Abstract

Buildings account for 40% of global energy consumption and emissions. Building façades determine thermal efficiency, daylighting, and occupant wellbeing, yet traditional assessment methodologies prove prohibitively expensive and time-intensive at urban scales. This research develops an integrated framework addressing four interconnected research questions. First, it establishes a comprehensive definition of high-performance façades integrating energy efficiency, occupant comfort, environmental sustainability, and durability, validated against occupant satisfaction data. Second, it develops an artificial intelligence pipeline for automated façade assessment from street-level imagery, enabling unprecedented urban-scale measurement capability. Third, it rigorously validates this AI approach through systematic error analysis and accuracy stratification across diverse building typologies. Fourth, it develops urban integration frameworks connecting building-level performance data to municipal decision-making systems supporting retrofit prioritization. Implementation across European urban districts demonstrates practical feasibility of evidence-based retrofit strategies and policy integration. The research demonstrates that urban sustainability challenges require simultaneous advancement in definitional clarity, technological innovation, rigorous validation, and governance integration. Results provide essential infrastructure for building decarbonization and climate action implementation.

DICATECh 2026 P. Eng. Vito Lamberti

Mapping Urban Complexity:
AI, Façades, and the Future of Environmental Risk Assessment

03

D.R.S.A.T.E.

PhD in Risk and Environmental, Territorial and Building Development

POLITECNICO DI BARI

03
2026

Coordinator: Prof. Francesco Fiorito

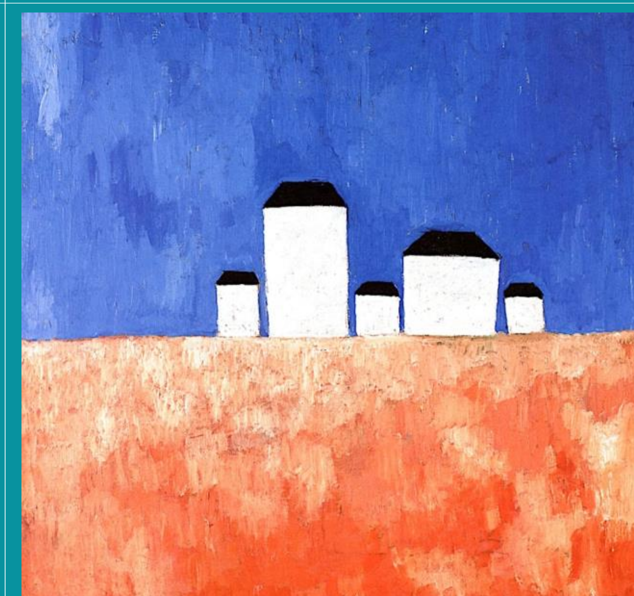
XXXVIII CYCLE
Curriculum: CEAR-08/A

DICATECh
Department of Civil, Environmental, Building Engineering and Chemistry

P. Eng. Vito Lamberti

Mapping Urban Complexity: AI, Façades, and the Future of Environmental Risk Assessment

Prof. P. Eng. Francesco Fiorito
Department of Civil, Environmental, Building Engineering and Chemistry, Polytechnic University of Bari
Dr. David Lehrer
Center for The Built Environment
University of California, Berkeley



The doctoral scholarship was funded by the European Union – Next Generation EU, Mission 4 Component 2 CUP D93D22001340001

Funded by the European Union NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

Abstract

Buildings account for 40% of global energy consumption and emissions. Building façades determine thermal efficiency, daylighting, and occupant wellbeing, yet traditional assessment methodologies prove prohibitively expensive and time-intensive at urban scales. This research develops an integrated framework addressing four interconnected research questions. First, it establishes a comprehensive definition of high-performance façades integrating energy efficiency, occupant comfort, environmental sustainability, and durability, validated against occupant satisfaction data. Second, it develops an artificial intelligence pipeline for automated façade assessment from street-level imagery, enabling unprecedented urban-scale measurement capability. Third, it rigorously validates this AI approach through systematic error analysis and accuracy stratification across diverse building typologies. Fourth, it develops urban integration frameworks connecting building-level performance data to municipal decision-making systems supporting retrofit prioritization. Implementation across European urban districts demonstrates practical feasibility of evidence-based retrofit strategies and policy integration. The research demonstrates that urban sustainability challenges require simultaneous advancement in definitional clarity, technological innovation, rigorous validation, and governance integration. Results provide essential infrastructure for building decarbonization and climate action implementation.

Cover image:
Kazimir Malevich "Landscape with five houses"
Original Title: Пейзаж с пятью домами
Date: c.1932
Style: Expressionism, Neo-Suprematism
Rights status: Public domain
Source: https://www.wikiart.org/en/kazimir-malevich/landscape-with-five-houses

DICATECh 2026 P. Eng. Vito Lamberti
Mapping Urban Complexity: AI, Façades, and the Future of Environmental Risk Assessment
03

D.R.S.A.T.E.

POLITECNICO DI BARI

03
2026

PhD in Risk and Environmental, Territorial and Building Development

Coordinator: Prof. Francesco Fiorito

XXXVIII CYCLE
Curriculum: CEAR-08/A

DICATECh
Department of Civil, Environmental, Land, Building Engineering and Chemistry

P. Eng. Vito Lamberti

Mapping Urban Complexity: AI, Façades, and the Future of Environmental Risk Assessment

Prof. P. Eng. Francesco Fiorito
Department of Civil, Environmental, Building Engineering and Chemistry, Polytechnic University of Bari
Dr. David Lehrer
Center for The Built Environment
University of California, Berkeley

The doctoral scholarship was funded by the European Union – Next Generation EU, Mission 4 Component 2 CUP D93D22001340001

Funded by the European Union NextGenerationEU
Ministero dell'Università e della Ricerca
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

D.R.S.A.T.E.

POLITECNICO DI BARI

03

2026

PhD in Risk and Environmental, Territorial and Building Development

Coordinator: Prof. Francesco Fiorito

XXXVIII CYCLE
Curriculum: CEAR-08/A

DICATECh
Department of Civil, Environmental, Land Building Engineering and Chemistry

P. Eng. Vito Lamberti

Mapping Urban Complexity: AI, Façades, and the Future of Environmental Risk Assessment

Prof. P. Eng. Francesco Fiorito
Department of Civil, Environmental, Building Engineering and Chemistry, Polytechnic University of Bari
Dr. David Lehrer
Center for The Built Environment
University of California, Berkeley

The doctoral scholarship was funded by the European Union – Next Generation EU, Mission 4 Component 2 CUP D93D22001340001

Funded by the European Union NextGenerationEU

Ministero dell'Università e della Ricerca

Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

In systems characterized by uncertainty and non-linearity—such as human behavior and social dynamics—rigid, formulaic responses often prove inadequate. Those who cultivate adaptive flexibility through repeated exposure to unpredictable contexts are better equipped to navigate complexity and respond effectively to the stochastic nature of real-world challenges.

EXTENDED ABSTRACT *(eng)*

Buildings account for 40% of global energy consumption and emissions. Building façades determine thermal efficiency, daylighting, and occupant wellbeing, yet traditional assessment methodologies prove prohibitively expensive and time-intensive at urban scales. This research develops an integrated framework addressing four interconnected research questions. First, it establishes a comprehensive definition of high-performance façades integrating energy efficiency, occupant comfort, environmental sustainability, and durability, validated against occupant satisfaction data. Second, it develops an artificial intelligence pipeline for automated façade assessment from street-level imagery, enabling unprecedented urban-scale measurement capability. Third, it rigorously validates this AI approach through systematic error analysis and accuracy stratification across diverse building typologies. Fourth, it develops urban integration frameworks connecting building-level performance data to municipal decision-making systems supporting retrofit prioritization. Implementation across European urban districts demonstrates practical feasibility of evidence-based retrofit strategies and policy integration. The research demonstrates that urban sustainability challenges require simultaneous advancement in definitional clarity, technological innovation, rigorous validation, and governance integration. Results provide essential infrastructure for building decarbonization and climate action implementation.

Keywords

High-Performance Facades; Building Performance Assessment; Artificial Intelligence; Computer Vision; Urban Sustainability; Multi-Criteria Evaluation; Occupant Comfort; Decision Support Systems; Building Retrofit; Climate Mitigation

EXTENDED ABSTRACT *(ita)*

Gli edifici rappresentano il 40% del consumo energetico globale e delle emissioni. Le facciate edilizie determinano l'efficienza termica, l'illuminazione naturale e il benessere degli occupanti, eppure le metodologie di valutazione tradizionali risultano proibitivamente costose e lunghe a scale urbane. Questa ricerca sviluppa un framework integrato affrontando quattro domande di ricerca interconnesse. Primo, stabilisce una definizione completa di facciate ad alta prestazione integrando efficienza energetica, comfort degli occupanti, sostenibilità ambientale e durabilità, validata rispetto ai dati di soddisfazione degli occupanti. Secondo, sviluppa una pipeline di intelligenza artificiale per la valutazione automatizzata delle facciate da immagini a livello stradale, consentendo capacità di misurazione a scala urbana senza precedenti. Terzo, valida rigorosamente questo approccio AI attraverso analisi sistematica degli errori e stratificazione dell'accuratezza tra diverse tipologie edilizie. Quarto, sviluppa framework di integrazione urbana collegando i dati sulla prestazione a livello di edificio ai sistemi decisionali municipali. L'implementazione in distretti urbani europei dimostra la fattibilità pratica di strategie di retrofit basate su evidenze e integrazione politica. La ricerca dimostra che le sfide di sostenibilità urbana richiedono avanzamenti simultanei nella chiarezza definitoria, innovazione tecnologica, validazione rigorosa e integrazione della governance.

Keywords

Facciate ad Alta Prestazione; Valutazione della Prestazione Energetica; Intelligenza Artificiale; Computer Vision; Sostenibilità Urbana; Valutazione Multi-Criteri; Comfort degli Occupanti; Sistemi di Supporto alle Decisioni; Retrofit Edilizio; Mitigazione del Clima

INDEX

1. INTRODUCTION 6
1.1. Research Objectives 9
1.2. Research Questions 14
1.3. Significance Of the Study 22
1.4. Scope And Limitations 27
1.5. Integration and Application Limitations 29
1.6. Thesis Structure 30
1.7. Research Methdology and Materials 35
1.8. The Research Context 41
1.9. SWOT Anaysis 51
2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK 64
2.1. High-Performance Facades: Definitions and Standards 67
2.2. Multi-Criteria Assessment Approaches in Literature 77
2.3. Energy Performance And Thermal Comfort 80
2.4. Daylighting, Visual Comfort and Occupant Wellbeing 90
2.5. Computer Vision in Building Analysis 96
2.6. Urban-Scale Building Performance Assessment 98
2.7. Research Gaps and Opportunities 103
3. DEFINING HIGH PERFORMANCE FACADES (RQ1) 110
3.1. Introduction and Research Approach 110
3.2. Framework Development 111
3.3. Manual WWR Assessment and Validation 132
3.4. Definition of High-Performance Façades 142
3.5. WWR and Occupant Comfort Correlations 146
3.6. Discussion: Validation and Implications 148
3.7. Research Question 1: Complete Answer 156
4. AI DRIVEN WWR ASSESSMENT (RQ2 + RQ3) 158
4.1. Methodology: AI Pipeline Development 161
4.2. Methodology: Validation Framework 182
4.3. Results: AI Model Performance 190
4.4. Results: Accuracy Validation and Comparative Analysis 205
4.5. Discussion: Capabilities, Limitations, and Trade-offs 210
4.6. Research Question 2 and 3: Complete Answers 223
4.7. Integration with Overall Research Framework 225
5. URBAN-SCALE INTEGRATION (RQ4) 227
5.1. Introduction and Research Approach 227

5.2. Results: Urban-Scale Case Studies 237
5.3. Results: Multi-Criteria Performance Assessment 239
5.4. Discussion: Policy Implications and Application 242
5.5. Discussion: Framework Validation and Generalizability 248
6. CONCLUSIONS AND FUTURE PERSPECTIVES 260
6.1. Contributions to Knowledge 263
6.2. Practical Implications for Stakeholders 267
6.3. Limitations and Risks 270
6.4. Future Research Directions 273
6.5. Vision for Sustainable Urban Futures 278
6.6. Final Remarks 283
ACKNOLEDGEMENTS 286
BIBLIOGRAPHY 288
LIST OF FIGURES 296
LIST OF TABLES 298
ANALYTICAL INDEX 299
CURRICULUM VITAE 305

1. INTRODUCTION

The global built environment stands at a critical inflection point in human history. Buildings consume approximately 40% of the world's energy and are responsible for nearly 38% of global CO_2 emissions, making them one of the largest contributors to climate change and environmental degradation (*United Nations Environment Programme (2021) 2021 global status report for buildings and construction*, n.d.). As urbanization accelerates—with projections indicating that two-thirds of the global population will reside in cities by 2050 (Armondi, 2018) the performance of individual building components and their collective impact on urban systems has become increasingly consequential for planetary sustainability, human wellbeing, and economic prosperity (U.N.-Habitat, 2022).

