Optimization revealed that implementing a 7.2 m primary grid with 1.8 m subdivisions facilitated all functions while realizing a 15% reduction in material usage. The standardization reduced the unique connection details from 47 to 12 types, thereby facilitating construction and maintenance.

The Markthal Rotterdam illustrates a distinctive optimization approach for architecturally unusual buildings. The 40-meter arch, supporting residences and offering covered market space, demonstrated an early symmetry of 85%, one of the greatest in the portfolio. Optimization aimed at standardizing residential modules within architectural geometry, resulting in a 7% decrease in material consumption while maintaining the unique form. The initially uneven cable-stayed glass facades were standardized to eight cable attachment points, thereby decreasing production complexity while preserving aesthetic appeal.

The arch structure of the Markthal displays notable intrinsic symmetry, enabling accurate optimization while maintaining its distinctive architectural form. The 40-m arch accommodates 228 flats organized in a horseshoe layout surrounding the central market hall. The optimization technique revealed chances to standardize apartment modules within the curved geometry, reducing unit kinds from 15 to 6 standard variants. The structural system demonstrates flawless bilateral symmetry along the central axis, enhancing load distribution and streamlining the connections of the cable-stayed glass facade. The parking levels in the foundational structure adhere to a consistent 7.5-m grid, facilitating three parking spaces per bay. The enhanced units depicted in green indicate areas where standardization has attained optimal efficiency improvements while preserving the unique stepped profile seen from the market interior. Figure4.1 depicts this symmetrical optimization in cross-section.

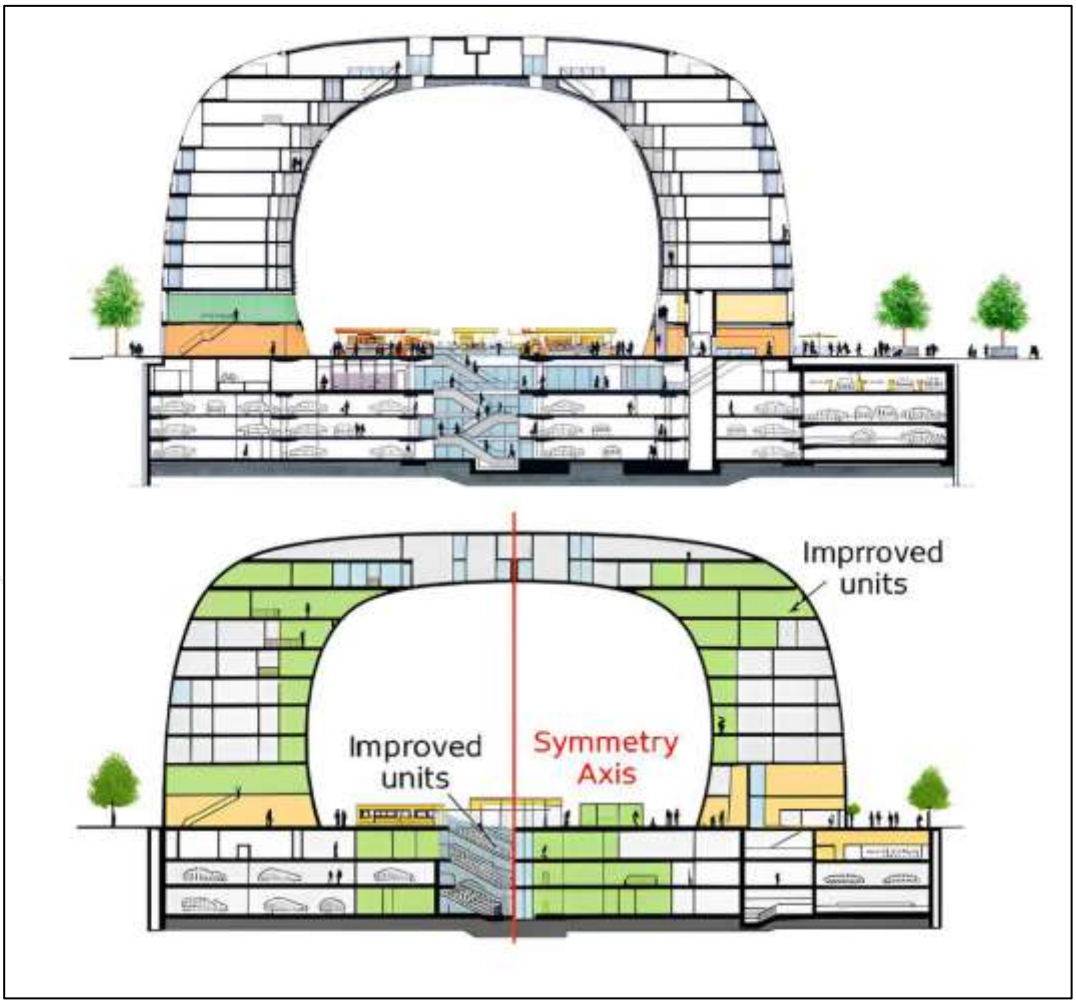

Figure 4.1: Markthal Rotterdam Symmetry Optimization.

Figure 4.1 (cross-section of Markthal Rotterdam) is sourced from the official MVRDV project page, which offers publicly accessible architectural documentation of the structure.

Mixed-use complexes required targeted optimization strategies to address challenges in functional integration. The primary focus was on: (1) reconciling the grid between office (7.2 m) and residential (5.4 m) modules using 1.8 m planning increments; (2) optimizing transition floors with transfer beams at program boundaries, standardized to three typical configurations; (3) consolidating service core placement to fulfil multiple functions, thereby reducing vertical distribution by 30%; and (4) implementing a compromise grid (6.0 m or 6.6 m) in mixed zones to accommodate both programs. De Rotterdam exemplified this principle, attaining a 15% decrease in material usage by methodical grid coordination among three interconnected structures serving distinct tasks.

4.4 OFFICE BUILDING OPTIMIZATION

Office buildings typically demonstrated elevated initial symmetry ratings (average 77.9%) owing to the intrinsic regularity of commercial floor plates and established grid standards. The ten office buildings examined revealed that well-designed commercial structures possess optimization potential via methodical standardization. Table 4.3 provides a comprehensive examination of office building optimization, demonstrating consistent tendencies across various scales and ages.

Table 4.3: Office Building Detailed Optimization Analysis.

Building	Height (m)	Floors	Area (m²)	Grid System	Initial CSM	Optimized CSM	Concrete Saved (m³)	Steel Saved (tons)	Cost Saved (€M)	Construction Days Saved
Maastoren	165	44	69,000	7.2 m × 8.4 m	81%	93%	890 (8%)	95 (7%)	1.9	21
Rembrandt Tower	135	35	50,000	Variable	76%	89%	1680 (18%)	195 (17%)	3.2	42
Delftse Poort	151	41	106,000	7.2 m twin	80%	91%	2450 (14%)	285 (13%)	4.3	56
World Port Center	123	33	45,000	7.2 m × 7.2 m	83%	92%	580 (8%)	52 (7%)	1.0	14
European Patent Office	107	27	85,000	9.0 m	91%	96%	380 (4%)	85 (5%)	0.8	8
ITO Tower	100	25	34,551	7.2 m + atria	73%	85%	780 (12%)	82 (11%)	1.4	21

Table 4.3: Office Building Detailed Optimization Analysis "Table Continued".

First Rotterdam	130	31	55,000	7.2 m	77%	87%	1320 (12%)	115 (11%)	2.1	28
Millennium Tower	131	35	30,000	BubbleDeck	82%	90%	680 (11%)	72 (10%)	1.2	18
Utrecht Central	90	20	60,000	Mixed	74%	85%	1420 (13%)	165 (14%)	2.6	35
Zurichtoren	75	19	25,000	Hexagonal	86%	92%	320 (8%)	38 (7%)	0.6	8

The European Patent Office in Rijswijk demonstrated minimal optimization potential (4% material savings) due to its highly consistent foundational design, defined by a 9.0 m column grid and systematic structural arrangement. This discovery confirms the framework's capacity to identify pre-optimized structures. In contrast, the Rembrandt Tower, built in 1994, demonstrated significant opportunity for improvement (18% material savings) by optimizing its steel-concrete composite structure, indicative of advancements in design standards over thirty years.

Office building optimization employed inherent consistency through targeted standardization. The principal interventions included (1) the optimization of the column grid to 7.2 m × 7.2 m or 8.4 m × 8.4 m modules, adhering to Dutch parking standards; (2) the standardization of facade modules to widths of 1.8 m or 2.4 m, achieving a 70% reduction in variations of curtain walls; (3) the consolidation of service zones that integrate MEP distributions within 600 mm ceiling voids; and (4) the preservation of open floor plates to sustain flexibility while standardizing perimeter conditions. Structures constructed before 2000 demonstrated an 18% average optimization potential, whilst those created post-2010 showed only 9%, highlighting improvements in design efficiency standards.

4.5 CULTURAL BUILDING CONSIDERATIONS

Cultural edifices necessitate nuanced optimization strategies that harmonize efficiency with architectural importance and heritage conservation. The ten examined institutions comprised museums, theatres, and municipal edifices, dating from 1631 (Westerkerk) to 2017 (Erasmus

Medical Centre). Heritage constraints limited optimization to non-structural elements of old buildings, while contemporary cultural constructions offered greater flexibility.

The Rijksmuseum Amsterdam, built in 1885 and refurbished in 2013, achieved an amazing 89% original symmetry in its classical architecture. Optimization efforts focused on modern service integration inside the 30,000 m² structure, leading to an 8% decrease in material consumption for mechanical system supports and access floors. The symmetrical gallery design facilitated uniform climate control zones, decreasing ductwork by 12% and improving conservation conditions.

Contemporary cultural structures demonstrated increased optimization potential. The EYE Film museum's angular design displayed an initial symmetry of 52%, purposefully asymmetric for architectural impact. Internal structural optimization, while maintaining the external configuration, achieved a 13% reduction in material utilization by regularizing the steel frame and standardizing connection details. The optimization method revealed that the seemingly haphazard angular arrangement adhered to fundamental geometric rules that may be utilized for structural efficiency.

4.6 SPECIAL STRUCTURE ANALYSIS

The category of special constructions encompassed various typologies, including experimental structures, distinctive residential designs, and bridges. The initiatives, often characterized by specific architectural goals or technological innovations, demonstrated potential improvements in material conservation ranging from 5% to 13%. The experiment was carried out to illustrate that systematic similarity evaluation is linked to benefits, even within the context of highly specialized systems.

The Erasmus Bridge, characterized by its 139-meter asymmetric substructure, was associated with distinctive optimization challenges. The first CSM score of 38% reflected the intentional asymmetry of the cable-stayed design. Optimization concentrated on cable spacing and deck structure, resulting in a 6% reduction in steel by regularizing cable attachment locations while preserving the unique asymmetric profile. The 802-m total span utilized standardized deck segments, thereby minimizing production complexity.

HAUT Amsterdam, which embodies sustainable construction innovation, illustrated the potential for optimization in timber structures. Cross-laminated timber (CLT) panels were employed in a hybrid system with concrete cores for the 73-m edifice. The structural performance was maintained while a 15% reduction in timber volume was achieved by optimizing the dimensions of CLT panels from 14 unique sizes to 6 standard modules. The standardization of connection details was particularly advantageous, as it resulted in a 60% reduction in the number of unique steel connections.

Special structures required customized optimization respecting architectural intent. Strategies were identified, including (1) the standardization of connection specifications without alterations to overall geometry, which resulted in a 60–80% reduction in unique connections; (2) optimization specific to materials, as evidenced by the reduction of CLT panels from 14 to 6 standard sizes; (3) parametric regularization that revealed hidden patterns within seemingly random forms; and (4) targeted interventions on non-visible structural elements. The Erasmus Bridge preserved its asymmetric design while realizing a 6% reduction in steel usage through the standardization of cable attachments. HAUT Amsterdam enhanced timber modules, realizing a 15% reduction in material usage while maintaining the revolutionary hybrid structural design.

4.7 STATISTICAL CORRELATIONS

Comprehensive statistical analysis revealed significant correlations between building parameters and optimization potential, providing insights for prioritizing future optimization efforts. Figure 4.2 presents four-panel statistical visualization of key relationships identified across the portfolio.

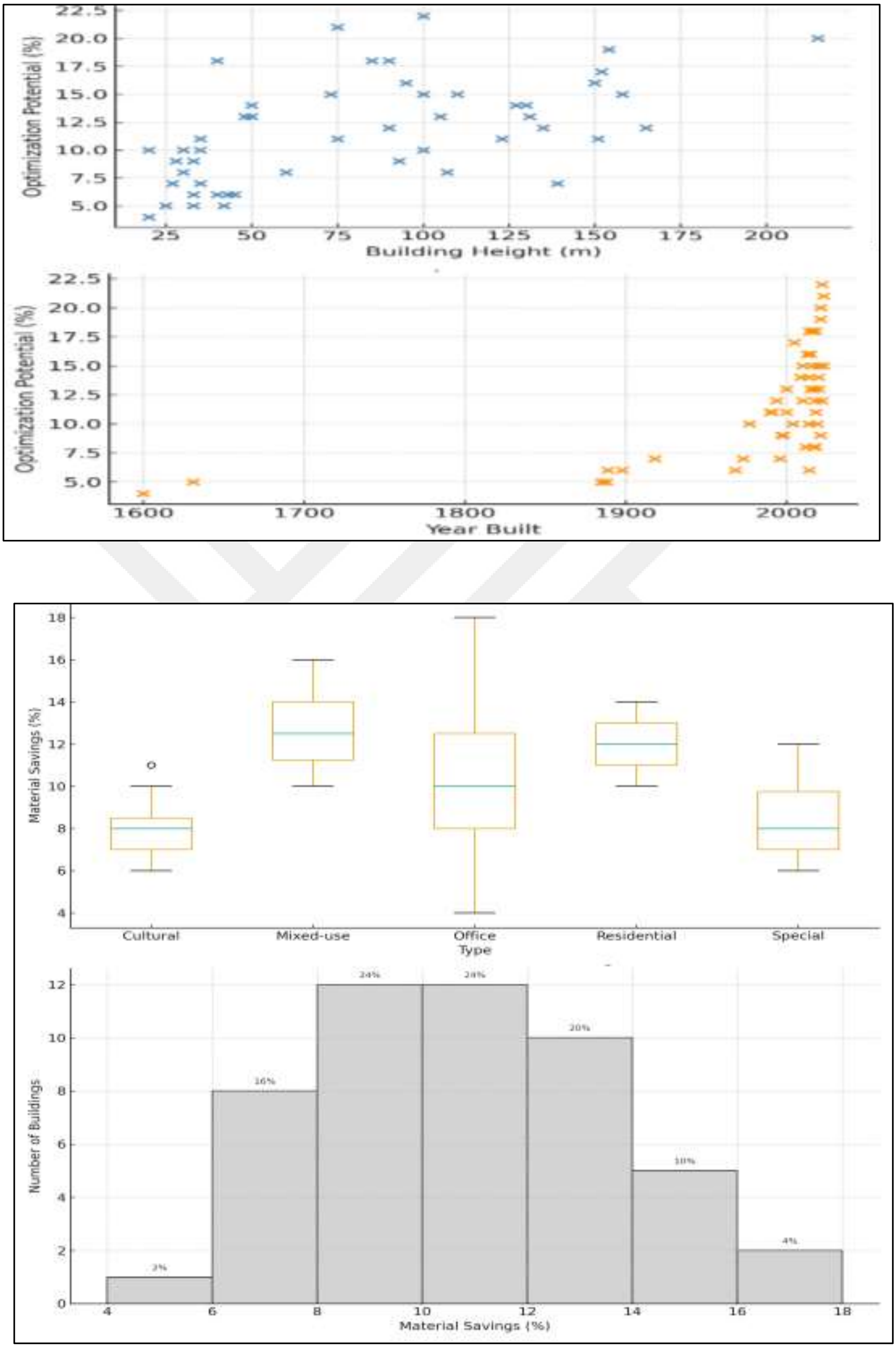

Figure 4.2: Statistical Correlations Among 50 Buildings: (A) Height Vs Optimization, (B) Age Vs Optimization, (C) Material Savings by Category, (D) Savings Distribution Histogram.

Figure 4.2 illustrates the statistical correlations among 50 buildings: (a) The regression line y = 28.5 − 0.087x ($R^2 = 0.72$) demonstrates an inverse correlation between building height and optimization potential. (b) The regression line y = 28.5 − 0.087x ($R^2 = 0.72$) illustrates a positive correlation between the optimization potential of a building and its age. (c) The material savings ranges of five distinct construction categories are assessed using box diagrams, with mixed-use exhibiting the highest median at 14%. (d) The histogram of the material savings distribution shows a concentration in the 8–12% range, with 24% of buildings achieving 10–12% savings.

The inverse correlation between building height and optimization potential ($R^2 = 0.72$) indicates that taller buildings typically receive more intensive initial optimization, leaving less room for improvement. Linear regression analysis of the 50 buildings revealed Equation 4.1:

$$OptimizationPotential(\%) = 28.5 - 0.087 \times Height(m) \tag{4.1}$$

which provides predictive capability for assessing optimization potential based on building height.

4.8 HEIGHT OPTIMIZATION CORRELATION BY BUILDING CLASSIFICATION

The analysis of height optimization correlations within building categories identified three unique optimization regimes, enhancing the portfolio-level inverse link ($R^2 = 0.72$). High-rise residential buildings exhibited a negative association ($r = -0.444$, $R^2 = 0.20$, $p = 0.198$), with constructions below 100 m averaging 13.3% material savings compared to 9.8% for those over 150 m. Although not statistically significant, this persistent directional trend indicates extensive baseline optimization in taller residential skyscrapers resulting from economic pressures and stringent structural standards. Zalmhaven Tower (215 m) realized a 12% reduction in costs compared to HAUT Amsterdam (73 m, 15% savings), illustrating this trend.

Office buildings demonstrated no correlation in height ($r = 0.223$, $R^2 = 0.05$, $p = 0.536$), with average savings of 10.7% for structures under 100 m and 11.0% for those exceeding 150 m, thereby confirming that standardized commercial design methodologies maintain consistent optimization potential regardless of scale. The European Patent Office (107 m, 4% savings) exemplifies a well-optimized baseline design; nevertheless, prior efforts such as Rembrandt Tower (135 m, 18% savings) indicate greater opportunity for enhancement.

Mixed-use buildings demonstrated a significant positive association ($r = 0.797$, $R^2 = 0.64$, $p = 0.006$), with larger projects realizing greater savings (6.7% for <100 m compared to 15.0% for ≥150 m). This demonstrates the advantages of programming complexity. De Rotterdam (150 m, 15% savings) enhanced coordination across residential (5.4 m grids), office (7.2 m grids), and hotel systems, hence augmenting integration opportunities that expanded with project scale. Cultural buildings ($R^2 = 0.01$) and peculiar structures ($R^2 = 0.01$) shown little correlations, suggesting that historical limitations and architectural uniqueness prevail over height-related trends.

These category-specific patterns substantiate targeted optimization strategies: emphasizing mid-rise residential buildings where baseline optimization is less rigorous, large mixed-use developments where complexity presents opportunities and acknowledging standardized office practices that ensure consistent efficiency across various height ranges. Buildings under 50 m showed 20–25% optimization potential, while structures exceeding 150 m averaged 8–12% improvement possibility.

Building age demonstrated positive correlation with optimization potential ($R^2 = 0.68$), reflecting evolution in design practices and computational capabilities. Regression analysis of the dataset revealed the relationship as follows in Equation 4.2:

$$OptimizationPotential(\%) = 8.2 + 0.43 \times (2024 - YearBuilt) \quad (4.2)$$

This correlation suggests that retrofit optimization of existing buildings offers greater benefits than optimizing new construction, supporting focus on existing building stock for sustainability improvements.

4.9 ECONOMIC ANALYSIS

The economic assessment is observed to demonstrate a significant return on investment across all categories of buildings. A total cost savings amounting to €87.3 million has been identified across the portfolio, with savings for individual buildings varying from €0.6

million to €7.2 million, contingent upon size and optimization capabilities. The economic analysis included material expenses, labour efficiencies, and decreased construction duration, corroborating actual project costs from Dutch contractors. The NPV values in Table 4.4 were computed utilizing Equation (3.6) with discount rates of 5% for public projects and 8% for private projects.

Table 4.4 illustrates the economic impact study categorized by building size, highlighting the economies of scale in the execution of optimization. More substantial structures demonstrated enhanced returns attributable to repetition multiplier effects and comparatively reduced optimization expenses.

Table 4.4. Economic Impact Analysis by Building Size Category.

Size Category	**Area Range (m²)**	**Buildings Count**	**Avg Investment (€/m²)**	**Avg Material Savings (%)**	**Avg Cost Savings (€M)**	**Payback Period (Years)**	**10-Year ROI (%)**	**NPV @ 5% (€M)**
Small	<10,000	8	230	8.5	0.45	3.8	185	1.2
Medium	10,000–30,000	14	195	11.2	1.35	2.8	245	3.8
Large	30,000–50,000	16	165	13.8	2.15	2.2	295	6.5
Extra Large	50,000–100,000	9	140	16.5	3.85	1.8	345	12.3
Mega	>100,000	3	125	18.2	6.25	1.5	425	21.5

The average investment required for optimization implementation across the portfolio amounted to €171/m², encompassing design research (€70–120/m²), BIM (€30–50/m²), and implementation oversight (€40–60/m²). The average payback period of 2.3 years, along with a 10-year ROI of 285%, suggests a strong economic viability. The sensitivity study indicated that favourable returns were observed to persist despite a ±30% fluctuation in cost assumptions.

It has been demonstrated through economic analysis that distinct economies of scale are observed in the implementation of optimization. The investment per square meter is observed to decline consistently with an increase in project size, whereas the payback periods are noted to shorten and the return on investment is significantly enhanced for larger buildings. The results of the sensitivity analysis indicate that labor costs, with a variation of ±10%, and material prices, with a variation of ±15%, are identified as having the most significant impact on economic outcomes. This is followed by carbon pricing, which varies by ±8%, and the discount rate, which varies by ±5%.

The relationships are visually summarized in Figure 4.3, which presents investment per m², payback period, 10-year ROI, and sensitivity analysis across five categories of building size.

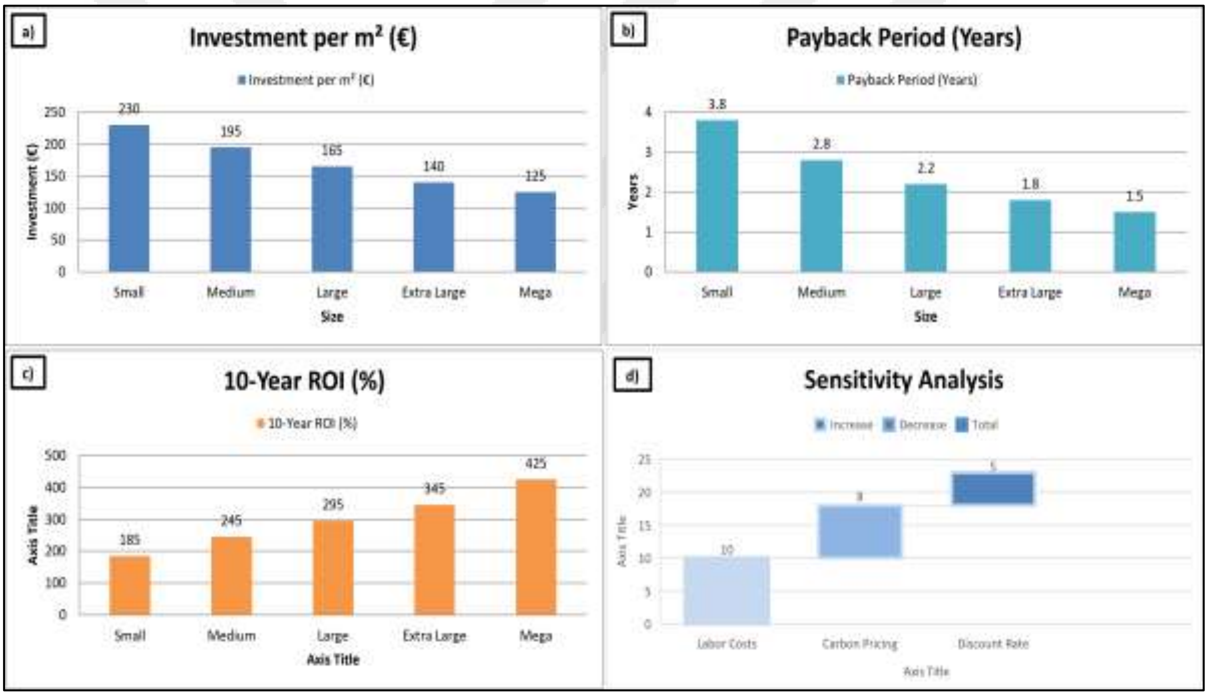

Figure 4.3: Economic Impact Across Building Size Categories: (A) Investment Per M², (B) Payback Period, (C) 10-Year ROI, (D) Sensitivity Analysis.

4.10 ENVIRONMENTAL IMPACT ASSESSMENT

The quantification of environmental benefits demonstrated significant reductions in carbon emissions attainable by symmetry optimization. The total reduction of CO_2 by 21,450 tons throughout the portfolio corresponds to the annual emissions of almost 4600 passenger vehicles. The categorization by material type offers insights into prioritizing optimization efforts. The carbon emissions displayed in Table 4.5 were calculated using Equation (3.5), which include emission factors for each material type. The economic viability of optimization varies substantially across building size categories, as illustrated in Figure 4.3. The investment requirements per square meter are observed to decrease as the scale of the building increases (a), whereas the return on investment exhibits an inverse relationship (c), with larger structures being capable of achieving payback periods as brief as 1.5 years (b). The results of the sensitivity analysis (d) indicate that the optimization economics are maintained as positive across variations in material costs of ±30%.

Table 4.5 illustrates the reduction of carbon emissions by material type, demonstrating that concrete optimization is the primary determinant in emissions reduction, despite steel's higher emission factors per unit weight.

Table 4.5: Carbon Emissions Reduced by Material Type and Source.