Within this complex landscape, building facades emerge as particularly critical elements that fundamentally determine a building's environmental performance, occupant comfort, and contribution to urban sustainability. Far from being merely aesthetic features or simple weather barriers, contemporary facades function as sophisticated, dynamic interfaces that mediate complex energy flows, control environmental conditions, and profoundly shape human experiences within built environments (Aksamija, 2015; Fiorito et al., 2016). The facade's role in determining thermal comfort, daylighting quality, energy consumption, indoor air quality, and visual connection to the exterior environment makes it a pivotal component in achieving high-performance buildings that can meet the demanding sustainability and comfort standards of the 21st century.

The evolution of facade technology over the past several decades reflects our growing understanding of buildings as complex, integrated systems where individual components must be optimized not in relation to overall building performance, occupant experience, and broader environmental goals (A. Cannavale, 2020; Fiorito, 2019).

This evolution has progressed from simple, static enclosure systems focused primarily on weather protection to intelligent, responsive building skins that can adapt to changing environmental conditions, optimize energy performance, and enhance occupant wellbeing through sophisticated control of light, air, temperature, and moisture.

However, this technological evolution has simultaneously created new challenges that current assessment and measurement methodologies struggle to address effectively. As facade systems become more complex and multifunctional, traditional methods for evaluating their performance have proven inadequate for addressing contemporary needs at the scales necessary to drive meaningful change in building stocks and urban sustainability initiatives (Attia et al., 2018)

The Window-to-Wall Ratio (WWR), defined as the ratio between a building's total window area and its overall external wall area, exemplifies both the importance and the complexity of facade performance assessment in contemporary practice. This seemingly straightforward metric profoundly influences multiple aspects of building performance: it directly affects energy consumption through its impact on solar heat gain, thermal bridging, and daylighting provision; it influences occupant comfort through its effects on thermal conditions, glare control, and visual connection to the exterior; it affects building durability through its impact on moisture management and structural performance; and it shapes the architectural character and urban context of buildings through its visual and compositional effects (Marino et al., 2017; Ashrafian and Moazzen, 2019)

The significance of WWR as a design and performance parameter has been well established through decades of building performance research conducted in various climatic contexts and building types. Studies have consistently demonstrated that optimal WWR varies significantly depending on climate conditions, building orientation, internal heat loads, shading strategies, glazing properties, and occupant preferences. (Guo and Bart, 2020; S. Yang et al., 2021). However, this same body of research has also revealed the complexity of determining optimal WWR values in practice, as the metric must be balanced against numerous other design considerations and performance objectives, including structural requirements, aesthetic preferences, code compliance, cost constraints, and maintainability concerns.

Despite its fundamental importance to building performance, WWR remains challenging to measure and analyze at the large scales necessary to support evidence-based policy development, urban planning initiatives, and building stock improvement strategies. Traditional WWR assessment methods typically rely on manual measurement techniques that, while potentially accurate for individual projects, become prohibitively time-consuming and resource-intensive when applied to larger building populations(Lamberti et al., n.d.; Szcześniak et al., 2022). These manual approaches require detailed analysis of architectural drawings, on-site surveys, or photogrammetric analysis, all of which demand significant expertise, specialized equipment, and substantial time investments that make them impractical for urban-scale applications.

The challenges associated with traditional WWR measurement are further compounded by issues of data standardization and accessibility. As documented in contemporary research observations: "even when partial WWR data is available, it might not be in a standardized format. Some buildings could have digital 3D models, while others might only have paper-based plans or incomplete documentation. Inconsistencies in how architectural information is recorded add to the complexity of generating uniform WWR measurements across large samples."

This fragmentation in data collection, storage, and standardization creates a cascading series of problems that extend far beyond simple measurement challenges.

Researchers and policymakers lack robust, updated databases of facade properties that could illuminate urban-scale trends, inform comprehensive building energy models, or support the development of targeted intervention strategies for building performance improvement (Schiavon et al., 2018). Building owners and designers struggle to benchmark their projects against broader performance standards or to learn from successful implementations in similar contexts. Urban planners and policymakers cannot develop effective strategies for building stock improvement because they lack reliable data about current performance characteristics across their jurisdictions.

The result is a critical gap between the theoretical understanding of facade performance developed through detailed case studies and the practical ability to implement this knowledge at the scales where it can have transformative impact on urban sustainability, energy consumption, and occupant wellbeing. This gap is particularly problematic given the urgent need for city-wide building retrofits, climate adaptation strategies, and energy transition policies that depend on comprehensive understanding of existing building stocks and their performance characteristics.

1.1. Research Objectives

This doctoral research, conducted within the interdisciplinary framework of "Rischio e Sviluppo Ambientale, Territoriale ed Edilizio" at Politecnico di Bari, addresses these fundamental challenges through four interconnected research objectives that span from theoretical foundation-building to practical implementation at urban scales.

Primary Objective 1: Develop Comprehensive Definitions and Assessment Frameworks for High-Performance Facades.

The first objective addresses the definitional ambiguity that currently limits progress in facade assessment and design by developing comprehensive, quantifiable definitions of what constitutes "high-performance" in contemporary facade systems (Attia et al., 2018; Enclos, 2020; Lehrer, 2011). This objective recognizes that effective assessment methodologies require clear, measurable criteria that can be applied consistently across different projects, climates, and contexts while remaining sufficiently flexible to accommodate diverse design approaches and performance priorities.

The framework to this objective synthesizes multiple perspectives and stakeholder needs, integrating technical performance criteria (such as energy efficiency, thermal comfort, and structural integrity) with occupant experience factors (including daylighting quality, visual comfort, and connection to nature), environmental impact considerations (encompassing embodied carbon, lifecycle assessment, and end-of-life scenarios), and long-term durability requirements (addressing maintenance needs, weather resistance, and adaptability to changing conditions)(F. Fiorito et al., 2020)

This comprehensive approach acknowledges that high-performance facades must satisfy multiple stakeholders with different priorities and operational requirements, and that successful definitions must be both theoretically sound and practically applicable for widespread adoption by designers, builders, building owners, and regulatory authorities. The objective includes the development of assessment matrices, scoring systems, and evaluation protocols that can be used to compare different facade solutions, establish performance targets, and guide design decision-making processes.

Primary Objective 2: Create Scalable, AI-Driven Tools for Automated Facade Assessment.

The second objective directly addresses the scalability challenge by developing and validating automated computer vision pipelines that can extract facade performance metrics from widely available data sources, particularly Google Street View imagery and similar street-level visual data (Szcześniak et al., 2022).This objective recognizes that achieving meaningful progress in urban sustainability requires assessment tools that can operate at scales ranging from individual buildings to entire city districts, while maintaining sufficient accuracy and reliability for practical decision-making applications.

The technological development component of this objective involves creating sophisticated image analysis algorithms that can identify, classify, and measure facade elements with accuracy comparable to manual measurement techniques, while operating at speeds and scales that make urban-wide analysis practical and cost-effective. The strategy leverages recent advances in computer vision, machine learning, and artificial intelligence to develop tools that can process thousands of building images rapidly and consistently.

The objective includes not only the development of technical tools, but also the creation of data processing workflows, quality control systems, and user interfaces that make these capabilities accessible to researchers, practitioners, and policymakers who may not have specialized technical expertise in computer vision or machine learning. The goal is to democratize access to advanced facade assessment capabilities while maintaining high standards for accuracy and reliability.

Primary Objective 3: Establish Methodological Standards and Validation Frameworks for AI-Based Assessment.

The third objective provides critical evaluation and validation of the technological approaches developed in Objective 2 by benchmarking them against established manual measurement practices and developing comprehensive understanding of their strengths, limitations, and appropriate applications. This objective reflects the doctoral program's emphasis on risk assessment and acknowledges that new technologies must be thoroughly validated before they can be trusted for important decision-making processes that affect building performance, occupant wellbeing, and environmental sustainability (Schiavon et al., 2019) .

The validation component includes extensive accuracy testing using ground-truth data from traditional measurement methods, analysis of error sources and propagation patterns, investigation of bias in algorithmic approaches, and assessment of reliability across different building types, architectural styles, and environmental conditions. The objective also addresses broader methodological questions about the appropriate role of artificial intelligence in architectural assessment, including the boundaries of automated analysis, the need for human oversight and validation, and the integration of quantitative measurement with qualitative assessment methods.

This objective recognizes that responsible development and deployment of AI-driven assessment tools require not only technical sophistication, but also careful consideration of ethical implications, potential misuse scenarios, and the need to preserve and enhance rather than replace human expertise and judgment in design and evaluation processes.

Primary Objective 4: Integrate Individual Building Assessment with Urban-Scale Planning and Policy Applications.

The fourth objective bridges individual building assessment with urban-scale policy applications, reflecting the doctoral program's emphasis on territorial development and environmental risk management. This objective addresses the critical gap between building-level performance understanding and urban-scale outcomes by developing frameworks for integrating standardized quantitative facade metrics with holistic risk assessment, sustainability evaluation, and wellbeing indicators that operate at neighborhood and city scales (Santamouris et al., 2017)

The integration component involves developing methodologies for scaling individual building assessments to urban systems analysis, creating frameworks for linking facade performance characteristics with broader urban environmental conditions (such as heat island effects, air quality, and energy infrastructure demands), and establishing connections between building envelope improvements and community resilience objectives.

The objective also addresses practical implementation challenges by exploring how automated assessment tools can support real-world decision-making processes for retrofit prioritization, climate adaptation planning, zoning and building code development, and sustainable development strategies. This application-oriented focus ensures that research outputs can contribute to addressing urgent contemporary challenges in urban sustainability and climate adaptation while providing evidence-based support for policy development and implementation.

The four objectives are designed to build systematically upon each other while also contributing independently to different aspects of facade performance assessment and application. Together, they represent a comprehensive system to addressing the scale, accuracy, and integration challenges that currently limit the field's ability to support evidence-based decision-making for sustainable building development and urban planning.

1.2. Research Questions

Building upon the research objectives outlined above, this study addresses four carefully structured research questions that progress systematically from fundamental definitional challenges to practical implementation at urban scales. These questions are designed to generate knowledge that is both theoretically significant and practically applicable for addressing contemporary challenges in building performance assessment and urban sustainability planning.

Research Question 1: What is a high-performance facade and what are its defining characteristics?

This foundational research question addresses the definitional ambiguity that currently limits progress in facade assessment and design practice. While the term "high-performance facade" is widely used in architectural and engineering discourse, there remains no consistent, quantifiable definition that can be applied reliably across different climatic contexts, building types, and performance priorities (Attia et al., 2018; A. Cannavale et al., 2020; Lamberti et al., 2024). This definitional gap creates significant challenges for comparing different facade solutions, establishing performance targets, developing evidence-based design guidelines, and creating policy frameworks that can drive market transformation toward higher-performing building envelopes.

The question is essential because effective assessment methodologies require clear, measurable criteria that define what constitutes good performance across multiple dimensions. Without such definitions, it becomes impossible to develop reliable measurement tools, establish meaningful performance benchmarks, or create consistent evaluation frameworks that can support both research advancement and practical decision-making processes(Enclos, 2020).

The method to this question involves comprehensive synthesis of multiple perspectives and information sources, including international building standards and certification systems (such as LEED, BREEAM, and Passivhaus), peer-reviewed research literature on facade performance, case study analysis of exemplary high-performance buildings, and stakeholder consultation with design professionals, building owners, and building occupants. The synthesis process integrates technical performance criteria (including energy efficiency, thermal comfort, daylighting provision, and structural integrity) with occupant experience factors (such as visual comfort, connection to nature, and perceived quality of the indoor environment), environmental impact considerations (encompassing embodied carbon, lifecycle environmental effects, and end-of-life scenarios), and long-term durability requirements (addressing maintenance needs, weather resistance, and adaptability to changing conditions).