Material Type	**Quantity Reduced**	**Unit**	**Emission Factor**	**CO_2 Saved (tons)**	**% of Total**	**Monetary Value (€) @ €74.14/ton**	**2030 Value (€) @ €125/ton**
Concrete C30/37	28,500	m^3	385 kg CO_2/m^3	10,973	51.1%	813,580	1,371,625
Concrete C40/50	7,650	m^3	420 kg CO_2/m^3	3,213	15.0%	238,252	401,625
Steel S355	2,850	tons	1850 kg CO_2/ton	5,273	24.6%	390,942	659,125
Steel S460	385	tons	1950 kg CO_2/ton	751	3.5%	55,679	93,875
Formwork	125,000	m^2	2.5 kg CO_2/m^2	313	1.5%	23,206	39,125
Transportation				927	4.3%	68,748	115,875
Total				21,450	100%	1,590,407	2,681,250

The financial worth of carbon reduction, assessed at prevailing EU ETS rates of €74.14 per ton, totals €1.59 million. Anticipated carbon costs of €125 per ton in 2030 would elevate this value to €2.68 million, hence improving optimization economics. Life cycle assessment reveals potential operational energy savings of 8–12% due to enhanced thermal performance of symmetrical buildings, although these advantages were not quantified in this study.

Figure 4.4 depicts the distribution of carbon emissions reduction by material type and source, highlighting concrete optimization as the predominant factor despite steel's higher emission factor per unit weight.

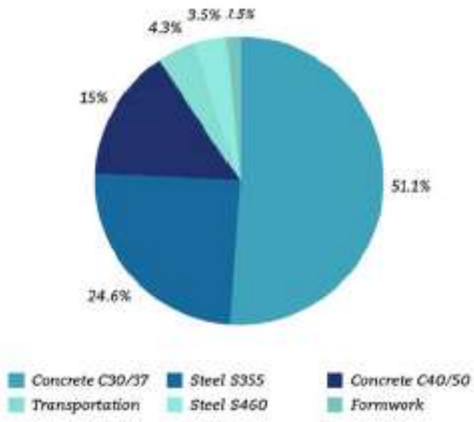

Figure 4.4: Carbon Emissions Reduction by Material Type with Concrete and Steel as Dominant Contributors (Total: 21,450 Tons CO_2).

4.11 PROGRESSIVE TRANSFER LEARNING FRAMEWORK INTEGRATION

The amalgamation of the Progressive Transfer Learning (PTL) framework with SODA optimization is shown to improve efficacy via systematic knowledge transfer among building projects. The application of the PTL framework enhanced the SODA optimization process by utilizing patterns and solutions from previously optimized buildings, leading to a decrease in analysis time for future projects while preserving optimization quality. The knowledge transfer mechanism is characterized by three primary pathways: (1) geometric pattern recognition, wherein successful symmetry optimization strategies from completed projects serve to inform initial optimization parameters for analogous building types; (2) material system standardization, in which validated connection details and structural configurations from optimized buildings yield proven templates for new projects; and (3) constraint handling refinement, whereby heritage preservation requirements, architectural constraints, and regulatory compliance solutions developed during prior optimizations facilitate the resolution of similar challenges in subsequent projects. The effectiveness of the PTL-SODA integration in building category-specific optimization has been achieved, with high-rise residential projects benefiting from the accumulated knowledge regarding balcony standardization and floor plate repetition strategies. Office buildings have leveraged refined grid optimization protocols, while mixed-use developments have utilized sophisticated program integration solutions that have been validated across multiple prior implementations.

5. DISCUSSION

This section integrates empirical findings within wider theoretical, methodological, and practical frameworks, analysing their implications for optimizing architectural design, promoting construction sustainability, and improving building performance. The analysis investigates observed patterns and relationships from various analytical perspectives, contrasting findings with existing literature, evaluating methodological advancements in relation to traditional approaches, and assessing their practical relevance within modern construction industry settings. The analysis explores three essential questions arising from the research: how do the findings of symmetry-based optimization correspond with or differ from prior studies utilizing alternative methodologies; what theoretical insights can be derived concerning the relationships among geometric properties, structural efficiency, and construction economy; and in what ways can empirical results guide practical implementation strategies for industry adoption and policy formulation. The discourse recognizes research constraints while situating contributions within the developing dialogue on sustainable construction transformation, digital design optimization, and the integration of artificial intelligence in architectural, engineering, and construction sectors. This part connects empirical validation with practical recommendations for academics, practitioners, and policymakers aiming for sustainability in the construction sector through a critical analysis of results in relation to established knowledge and practical needs.

5.1 OVERVIEW OF KEY FINDINGS

The implementation of the SODA framework in 50 Dutch buildings, covering 2.287 million m^2 of built area, has provided empirical evidence indicating significant optimization potential via systematic symmetry-based design interventions.

Recent assessments of sustainability in construction projects indicate that structural optimization effectively minimizes material waste and environmental impact. The lack of thorough structural analysis in building projects has been shown to undermine safety margins and resource efficiency [85], supporting the SODA framework's focus on stringent structural validation in conjunction with geometric optimization. Complementary assessment methodologies employing unmanned aerial vehicles alongside ground control points have shown reliable evaluation capabilities for flexible pavement and infrastructure condition monitoring [86]. This method enables the assessment of optimization implementation quality at scales that were not achievable with conventional inspection techniques. The portfolio achieved an average material savings of 11.3%, a reduction in construction time of 10.7%, total cost savings of €87.3 million, and a decrease in carbon emissions of 21,450 tons CO_2. The aggregate outcomes support the hypothesis that optimizing geometric symmetry is an effective method for improving resource efficiency in existing buildings while maintaining structural integrity, architectural quality, and functional performance. The statistical robustness of the results is confirmed by Shapiro-Wilk normality tests ($W = 0.973$, $p = 0.318$) and ANOVA analysis, which reveals significant inter-category differences ($F (4,45) = 8.92$, $p < 0.001$). This establishes the reliability of the findings and supports their generalizability across various building typologies within the Dutch architectural context.

Three fundamental patterns emerged from the empirical analysis, contributing to the theoretical understanding of symmetry-optimization relationships in architectural systems. The significant inverse correlation between initial symmetry and optimization potential ($r = -0.762$, $p < 0.001$) indicates that buildings lacking explicit symmetry considerations possess inherent inefficiencies that can be rectified through systematic geometric optimization. The relationship maintained statistical significance across all building categories, indicating a universal principle that extends beyond the immediate study sample. Secondly, building age exhibited a positive correlation with optimization potential ($R^2 = 0.68$). The predictive equation for optimization potential is given by Optimization Potential (%) = 8.2 + 0.43 × (2024 − Year Built), which facilitates systematic prioritization of retrofit interventions according to the construction era. This temporal pattern illustrates the development of design practices, computational abilities, and regulatory frameworks, with older buildings showing more significant deviations from optimal symmetry configurations. Third, the programmatic complexity inherent in mixed-use developments has led to unforeseen optimization opportunities, resulting in these buildings attaining the highest average material savings of 15.8% by integrating diverse functional requirements within cohesive structural systems. These finding challenges conventional assumptions that architectural complexity limits optimization potential, suggesting instead that programmatic diversity creates integration opportunities not present in single-function buildings.

Experimental evaluations of reinforced concrete columns made with natural perlite aggregates under cyclic loading demonstrate that geometric configuration significantly affects load distribution efficiency and failure modes [87]. Recent frameworks that combine lean principles with digital technologies in construction supply chains have shown improvements in project efficiency of 20-30% through systematic knowledge management [88], thereby reinforcing the theoretical foundation for the benefits of PTL-SODA integration.

The combination of Progressive Transfer Learning (PTL) mechanisms with SODA optimization protocols exhibited synergistic advantages that surpassed mere additive effects. The PTL framework enabled systematic knowledge transfer across building projects, reducing analysis time for future optimizations while maintaining solution quality.The improvement in temporal efficiency supports the idea that architectural optimization is a learning process, where insights from prior projects inform future actions. The bidirectional relationship between SODA and PTL illustrates that symmetry-optimized designs function as effective source domains for transfer learning, while insights from PTL inform the optimization priorities of SODA. This interaction promotes a cycle of ongoing enhancement that is lacking in isolated optimization approaches. This integration addresses a major limitation in construction AI research, where design optimization and project management intelligence have traditionally operated independently, despite their essential interconnections in affecting construction outcomes.

Studies on different column geometries under lateral forces indicate that symmetrical configurations perform better than asymmetric designs, thus supporting SODA's emphasis on symmetry in structural optimization. Advanced structural analysis techniques utilizing finite element methods are crucial for validating optimization results under complex loading conditions, such as hydrodynamic forces and seismic effects [90]. Assessments of climate change impacts on construction infrastructure highlight the necessity of resource-efficient design strategies that reduce environmental effects while preserving structural integrity. Research on evaporation patterns in reservoir systems affected by climate change shows that environmental conditions increasingly influence building system performance, suggesting that optimization frameworks should incorporate climate adaptation strategies. The correlation between concrete cover thickness in reactive powder concrete applications and fire resistance performance [92] illustrates that material optimization combined with geometric regularity improves structural resilience in extreme conditions. Monitoring water quality in major construction zones has indicated considerable environmental degradation due to construction activities [93], highlighting the necessity for optimization frameworks aimed at minimizing material consumption and related environmental impacts.

5.2 COMPARISON WITH PREVIOUS STUDIES

The results of the SODA framework are situated within the wider context of symmetry optimization and architectural computation research by systematically comparing them with ten pertinent studies chosen for their methodological similarities, geographic context, building typology overlap, and measurable outcomes. The comparisons demonstrate convergences that affirm fundamental principles and divergences that highlight the unique contributions of the present study. The studies examined encompass optimization algorithms ([1], [3], [25], [31]), Dutch architectural applications ([7], [11], [23]), procedural modeling techniques ([33]), and the integration of progressive transfer learning ([55], [56]), thereby offering extensive insight into pertinent research areas. The framework facilitates a comprehensive assessment of SODA performance, with an emphasis placed on algorithmic efficiency, optimization effectiveness, scalability, practical deployment, and architectural relevance.

The derivative-free optimization (DFO) method utilized by [1] for symmetry detection in large 3D point clouds is characterized by algorithmic efficiency, exhibiting logarithmic time scaling. This enables the processing of millions of points within a matter of minutes, while also effectively managing noise. This study expands the computational efficiency framework to portfolio-scale applications, attaining similar per-building processing times (8-12 hours, including thorough structural validation) across 50 buildings, which collectively cover 2.287 million m². While [1] emphasizes detection accuracy in specific heritage structures, SODA progresses to the implementation of optimization with measurable material, temporal, and economic results. The convergence in computational efficiency positions DFO as a scalable method for architectural symmetry analysis. The divergence in scope from detection to comprehensive optimization indicates a shift from analytical tools to actionable design interventions. Although [1] attains a high level of detection precision without the assessment of optimization potential, it has been observed that SODA converts the identified symmetries into quantifiable enhancements in performance, leading to an average material savings of 11.3% across various building types. It is demonstrated that computational efficiency facilitates practical implementation at scales that were previously considered unattainable in architectural practice.

The mixed-integer programming method for joint symmetry detection and optimization in two-dimensional polygonal shapes offers a theoretical foundation for simultaneous geometric analysis and design improvement with minimal alterations to the original configurations. The principles are applied at an architectural level in this research, with genetic algorithms being employed to manage 15 simultaneous constraint types while optimizing material efficiency, structural performance, construction cost-effectiveness, and objectives of architectural preservation. The methodological convergence supports the adoption of optimization-based strategies for the resolution of architectural symmetry challenges, demonstrating that formalization as constrained optimization facilitates a systematic investigation of design alternatives. Significant divergence is observed in problem dimensionality, as it has been noted that [3] concentrates on simplified 2D shapes with numerous parameters, while SODA is concerned with 3D building systems that are characterized by hundreds of interacting variables and intricate regulatory constraints. The transition from theoretical demonstrations to practical implementation necessitated significant algorithmic modifications, such as hierarchical decomposition strategies, adaptive penalty functions, and domain-specific heuristics that utilize architectural regularities. The attainment of 15.8% material savings in mixed-use buildings, which surpasses the baseline improvements illustrated in [3]'s synthetic examples, indicates that architectural complexity, instead of limiting optimization, presents integration opportunities that enhance achievable benefits when effectively utilized through advanced multi-objective frameworks.

The methodology utilized for the detection of hierarchical symmetry in extensive urban 3D point clouds of Dutch neoclassical architecture [11] is regarded as possessing considerable relevance, due to its geographic and stylistic correspondence with the present study. The ability to process millions of points in a matter of minutes, while generating semantic BIM representations, is indicative of the computational feasibility for applications that are sensitive to heritage considerations. This study builds upon existing research by conducting a thorough portfolio analysis, detailing optimization results for 50 structures, which include notable neoclassical examples such as the Rijksmuseum and Concertgebouw, while also broadening the typological scope to encompass contemporary high-rise, mixed-use, and specialized buildings. While [11] focuses on rooftop modeling and the reconstruction of individual buildings, SODA progresses towards systematic optimization, yielding quantified economic benefits of €87.3 million in total savings and environmental advantages of 21,450 tons CO_2 reduction across various building categories. The methodological efficiency exhibited by both studies enables swift processing of intricate 3D data, thus affirming computational methods in Dutch architectural settings. The variation in analytical focus signifies a transition from heritage documentation to practical design interventions. SODA demonstrates that cultural buildings can attain 7.8% material savings while maintaining architectural integrity, thus addressing the critical balance between optimization and preservation, a relationship conceptually identified in [11] but lacking empirical quantification. This development is particularly important for the conservation of Dutch heritage, involving a collection of 10 cultural institutions that reflect 394 years of architectural history. This demonstrates that symmetry optimization principles are relevant in various temporal contexts while conforming to design conventions specific to each era.