The preliminary research approach suggests that comprehensive facade performance assessment must integrate multiple criteria simultaneously: "Moisture resistance and condensation risk are also evaluated to guarantee the long-term durability of the facade and the health of occupants, especially in climates with significant temperature swings. Finally, the environmental impact of the facade is increasingly assessed through embodied carbon calculations, using Environmental Product Declarations (EPDs) and Life Cycle Assessment (LCA) to quantify the total carbon footprint of materials and construction processes."

This multi-criteria method reflects the reality that contemporary facades must perform well across numerous dimensions simultaneously, but it also highlights the methodological challenges in developing assessment frameworks that can evaluate performance holistically while remaining practical for widespread application. The research question addresses these challenges by developing integrated assessment matrices, scoring systems, and evaluation protocols that can handle complex trade-offs and interactions between different performance objectives.

Research Question 2: How can Artificial Intelligence and Google Street View imagery be used to estimate Window-to-Wall Ratio (WWR) at scale?

This research question directly addresses the scalability challenge that prevents traditional facade assessment methods from supporting urban-scale analysis and policy development. The question focuses specifically on WWR as a critical facade performance parameter while developing methodological approaches that can be extended to other facade characteristics and metrics(Szcześniak et al., 2022).

The question builds directly on the definitional work of RQ1 by operationalizing key facade metrics in ways that can be measured automatically and consistently across large building datasets. This connection between definition and measurement is crucial for ensuring that theoretical frameworks can be translated into practical assessment tools that can support evidence-based decision-making processes at scales ranging from individual buildings to entire urban districts.

The technological development component involves creating sophisticated computer vision algorithms that can identify, segment, and measure building facade elements from street-level imagery with accuracy comparable to manual measurement techniques. The framework leverages recent advances in deep learning, semantic segmentation, and object recognition to develop tools that can process thousands of building images rapidly while maintaining consistent measurement standards across different architectural styles, lighting conditions, and image quality levels.

The focus on Google Street View imagery reflects the strategic decision to utilize widely available data sources that can enable analysis at urban scales without requiring specialized data collection efforts or expensive sensor deployments. This approach has the potential to democratize access to facade assessment capabilities while enabling analyses that would be prohibitively expensive using traditional survey methods.

The research objective of developing "an automated system, driven by Artificial Intelligence and Google Street View imagery, capable of rapidly and accurately estimating the WWR at scale" addresses fundamental limitations in current assessment approaches while opening new possibilities for understanding facade performance at unprecedented scales. The framework "addresses the drawbacks of traditional measurement methods, often time-consuming and limited to small samples, by relying on computer vision tools and neural networks to identify and classify transparent surfaces on building façades."

From Definition (RQ1) to Measurement (RQ2)

The progression from Research Question 1 to Research Question 2 represents not a shift in topic but a methodological necessity that emerges directly from RQ1. To understand this connection, it is important to recognise how definitional clarity and measurement capability are interdependent elements of research design.

Research Question 1 establishes that high-performance facades must be understood as multidimensional phenomena that integrate energy efficiency, occupant comfort, environmental sustainability, and durability. Within this comprehensive framework, the Window-to-Wall Ratio emerges as one of the most critical geometric parameters precisely because it influences multiple performance dimensions simultaneously. A particular WWR value affects thermal comfort through its impact on thermal bridging and radiant asymmetry near windows. It determines daylighting availability, which directly influences visual comfort and occupant wellbeing. It shapes the building's energy consumption through its effects on solar heat gain and cooling load. And it has profound implications for facade durability through its relationship to moisture management and material exposure.

However, establishing these theoretical relationships is insufficient for advancing knowledge toward urban-scale implementation. The definition of high performance, while theoretically sound, remains ineffective for driving building stock improvement unless the performance metrics that characterise facades can be measured consistently, reliably, and at scales commensurate with the magnitude of the urban sustainability challenge. This is where RQ2 becomes essential.

Research Question 2 operationalises the theoretical understanding developed in RQ1 by asking how one of the most important facade characteristics identified in the definitional work—the Window-to-Wall Ratio—can be measured automatically and at unprecedented scale. The AI-driven approach to WWR estimation is not an arbitrary technical exercise but a direct response to the measurement challenge created by the scaling requirement. Traditional manual measurement methods, while potentially accurate for individual buildings, become prohibitively expensive and time-consuming when applied to the thousands or tens of thousands of buildings necessary to understand urban building stocks and support city-wide sustainability strategies.

In this sense, RQ2 exists in service of RQ1. The automated measurement capability developed in response to RQ2 enables the performance assessment framework defined in RQ1 to be applied systematically across large populations of buildings. Without RQ2's technological innovation, the definitions and performance criteria established in RQ1 would remain confined to design research and detailed case studies, unable to contribute to the evidence base necessary for urban policy development and building stock transformation.

The relationship between the two questions also shapes the validation approach that follows in RQ3. Because RQ2 introduces a new measurement methodology (AI-based, rather than manual), rigorous validation becomes essential. The ground-truth measurements established through the manual protocols developed in RQ1 thus become the reference baseline against which the automated methods developed in RQ2 are systematically evaluated. This evaluation, addressed through RQ3, is necessary before the automated capabilities can be deployed responsibly for urban-scale applications.**Research Question 3:** What are the methodological challenges and accuracy limitations in extracting facade data through AI-based approaches, compared to traditional methods?

This research question provides critical evaluation and validation of the technological approaches developed in RQ2 by conducting comprehensive comparisons with established manual measurement practices. The question reflects the doctoral program's emphasis on risk assessment and acknowledges that new technologies must be thoroughly validated before they can be trusted for important decision-making processes that affect building performance, occupant wellbeing, and environmental sustainability(Schiavon et al., 2019; Schiavon and Altomonte, 2015).

The validation component addresses multiple dimensions of methodological assessment, including accuracy evaluation through comparison with ground-truth data from traditional measurement methods, analysis of error sources and propagation patterns in automated systems, investigation of algorithmic bias and its potential impacts on assessment outcomes, and evaluation of reliability across different building types, architectural styles, environmental conditions, and image quality scenarios.

The question also addresses broader methodological and philosophical concerns about the appropriate role of artificial intelligence in architectural assessment. These concerns include questions about the boundaries of automated analysis, the need for human oversight and validation in assessment processes, the integration of quantitative measurement with qualitative evaluation approaches, and the preservation of professional expertise and judgment in design and evaluation processes(Kim et al., 2018; Schiavon and Melikov, 2008).

The comparative analysis component examines both the advantages and limitations of AI-driven strategies relative to traditional methods. While automated systems offer unprecedented scale and efficiency advantages, they may also introduce new types of errors, biases, or limitations that must be understood and managed carefully. The research question addresses these trade-offs by developing comprehensive understanding of when and how different assessment approaches should be applied, and how they can be combined to leverage their respective strengths while mitigating their individual limitations.

Research Question 4: How can scalable facade metrics (like WWR) and multi-criteria performance data be integrated for urban-scale risk and sustainability assessment?

This research question bridges individual building assessment with urban-scale policy applications, reflecting the doctoral program's emphasis on territorial development and environmental risk management. The question addresses the critical gap between building-level performance understanding and urban-scale outcomes by developing frameworks for integrating standardized quantitative facade metrics with holistic risk assessment, sustainability evaluation, and wellbeing indicators that operate at neighborhood and city scales (Santamouris et al., 2017).

The integration challenge involves developing methodologies that can scale individual building assessments to urban systems analysis while maintaining sufficient accuracy and relevance for practical decision-making applications. This requires creating frameworks for linking facade performance characteristics with broader urban environmental conditions, such as heat island effects, air quality patterns, energy infrastructure demands, and community resilience factors.

The question also addresses practical implementation challenges by exploring how automated assessment tools can support real-world decision-making processes across multiple scales and stakeholder needs. Applications include retrofit prioritization strategies that can identify buildings and neighborhoods where facade improvements would have the greatest impact on energy consumption, comfort, or environmental performance; climate adaptation planning that considers how facade characteristics affect building and community resilience to extreme weather events; zoning and building code development that can establish performance requirements based on empirical understanding of existing building stocks; and sustainable development strategies that integrate building performance considerations with broader urban planning objectives.

The urban-scale focus reflects recognition that meaningful progress in building sustainability requires approaches that can address the collective performance of building stocks rather than optimizing individual buildings in isolation. This systems-level perspective is essential for understanding how individual building improvements can contribute to broader sustainability and resilience objectives, and for developing policy frameworks that can drive market transformation toward higher-performing building envelopes.

In summary, the logical flow RQ1→RQ2→RQ3→RQ4 reflects a research strategy in which each question builds upon and enables the previous question, while the answers to each question contribute essential pieces of the overall investigation into facade performance assessment at urban scales.

Table 1 - Research Questions Framework and Objectives

RQ	Research Question	Primary Objective	Methodology	Expected Outcome	Chapter
RQ1	What constitutes a high-performance façade?	Define HPF comprehensively	Literature synthesis + empirical validation	Operationalized definition with 6 characteristics	3
RQ2	Can AI enable scalable WWR assessment?	Develop AI pipeline	Computer vision + deep learning	Validated automated system	4
RQ3	What are accuracy limitations of AI?	Quantify accuracy	Systematic validation testing	Error documentation & bounds	4
RQ4	How to integrate assessment at urban scale?	Urban framework development	Case study implementation	Decision-support integration	5

1.3. Significance Of the Study

This research addresses fundamental challenges in building performance assessment and urban sustainability planning that have significant implications for academic knowledge, professional practice, policy development, and societal wellbeing. The significance operates across multiple scales and stakeholder communities, from individual building designers to urban planners to policymakers working on climate adaptation and energy transition strategies.

From a theoretical perspective, this research contributes to several interconnected bodies of knowledge that have developed largely in isolation from each other. The integration of facade performance assessment with urban-scale sustainability analysis bridges traditionally separate domains of building science, urban planning, and environmental risk management(Santamouris et al., 2018; Sangiorgio et al., 2020). This interdisciplinary way generates new theoretical frameworks for understanding how individual building components contribute to urban-scale environmental outcomes, occupant wellbeing, and community resilience.

The development of comprehensive, quantifiable definitions for high-performance facades addresses a significant gap in the academic literature, where performance criteria are often discussed in qualitative terms or limited to narrow technical metrics such as energy efficiency or structural adequacy (Attia et al., 2018). The multi-criteria framework developed in this research provides a foundation for future research that can build upon consistent, standardized definitions while exploring more sophisticated relationships between facade characteristics and building performance outcomes.

The validation and critical evaluation of AI-driven assessment methodologies contribute to emerging discussions about the appropriate role of artificial intelligence in architectural and urban analysis. The research provides empirical evidence about the capabilities and limitations of automated assessment approaches, which is essential for responsible development and application of these technologies in professional practice and policy development. (Tarkhan et al., 2024, 2022)

The integration of individual building assessment with urban-scale analysis contributes to theoretical understanding of complex urban systems and the relationships between building-level interventions and city-wide sustainability outcomes. This systems-level perspective is increasingly important as cities seek to develop comprehensive strategies for climate adaptation, energy transition, and sustainable development that must address the collective performance of large building stocks.

The research makes significant methodological contributions by developing and validating new methods to facade assessment that overcome fundamental limitations of traditional methods. The creation of scalable, automated assessment tools represents a substantial advance in the practical capabilities available to researchers, practitioners, and policymakers for understanding building performance at urban scales (Szcześniak et al., 2022; Tarkhan et al., 2024).

The computer vision and machine learning methodologies developed in this research have applications extending beyond facade assessment to other aspects of building and urban analysis. The approaches to image analysis, feature extraction, and performance metric calculation can be adapted for assessing other building characteristics, urban form parameters, and environmental conditions that are difficult to measure using traditional survey methods.

The validation frameworks developed for comparing AI-driven and traditional assessment methods provide templates for evaluating other automated analysis tools in building and urban research. The comprehensive strategy to accuracy assessment, bias analysis, and reliability evaluation establishes standards for responsible development and deployment of AI technologies in built environment applications.

The approaches to data aggregation, spatial analysis, and multi-scale assessment have broad applicability for urban planning, policy development, and environmental management applications.

For architectural and engineering practice, this research provides practical tools and frameworks that can enhance design decision-making, performance evaluation, and project benchmarking capabilities(Alessandro Cannavale, 2020). The automated assessment tools enable practitioners to analyze facade performance more efficiently and comprehensively than traditional methods allow, while the multi-criteria evaluation frameworks support more holistic approaches to facade design that consider multiple performance objectives simultaneously.

The research supports evidence-based design practices by providing access to performance data from large building samples that can inform design decisions, establish realistic performance targets, and identify successful strategies for achieving high performance in different contexts. This capability is particularly valuable for practitioners working on sustainable design projects, building retrofits, and performance-based design methods.