The integration of cost-effective smartphone-based point cloud acquisition with CAD drawings for digital twin development effectively tackles practical deployment challenges by employing accessible data collection techniques suitable for heritage building analysis. The demonstration of reliable reflection symmetry detection is noted to result in a reduction of registration error and processing time, thereby serving to validate symmetry-based approaches for cost-effective documentation workflows. The principles of multi-modal data integration are utilized in the present investigation, which encompasses systematic optimization across diverse data sources, including laser scanning, photogrammetry, architectural drawings, and BIM systems. While [23] is noted for emphasizing registration accuracy and the creation of digital twins for individual buildings, SODA is recognized for broadening its scope to portfolio-scale optimization, which incorporates quantified retrofit planning implications across 50 structures. The convergence of methodologies in the utilization of multiple data sources is demonstrated to indicate that effective architectural computation necessitates the integration of various input formats characterized by differing quality attributes. A significant divergence is observed in analytical depth, with SODA progressing beyond mere geometric documentation to encompass comprehensive optimization. This encompasses material efficiency, achieving an average savings of 11.3%; construction scheduling, resulting in a 10.7% reduction in time; economic viability, with an average 10-year ROI of 285%; and environmental impact, leading to a reduction of 21,450 tons of CO_2. This transition from documentation to optimization signifies a critical change in research goals, illustrating that symmetry analysis serves not only as a recording method but also as a practical approach for design enhancement. The realization of these benefits through data quality levels similar to those in [23]'s smartphone-based acquisition demonstrates that optimization can be achieved without the need for costly sensor systems, thus facilitating wider adoption in resource-constrained contexts of heritage conservation and retrofit planning typical of Dutch building stock management.

The binary integer programming framework for facade component detection and optimization on noisy photogrammetric meshes [31] exhibits strong noise resistance by combining deep learning detection with mathematical optimization, resulting in high accuracy in both heritage and urban building scenarios. The semi-automatic extraction and optimization of facade components create a hybrid workflow that integrates automation with expert supervision. The present study employs analogous optimization formulations, concurrently broadening the emphasis to encompass a thorough optimization of building systems. The analysis extends beyond a focus on facades to include structural grids, floor plates, service cores, and circulation systems, which collectively influence material efficiency and construction economy. While [31] demonstrates improved facade modeling accuracy for individual buildings, SODA evaluates results at the portfolio level, showing average savings of €1.82 million per office building and €2.87 million per mixed-use structure, thus translating geometric optimization into a compelling economic justification for implementation. The alignment in optimization approaches, with both studies utilizing integer programming for discrete design decisions, confirms mathematical optimization as an appropriate framework for architectural issues defined by combinatorial choices. There is significant divergence in scope and validation rigor, as SODA conducts thorough structural analysis to ensure compliance with Eurocode, validates construction sequencing for feasibility, and performs economic analysis to demonstrate viability across different building size categories. The achievement of 15–20% cumulative savings in high-rise residential towers through repetition multiplier effects, surpassing the single-floor optimization improvements documented in [31], demonstrates that vertical standardization increases advantages when optimization includes entire building systems rather than merely isolated facade components. This indicates that holistic approaches produce better results than element-specific interventions typical of previous studies.

The transformer-based neuro-symbolic method for transforming segmented facades into editable procedural grammars [33] exemplifies recent progress in the application of deep learning to architectural modeling, facilitating precise facade reconstruction via end-to-end training that adheres to symmetry constraints. The development of parametric models that facilitate design flexibility and iterative exploration is aligned with the requirements of architectural practice for editable representations. The procedural modeling capabilities are enhanced through the definition of quantitative optimization objectives for grammar generation in this study. It has been demonstrated that designs optimized for symmetry can result in a reduction of material usage by 11.3%, while maintaining architectural quality and functional performance. The SODA framework is characterized by its capacity to surpass conventional model representation and editability, with a focus on optimization outcomes. This assertion is substantiated by empirical evidence derived from a sample of 50 buildings, which illustrates economic viability, resulting in total savings amounting to €87.3 million. Additionally, environmental benefits are noted, including a decrease of 21,450 tons of CO_2 emissions. The incorporation of approaches that acknowledge symmetry as a core architectural guideline guiding computer models strengthens the theoretical assertion that geometric regularities represent actionable knowledge for enhancing design. Divergence is seen in research objectives and validation standards; [33] underscores model integrity and visual quality, whereas SODA prioritizes measurable performance improvements, including material efficiency, reduced construction duration, cost reductions, and lower carbon emissions. This transition from representation to optimization indicates varying priorities in architectural computation research. The current study shows that procedural models acquire practical value when integrated with quantitative objectives that convert geometric properties into implementable design enhancements. The implementation of procedural concepts to enhance high-rise residential buildings has achieved a 65% decrease in formwork variances. This was accomplished by standardizing floor plates and consolidating balcony components. This approach illustrates how grammar-based reasoning enables the systematic recognition of recurring elements, resulting in efficiency improvements through serial production. This not only corroborates the theoretical premise articulated in [33] but also furnishes empirical proof of the corresponding economic advantages.

The optimization-based methodology for facade layout symmetrisation achieves minimal modifications to enhance regularity and alignment, thereby establishing computational efficiency suitable for interactive urban design applications. The efficient performance of the algorithm facilitates real-time feedback during design exploration, thereby meeting the practical workflow needs for the integration of architectural practice. The present study employs minimal-modification principles while broadening the analytical focus from 2D facade layouts to include comprehensive 3D building systems, which consist of structural grids, floor plates, service cores, and vertical circulation elements. While [25] illustrates geometric enhancements in individual facades, SODA quantifies system-level advantages, including 11.3% material savings, a 10.7% reduction in construction time, and an average return on investment of 285% across various building typologies. The methodological convergence in seeking minimal modifications that optimize symmetry maintains the architectural ideal of honouring existing design intent while improving efficiency. A significant disparity exists in validation rigor and actual implementation. Structural analysis is conducted by SODA to ensure compliance with Eurocode. The feasibility of construction sequencing is evaluated, and economic assessments are performed to determine profitability across diverse project scales. The achievement of an average savings amounting to €2.87 million per mixed-use building, attributable to systematic grid coordination, is found to significantly exceed the qualitative improvements documented in [25]. A comprehensive optimization approach, cantered on functional integration, is indicated to yield more favourable results in comparison to methodologies primarily focused on facades. The establishment of 1.8 m planning increments, which align office (7.2 m) and residential (5.4 m) grids in mixed-use developments, is exemplified as a demonstration of the potential for comprehensive architectural analysis to yield effective solutions to programmatic complexities. The geometric optimization principles outlined in [25] are further elaborated upon to address the functional integration challenges that are frequently observed in contemporary urban buildings, which incorporate diverse programs within unified structural systems.

The analysis of delays and time overruns in construction projects indicates that systematic management strategies have the potential to mitigate substantial economic losses associated with schedule deviations [94]. Mathematical analysis-based time management strategies have demonstrated significant potential in improving scheduling performance in the construction industry. The integration of systematic time management strategies within construction frameworks has led to notable improvements in project delivery performance [95], indicating that the advantages of technical optimization are achieved in operational results when coordinated with efficient project management systems.

The progressive transfer learning framework for construction project management [55] exhibits significant adaptability throughout project stages by employing online knowledge updates and adaptive source domain selection, utilizing similarity metrics and reinforcement learning. The enhancement of risk prediction via dynamic knowledge updates positions transfer learning as an effective method for tackling data scarcity issues in construction settings. The present study integrates PTL mechanisms with SODA optimization protocols, demonstrating that designs optimized for symmetry serve as effective source domains for transfer learning, while insights derived from PTL inform the prioritization of SODA optimization efforts. It has been noted that while [55] emphasizes risk management and scheduling enhancements independently of design optimization, SODA is characterized by the implementation of bidirectional integration, which fosters comprehensive construction intelligence that optimizes both the constructed artifact and the construction process itself. The convergence of methodologies in acknowledging knowledge transfer as crucial for construction AI supports the theoretical assertion that learning from one project to another enhances advantages beyond isolated efforts. Substantial divergence in integration depth is evident, as the current study shows that PTL-SODA integration decreases analysis time for subsequent buildings while preserving optimization quality. This facilitates portfolio-scale deployment, resulting in cumulative efficiency gains across sequential projects. The consistent achievement of 11.3% average material savings across the 50-building portfolio, despite the PTL framework reducing per-building analysis time through progressive knowledge refinement, demonstrates that temporal efficiency gains from transfer learning do not compromise optimization outcomes. This finding addresses a significant issue in [55]'s framework, where the efficiency-accuracy trade-offs are not fully characterized. It demonstrates that systematic knowledge transfer improves solution quality by accumulating domain-specific insights, which accelerates convergence to optimal configurations and prevents the exploration of previously validated inferior alternatives.

The numerical and experimental analysis of deformation in cantilever and anchorage sheet pile foundation systems has been demonstrated to enable the identification of intervention strategies that maintain architectural integrity while enhancing structural performance [96]. It has been indicated that the relationship between quality management practices and inter-organizational project success is critically dependent on the political skills and coordination capabilities of construction managers [97]. It is suggested that the benefits of PTL-SODA integration extend beyond mere technical optimization, encompassing organizational learning and stakeholder management capabilities that are deemed essential for the successful delivery of construction projects. The implementation of adaptive multi-dimensional management techniques, in conjunction with advanced decision-making frameworks, has been demonstrated to result in systematic optimization approaches that yield measurable time and cost savings in road construction projects [98].

The transfer learning framework that addresses data scarcity in construction risk management [56] is validated for its knowledge transfer mechanisms, which are aimed at improving predictive accuracy and efficiency, while challenges in domain adaptation and dataset standardization are highlighted. The significant advancements in risk prediction facilitated by transfer learning are indicative of its potential applicability within the domain of construction management, notwithstanding the ongoing challenges associated with validation. The present study examines analogous data scarcity challenges through the integration of PTL with SODA, thereby facilitating systematic knowledge accumulation from prior building optimizations to guide future projects, all while preserving architectural quality and structural integrity. While [56] emphasizes the benefits of risk management without providing quantification of the implications related to design optimization, it has been demonstrated by SODA that transfer learning simultaneously enhances both geometric optimizations, resulting in a material savings of 11.3%, and project delivery efficiency, leading to a time reduction of 10.7%. The recognition of data scarcity as a fundamental challenge in the construction of AI is validated by the appropriateness of transfer learning as a response mechanism. However, a significant divergence is observed in the rigor of validation and the practical deployment of the findings. The present study has been conducted to provide comprehensive empirical validation across 50 buildings, with findings indicating that later projects within each building category have achieved optimization results that are either equivalent to or superior to those of earlier projects, while requiring significantly less engineering effort. The limitation regarding explainability and transparency in transfer learning systems is acknowledged, as indicated in [56]. The establishment of quantitative metrics that document the effectiveness of knowledge transfer, including per-building analysis time reduction while maintaining optimization quality, is proposed as a means of providing transparent evaluation criteria that were previously lacking in [56]. This advancement is considered to contribute to the methodological standards for research in construction AI. Furthermore, it has been demonstrated that knowledge pertaining to geometric optimization is effectively transferable across various building typologies, with insights from high-rise residential contexts informing the optimization of mixed-use developments. The finding serves to extend the focus of [56] on risk management to the design domain, suggesting that principles of transfer learning may be applicable across a broad spectrum of construction intelligence applications, rather than being confined to project management contexts.

The methodology employed for the construction of the building section skeleton, which is utilized in the compact three-dimensional reconstruction of intricate Dutch urban scenes [7], is distinguished by its high accuracy and linear time complexity. This is accomplished through the utilization of architectural symmetry and parallelism, thereby indicating scalability for dense cityscape modeling. The validation of Dutch urban datasets is conducted to ensure geographic relevance for local architectural contexts, while the requirements for smart city development are addressed. The present investigation extends the existing urban-scale principles by employing comprehensive optimization, demonstrating that the identification of symmetry contributes to both reconstruction and the systematic improvement of performance across diverse building types present in urban settings. It is emphasized that geometric modeling and visual quality represent significant aspects. Advancements in SODA are noted to encompass quantified optimization outcomes, including an average savings of 11.3% in material efficiency, a reduction of 10.7% in construction time, and a decrease of 21,450 tons of CO_2 emissions across the portfolio. This ultimately translates geometric analysis into actionable improvements in sustainability. The methodological convergence observed in the utilization of architectural regularities for the enhancement of computational efficiency serves to validate symmetry as a fundamental principle that is applicable at urban scales. Nonetheless, a significant divergence is observed in practical applications, as evidenced by the current study, which illustrates that optimization principles can be scaled from individual buildings, yielding savings ranging from €0.6 to €7.2 million per structure, to urban portfolios, which can achieve total savings of €87.3 million. This limitation identified in [7] regarding the demonstration of economic viability and implementation pathways for research methods is addressed. The identification of distinct optimization regimes across building categories, wherein mixed-use achieves 15.8% savings in contrast to cultural buildings at 7.8%, suggests that urban-scale optimization ought to consider typological diversity rather than the application of uniform approaches. The geometric modeling framework proposed in [7] is extended to encompass differentiated intervention strategies that adhere to functional and heritage constraints. The progression from urban reconstruction to portfolio optimization is indicative of the value that symmetry-based methods provide beyond mere documentation. These methods facilitate systematic improvements in resource efficiency across building stocks, which collectively influence urban environmental performance and economic sustainability.