For building owners and facility managers, the research provides tools for evaluating the performance of existing facades, identifying opportunities for improvement, and prioritizing maintenance and upgrade investments. The scalable assessment capabilities enable portfolio-level analysis that can support strategic decision-making about building operations and capital investments.

The research provides evidence-based support for policy development in multiple areas related to building performance, energy efficiency, and urban sustainability. The ability to rapidly assess facade characteristics across large building stocks provides policymakers with empirical data needed to develop effective building codes, energy efficiency standards, and retrofit incentive programs(L. Yang et al., 2021)

The urban-scale assessment capabilities support comprehensive planning approaches that can consider the collective performance of building stocks when developing zoning regulations, urban design guidelines, and infrastructure planning strategies. This capability is particularly important for cities developing climate action plans, sustainable development strategies, and resilience planning initiatives that must address building performance at district and city scales.

The research supports evidence-based policy evaluation by providing tools for monitoring the effectiveness of building performance regulations, incentive programs, and sustainability initiatives. The ability to track changes in building stock characteristics over time enables adaptive management methods that can refine policies based on empirical evidence of their impacts.

The broader environmental significance of this research lies in its potential to accelerate improvement in building performance across urban building stocks, which could have substantial impacts on energy consumption, greenhouse gas emissions, and environmental sustainability. Buildings represent one of the largest opportunities for reducing energy consumption and carbon emissions, but realizing this potential requires ways that can address building performance at scales commensurate with the climate challenge (Marino et al., 2017)

The research supports more effective targeting of building improvement efforts by identifying buildings and neighborhoods where facade upgrades would have the greatest impact on energy performance, occupant comfort, or environmental sustainability. This targeting capability can increase the cost-effectiveness of retrofit programs while maximizing their environmental and social benefits.

The focus on occupant comfort and wellbeing recognizes that building performance must serve human needs as well as environmental objectives. The research contributes to understanding of how facade characteristics affect occupant satisfaction, comfort, and productivity, which is essential for developing building solutions that are both environmentally sustainable and socially beneficial (Schiavon et al., 2017)

1.4. Scope And Limitations

This research operates within several defined boundaries that shape its methodology, applications, and interpretation of results. Understanding these limitations is essential for appropriate application of research findings and identification of areas requiring future investigation.

The geographic focus reflects the research context within the European building regulatory environment and the availability of suitable data sources for method development and validation.

The climate focus has implications for the generalizability of specific performance criteria and optimization strategies, as facade design strategies that are appropriate for temperate climates may not be optimal for tropical, arctic, or desert conditions. However, the methodological frameworks and assessment tools developed in this research are designed to be adaptable to different climatic contexts through adjustment of performance criteria, weighting factors, and assessment thresholds.

The research focuses primarily on residential and commercial building types that are well-represented in urban building stocks and street-view imagery datasets. Industrial buildings, specialized facilities, and buildings with unusual architectural characteristics may not be adequately represented in the assessment methodologies, although the general technique can be adapted for these building types with appropriate modifications.

The scale of analysis ranges from individual buildings to urban districts, but does not extend to regional or national scales where data availability, processing requirements, and validation challenges become substantially more complex. The urban-scale applications focus on dense urban environments where street-view imagery provides adequate coverage and resolution for facade assessment.

The AI-driven assessment methodologies depend on the availability and quality of street-view imagery, which may not be uniformly available across all geographic regions or may not provide adequate coverage of all building facades due to site conditions, vegetation, or urban geometry. The research addresses these limitations by developing framework for handling missing data and assessing the reliability of results based on image quality and coverage characteristics.(Tarkhan et al., 2024)

The computer vision algorithms are trained and validated using contemporary imagery and building types, which may limit their accuracy when applied to historical buildings, unusual architectural styles, or building types that are not well-represented in training datasets. The research includes analysis of these limitations and provides guidance for identifying situations where manual validation or alternative assessment approaches may be necessary.

While the research focuses on WWR as a critical facade performance parameter, this represents only one aspect of facade performance, and optimization of WWR alone does not guarantee overall facade performance. The research acknowledges this limitation by developing multi-criteria assessment frameworks, but the depth of analysis for performance characteristics other than WWR is necessarily limited by scope constraints.

The research does not include detailed analysis of dynamic facade performance, seasonal variations, or long-term performance changes due to aging, maintenance, or environmental exposure. These temporal aspects of facade performance represent important areas for future research that build upon the foundational assessment capabilities developed in this study.

The validation of AI-driven assessment methods is constrained by the availability of high-quality ground-truth data from traditional measurement frameworks. While the research includes comprehensive validation studies, the accuracy assessment is limited to buildings and conditions where reliable comparison data can be obtained through manual measurement or detailed building documentation.

The accuracy of automated assessment methods may vary based on building characteristics, image quality, lighting conditions, and architectural complexity in ways that are not fully captured by validation studies conducted within the research timeframe. The research addresses these limitations by providing uncertainty estimates and reliability indicators, but users of the assessment tools must consider these limitations when interpreting results for specific applications.

1.5. Integration and Application Limitations

The integration of individual building assessment with urban-scale analysis requires simplifying assumptions about the relationships between facade characteristics and broader urban environmental conditions. While these relationships are supported by existing research and validated through case study applications, they may not capture the full complexity of urban environmental systems or the interactions between multiple buildings and urban infrastructure.

The policy and planning applications developed in this research provide frameworks and tools for evidence-based decision-making, but the effectiveness of these applications depends on their integration with broader planning processes, stakeholder engagement, and implementation mechanisms that are beyond the scope of this research. The research provides evidence and tools to support decision-making, but does not address the full range of institutional, economic, and social factors that influence policy implementation and effectiveness.

1.6. Thesis Structure

This thesis is organized into six chapters that follow a classical academic structure while maintaining thematic coherence around four research questions that progress systematically from definitional foundations to practical urban-scale applications.

Chapter 1: Introduction establishes the research context by situating facade performance within contemporary sustainability, climate change, and urban development challenges. The chapter articulates research objectives grounded in both academic advancement and practical application needs, presents the four research questions that structure the subsequent investigation, and defines the scope and limitations of the research enterprise. The introduction positions facade assessment within the intersection of building science, urban sustainability, and artificial intelligence applications, demonstrating how these traditionally separate domains converge around fundamental questions of measurement, definition, and implementation at scale.

Chapter 2: Literature Review and Theoretical Framework provides comprehensive synthesis of existing knowledge across the multiple disciplinary domains that inform facade performance assessment. The chapter begins with evolution of facade performance conceptualization from simple structural adequacy to contemporary multi-criteria frameworks encompassing energy efficiency, occupant comfort, environmental sustainability, and durability. Sections addressing high-performance facade definitions, multi-criteria assessment frameworks, and specific performance dimensions (energy, thermal comfort, daylighting, visual comfort, occupant wellbeing) establish theoretical foundations for the research. Introduction of manual assessment methods and their limitations motivates the subsequent technological development, while sections on computer vision and artificial intelligence applications situate this research within emerging opportunities for scalability. The chapter concludes by identifying research gaps that the subsequent investigation addresses, explicitly connecting literature synthesis to the four research questions that structure the thesis.

Chapter 3: Defining High-Performance Façades (RQ1) addresses the foundational research question through complete integration of theoretical development, empirical validation, and critical evaluation. The chapter begins with introduction and research approach, explaining how RQ1 simultaneously requires both rigorous theoretical synthesis and empirical grounding in occupant comfort data. Section 3.2 develops the methodology for comprehensive facade performance framework through systematic literature synthesis, multi-criteria integration approaches, and stakeholder consultation processes. Section 3.3 presents the methodology for manual Window-to-Wall Ratio (WWR) assessment using the Center for the Built Environment (CBE) occupant survey database, describing data collection, geometric calibration, and statistical analysis approaches. Results are then presented in two complementary components: Section 3.4 articulates the explicit definition of high-performance facades with six defining characteristics and quantitative performance thresholds, while Section 3.5 presents empirical correlations between WWR and occupant comfort metrics. Section 3.6 provides comprehensive discussion that validates the proposed definition against existing frameworks, addresses limitations of the manual assessment approach, and articulates implications for automated assessment development. The chapter concludes with explicit synthesis of the complete answer to RQ1, demonstrating how the integrated theoretical and empirical investigation produces coherent, actionable definition of high-performance facades.

Chapter 4: AI-Driven WWR Assessment (RQ2 + RQ3) addresses technological development and validation through systematic investigation of artificial intelligence capabilities and limitations. The chapter begins by introducing research approach explaining how RQ2 and RQ3 are intrinsically connected through the complementary focus on pipeline development and rigorous accuracy validation. Section 4.1 (now labeled Methodology: AI Pipeline Development) presents comprehensive description of the AI pipeline architecture integrating Grounding DINO for window detection and Segment Anything Model (SAM) for precise segmentation, while describing image preprocessing, training dataset development, and optimization protocols. Section 4.2 (Methodology: Validation Framework) establishes the methodological approach for comparing AI-derived assessments with manual measurements, describing performance metrics, comparative analysis design, and error analysis protocols. Section 4.3 (Results: AI Model Performance) presents technical implementation details and performance characteristics across multiple case studies representing diverse architectural typologies and complexity levels, including baseline buildings, occlusion challenges, multi-building scenarios, and architectural complexity cases. Section 4.4 (Results: Accuracy Validation and Comparative Analysis) provides detailed comparative analysis between AI and manual methods, statistical performance evaluation, accuracy stratification by building type, and comparison with traditional assessment approaches. Section 4.5 (Discussion: Capabilities, Limitations, and Trade-offs) synthesizes methodological insights, examines error sources and mitigation strategies, addresses accuracy-scalability trade-offs, discusses ethical considerations including privacy and algorithmic bias, and explicitly answers RQ2 and RQ3 through comprehensive synthesis demonstrating how the research successfully addresses both the technological development and rigorous validation questions that structure this chapter. Section 4.6 (Integration with

Overall Research Framework) connects AI assessment outcomes to the broader research enterprise, demonstrating how empirically validated WWR measurement capabilities enable urban-scale assessment integration addressed in Chapter 5.

Chapter 5: Urban-Scale Integration (RQ4) extends validated facade assessment capabilities to city-scale implementation and policy applications, addressing the fourth research question through complete integration of methodology, results, and practical implications. Section 5.1 introduces research approach explaining how RQ4 builds upon RQ1-3 findings to address integration challenges at urban scales. Section 5.2 (Methodology: Integration Framework and Implementation) describes development of comprehensive integration framework encompassing GIS-based spatial analysis, multi-criteria performance evaluation algorithms, municipal systems integration, and implementation workflows. Section 5.3 (Results: Urban-Scale Case Studies) presents findings from urban-scale implementation demonstrating practical feasibility and generating performance insights across residential, commercial, and institutional building typologies. Section 5.4 (Results: Multi-Criteria Performance Assessment) demonstrates integration of automated WWR assessment with occupant comfort metrics and energy performance data, generating holistic building performance evaluations that support prioritization and retrofit planning. Section 5.5 (Discussion: Policy Implications and Applications) addresses how urban-scale assessment capabilities support evidence-based policy development for building performance standards, retrofit prioritization, and municipal decision-making. Section 5.6 (Discussion: Framework Validation and Generalizability) synthesizes findings demonstrating how the integrated framework successfully addresses RQ4 through validation of urban-scale implementation feasibility, assessment of generalizability across diverse contexts, and explicit articulation of boundary conditions and applicability constraints. This chapter demonstrates successful integration of all prior research questions into operational systems capable of supporting real-world decision-making at urban scales.

Chapter 6: Conclusions and Future Perspectives synthesizes findings across all research questions and chapters while articulating research contributions, practical implications, and opportunities for future investigation. Section 6.1 provides comprehensive summary of key findings for each research question, demonstrating how the investigation collectively addresses the original research objectives. Section 6.2 articulates theoretical, methodological, and technical contributions showing how the research advances understanding of facade performance assessment, develops new technological capabilities, and creates frameworks for applied implementation. Section 6.3 discusses practical implications for multiple stakeholder communities including researchers, policymakers, building professionals, property owners, and municipal authorities, demonstrating broad relevance of the research findings. Section 6.4 acknowledges limitations of the research including data constraints, technical limitations, methodological assumptions, and applicability boundaries while describing mitigation strategies employed. Section 6.5 identifies future research directions addressing methodological extensions, technology development opportunities, new application domains, and global implementation possibilities. Section 6.6 presents vision for sustainable urban futures articulating how facade assessment research contributes to net-zero building transitions, climate resilience, and equitable sustainable development. Section 6.7 provides final remarks reflecting on the significance of advancing from building-level performance understanding to urban systems integration and the potential for evidence-based approaches to support fundamental transformations in how societies approach building sustainability and urban development.

The six-chapter structure maintains classical academic organization while enabling thematic coherence through progressive building of knowledge from theoretical foundations (Chapters 1-2) through single-theme research cycles (Chapters 3-5) to synthetic conclusions and future perspectives (Chapter 6). Each thematic chapter (3-5) integrates methodology, results, and discussion internally, enabling readers to follow complete research narratives for each question while also maintaining ability to understand how individual contributions integrate into comprehensive framework addressing urgent contemporary challenges in building performance assessment and urban sustainability.

1.7. Research Methdology and Materials

This doctoral research adopts an integrated mixed-methods approach that combines qualitative synthesis with quantitative measurement and validation. The methodology is structured around the four research questions introduced in Section 1.2, and operationalised through distinct but interconnected phases that progress from definitional foundation to technological development, rigorous validation, and finally urban-scale implementation.

The methodological framework addresses a fundamental challenge in contemporary building science: how to move from detailed, case-study-based understanding of facade performance to systematic, evidence-based assessment at urban scales. This transition requires both theoretical clarity about what constitutes high performance and practical measurement capabilities that can operate across thousands of buildings. The methodology developed here addresses both requirements through careful integration of multiple research approaches.

The research develops through four main phases, each corresponding to one of the research questions and structured to build systematically upon previous findings while also contributing independently to advancing knowledge in facade assessment and urban sustainability.

Phase 1: Definitional Foundation (Research Question 1, Chapter 3)

The first phase establishes comprehensive definitions of high-performance facades through systematic synthesis of multiple knowledge sources and empirical validation against occupant satisfaction data. This phase employs qualitative research methods including critical literature review, analysis of international building standards and certification systems, and consultation with multiple stakeholder communities. The definitional framework integrates six primary performance dimensions: energy efficiency, thermal comfort, visual comfort and daylighting, environmental sustainability, structural and functional durability, and safety and resilience.

A critical component of this phase involves establishing empirical correlations between Window-to-Wall Ratio and occupant comfort metrics using the Centre for the Built Environment survey database, which comprises over 90,000 occupant responses from real commercial buildings. This empirical grounding ensures that the definitions developed are not merely theoretical constructs but are validated against actual human experience in buildings. The manual WWR assessment protocols developed in this phase also establish the ground-truth baseline against which the AI-driven automated methods developed in Phase 2 will be validated.

Phase 2: Technological Development (Research Question 2, Chapter 4)

The second phase develops automated assessment capabilities through sophisticated computer vision and machine learning approaches. This phase employs quantitative methods focused on algorithm development, training dataset creation, and system optimization. The core technological contribution involves integrating state-of-the-art detection models with segmentation frameworks to extract Window-to-Wall Ratio measurements from widely available street-level imagery.

The methodological approach leverages Google Street View as a primary data source, recognising both its advantages in terms of global coverage and accessibility, and its limitations regarding image quality variability and temporal currency. The AI pipeline architecture combines object detection capabilities for identifying facade elements with precise segmentation methods for calculating geometric properties. This phase produces not merely a technical proof-of-concept but a complete workflow from image acquisition through quality assurance to final WWR estimation.

Phase 3: Validation and Accuracy Assessment (Research Question 3, Chapter 4)

The third phase provides rigorous validation of the automated assessment methods through systematic comparison with manual measurement approaches across diverse building typologies and contexts. This phase employs quantitative validation methods including accuracy metrics calculation, error distribution analysis, and performance stratification across multiple dimensions.

The validation framework addresses not only average performance but also characterises the full distribution of errors, identifies conditions under which automated methods perform well or poorly, and documents limitations and boundary conditions. This comprehensive validation approach ensures that the automated tools developed can be deployed responsibly, with clear understanding of their appropriate applications and necessary constraints. The validation sample includes buildings representing diverse architectural styles, construction periods, climatic contexts, and facade configurations, ensuring that performance assessment reflects real-world heterogeneity rather than idealised conditions.

Phase 4: Urban Integration and Policy Application (Research Question 4, Chapter 5)

The fourth phase integrates validated building-level assessment capabilities into urban-scale frameworks that support municipal decision-making, retrofit prioritisation, and policy development. This phase employs multi-criteria assessment methods, geographic information system integration, and scenario analysis approaches. The integration framework connects individual building metrics to urban-scale indicators including district-level energy demand, retrofit investment priorities, and climate adaptation strategies.

The methodological approach recognises that urban-scale implementation requires not merely technical scaling but also integration with governance systems, stakeholder engagement processes, and policy frameworks. Case study implementations in European urban contexts demonstrate practical feasibility while identifying implementation challenges and opportunities for refinement. The urban-scale work addresses how automated facade assessment can support evidence-based policy-making for building performance standards, energy transition planning, and sustainable urban development.

Data Sources and Integration

The research integrates multiple data sources, each contributing distinct types of information essential to different phases of the investigation. Academic literature and international building standards provide theoretical foundations and performance criteria. Google Street View imagery and OpenStreetMap building data enable scalable geometric characterisation of building facades. The Centre for the Built Environment occupant satisfaction database provides empirical evidence linking facade characteristics to human comfort and wellbeing. Building energy performance data, where available, enables validation of performance predictions against actual operational outcomes. Municipal building registries and urban planning documents provide contextual information necessary for urban-scale integration.

Data integration protocols ensure consistency, traceability, and quality control across heterogeneous sources. Geographic information systems provide the spatial framework for linking building-level data to urban contexts. Statistical analysis methods enable identification of patterns, correlations, and performance distributions across building populations. Multi-criteria decision-making frameworks provide structured approaches for integrating multiple performance dimensions into coherent assessment outcomes.

Validation and Quality Assurance

Throughout all phases, the research employs multiple validation and quality assurance strategies to ensure credibility and reliability. Triangulation across multiple data sources and methods provides cross-validation of findings. Ground-truth comparison with manual measurements establishes accuracy baselines for automated approaches. Stakeholder consultation ensures practical relevance and applicability of research outputs. Systematic documentation of limitations, assumptions, and boundary conditions enables appropriate interpretation and application of results.

The methodological approach acknowledges that building performance assessment involves both technical measurement and human judgment, and that automated tools should enhance rather than replace professional expertise. The validation frameworks developed here establish standards for responsible deployment of AI technologies in built environment applications, addressing concerns about algorithmic bias, privacy implications, and appropriate governance mechanisms.

The detailed methodologies specific to each research question, including data collection protocols, analytical techniques, and validation procedures, are presented comprehensively in the respective chapters where they are applied. Chapter 3 details the framework development and manual assessment methods for RQ1, Chapter 4 presents the AI pipeline development and validation protocols for RQ2 and RQ3, and Chapter 5 describes the urban integration methodology and case study implementation for RQ4.

1.8. The Research Context

The global built environment stands at a critical inflection point in human history, positioned at the intersection of escalating climate imperatives, accelerating urbanization, and emerging technological capabilities that fundamentally reshape our capacity to measure, assess, and optimize building performance at unprecedented scales. Understanding this multi-faceted context—encompassing climate change, urbanization trends, technological advancement, and policy evolution—provides essential framing for the research questions and methodological approaches that structure this doctoral investigation.

a. Climate Change and Building Sector Decarbonization

Buildings represent one of the largest contributors to global greenhouse gas emissions and energy consumption, accounting for approximately 40 percent of global energy use and approximately 38 percent of carbon dioxide emissions associated with energy systems (UN Environment Programme, 2021). This substantial environmental footprint reflects the combined impacts of embodied carbon in building materials and construction processes, operational energy consumption throughout building lifecycles spanning decades, and end-of-life demolition impacts and waste generation. The urgency of climate change mitigation establishes building decarbonization as one of the most critical frontiers for achieving global climate targets, with the International Energy Agency estimating that the built environment must contribute approximately 30 percent of the emission reductions required to achieve Paris Agreement objectives of limiting global warming to 1.5 degrees Celsius.

This decarbonization imperative intersects fundamentally with facade performance, as building envelopes determine thermal efficiency, daylighting provision, occupant comfort conditions, and overall building energy demand. The facade's role as the critical interface between internal conditioned environments and external environmental conditions means that facade optimization represents one of the most direct, cost-effective, and scalable opportunities for building energy reduction. However, realizing this potential requires systematic understanding of how facade characteristics influence building performance across diverse climatic contexts, building types, and occupant populations—understanding that remains fragmented across disciplinary boundaries and geographic contexts.

b. Urbanization and Urban-Scale Sustainability Challenges

Parallel to climate change urgency, global urbanization represents a defining feature of contemporary development, with the United Nations projecting that approximately two-thirds of the global population will reside in urban areas by 2050 (UN-Habitat, 2022). This accelerating urbanization concentrates both sustainability challenges and opportunities within urban systems, where the collective performance of building stocks fundamentally determines urban environmental conditions, energy infrastructure demands, occupant wellbeing, and economic sustainability. Cities currently account for approximately 75 percent of global carbon dioxide emissions, with buildings representing the dominant contributor through operational energy consumption and embodied impacts of new construction and renovation activities.

Urban sustainability challenges operate at multiple spatial and temporal scales, from individual building performance optimization to city-wide energy systems and long-term climate resilience planning. Traditional building assessment methodologies developed for individual project evaluation prove inadequate for addressing urban-scale challenges, as they cannot operate at the scales required to inform comprehensive building stock improvement strategies, climate adaptation planning, or evidence-based municipal decision-making. The gap between theoretical understanding of building performance developed through detailed case studies and the practical ability to implement this knowledge at urban scales represents a fundamental constraint limiting progress toward sustainable cities and buildings.

c. The Window-to-Wall Ratio as Critical Facade Performance Metric

Within the broader context of facade performance assessment, the Window-to-Wall Ratio (WWR)—defined as the ratio between a building's total window area and its overall external wall area—emerges as a particularly significant yet challenging metric. This seemingly straightforward geometric parameter profoundly influences multiple aspects of building performance: it directly affects energy consumption through its impacts on solar heat gain, thermal bridging, and conductive heat transfer; it determines occupant visual comfort and psychological wellbeing through its influence on daylighting quality and connection to the external environment; it influences thermal comfort through its effects on radiant asymmetry and surface temperatures near glazed facades; it affects building durability through its impact on moisture management and structural performance; and it shapes architectural character and urban context through its visual and compositional effects.

Decades of building performance research conducted across diverse climatic contexts and building typologies have consistently demonstrated that optimal WWR values vary significantly depending on climate conditions, building orientation, internal heat loads, shading strategies, glazing properties, and occupant preferences. Studies have established that optimal WWR ranges typically fall between 20 and 45 percent depending on context-specific factors, though this research simultaneously reveals the substantial complexity involved in determining optimal values within specific design contexts where multiple performance objectives must be balanced against structural requirements, aesthetic preferences, code compliance expectations, cost constraints, and maintainability concerns.

Despite its fundamental importance to building performance, WWR remains challenging to measure and analyze at the scales necessary to support evidence-based policy development, urban planning initiatives, and building stock improvement strategies. Traditional WWR assessment methods rely on manual measurement techniques that, while potentially accurate for individual projects, become prohibitively time-consuming and resource-intensive when applied to larger building populations. These approaches require detailed analysis of architectural drawings, on-site surveys, or photogrammetric analysis—all demanding significant expertise, specialized equipment, and substantial time investments that render them impractical for urban-scale applications.

d. Data Fragmentation and Information Asymmetries

Compounding these technical challenges, the facade assessment field faces systematic problems of data standardization and accessibility that extend far beyond measurement challenges alone. Architectural information remains inconsistently recorded across different formats and systems—some buildings possess detailed digital three-dimensional models while others retain only paper-based plans or incomplete documentation. This fragmentation creates cascading problems that constrain research advancement and evidence-based decision-making: researchers and policymakers lack robust, systematically updated databases of facade properties that could illuminate urban-scale trends; building owners and designers struggle to benchmark their projects against broader performance standards or learn from successful implementations in comparable contexts; urban planners and policymakers cannot develop effective strategies for building stock improvement because they lack reliable data about current performance characteristics across their jurisdictions.