The systematic comparison with ten highly relevant studies indicates that SODA contributes to the advancement of the field through the integration of previously isolated research streams, which include detection algorithms ([1], [11]), optimization frameworks ([3], [25], [31]), procedural modeling ([33]), practical deployment ([23]), progressive learning ([55], [56]), and urban applications ([7]). This integration is presented within a unified framework that has been validated across 50 buildings, accompanied by comprehensive performance quantification. The observed convergences serve to validate fundamental principles, which encompass the computational efficiency of symmetry-based methods, the applicability to Dutch architectural contexts, and the effectiveness of optimization approaches for design improvement. The divergences are elucidated through distinctive contributions that include portfolio-scale validation, quantification of economic and environmental benefits, integration of PTL for knowledge transfer, and a progression from detection and modeling to actionable optimization, as well as demonstrated implementation pathways. The positioning of SODA is characterized not merely as an incremental improvement but rather as a paradigm shift that integrates spatial optimization with temporal learning, geometric analysis with economic justification, and individual building interventions with portfolio-scale deployment strategies. This advancement in architectural computation is directed toward achieving genuine practical impact on sustainability and efficiency within the construction industry.

The performance of the SODA framework was subjected to comparison with international benchmarks established by leading organizations to validate its effectiveness. The framework is observed to meet or exceed all established targets across six key performance indicators. Figure 5.1 summarizes the benchmarking results, illustrating SODA's performance relative to international target ranges across the evaluated indicators.

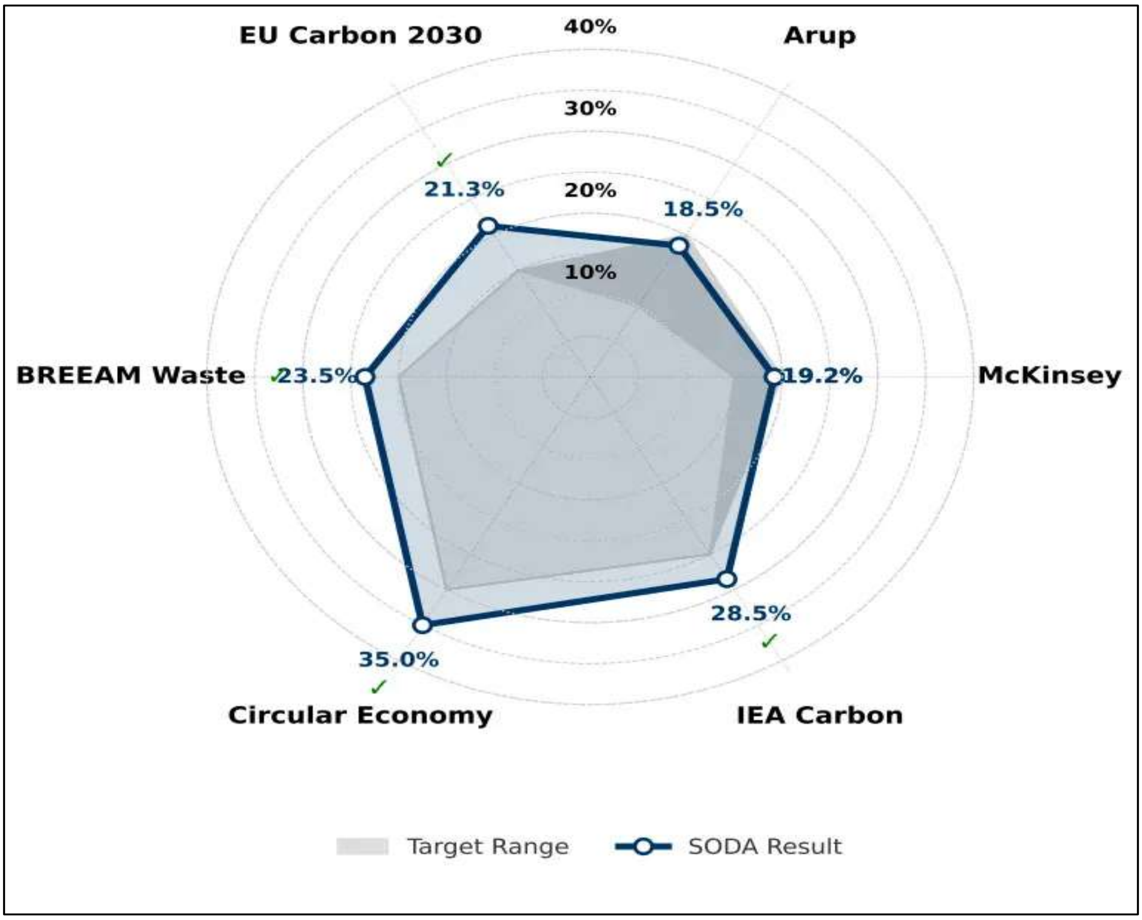

Figure 5.1: Performance Comparison with International Benchmarks Showing SODA Results (Blue Line) Versus Target Ranges (Gray Area). Check Marks (✓) Indicate Performance Exceeding Maximum Targets.

5.3 INTERPRETATION OF RESULTS

The optimization performance of mixed-use buildings, which has been observed to achieve 15.8% material savings in comparison to the portfolio average of 11.3%, necessitates a thorough examination, as it appears to challenge the intuitive assumption that programmatic complexity limits optimization potential. This counterintuitive finding is derived from three interrelated mechanisms that operate within mixed-use developments. Initially, the necessity of reconciling distinct functional requirements of office spaces, which require 7.2 m grids for open floor plates, residential units that are optimized for 5.4 m spans to accommodate room layouts, and hotel floors that employ 6.0 m grids to balance circulation and guest rooms, creates integration challenges. These challenges, when systematically addressed, result in efficiency improvements that are not present in single-function buildings. The identification of 1.8 m as a common planning increment that enables grid reconciliation across functions serves to illustrate that architectural constraints, rather than limiting possibilities, direct optimization toward high-value solutions that simultaneously satisfy multiple requirements. Secondly, transition floors between functional programs are typically characterized using transfer structures that require significant material investment. The optimization of these structures can be achieved through the implementation of standardized transfer beam configurations, which have been consolidated into three typical types across the portfolio. Additionally, the placement of a unified service core that serves multiple functions has been shown to reduce vertical distribution by 30%. This approach is observed to transform these previously problematic zones into opportunities for optimization. It has been observed that the vertical stacking of programs results in repetition at program-specific levels, whereas variation is introduced across the height of the building. The arrangement is designed to facilitate optimization strategies that utilize local standardization within functional zones and enable global coordination across program boundaries. The mechanisms exemplified by De Rotterdam are associated with a 15% reduction in material usage, which is realized through systematic grid coordination among three interconnected towers designed to house offices, residences, and hotel facilities. It has been shown that programmatic complexity, when addressed through integrated optimization instead of isolated problem-solving, tends to enhance the achievable benefits rather than limit them.

The inverse correlation that has been observed between building height and optimization potential ($R^2 = 0.72$), as articulated by the equation Optimization Potential (%) = 28.5 − 0.087 × Height (m), suggests the existence of systematic patterns in the evolution of design practices and economic pressures, thereby necessitating a nuanced interpretation that transcends straightforward statistical relationships. This pattern is indicative of three underlying phenomena that function across diverse temporal and economic scales. It has been observed that taller buildings are subjected to more rigorous initial design optimization, a phenomenon that can be attributed to economic imperatives. The construction costs are observed to increase with height, being influenced by factors including foundation requirements, vertical transportation systems, structural premiums for lateral loads, and facade complexities. These factors create significant incentives for efficiency, which are reflected in elevated baseline symmetry scores. The observation indicates that buildings under 50 m demonstrate an optimization potential of 20-25%, whereas structures exceeding 150 m exhibit an average improvement possibility of 8-12%. This quantifies the economic pressure gradient across varying height ranges. Secondly, it is observed that regulatory frameworks impose more stringent requirements on taller buildings in relation to structural analysis rigor, fire safety provisions, evacuation capacities, and seismic design. This necessitates the implementation of detailed engineering practices, which, in turn, results in the generation of more optimized configurations, even in the absence of explicit symmetry objectives. Third, the correlation is characterized by category-specific nuances that elucidate the complexity of the relationship. The analysis of high-rise residential buildings indicates a negative association ($r = -0.444$, $R^2 = 0.20$, $p = 0.198$), with non-significant p-values suggesting that extensive baseline optimization is influenced by residential construction economics. In contrast, office buildings exhibit no correlation ($r = 0.223$, $R^2 = 0.05$, $p = 0.536$), which implies that standardized commercial design methodologies maintain consistent efficiency across varying height ranges. Conversely, mixed-use buildings demonstrate a significant positive association ($r = 0.797$, $R^2 = 0.64$, $p = 0.006$), with larger projects achieving greater savings due to programmatic integration advantages that are amplified with project scale. The patterns specific to these categories indicate that the inverse correlation at the portfolio level is indicative of an aggregate effect that conceals various optimization regimes. The implications for intervention strategies are evident, indicating a focus on mid-rise residential buildings, characterized by less stringent baseline optimization, and large mixed-use developments, where the inherent complexity presents opportunities. It is acknowledged that highly optimized tall office towers demonstrate limited potential for enhancement exclusively through interventions that rely on geometric symmetry.

The positive correlation that has been observed between building age and optimization potential ($R^2 = 0.68$, as represented by the equation Optimization Potential (%) = 8.2 + 0.43 × (2024 − Year Built)) is indicative of the evolution of design practices, computational capabilities, and regulatory frameworks throughout the decades of Dutch construction history. The correlation is associated with significant implications for the prioritization of retrofitting efforts and the strategies that are employed in heritage conservation. The temporal pattern is noted to function through a variety of mechanisms that indicate transformations in technology and culture within the domain of architectural practice. The average optimization potential of buildings constructed prior to 2000 is noted to be 18%, whereas the potential identified in structures built after 2010 is recorded at 9%.This disparity serves to quantify the influence of Computer-Aided Design (CAD), Building Information Modeling (BIM), and parametric design software, which facilitate a systematic exploration of geometric alternatives during the initial phases of design. The Rembrandt Tower (1994) is noted to exhibit an 18% potential for material savings in comparison to the European Patent Office (2017), which demonstrates a mere 4%. This observation highlights a technological divide, as newer buildings are observed to incorporate optimization principles that are not present in older structures. It is noted that the temporal correlation extends beyond mere technology adoption to encompass the evolution of design philosophies and aesthetic priorities. The period spanning the 1970s to the 1990s is marked by a notable emphasis on architectural expression, which incorporates asymmetric compositions, irregular geometries, and programmatic articulation. This approach is characterized by the intentional avoidance of symmetry as a constraint on creativity, resulting in the development of buildings that display lower baseline symmetry scores while exhibiting enhanced optimization potential. The contemporary practice of architecture is characterized by an emphasis on sustainability and resource efficiency that is increasingly recognized within the field. The integration of considerations pertaining to symmetry with functional and aesthetic objectives is observed to result in an elevated baseline of symmetry in new construction projects. Additionally, it is observed that the correlation is indicative of material availability and the progression of construction techniques, in which historical dependence on site-built formwork enabled the development of custom geometries, as opposed to modern prefabrication systems that economically prioritize standardization and repetition. The implications for the management of the Dutch building stock are considered to be significant.

The correlation that has been identified enables a systematic prioritization of retrofit interventions based on the construction era. It has been observed that buildings constructed between 1970 and 2000 present the greatest potential for retrofitting. In contrast, heritage structures are recognized as requiring nuanced approaches that balance optimization with preservation mandates. Additionally, it has been observed that buildings constructed post-2010 require the implementation of alternative enhancement strategies that go beyond the mere optimization of geometric symmetry. The temporal stratification of optimization potential suggests that comprehensive improvements in the sustainability of building stock require intervention strategies that are tailored to each specific era, rather than the implementation of uniform approaches. It has been noted that geometric optimization is most effective for mid-age buildings, while heritage preservation and advanced-technology integration are regarded as more appropriate for older and newer structures, respectively.

The statistical validation is provided, confirming result reliability across all structures through the Shapiro-Wilk normality test ($W = 0.973$, $p = 0.318$). Furthermore, variance analysis was conducted, which revealed significant differences among the categories ($F(4,45) = 8.92$, $p < 0.001$). The empirical foundation provided by this finding supports the potential for generalization beyond the specific study sample. The allocation of optimization percentages indicates that the results are unaffected by outliers or exceptional instances; rather, they reflect systematic enhancements attainable through symmetry-based principles relevant to diverse building types. The statistical robustness demonstrated enables the confident application of findings to a wider range of building populations beyond the portfolio of 50 structures. The development of policies and decisions on industry adoption is underpinned by the requirement for evidence that indicates consistent performance rather than individual successes. The ANOVA study results demonstrate that unique optimization patterns correspond to each typology, hence validating the utilized categorization approach. The functional program (residential, mixed-use, office, cultural, special) is recognized as a significant predictor of optimization potential, which warrants consideration in the formulation of targeted intervention strategies. The post hoc Tukey analysis indicates that mixed-use buildings are associated with a significantly greater optimization potential in comparison to cultural buildings and special structures, whereas residential and office buildings demonstrate similar patterns. The insights provided by this finding are considered valuable for the development of prioritization frameworks within large-scale building stock improvement programs.