This gap between theoretical understanding and practical ability to implement at scale proves particularly problematic given urgent contemporary needs for city-wide building retrofits aligned with EU renovation wave objectives, climate adaptation strategies, and energy transition policies that depend fundamentally on comprehensive understanding of existing building stocks and their performance characteristics. The European Commission estimates that achieving EU renovation wave targets requires evaluation of approximately 280 million residential buildings across the European Union, a scale that renders traditional assessment methodologies fundamentally impractical without technological innovation and systematic methodology development.

e. Technological Advancement and Emerging Opportunities

Against this backdrop of urgent policy needs and technical constraints, rapid advancement in artificial intelligence, computer vision, and machine learning technologies creates unprecedented opportunities for addressing facade assessment challenges at scale. Recent developments in deep learning semantic segmentation, object detection algorithms, and image recognition systems have demonstrated remarkable capabilities for analyzing visual information and extracting quantitative data from photographic sources. Simultaneously, the widespread availability of street-level imagery through Google Street View and similar platforms provides comprehensive, cost-effective global coverage of building facades accessible for systematic analysis without requiring specialized data collection efforts.

The convergence of policy urgency, technical constraints, available data sources, and emerging technological capabilities creates a distinctive moment where previously intractable challenges become potentially addressable through systematic integration of advanced methodologies with rigorous evaluation frameworks. However, the application of artificial intelligence to building performance assessment remains relatively nascent, with limited validation frameworks, unclear boundary conditions, and substantial gaps in understanding appropriate roles for automated analysis versus human expertise and judgment in evaluation processes.

f. Environmental Risk Management and Urban Resilience Framework

While the research questions presented above establish the investigation's technical and methodological structure, it is essential to explicitly situate this work within the broader context of environmental risk management—a central theme of the doctoral program "Rischio e Sviluppo Ambientale, Territoriale ed Edilizio" at Politecnico di Bari. The term "environmental risk" in the dissertation title is not merely contextual but reflects a fundamental framing that connects facade performance assessment with urban vulnerability, climate adaptation, and resilience planning.

Environmental risks in the built environment encompass multiple interconnected hazards that threaten building performance, occupant safety, and urban system functionality. These risks can be categorized into:

1. Climate-driven risks: extreme weather events (heatwaves, storms, flooding), progressive climate change impacts (temperature rise, precipitation pattern shifts), and urban heat island intensification (Castelluccio et al., 2025; Øyen, 2012)

2. Building envelope vulnerability risks: material degradation, moisture infiltration leading to rot decay and mold growth, thermal bridge failures, and cascading effects from facade technical element deterioration(Kesik, Ted, 2023)

3. Urban system risks: energy infrastructure strain during peak demand, occupant health impacts from inadequate thermal comfort, and economic risks from building performance degradation (Castelluccio et al., 2025)

The integration of facade performance assessment with environmental risk management addresses a critical gap in contemporary urban planning practice. Traditional risk assessment frameworks focus predominantly on intensive hazards (earthquakes, floods, fires) that pose immediate structural threats, while largely overlooking the extensive hazards posed by gradual environmental stressors acting on building envelopes (Ferreira and Ramírez Eudave, 2022). Climate change exacerbates this second category of risks through increased precipitation, temperature fluctuations, and extreme weather frequency—factors that continuously degrade facade technical elements and amplify vulnerability over time.

Research conducted by Norwegian institutions demonstrates that climate change could increase rot decay risk exposure for building envelopes from 615,000 buildings currently to 2.4 million buildings by 2100 in Norway alone, primarily due to increased moisture loads and temperature variations(Øyen, 2012). This projection illustrates how gradual environmental stressors, when inadequately addressed through building envelope design and performance monitoring, transform into significant building risks (Rb) with cascading impacts on urban systems, including potential facade element detachment, pedestrian safety hazards, and infrastructure damage.

The automated facade assessment methodology developed in this research directly addresses environmental risk management through several interconnected mechanisms:

Risk Identification and Quantification: The AI-driven WWR assessment pipeline enables systematic identification of buildings with potentially vulnerable facade configurations across entire urban districts. Buildings with suboptimal WWR values—either too low (inadequate daylighting, excessive artificial lighting energy demand) or too high (thermal discomfort risk, overheating vulnerability, excessive cooling loads)—can be rapidly identified and prioritized for detailed vulnerability assessment.

Climate Adaptation Planning: Urban-scale facade performance data supports evidence-based climate adaptation strategies by identifying neighborhoods and building typologies most vulnerable to climate-driven risks. The framework enables municipal authorities to develop targeted intervention strategies that enhance building resilience to extreme heat events, reduce urban heat island contributions, and improve passive survivability during extended power outages coinciding with extreme weather.

Vulnerability Reduction through Retrofit Prioritization: By integrating facade performance assessment with multi-criteria evaluation frameworks, the research enables risk-based retrofit prioritization that considers not only energy efficiency gains but also occupant health protection, thermal resilience enhancement, and adaptation to changing climate conditions. This holistic approach ensures that limited municipal resources are directed toward interventions that provide maximum risk reduction benefits.

The research explicitly addresses the doctoral program's emphasis on territorial development and environmental engineering by demonstrating how building-level performance assessment scales to urban-territorial analysis, supporting comprehensive risk management at multiple spatial scales. The framework connects individual building facade characteristics to district-level environmental outcomes including urban microclimate effects, peak energy demand patterns, and spatial distribution of climate vulnerability across urban populations.

Moreover, the risk management framework explicitly incorporates equity and environmental justice considerations. Climate vulnerability and building quality are not uniformly distributed across urban areas—lower-income neighborhoods often concentrate older buildings with poor envelope performance, inadequate maintenance, and higher exposure to environmental risks. The automated assessment capabilities developed in this research enable systematic identification of these environmental justice concerns, supporting equitable resource allocation for building stock improvement and ensuring that climate adaptation efforts address the needs of the most vulnerable populations rather than concentrating benefits in already high-performing areas.

The integration of facade assessment with environmental risk management also addresses the temporal dimensions of climate change adaptation. Building envelopes have design lifetimes of 60-100 years, meaning that facades designed today must maintain adequate performance under future climate conditions that may differ substantially from current design parameters(Øyen, 2012). The assessment framework supports climate scenario analysis and future-oriented design optimization that enhances long-term resilience rather than merely addressing present-day performance criteria.

In synthesis, this research positions automated facade performance assessment not merely as a technical measurement exercise but as an essential infrastructure for environmental risk management at urban scales. The capability to rapidly assess, quantify, and monitor facade performance across large building populations provides municipal authorities, policymakers, and building professionals with the empirical evidence necessary to develop and implement comprehensive risk reduction strategies, climate adaptation planning, and building stock improvement initiatives that enhance urban resilience while advancing toward sustainability objectives.

g. Research Context and Positioning

This doctoral research, conducted within the interdisciplinary framework of Environmental Risk, Territorial Development, and Building Engineering at Politecnico di Bari, addresses these converging challenges through systematic investigation of facade performance assessment methodologies that span from theoretical foundation-building through practical implementation at urban scales. The research is explicitly positioned at the intersection of multiple disciplinary perspectives—building science providing rigorous performance understanding, computer vision and artificial intelligence enabling technical innovation, urban sustainability incorporating systems-level thinking, and policy sciences connecting research to real-world decision-making contexts.

The four research questions that structure this investigation—addressing facade definition, automated assessment development, methodological validation, and urban-scale integration—reflect this interdisciplinary positioning while acknowledging that sustainable progress requires not only technical innovation but also careful validation of new approaches, explicit integration with existing policy frameworks, and demonstration of practical applicability in real-world contexts where building stock assessment must support consequential decisions affecting occupant wellbeing, urban environmental conditions, and climate mitigation outcomes.

1.9. SWOT Anaysis

To critically evaluate and contextualise the research strategy adopted in this dissertation, a comprehensive SWOT (Strengths, Weaknesses, Opportunities, and Threats) analysis was conducted. This strategic assessment framework, widely applied in research planning, architectural management, and urban development initiatives (Zhang, 2025) provides a structured methodology for evaluating both internal capabilities and external factors influencing research success, impact, and long-term applicability.

The SWOT analysis specifically examines the strategic positioning of the AI-driven urban-scale facade assessment methodology within the contemporary scientific, technological, and policy landscape. Unlike traditional methodological discussions that focus primarily on technical validation, the SWOT framework enables systematic consideration of how this research responds to broader societal needs, technological trends, and institutional constraints that determine whether scientific innovations successfully transition from academic investigation to practical implementation. This analysis addresses four distinct dimensions: Strengths identify the inherent capabilities and advantages of the proposed methodology that differentiate it from existing assessment approaches; Weaknesses acknowledge internal limitations, methodological constraints, and areas where the research does not achieve optimal performance; Opportunities examine external conditions, policy developments, and technological trends that create favorable contexts for research application and impact; and Threats identify external risks, institutional barriers, and competitive factors that could limit the research's relevance or effectiveness over time.

Strengths: Internal Capabilities and Methodological Advantages

1. Unprecedented Scalability Through Automation

The most significant strength of the AI-driven methodology lies in its fundamental transformation of assessment scalability. Traditional manual facade assessment methods, while potentially accurate for individual buildings, require approximately 2-4 hours per building for comprehensive WWR measurement including site visits, photogrammetric analysis, and geometric calculations. This time investment becomes prohibitive when applied at urban scales—assessing a medium-sized European city of 50,000 buildings would require approximately 100,000-200,000 person-hours using manual methods, representing 2-4 years of full-time work for a team of 25 professionals. In contrast, the automated AI pipeline processes facade imagery at approximately 0.5-2 seconds per building (depending on architectural complexity), enabling assessment of 50,000 buildings in approximately 7-28 hours of computational time. This three-orders-of-magnitude improvement in processing speed fundamentally changes what is methodologically feasible, enabling urban-scale analyses that would be economically impossible using traditional approaches.

2. Methodological Integration Across Disciplinary Boundaries

The research uniquely integrates quantitative computer vision analysis with qualitative occupant satisfaction data from the Centre for the Built Environment (CBE) survey database. This integration addresses a persistent gap in building performance assessment where technical measurements of physical characteristics (U-values, WWR, thermal mass) often proceed independently from occupant experience research focusing on comfort, satisfaction, and wellbeing.

By empirically correlating automated WWR measurements with occupant satisfaction metrics across 150+ buildings, the research establishes a validated connection between objectively measurable facade geometry and subjectively experienced environmental quality. This methodological integration creates assessment frameworks that can simultaneously address engineering performance criteria and human-centered design objectives—a synthesis that has proven difficult to achieve in traditional facade assessment methodologies.

3. Reproducibility and Standardization

Automated assessment workflows substantially reduce subjective variation inherent in manual measurement processes where different evaluators may apply inconsistent criteria, measurement boundaries, or classification schemes. The AI pipeline applies identical segmentation algorithms and geometric calculations to all analyzed buildings, ensuring methodological consistency across diverse architectural contexts. This reproducibility advantage extends beyond individual research applications to enable comparative analyses across different cities, building typologies, and temporal periods using standardized assessment protocols. The methodology creates opportunities for longitudinal monitoring of building stock evolution, cross-national comparisons of facade performance characteristics, and meta-analyses combining datasets from multiple research initiatives—capabilities difficult to achieve when different studies employ incompatible manual measurement approaches.

4. Modularity and Technological Adaptability

The research architecture employs a modular pipeline design where individual algorithmic components (object detection, semantic segmentation, geometric calculation) can be independently upgraded without invalidating the overall assessment framework. As computer vision capabilities advance through foundation models, transformer architectures, and multimodal AI systems, specific algorithmic elements can be replaced with state-of-the-art alternatives while maintaining compatibility with existing workflows, databases, and validation protocols. This modularity provides resilience against technological obsolescence and creates pathways for continuous performance improvement as AI capabilities evolve. The research establishes conceptual frameworks, validation methodologies, and integration protocols that remain relevant even as specific algorithmic implementations advance.

Weaknesses: Limitations and Methodological Constraints

1. Data Source Dependencies and Quality Constraints

The methodology's reliance on Google Street View imagery introduces multiple interconnected limitations affecting assessment coverage, accuracy, and temporal currency. Street View coverage remains incomplete in many global regions, particularly in Africa, South Asia, and rural areas, limiting the methodology's direct applicability in these contexts without alternative data sources. Image quality varies substantially based on capture conditions, camera specifications, and environmental factors. Lighting conditions (shadows, glare, nighttime captures), weather effects (rain, snow, fog), and seasonal variations (vegetation occlusion) create inconsistent visual information that impacts segmentation accuracy. The research validation demonstrates that error rates increase from approximately 3.2% for optimal visibility conditions to 8.7% for images with substantial occlusions or poor lighting.

Temporal currency presents another significant constraint. Street View imagery updates occur irregularly, ranging from 6 months to 5+ years between successive captures in different locations. Buildings may have undergone renovations, facade replacements, or demolition since imagery capture, meaning automated assessments may not reflect current conditions. This temporal lag limits the methodology's utility for near-real-time monitoring applications or rapidly changing urban environments.

2. Geographic and Architectural Bias in Training Data

The validation datasets employed in this research predominantly comprise European and North American buildings representing Western architectural traditions, construction practices, and regulatory environments. The training dataset's composition introduces potential algorithmic bias where model performance may degrade when applied to architectural typologies, material palettes, or facade configurations underrepresented in training data. Non-Western architectural traditions employing distinctive facade elements (mashrabiya screens, jali patterns, traditional shutters), vernacular construction methods (adobe, rammed earth), or building forms (courtyard typologies, dense urban fabric) may present segmentation challenges not adequately addressed through European-focused training. Direct application of the trained models to these contexts without validation or model adaptation could yield systematic errors that compromise assessment accuracy

3. Scope Limitations in Performance Characterization

While the research successfully automates WWR measurement, many other critical facade performance parameters remain beyond the current scope. Glazing thermal properties (U-values, Solar Heat Gain Coefficient), shading device operability and control systems, material degradation and maintenance conditions, air infiltration characteristics, and dynamic facade behavior cannot be reliably extracted from static street-level imagery alone. This scope constraint means that automated WWR assessment provides valuable but incomplete facade performance characterization. Comprehensive building energy modeling or detailed retrofit planning still requires supplementary data collection through building inspections, infrared thermography, or computational fluid dynamics simulation. The methodology enables efficient preliminary screening and prioritization but cannot fully replace detailed building-level audits for high-stakes decision-making.

4. Interpretability and Algorithmic Transparency Challenges

Deep learning models employed for semantic segmentation function as complex non-linear systems where specific predictions result from millions of learned parameters interacting in ways that resist straightforward human interpretation. When the AI pipeline misclassifies a facade element or produces erroneous WWR calculations, determining the root cause (algorithmic limitation, training data gap, image quality issue) requires sophisticated diagnostic analysis. This "black box" characteristic creates challenges for building trust among non-technical stakeholders, explaining model behavior to policymakers, addressing skepticism from traditional building professionals, and providing transparency in assessment processes that inform consequential retrofit investment decisions. The research partially mitigates this through comprehensive error analysis and uncertainty quantification, but fundamental interpretability limitations persist in current deep learning architectures.

5. Computational Resource Requirements and Technical Expertise Barriers

While substantially more cost-effective than manual surveys, the methodology still requires significant computational infrastructure (GPU-equipped servers for model inference), technical expertise (machine learning, geospatial data processing, API integration), and software development capabilities (Python programming, database management, web service deployment) that may exceed the capacity of smaller municipalities, consulting firms, or researchers in resource-constrained institutions. The research produces a functioning technical pipeline but does not yet offer user-friendly software interfaces, automated error handling, or simplified deployment workflows that would enable widespread adoption by non-specialist users. Translating research prototypes into production-ready tools accessible to building professionals without data science backgrounds remains a substantial implementation challenge.

Opportunities: External Factors Enabling Research Impact

1. Policy Alignment with European Renovation Wave Initiatives

The European Commission's Renovation Wave strategy aims to at least double annual energy renovation rates by 2030, targeting the improvement of 35 million building units by that date. Achieving these ambitious targets requires systematic methods for identifying renovation priorities, estimating energy savings potential, and monitoring implementation progress across Europe's approximately 220 million residential buildings and millions of non-residential structures. The automated facade assessment methodology directly addresses critical data gaps limiting Renovation Wave implementation. Municipal authorities currently lack comprehensive building stock characterizations needed for evidence-based policy development, energy efficiency program targeting, and renovation impact evaluation. The research provides methodological infrastructure that could support Renovation Wave objectives through rapid building stock assessment, retrofit prioritization frameworks, and longitudinal performance monitoring.

2. Digital Twin and Smart City Integration Synergies

The proliferation of Urban Digital Twins and 3D city models creates immediate integration opportunities for automated facade data. Municipalities increasingly develop digital representations of urban environments for infrastructure planning, emergency response, urban climate modeling, and participatory planning processes. These digital platforms require comprehensive building attribute data, including facade characteristics, that determine energy performance, microclimate effects, and visual quality. This generates facade datasets in formats compatible with CityGML, IFC, and other Building Information Modeling standards, enabling direct integration into urban digital infrastructure. This interoperability positions the methodology as a data generation tool for broader smart city initiatives, potentially leveraging municipal digitalization budgets and institutional partnerships beyond traditional building performance research communities.

3. Climate Adaptation Planning and Resilience Assessment

Increasing frequency and intensity of extreme heat events, driven by climate change and urban heat island effects, creates urgent needs for identifying climate-vulnerable buildings and prioritizing resilience improvements. Facade characteristics directly influence buildings' passive survivability during extended power outages, overheating risk, and thermal comfort under extreme conditions. The methodology enables rapid vulnerability screening across building stocks, identifying neighborhoods and populations at elevated climate risk due to poor facade performance. This capability aligns with growing municipal climate adaptation planning activities, potentially accessing climate resilience funding streams, emergency preparedness programs, and public health initiatives addressing heat-related mortality.

4. Foundation Model Revolution in Computer Vision

Recent advances in foundation models (SAM, CLIP, GPT-4V) and multimodal AI systems create opportunities for substantial accuracy improvements and expanded capability without fundamental methodology changes. These models, trained on massive diverse datasets, demonstrate strong generalization to architectural contexts and zero-shot learning capabilities that could reduce geographic bias and training data requirements. The research's modular architecture positions it to leverage these technological advances by substituting foundation model components for current segmentation algorithms. Early experiments suggest foundation model integration could reduce error rates by 15-25% while improving performance on under-represented architectural typologies, directly addressing several identified weaknesses.

5. Growing ESG and Building Transparency Mandates

Environmental, Social, and Governance (ESG) reporting requirements increasingly demand comprehensive building performance disclosure from real estate portfolios, institutional investors, and public entities. The EU Taxonomy Regulation and Sustainable Finance Disclosure Regulation create regulatory frameworks requiring quantitative environmental performance data for building assets. Automated facade assessment provides scalable methods for generating building performance data needed for ESG compliance, real estate benchmarking, and sustainability certification. This creates potential commercial applications and public-private partnership opportunities that could support continued methodology development and wider adoption beyond academic research contexts.

Threats: External Risks and Implementation Barriers

1. Rapid Technological Change and Algorithmic Obsolescence

The accelerating pace of AI development creates risks that specific algorithmic choices and technical implementations become outdated quickly. Transformer architectures are displacing convolutional neural networks; foundation models are supplanting task-specific models; generative AI is enabling novel computer vision approaches that may fundamentally change facade analysis methodologies within 3-5 years.

While the modular architecture provides some protection, rapid technological change could still render aspects of the current implementation obsolete before research findings fully disseminate through peer review, policy adoption, and professional practice integration. Maintaining the methodology's relevance requires ongoing investment in technical updates and continuous engagement with evolving computer vision capabilities.

2. Data Access Restrictions and Privacy Regulations

Evolving privacy regulations, particularly the EU General Data Protection Regulation (GDPR) and equivalent frameworks in other jurisdictions, create potential restrictions on street-level imagery collection, processing, and dissemination. While facade images generally avoid direct personal identification, concerns about surveillance, license plate capture, and inadvertent inclusion of individuals create regulatory uncertainty.

Changes in Google Street View API pricing models, access restrictions, or data availability could substantially impact the methodology's economic viability. Academic research benefits from relatively generous API quotas, but scaling to commercial applications or continuous municipal monitoring could encounter prohibitive costs if pricing structures change. Alternative data sources (municipal imagery, open-source mapping initiatives, drone photography) may offer resilience but introduce new technical challenges and data quality variations.

3. Institutional Resistance and Professional Skepticism

Traditional building assessment practices are deeply embedded in professional cultures, regulatory frameworks, and liability structures. Introducing automated AI-driven methodologies challenges established professional roles, questions the necessity of certain technical expertise, and disrupts business models based on manual survey services. Professional organizations, building inspectors, energy auditors, and architects may resist automated assessment adoption due to concerns about accuracy, liability, job displacement, or perceived devaluation of experiential expertise. This resistance could manifest through advocacy for regulatory restrictions on AI-based assessments, skepticism about validation evidence, or preference for familiar manual methods despite their limitations. Overcoming institutional inertia requires not only technical excellence but also stakeholder engagement, professional training, and demonstration of complementarity rather than replacement of human expertise.

4. Computational Cost Escalation and Infrastructure Dependencies

While currently cost-effective, the methodology's computational requirements could escalate substantially if applied at continental or global scales. Processing

Europe's 220 million buildings would require approximately 12,500-50,000 GPU-hours, representing substantial cloud computing costs even at current favorable pricing for academic research. Infrastructure dependencies on commercial cloud platforms (AWS, Google Cloud, Microsoft Azure) create vulnerabilities to pricing changes, service interruptions, or geopolitical disruptions. The methodology's utility for crisis response or emergency applications depends on reliable computational access that may not be assured during the very emergencies where rapid building assessment proves most valuable.

5. Competitive Methodologies and Alternative Technological Approaches

Alternative technological approaches to automated building assessment are developing in parallel, including LiDAR-based 3D scanning with increasingly affordable sensor systems, thermal infrared imaging enabling direct thermal performance measurement, drone-based photogrammetry with higher resolution than street-level imagery, and satellite remote sensing leveraging hyperspectral and radar data. Each alternative approach offers distinct advantages addressing specific limitations of street-level imagery analysis. If these competing methodologies achieve superior performance, lower costs, or better regulatory acceptance, they could reduce the relevance and impact of the Street View-based approach developed in this research. Maintaining competitiveness requires continuous comparative evaluation and potential integration of complementary methodologies rather than exclusive reliance on a single technical approach.

Strategic Synthesis and Implications

The SWOT analysis reveals that the research strategy occupies a favorable strategic position where substantial internal Strengths (scalability, integration, cost-effectiveness) align well with significant external Opportunities (policy needs, digital twin synergies, climate adaptation priorities). This alignment suggests strong potential for research impact and practical application, particularly within European urban contexts addressing building stock improvement and climate adaptation challenges.

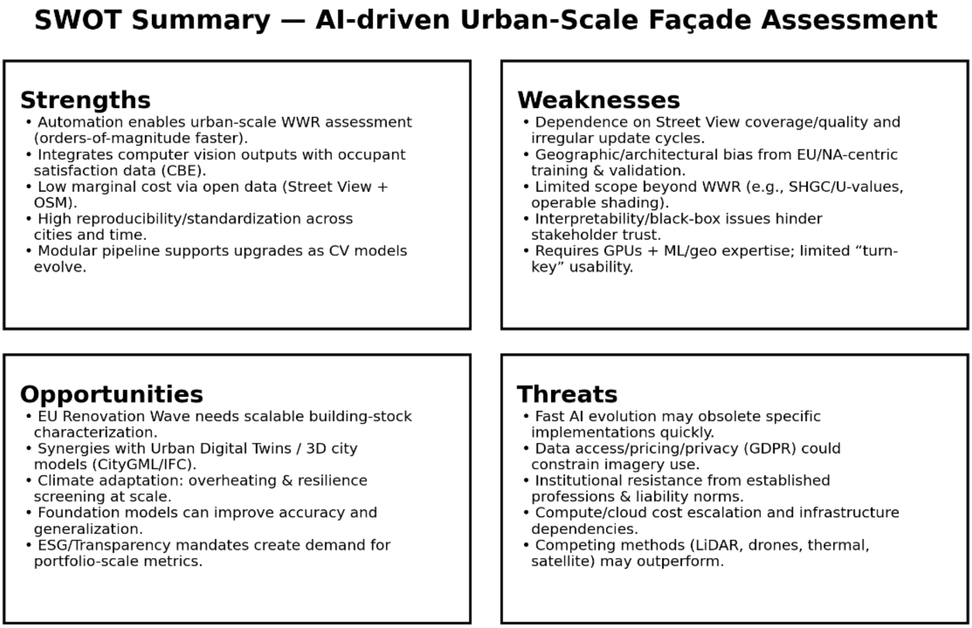


Figure 1 - SWOT Analysis Synthesis

However, the analysis also identifies important vulnerabilities requiring proactive mitigation. The most significant strategic risk emerges from the intersection of technological Threats (rapid AI evolution, alternative methodologies) with internal Weaknesses (geographic bias, scope limitations). This combination could potentially reduce the methodology's long-term relevance if not addressed through continuous technical updates and expansion of assessment capabilities.