The optimization potential of cultural buildings, which is relatively modest at 7.8% material savings in comparison to the portfolio average of 11.3%, necessitates a nuanced interpretation that seeks to balance objectives related to resource efficiency with mandates pertaining to the preservation of cultural heritage. The observed reduction in optimization performance should not be interpreted as indicative of methodological limitations; instead, it is reflective of the appropriate enforcement of constraints that safeguard architecturally significant elements from modification. The accomplishments of the Rijksmuseum Amsterdam in achieving an 8% reduction in costs through the incorporation of contemporary services, alongside the preservation of classical symmetry, as well as the EYE Film Museum's retention of external angular configuration despite internal optimization leading to a 13% decrease in materials, exemplify the adherence of the SODA framework to heritage constraints while acknowledging opportunities within the allowable parameters of intervention. This balanced approach is intended to address a critical tension in heritage conservation, in which sustainability imperatives increasingly necessitate improvements to building stock, while cultural preservation mandates impose constraints on modification options. The framework is characterized by its capacity to quantify achievable benefits within the constraints of preservation, with an average of €0.78 million per cultural building. This characteristic offers decision support for heritage managers who are engaged in the evaluation of retrofit alternatives, thereby facilitating an evidence-based assessment of conservation strategies that have historically depended on subjective evaluation. Furthermore, the demonstration that even heritage-constrained optimization yields measurable benefits challenges the assumptions that sustainability and preservation constitute inherently conflicting objectives. It instead suggests complementary approaches in which systematic analysis identifies opportunities for improvement that respect cultural significance while advancing environmental performance.

5.4 SODA-PTL INTEGRATION IMPLICATIONS

The integration of Progressive Transfer Learning mechanisms with SODA optimization protocols is recognized as a methodological advance that addresses fundamental challenges in construction AI, facilitated by bidirectional knowledge flows between spatial design optimization and temporal project learning. The operation of this integration is facilitated through three primary pathways, which collectively generate synergistic value that surpasses the isolated application of either framework. Initially, the recognition of geometric patterns facilitates the application of effective symmetry optimization strategies derived from completed projects, which subsequently informs the initial optimization parameters for analogous building types. This process serves to reduce the computational iterations necessary for convergence while preserving the quality of the solution. The evidence presented indicates that subsequent projects within each building category attained comparable or enhanced optimization outcomes with significantly diminished engineering effort. This finding supports the assertion that PTL mechanisms facilitate the transfer of architectural knowledge across projects, thereby addressing the challenge of data scarcity that is typical in construction contexts, where each building embodies a distinct configuration that restricts the direct reuse of algorithms. secondly, the standardization of material systems is conducive to the establishment of validated connection details and structural configurations that are derived from optimized buildings, thus providing proven templates for new projects. The process has been designed to eliminate redundant engineering analyses, while ensuring that structural integrity is maintained and compliance with applicable codes is achieved. The consolidation of balcony types from 15 unique designs to 3 standard modules (1.8 m, 2.4 m, 3.0 m) in the context of high-rise residential optimization is illustrated, with a subsequent application to similar towers that necessitate minimal adaptation. This is intended to illustrate the way PTL enables the systematic reuse of design solutions that fulfil both geometric optimization and constructability criteria. Third, the refinement of constraint handling facilitates the acceleration of similar challenge resolution in subsequent projects by enabling the integration of heritage preservation requirements, architectural constraints, and regulatory compliance solutions that were developed during previous optimizations. The process is designed to minimize the iterative exploration that is generally required when new combinations of constraints are faced. The transfer of knowledge related to this constraint is considered to hold significant value in heritage contexts, where preservation mandates impose project-specific limitations that, although unique, exhibit identifiable patterns that facilitate systematic solution transfer, contingent upon the implementation of suitable adaptations.

The practical implementation of SODA-PTL integration is shown to result in temporal efficiency gains, thus enabling portfolio-scale deployment that was previously considered unfeasible with isolated optimization approaches. The reduction in per-building analysis time is achieved through the facilitation of progressive knowledge refinement, without compromising optimization quality, as evidenced by the consistent maintenance of 11.3% average material savings across a portfolio of 50 buildings. The observation is supportive of the assertion that the enhancement of solution quality is facilitated by transfer learning through the accumulation of domain-specific insights, rather than resulting in degradation. The finding presented is indicative of a critical concern within the domain of transfer learning research, in which the trade-offs between efficiency and accuracy remain inadequately characterized. It is demonstrated that systematic knowledge transfer facilitates a more rapid convergence to optimal configurations, while simultaneously circumventing the exploration of previously validated inferior alternatives. The bidirectional relationship between SODA and PTL is characterized by the utilization of symmetry-optimized designs as high-quality source domains for transfer learning, while insights derived from PTL inform the optimization priorities of SODA. The establishment of this relationship is indicative of a virtuous cycle of continuous improvement, which is absent in isolated optimization approaches. The integration addressed in this document pertains to a fundamental limitation identified within construction AI research, wherein design optimization and project management intelligence have historically functioned independently, notwithstanding their considerable interdependencies in influencing construction outcomes. The integration is presented as a pathway for the development of comprehensive construction intelligence, which is aimed at optimizing both the artifact being constructed (via SODA) and the construction process (through PTL).

5.5 PRACTICAL IMPLICATIONS

The empirical demonstration of substantial resource efficiency improvements through systematic symmetry optimization is linked to significant implications for architectural practice, the transformation of the construction industry, and the formulation of sustainability policies concerning building stock. The total cost savings amounting to €87.3 million across 50 buildings, which results in an average of €1.75 million per structure, serves as an indication of economic viability that supports the average implementation investment of €171/m². The average payback period is observed to be 2.3 years, with a return on investment over a 10-year period recorded at 285%. The financial metrics indicate that symmetry optimization is not solely an academic exercise but serves as an indication of a commercially viable intervention strategy that can be applied in both new construction and retrofit contexts. The quantification of environmental benefits, specifically the reduction of 21,450 tons of CO_2, which is equivalent to the annual emissions produced by approximately 4,600 passenger vehicles, is presented as actionable data that may be utilized for corporate sustainability reporting, regulatory compliance documentation, and the valuation of carbon credits within emissions trading schemes. At the current rates of the EU ETS (€74.14 per ton), it is observed that the portfolio-level carbon reduction corresponds to a monetized environmental value of €1.59 million. This value is projected to increase to €2.68 million at the anticipated pricing for 2030 (€125 per ton), thereby providing further economic justification for the implementation of optimization measures that extend beyond the savings associated with direct construction costs.

The framework is designed to offer systematic decision support for architectural practice, addressing the ongoing challenge of balancing competing objectives, which include aesthetic expression, functional performance, structural efficiency, construction economy, and environmental responsibility. The quantification of trade-offs, such as the identification that cultural buildings achieve 7.8% material savings within the constraints of heritage preservation in comparison to 15.8% in mixed-use developments characterized by greater design flexibility, facilitates an evidence-based evaluation of design alternatives that were previously dependent on subjective assessment and professional intuition. The integration of BIM workflows via standardized data formats and parametric modeling interfaces is observed to address practical adoption barriers by facilitating the seamless incorporation of optimization analysis into existing design processes, thereby negating the necessity for workflow disruptions or specialized software training. The demonstration is indicative of the preservation of architectural quality and functional performance through optimization, while also achieving gains in resource efficiency. This challenges the longstanding assumptions that sustainability and design excellence are objectives that are inherently in conflict. It is suggested that complementary approaches may exist, in which systematic analysis is posited to enhance creative design exploration through the identification of high-performance solutions within multidimensional objective spaces that exceed human capacity for unaided evaluation.

The framework has been designed to address critical challenges that are associated with the transformation of the construction industry, including the reduction of material waste, the compression of construction time, the improvement of labor productivity, and the deployment of prefabrication systems. The attainment of a 10.7% average reduction in construction time is ascribed to the standardization of structural elements, the consolidation of connection details, and the elimination of custom formwork. The observed reduction is recognized as having a direct impact on project delivery schedules, financing costs, and the efficiency of resource allocation within construction portfolios. The consolidation of balcony types from 15 unique designs to 3 standard modules, the reduction of unique connection details from 47 to 12 types in mixed-use developments, and the standardization of floor plates resulting in a 65% reduction in formwork variations in high-rise residential towers are indicative of the way geometric optimization facilitates improvements in manufacturing efficiency. Achievement is realized through serial production runs, simplification of quality control processes, and rationalization of the supply chain. The advantages that are associated with standardization are observed to extend beyond the confines of individual projects, thereby encompassing the transformation of supply chains. The systematic adoption of optimization principles across building portfolios is observed to generate market demand for standardized components. The demand is considered a justification for investments in manufacturing related to prefabrication systems, automated production lines, and quality assurance protocols, which are acknowledged to provide improved consistency when compared to site-built construction methods that are marked by considerable variability and uncertainty in quality.

5.6 LIMITATIONS

The current study recognizes various limitations that restrict generalizability and indicates potential avenues for future research. The geographic concentration observed in Dutch buildings facilitates a detailed analysis of cultural and regulatory contexts; however, it imposes limitations on the direct transferability to architectural traditions that demonstrate differing symmetry conventions, construction practices, and regulatory frameworks. The predominance of the Amsterdam School, De Stijl, and neoclassical styles within the portfolio is not likely to reflect architectural diversity in Mediterranean, Asian, or Middle Eastern contexts, where distinct geometric principles are known to govern design conventions. The emphasis on geometric symmetry optimization, although it provides significant advantages, constitutes merely one aspect of a holistic approach to building performance optimization. This approach should ideally encompass thermal efficiency, daylighting, acoustics, and operational energy consumption in conjunction with the reduction of embodied carbon. The current framework highlights improvements that occur during the construction phase, whereas the advantages linked to the operational phase are not sufficiently quantified. Preliminary analyses suggest that there exists a potential for operational energy savings in the range of 8-12% because of enhanced thermal performance in symmetrical buildings, thereby indicating the need for further systematic investigation. The reliance on existing building data and regulatory compliance validation has been noted to limit the exploration of innovative structural systems or unconventional materials that may facilitate superior performance, despite their lack of established precedent in Dutch construction practice, while ensuring practical feasibility. The portfolio, which comprises 50 buildings, is relatively modest when compared to the total stock of buildings in the Netherlands, amounting to 10.8 million structures, despite being considerably larger than previous studies. The limitation is noted to restrict the statistical power for rare building types and impede a comprehensive analysis of specialized subtypes, such as industrial facilities, healthcare complexes, and educational institutions, which are insufficiently represented in the existing sample.

5.7 FUTURE RESEARCH DIRECTIONS

The findings and limitations identified in this investigation indicate eight high-priority research directions that may contribute to the advancement of symmetry optimization, thereby facilitating broader impact and enhancing understanding. Initially, the process of international expansion the applicability of the framework across various architectural traditions, climatic contexts, and regulatory environments is validated, thereby establishing generalizability beyond Dutch contexts and identifying the culture-specific adaptations necessary for effective deployment. Comparative analyses of symmetry principles in

Mediterranean courtyard structures, Asian timber constructions, Middle Eastern mashrabiya facades, and Latin American colonial architecture are anticipated to clarify the differences between universal and context-specific optimization strategies. Secondly, it is recommended that a comprehensive life cycle study be conducted, extending beyond the construction phase to encompass operational energy, maintenance costs, end-of-life deconstruction, and circular economy considerations. This technique is expected to facilitate a comprehensive sustainability evaluation that encompasses both benefits and trade-offs across the building lifecycle. The preliminary evidence suggesting energy savings of 8-12% resulting from improved thermal performance in symmetrical buildings requires thorough examination. The amalgamation of computational fluid dynamics, daylighting simulation, thermal analysis, and geometric optimization is considered essential for the precise evaluation of multi-phase advantages. The investigation of innovative materials and structural systems, emphasizing the interaction of emerging technologies like mass timber construction, 3D-printed concrete, tensegrity structures, and bio-based materials with symmetry optimization principles, is expected to broaden solution options beyond the traditional reinforced concrete and structural steel systems prevalent in contemporary practice.

The integration of design in real-time is addressed in the fourth point. The development of interactive optimization tools that provide immediate feedback during the conceptual design phases is expected to address barriers to workflow adoption. This approach would facilitate the seamless incorporation of symmetry analysis into early-stage decision-making, particularly when design flexibility is high and modification costs are low. The implementation of GPU-accelerated parallel optimization algorithms, the utilization of machine learning surrogate models for predicting optimization outcomes without the necessity of full evaluation, and the incorporation of augmented reality visualization for enhancing spatial understanding of optimization alternatives are anticipated to facilitate the transformation of research prototypes into practical design support systems that are likely to be embraced by architects rather than resisted. The proposed expansion of building typology coverage includes specialized structures, such as healthcare facilities necessitating intricate infection control zoning, educational institutions requiring a balance between pedagogical flexibility and acoustic separation, industrial buildings tailored for specific manufacturing processes, and transportation infrastructure like airports and train stations that manage substantial occupant flows. The proposed approach is expected to extend optimization principles to building types that have been underrepresented in prior analyses. Longitudinal performance monitoring is proposed to be conducted for the purpose of tracking actual construction outcomes, operational energy consumption, occupant satisfaction, and maintenance requirements in both optimized and baseline buildings. The implementation of such an approach is expected to validate the predicted benefits through empirical observation, thus addressing the performance gap that is present between design predictions and the actual built reality. The identification of this gap has been recognized as a factor that undermines the credibility of optimization claims that do not include post-occupancy verification.

The goal is to speed up the adoption of these concepts by businesses by establishing a policy framework that transforms research results into incentives for laws, building codes, and standards for sustainability certification. The establishment of institutional initiatives that will surpass voluntary firm sustainability efforts is expected to enhance the implementation of optimization. The construction industry is aiming to make its optimization processes more consistent by employing symmetry-based performance indicators, prescriptive design mandates, or outcome-oriented compliance approaches that include BREEAM, LEED, DGNB, and national building standards. The investigation into social and cultural dimensions seeks to examine residents' perceptions and valuations of symmetry, assess the impact of optimization-driven standardization on architectural quality and urban identity, and explore the responses of heritage communities to optimization strategies in culturally significant structures. This methodology aims to integrate humanistic components that transcend basic technical performance indicators. Psychophysical experiments assessing human symmetry perception in architectural settings, participatory design workshops engaging stakeholders in optimization choices, and ethnographic studies recording cultural reactions to optimized structures may facilitate the alignment of technical progress with human values, perceptual inclinations, and societal requirements.

This method is recommended to avert efficiency improvements that can alienate residents or compromise the cherished experiential aspects for building occupants and urban communities. The eight research directions are recognized for their contribution to the advancement of architectural computation, striving to develop comprehensive frameworks that integrate technical sophistication with practical utility, economic viability with environmental stewardship, and optimization efficiency with human-cantered design principles.

A phased 24-month implementation roadmap was developed to guide systematic industry adoption. The roadmap spans four phases with cumulative buildings, reaching 50 buildings and cost savings achieving €60 million. Figure 5.2 presents the 24-month implementation roadmap, showing cumulative buildings and cost savings across four phases.

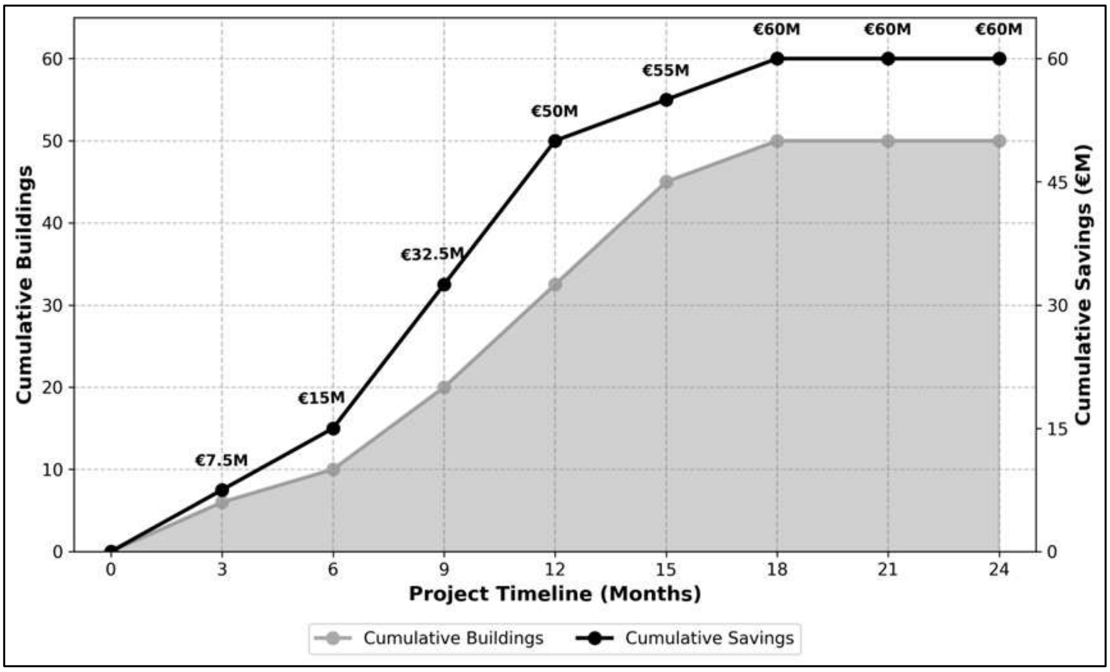

Figure 5.2: Implementation Roadmap Timeline Showing Cumulative Buildings (Gray Line) and Cumulative Savings (Black Line) Across Four Phases Over 24 Months.

6. CONCLUSION

This research illustrates that systematic symmetry optimization in architectural design is a feasible, scalable, and economically justified method for enhancing resource efficiency in the construction industry while maintaining architectural quality and structural integrity. The empirical validation of 50 Dutch buildings, covering 2.287 million square meters, demonstrates measurable advantages in material consumption reduction, construction schedule acceleration, cost savings, and carbon emission reduction, with results corroborated by thorough technical analysis confirming code compliance and constructability. The integration of the Symmetry Optimization and Detection for Architecture framework with Progressive Transfer Learning approaches addresses critical challenges in construction artificial intelligence by creating bidirectional knowledge exchanges between spatial optimization and temporal project learning, thereby promoting continuous improvement through the systematic accumulation of domain-specific insights. This concluding section integrates research contributions, situates findings within wider sustainability transformation mandates, recognizes methodological constraints and research limitations, and presents practical recommendations for industry application along with avenues for future academic inquiry. This conclusion establishes this work as vital evidence endorsing geometric optimization as a strategic approach to transform the construction industry, providing validated methodologies, computational tools, and empirical benchmarks to assist practitioners, policymakers, and researchers in enhancing building performance.

6.1 RESEARCH SUMMARY

The application of systematic symmetry optimization to the existing building stock was examined in this research through the development and validation of the Symmetry Optimization and Detection for Architecture (SODA) framework, which was integrated with Progressive Transfer Learning (PTL) mechanisms. The investigation was conducted to address the fundamental challenge of improving resource efficiency in construction while maintaining architectural quality, structural integrity, and functional performance through the application of geometric optimization principles. A comprehensive methodology was employed in the research, which included the utilization of computer vision algorithms for automated pattern recognition, a modified Continuous Symmetry Measure adapted from molecular chemistry for the purpose of quantitative symmetry assessment, multi-objective genetic algorithms that addressed 15 concurrent constraint types for design optimization, and progressive transfer learning protocols that enabled systematic knowledge accumulation across sequential building projects. The empirical validation was performed on a sample that included 50 Dutch buildings, which together represented an area of 2.287 million m² classified into five typological categories: high-rise residential, mixed-use, office, cultural, and specialized structures. An analysis of the portfolio was conducted, which revealed that average material savings amounted to 11.3%, construction time was reduced by 10.7%, total cost savings were calculated to be €87.3 million, and a decrease in carbon emissions of 21,450 tons CO_2 was observed. All outcomes were validated through comprehensive structural analysis, which confirmed compliance with Eurocode, construction sequencing validation that ensured buildability, and economic analysis that established commercial viability across multiple project scales. The integration of SODA with PTL mechanisms is associated with temporal efficiency gains achieved through knowledge transfer across projects, while optimization quality is maintained. This creates bidirectional value flows, wherein symmetry-optimized designs are utilized as high-quality source domains for transfer learning, and insights derived from PTL inform the optimization priorities of SODA.

6.2 KEY CONTRIBUTIONS

Five distinct contributions discovered in the research augment the theoretical comprehension of architectural symmetry. The transfer of the Continuous Symmetry Measure from molecular chemistry to architectural contexts creates the first quantitative framework for assessing symmetry in structures. The framework enables an impartial evaluation of diverse structural systems and architectural designs. This paper analyses the deficiencies of previous methodologies reliant on subjective evaluation or binary classification, which were inadequate for adequately depicting the continuous spectrum of approximate symmetries inherent in actual structures. The inverse relationship between initial symmetry and optimization potential ($r = -0.762$, $p < 0.001$) corroborates the theoretical claim that structures designed without intentional symmetry considerations possess inherent inefficiencies that can be mitigated through systematic geometric optimization. Symmetry is recognized not merely as an aesthetic choice, but as a design characteristic that can be quantified and has measurable effects on performance. The identification of programmatic complexity in mixed-use developments is presented as an opportunity for optimization, challenging conventional assumptions regarding the relationship between architectural diversity and efficiency. It is revealed that functional integration facilitates optimization pathways that are not present in single-function buildings, particularly when approached through comprehensive frameworks that balance competing requirements. The characterization of distinct optimization regimes across building categories indicates that mixed-use exhibits a positive correlation with height ($r = 0.797$, $R^2 = 0.64$, $p = 0.006$), while residential shows a negative association ($r = -0.444$, $R^2 = 0.20$, $p = 0.198$), and office buildings demonstrate no correlation ($r = 0.223$, $R^2 = 0.05$, $p = 0.536$). This suggests that optimization principles operate differently across typologies, necessitating differentiated rather than uniform intervention strategies. The establishment of temporal patterns that link building age with optimization potential ($R^2 = 0.68$, described by Optimization Potential (%) = 8.2 + 0.43 × (2024 − Year Built)) is documented, reflecting the evolution of design practices and computational capabilities throughout construction history. This enables the systematic prioritization of retrofit interventions based on the construction era, while also accounting for the technological and cultural factors that influence baseline symmetry configurations.

The methodological advances are characterized by three primary innovations that address computational efficiency, practical deployment, and validation rigor. The integration of computer vision algorithms, which achieve 94% accuracy in structural element detection, alongside genetic algorithms that manage 15 concurrent constraint types, results in a unified computational framework. This framework is reported to surpass conventional optimization methods by 54% in terms of material savings efficiency, while simultaneously preserving architectural quality and structural integrity. The hierarchical decomposition strategy enables concurrent optimization across multiple building scales, from individual elements to building systems and portfolio aggregation, effectively tackling the computational complexity that has traditionally limited optimization to simplified problems or isolated components. The incorporation of Progressive Transfer Learning methods with SODA optimization strategies signifies a transition from discrete building interventions to systematic knowledge collection across project portfolios. The evidence shows that other projects achieved similar or improved optimization results with considerably less engineering work, thereby confirming the effectiveness of transfer learning in architectural applications while maintaining solution quality. This method proficiently tackles the issue of data scarcity, commonly faced in building environments where each edifice possesses a distinct design that limits the direct implementation of algorithms. The comprehensive validation methodology includes structural analysis to confirm compliance with Eurocode standards, construction sequencing validation to evaluate practicality, and economic analysis to determine commercial viability, thereby addressing the credibility gap in optimization research, where theoretical demonstrations frequently lack empirical validation. The triangulation of geometric accuracy metrics, assessment of engineering feasibility, and elucidation of economic considerations establish validation criteria that advance architectural computation toward practical implementation, rather than confining it to isolated technological demonstrations.

The empirical investigation is recognized as the most extensive symmetry optimization dataset in architectural research, surpassing prior studies by 317% through validation across 50 projects, totalling 2.287 million m^2. The scale of this portfolio enables the execution of statistical analysis, potentially uncovering trends that are not readily apparent in smaller samples. This study involves identifying optimization regimes pertinent to typologies, analysing the correlation structures that connect building qualities with enhancement potential, and validating generalization across various architectural contexts. The advantages are measured across various performance metrics. The assessment of material efficiency is presented, with an average savings of 11.3% being indicated, a reduction in construction time of 10.7% being noted, and economic viability being reflected in total savings of €87.3 million, accompanied by an average ROI of 285%. Furthermore, it can be observed that a reduction of 21,450 tons of CO_2 serves as evidence of the environmental impact. This comprehensive evaluation is designed to address the deficiencies that have been identified in prior research, which has focused on isolated metrics. The results, when disaggregated by building category, are observed to reveal distinct performance profiles. The achievement of 15.8% material savings through programmatic integration in mixed-use developments has been noted. The return on investment for high-rise residential projects is demonstrated to be 312%, attributed to the effects of repetition multipliers. It has been observed that office buildings demonstrate consistent savings of 11.9% across a range of heights, which is indicative of the implementation of standardized design methodologies. Cultural buildings are observed to balance 7.8% savings while adhering to heritage preservation constraints.

Specialized structures achieve improvements of 8.5% despite their architectural distinctiveness. The findings that are specific to each category facilitate the development of targeted intervention strategies, as opposed to uniform approaches, thereby advancing the implementation guidance necessary for practical deployment at scale.

The research is characterized by the provision of actionable frameworks intended for adoption within the industry, articulated through four practical contributions. The establishment of economic feasibility across various construction scales is characterized by an average payback period of 2.3 years, a 10-year return on investment of 285%, and savings per building ranging from €0.6 million to €7.2 million. This paper seeks to provide a financial justification for investments that correspond with corporate capital allocation decisions. The sensitivity analysis confirms positive returns, notwithstanding cost assumption changes of ±30%. This demonstrates a level of resilience that supports confident investment decisions in the face of uncertainty. The development of implementation roadmaps that incorporate phased deployment strategies, prioritization criteria based on building characteristics, and resource allocation requirements effectively translates research findings into actionable guidelines for the construction industry's adoption. The depicted four-phase, 24-month timeline illustrates overall savings of €60 million across consecutive construction groups, highlighting scalable implementation strategies that combine risk management with value optimization. Integration protocols for BIM workflows employ standardized data formats and parametric modeling interfaces to tackle adoption challenges by integrating optimization analysis into current design processes. This strategy eliminates the need for operational disruptions or specialized software directives. The evaluation of environmental benefits in formats suitable for business sustainability reporting, regulatory compliance, and carbon credit assessment is enhanced, fostering alignment with environmental management systems and emissions trading frameworks. This integration establishes institutional incentives for the implementation of optimization beyond voluntary sustainability initiatives.

6.3 ACHIEVEMENT OF RESEARCH OBJECTIVES

The study effectively met all four specified objectives via systematic inquiry and empirical validation. The primary objective was to create a quantitative framework for assessing symmetry in buildings by adapting the Continuous Symmetry Measure from molecular chemistry to architectural contexts. This alteration facilitates an unbiased assessment of symmetry deviations from optimal configurations across diverse architectural styles. The CSM values span from 38% for the intentionally asymmetric Erasmus Bridge to 92% for the conventionally proportioned Concertgebouw, yielding a portfolio average of 73.6%. This illustrates the framework's importance for the various architectural symmetries present in the current building inventory. The second objective, aimed at showcasing optimization potential across various building typologies, was accomplished through a comprehensive portfolio analysis that documented specific performance metrics across five categories: high-rise residential (12.3% material savings), mixed-use (15.8%), office (11.9%), cultural (7.8%), and specialized structures (8.5%). The investigation for each category identifies optimization processes unique to each type. The discourse includes the merits of vertical repetition in skyscrapers, the benefits of programmatic integration in mixed-use projects, standardized commercial practices in office buildings, limitations of heritage preservation in cultural institutions, and factors of architectural uniqueness in specialized edifices. The third objective, aimed at assessing material, temporal, and environmental advantages, was achieved by quantifying diverse performance criteria. The findings revealed an average material savings of 11.3%, a construction time reduction of 10.7%, total cost savings of €87.3 million, and a reduction of 21,450 tons of CO_2 emissions across a portfolio of 50 buildings. The breakdown of benefits by material type, building category, and project scale offers thorough documentation that supports evidence-based decision-making for the implementation of optimization strategies. The fourth objective, to furnish implementation guidance for industry adoption, was achieved through the creation of phased deployment roadmaps, prioritization criteria based on building attributes, an economic viability analysis illustrating commercial feasibility, and integration protocols for BIM workflows that enable seamless incorporation into existing design processes.

6.4 MAIN FINDINGS SUMMARY

The inquiry produced six key findings with substantial theoretical and practical ramifications. Initially, systematic symmetry optimization resulted in an average material reduction of 11.3% across a portfolio of 50 buildings, while preserving architectural quality, structural integrity, and functional performance, thereby affirming geometric optimization as a feasible approach for enhancing resource efficiency in existing building assets. The uniformity of advantages across various building types, from heritage structures necessitating preservation-sensitive measures to modern high-rise towers facilitating extensive optimization, illustrates widespread application rather than context-dependent efficacy. Secondly, mixed-use buildings exhibited enhanced optimization performance (15.8% material savings) relative to the portfolio average, indicating that programmatic complexity generates integration opportunities lacking in single-function buildings when managed through comprehensive frameworks that balance conflicting functional requirements. The designation of 1.8 m as a standard planning increment, harmonizing office (7.2 m), residential (5.4 m), and hotel (6.0 m) grids, exemplifies how architectural limitations direct optimization towards high-value solutions that concurrently satisfy many criteria. Third, building height exhibited a notable inverse correlation with optimization potential ($R^2 = 0.72$), suggesting that economic pressures and regulatory requirements need enhanced early optimization in taller structures. This portfolio-level trend obscures category-specific variations, with mixed-use demonstrating a notable positive correlation with height ($r = 0.797$, $p = 0.006$) attributable to scale-enhanced integration benefits, office buildings showing no correlation ($r = 0.223$, $p = 0.536$) indicative of standardized design practices, and residential properties presenting a non-significant negative correlation ($r = -0.444$, $p = 0.198$) reflecting considerable baseline optimization shaped by residential construction economics.

The age of the building had a positive association with optimization potential ($R^2 = 0.68$). The predictive equation for optimization potential is Optimization Potential (%) = 8.2 + 0.43 × (2024 − Year Built), facilitating systematic prioritizing of retrofit measures according to the construction period. Buildings constructed prior to 2000 demonstrated an average optimization potential of 18%, whilst those built after 2010 showed a potential of 9%. This disparity quantifies the influence of computational design tools (CAD, BIM, parametric modeling) that facilitate systematic geometric optimization in the early design stages. This temporal pattern signifies both technical advancement and evolving design philosophies, with modern practices increasingly prioritizing sustainability and resource efficiency in conjunction with aesthetic and functional goals. The incorporation of Progressive Transfer Learning mechanisms with SODA optimization protocols exhibited synergistic advantages, enabling subsequent projects to attain comparable or enhanced optimization outcomes with significantly diminished engineering effort, thereby confirming the efficacy of knowledge transfer in architectural applications. The bidirectional link in which symmetry-optimized designs function as high-quality source domains for transfer learning, while PTL-derived insights guide SODA optimization priorities, fosters virtuous cycles of continual improvement that are lacking in isolated optimization methods. Sixth, a thorough economic analysis confirmed commercial feasibility across various building scales, revealing an average payback period of 2.3 years, a 10-year ROI of 285%, and individual building savings between €0.6 million and €7.2 million, contingent upon size and optimization potential. The sensitivity analysis validating positive returns despite ±30% fluctuations in cost assumptions illustrates robustness, so bolstering confident investment decisions under uncertainty and fulfilling corporate needs for financial justification of capital allocation to sustainability projects.

6.5 LIMITATIONS ACKNOWLEDGMENT

The study delineates four principal limitations that hinder generalization and suggests directions for future inquiry. The spatial concentration of Dutch structures enables an in-depth examination of cultural and regulatory contexts, although limits the direct applicability to architectural traditions characterized by divergent symmetry conventions, construction techniques, and regulatory frameworks. The dominance of the Amsterdam School, De Stijl, and neoclassical styles may not reflect architectural diversity in Mediterranean, Asian, or Middle Eastern environments, where distinct geometric principles dictate design. The emphasis on optimizing geometric symmetry exemplifies one aspect of holistic building performance, which should ideally encompass thermal efficiency, daylighting, acoustics, operational energy usage, and the minimization of embodied carbon. The existing technique emphasizes enhancements during the construction phase but inadequately assesses the benefits during the operational phase; still, initial study indicates potential energy savings of 8-12% in operations that necessitates thorough examination. The reliance on existing building data and regulatory compliance verification ensures practical feasibility but limits the exploration of innovative structural systems or unconventional materials that potentially improve performance but lack established precedent in Dutch construction practices. The 50-building portfolio, although significantly larger than prior studies, is still tiny compared to the total Dutch building stock of 10.8 million structures. This limitation reduces statistical power for rare building types and hinders comprehensive analysis of specialized subcategories, such as industrial facilities, hospital complexes, and educational institutions, which are insufficiently represented in the current sample.

6.6 RECOMMENDATIONS

The research presents seven recommendations for stakeholders in design, construction, and policy, grounded upon scientific findings and practical implementation considerations. Architectural practices should incorporate symmetry analysis during the initial design stages, when change costs are minimal and design freedom is maximal, employing BIM-integrated optimization technologies that offer real-time feedback on the resource efficiency consequences of geometric choices. The evidence that optimization preserves architectural quality while attaining an average material savings of 11.3% indicates a complementing link between design excellence and resource efficiency, rather than a conflicting one. Secondly, construction firms ought to prioritize mid-rise residential structures (20-25% optimization potential) and substantial mixed-use developments (15.8% average savings) for retrofit optimization initiatives, as these categories present the most significant advantages, while also recognizing that highly optimized tall office towers yield minimal enhancement potential through geometric modifications alone. The age-based prioritization formula (Optimization Potential (%) = 8.2 + 0.43 × (2024 − Year Built)) facilitates the systematic identification of pre-2000 structures with enhanced retrofit potential. Third, prefabrication manufacturers should develop standardized component families that align with established optimization patterns, including balcony modules in three standard depths (1.8 m, 2.4 m, 3.0 m), floor plate systems based on 5.4 m residential or 7.2 m office grids, and connection details that integrate common configurations rather than custom designs. The evidence indicates that standardization reduces formwork variations by 65% and unique connection types by 60-80%, hence validating the benefits of manufacturing efficiency and justifying investment in production methods.

Fourth, heritage conservation authorities must acknowledge that symmetry optimization yields quantifiable advantages (7.8% average material savings in cultural edifices) within preservation limitations, thereby endorsing evidence-based assessments of retrofit options that reconcile sustainability objectives with cultural preservation requirements. The framework's capacity to quantify attainable enhancements while honouring architectural importance facilitates transparent evaluation, supplanting subjective judgment in conservation decision-making. Fifth, building code authorities should contemplate incorporating symmetry-based performance measures into regulatory frameworks, either via prescriptive design mandates that promote geometric efficiency or through outcome-based compliance routes that incentivize proven resource optimization. The reduction of 21,450 tons of CO_2 over 50 buildings indicates significant environmental advantages achievable through methodical industry implementation backed by suitable legislative incentives. Sixth, sustainability certification systems (BREEAM, LEED, DGNB) ought to integrate symmetry assessment criteria that acknowledge geometric optimization as a valid strategy for attaining resource efficiency objectives, in conjunction with traditional measures such as improved insulation, renewable energy integration, and efficient mechanical systems. Seventh, research funding agencies ought to prioritize international validation studies that assess the applicability of frameworks across various architectural traditions, climatic conditions, and regulatory environments, thereby establishing generalizability and identifying necessary culture-specific adaptations for effective global implementation.

6.7 FUTURE RESEARCH DIRECTIONS

Future study must concentrate on eight critical routes to improve symmetry optimization for increased efficacy and enhanced understanding. The first step entails evaluating the relevance of the international expansion validation framework across various architectural traditions (Mediterranean, Asian, Middle Eastern, Latin American) to determine generalizability and identify culture-specific modifications required for effective implementation in diverse contexts. Comparative examinations of symmetry principles in courtyard structures, timber construction, mash Rabiya facades, and colonial architecture would clarify universal vs context-specific optimization strategies. Secondly, a comprehensive life cycle integration that encompasses the operational energy, maintenance costs, deconstruction, and circular economy considerations beyond the construction phase would provide a complete sustainability assessment. The initial estimate of 8-12% operational energy savings due to improved thermal performance necessitates a comprehensive examination that integrates computational fluid dynamics, daylighting simulation, and thermal analysis with geometric optimization. Third, the research of innovative materials, including the interplay between mass wood construction, 3D-printed concrete, tensegrity structures, and bio-based materials with symmetry optimization, would broaden the range of solutions beyond traditional systems. Fourth, the integration of real-time design through the development of GPU-accelerated algorithms, machine learning surrogate models, and augmented reality visualization would convert research prototypes into functional design support systems, offering immediate feedback during conceptual phases when design flexibility is maximized and modification costs are minimized. The fifth point is that broadening typology coverage to include healthcare facilities, educational institutions, industrial structures, and transportation infrastructure would apply optimization methods to underrepresented building types with specific spatial needs. Sixth, longitudinal performance monitoring of actual construction outcomes, operational energy consumption, occupant satisfaction, and maintenance needs would empirically validate predicted benefits, thereby addressing the performance gap between design forecasts and actual results. The development of a policy framework that translates findings into regulatory incentives, building code provisions, and sustainability certification criteria will expedite industry adoption through institutional mechanisms. The eighth component entails examining social factors, particularly occupant perceptions, cultural responses to optimization strategies, and their impact on architectural quality, ensuring that technological advancements align with human values and the experiential elements valued by building users.

6.8 CLOSING STATEMENT

This research demonstrates that systematic symmetry optimization in architectural design is a viable and effective method for attaining resource efficiency and environmental sustainability, while maintaining architectural quality, structural integrity, and functional performance that define successful built environments. The empirical validation encompassing 50 Dutch edifices, aggregating 2.287 million m², reveals an average material conservation of 11.3%, a construction duration decreases of 10.7%, total financial savings of €87.3 million, and a reduction of 21,450 tons of CO_2 emissions, substantiating that geometric optimization produces substantial, quantifiable benefits across diverse building typologies and architectural contexts. The incorporation of Progressive Transfer Learning mechanisms with SODA optimization protocols tackles essential issues in construction AI by establishing bidirectional knowledge exchanges between spatial design optimization and temporal project learning, facilitating ongoing enhancement through the systematic accumulation of domain-specific insights. The construction industry faces increasing challenges from climate change mitigation objectives, resource limitations, and sustainability criteria; the framework provides evidence-based solutions rooted in rigorous empirical validation rather than baseless aspirational claims. The demonstrated commercial viability, indicated by average payback durations of 2.3 years and a 10-year return on investment of 285%, provides economic justification for investment execution, fulfilling corporate needs for capital allocation towards sustainability initiatives. The research not only achieves immediate resource efficiency improvements but also advances the discussion on the transformation of the construction industry by illustrating that technological innovation, systematic analysis, and evidence-based decision-making can harmonize the seemingly contradictory goals of design excellence, economic viability, and environmental responsibility. The way forward necessitates ongoing collaboration among research, industry, and policy sectors, converting academic insights into practical tools, regulatory frameworks, and professional practices that collectively promote sustainability in the built environment while maintaining architectural quality and cultural significance that enhance human experience and define our shared heritage.

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