The research strategy partially addresses these risks through its modular architecture enabling component substitution, rigorous validation providing transparent accuracy characterization, multi-criteria framework integrating WWR with broader performance assessment, and explicit limitation reporting guiding appropriate application contexts.

This strategic assessment confirms that while the AI-driven approach introduces specific risks and limitations, these are manageable through the methodological safeguards implemented in the research design. The potential benefits in terms of scalability, policy impact, and enablement of urban-scale building performance improvement significantly outweigh the constraints of traditional manual assessment alternatives, supporting the overall strategic rationale for the chosen research approach.

2. LITERATURE REVIEW AND THEORETICAL FRAMEWORK

Contemporary facade performance has evolved from a narrow focus on structural adequacy and weather protection into a multidimensional construct encompassing energy efficiency, occupant comfort, environmental sustainability, durability, and health outcomes. This literature review synthesizes four decades of research across multiple disciplinary perspectives.

The earliest systematic ways to facade performance emerged in the post-World War II period, when rapid urbanization and industrialization created demands for efficient building construction methods that could address both functional requirements and economic constraints. Early performance concepts focused primarily on structural integrity, weather resistance, and basic thermal properties, with evaluation methodologies limited to standardized testing protocols for individual components such as windows, insulation materials, and cladding systems (Aksamija, 2015)

The energy crises of the 1970s marked a pivotal moment in facade performance conceptualization, as architects and engineers began to recognize the critical role of building envelopes in overall energy consumption. This period saw the emergence of thermal performance as a central evaluation criterion, with the development of standardized metrics such as U-values, air leakage rates, and solar heat gain coefficients. However, these early methods remained largely component-focused, treating facades as assemblies of discrete elements rather than integrated systems with complex interdependencies.

The 1980s and 1990s witnessed the gradual expansion of performance concepts to include occupant comfort considerations, driven by growing awareness of the relationships between physical environments and human wellbeing. Research conducted during this period established empirical connections between facade characteristics and occupant satisfaction with thermal comfort, daylighting quality, and visual access to the exterior environment (Ko et al., 2021). These findings began to challenge purely technical strategies to facade evaluation by introducing subjective, experiential criteria that could not be easily quantified using traditional engineering methodologies.

Current views of facade performance represent a fundamental change from the older single-criterion optimizations to multi-criteria evaluation frameworks that recognize the interconnectedness and complexity present in building envelope performance. This trend has been fueled by multiple factors that have converged – from advancements in building science research, to a growing environmental conscientiousness, to the maturing of computational tools able to address complex optimization problems with multiple (and occasionally competing) scalar objectives.

Current performance frameworks typically integrate four primary categories of criteria: energy and environmental performance, occupant comfort and wellbeing, durability and maintainability, and economic considerations over the building lifecycle (Roberts et al., 2020) Each category encompasses multiple sub-criteria that must be balanced against each other through sophisticated assessment methodologies that can accommodate diverse stakeholder priorities and contextual constraints.

Performance requirements for energy and environment long ago evolved from simple thermal resistance to embodied energy, lifecycle carbon emissions, potential for renewable-energy integration, and benefits for urban environmental quality. These broader criteria also reflect an increasing awareness that building-level environmental performance needs to be assessed within the context of wider ecological and urban systems, acknowledging impacts stretching beyond individual building perimeters (Francesco Fiorito et al., 2020)

Occupant comfort and wellbeing criteria now encompass not only traditional thermal and visual comfort considerations, but also acoustic performance, indoor air quality impacts, psychological benefits of natural light and views, and support for occupant productivity and satisfaction. This expansion reflects extensive research demonstrating the complex relationships between physical environments and human performance, health, and wellbeing (Schiavon and Altomonte, 2015)

Recent developments in facade performance conceptualization increasingly emphasize the integration of individual building performance with broader urban and environmental systems. This systems-level perspective recognizes that facades contribute to urban-scale phenomena such as heat island effects, air quality patterns, energy infrastructure demands, and urban biodiversity, requiring assessment methodologies that can address performance at multiple spatial and temporal scales (Santamouris et al., 2018)

The integration of facade performance with urban systems has been facilitated by advances in computational modeling, remote sensing technologies, and data analytics that enable comprehensive analysis of building-environment interactions. These technological capabilities have revealed previously unrecognized relationships between facade characteristics and urban environmental quality, supporting the development of performance criteria that explicitly consider urban-scale impacts and benefits.

Climate change adaptation has emerged as a critical driver of facade performance evolution, as building envelopes must increasingly be designed to maintain performance under changing and more extreme environmental conditions. This adaptation focus has led to increased emphasis on resilience, flexibility, and long-term durability as fundamental performance criteria, while also highlighting the importance of facade contributions to broader community resilience and climate adaptation strategies.

2.1. High-Performance Facades: Definitions and Standards

Despite conceptual advances, the professional landscape reveals significant fragmentation in how 'high-performance' facades are defined across different communities. Industry definitions emphasize technical metrics, regulatory frameworks establish minimum thresholds, European standards integrate lifecycle thinking, while research communities contribute sophisticated theoretical frameworks. Understanding this diversity is essential for developing unified assessment approaches that accommodate both technical rigor and practical applicability.

The Lawrence Berkeley National Laboratory (LBNL), in its seminal 2006 report for the California Energy Commission, defined facade performance as a product of technological solutions "based on fundamental building concepts for daylighting, solar heat gain control, ventilation and space conditioning". This definition establishes a foundation based on measurable environmental control capabilities while acknowledging that "high" performance signifies an intelligent combination of strategies based on project-specific contextual factors.

Contemporary industry definitions have expanded to include broader sustainability considerations while maintaining focus on measurable outcomes. Leading facade manufacturers and design consultants typically define high-performance facades as systems that optimize multiple performance criteria simultaneously, including energy efficiency, occupant comfort, durability, and environmental impact, while providing economic value over the building lifecycle (Corp, 2025)These definitions emphasize the importance of integrated design approaches that consider facade performance within the context of whole-building systems optimization.

Professional organizations such as the American Institute of Architects (AIA) and the Royal Institute of British Architects (RIBA) have developed definitions that incorporate both technical performance criteria and broader architectural design considerations. These definitions typically emphasize the role of facades in creating high-quality architectural environments that serve both functional and aesthetic objectives while contributing to sustainable development goals.

Building codes and energy efficiency standards provide regulatory definitions of high-performance facades that establish minimum performance thresholds for various criteria. The International Energy Conservation Code (IECC) and ASHRAE standards establish baseline performance requirements for thermal transmittance, air leakage, and fenestration efficiency that effectively define minimum acceptable performance levels for contemporary facades.

Green building certification systems have developed more comprehensive definitions that integrate multiple performance criteria with standardized assessment methodologies. The Leadership in Energy and Environmental Design (LEED) system defines high-performance facades through a combination of energy efficiency credits, materials and resources criteria, and indoor environmental quality requirements that collectively establish performance thresholds across multiple domains (Green Building Council, 2023). The Building Research Establishment Environmental Assessment Method (BREEAM) provides similar multi-criteria definitions with additional emphasis on lifecycle environmental impact and occupant health and wellbeing considerations. The Passivhaus standard offers one of the most rigorous definitions of facade performance, establishing extremely demanding thermal performance criteria while also addressing air quality, comfort, and durability requirements.

European standards for facade performance have evolved to encompass comprehensive assessment frameworks that address the full range of contemporary performance concerns. The EN 13830 standard for curtain walling provides technical definitions focused on structural performance, weather resistance, and safety criteria, while EN 15232 addresses the integration of facade systems with building automation and energy management systems. Another one is the ISO 52000 series of standards establishes comprehensive frameworks for building energy performance assessment that include detailed consideration of facade contributions to overall building performance. These standards provide standardized calculation methodologies for thermal performance, solar energy utilization, and daylighting provision that support consistent evaluation of facade performance across different projects and contexts.

Recent developments in European standardization have increasingly emphasized lifecycle assessment methodologies and circular economy principles in facade performance definition. The EN 15804 standard for Environmental Product Declarations (EPDs) provides frameworks for quantifying the environmental impact of facade materials and systems throughout their lifecycle, supporting more comprehensive sustainability assessment approaches.

The academic research community has developed sophisticated theoretical frameworks for facade performance that often extend beyond practical application in design and construction. Leading researchers such as Francesco Fiorito have contributed comprehensive definitions that integrate technological innovation with environmental responsiveness, emphasizing the potential for facades to function as adaptive, intelligent building skins that respond dynamically to changing environmental conditions. (Fiorito et al., 2019). For instance, research-based definitions frequently emphasize the systems integration aspects of high-performance facades, recognizing that optimal performance requires sophisticated coordination between facade elements and other building systems including HVAC, lighting, and building automation systems. This systems perspective supports definitions that focus on whole-building performance outcomes rather than component-level characteristics.

Contemporary facade research has also contributed definitions that explicitly consider occupant experience and behavior as central performance criteria. Work by researchers such as Stefano Schiavon has demonstrated the critical importance of occupant satisfaction and comfort in facade performance evaluation, supporting definitions that balance technical performance metrics with subjective human experience factors (Schiavon et al., 2019)

Recent efforts to systematize and disseminate knowledge about high-performance facade design have led to the development of comprehensive digital platforms that document real-world applications and their performance characteristics. The

Facade Map, developed through a collaboration between the Center for the Built Environment at UC Berkeley and the Polytechnic University of Bari, represents a significant advancement in the documentation and analysis of exemplary facade solutions worldwide (Lamberti et al., 2024)

This interactive mapping platform addresses the critical gap between theoretical facade performance concepts and practical implementation by documenting over 40 case study buildings that demonstrate advanced facade design strategies and technologies. The platform employs a sophisticated taxonomy that enables users to filter projects based on multiple performance criteria including daylight control, solar control, natural ventilation, noise control, embodied carbon considerations, energy generation capabilities, and innovative insulation systems.

The development of the Facade Map required the research team to grapple with fundamental questions about what constitutes high-performance facade design, ultimately focusing on nine key considerations relevant to sustainable and comfortable building design. This curation process involved extensive deliberation about performance metrics and evaluation criteria while accommodating diverse architectural expressions and climatic contexts (Lamberti et al., 2024)

The platform's comprehensive data collection methodology combines independent online research with direct input from design team members, enabling the documentation of detailed technical information that is often unavailable through conventional sources. Design teams from leading firms including Foster + Partners, DIALOG, and Transsolar/KlimaEngineering have contributed detailed project information, providing unprecedented access to technical details about innovative facade solutions and their performance outcomes.

Despite the diversity of existing definitions, several areas of emerging consensus can be identified across different professional and institutional contexts. Most contemporary definitions acknowledge the multi-criteria nature of facade performance, the importance of lifecycle thinking, and the need for integrated design methods that consider facade performance within broader building and urban systems contexts.

However, significant challenges remain in developing universally applicable definitions that can accommodate diverse climatic contexts, building types, and stakeholder priorities while maintaining sufficient specificity to guide design decision-making and performance evaluation. The tension between comprehensive assessment and practical applicability continues to complicate efforts to establish standardized definitions that can support both research advancement and practical implementation.

As building operational efficiency improves and embodied impacts are optimized, the persistence of facade systems over extended periods necessitates attention to durability and long-term performance degradation that significantly influences both lifecycle costs and environmental benefits. This durability that could affect also contemporary facade systems employ diverse materials including metals, ceramics, polymers, composites, and bio-based materials, each subject to different degradation mechanisms that must be understood and evaluated for comprehensive durability assessment. Common degradation mechanisms include ultraviolet radiation damage, thermal cycling effects, moisture-related deterioration, chemical attack from atmospheric pollutants, and mechanical degradation from wind loading and thermal expansion.

About this, accelerating aging test methodologies provide essential tools for durability assessment by simulating the effects of extended environmental exposure in compressed timeframes. However, the application of accelerated aging results to real-world performance prediction requires sophisticated understanding of the relationships between accelerated test conditions and actual building exposure environments, which vary significantly based on geographic location, building height, facade orientation, and local microclimate conditions. The assessment of facade durability must consider not only the degradation of individual materials, but also the deterioration of interfaces between different materials and components. Sealant failure, gasket degradation, and corrosion at material interfaces often represent the most significant durability challenges in contemporary facade systems, requiring assessment methodologies that can evaluate system-level performance rather than individual component characteristics.

Is the reason why industry needs modeling strategies for facade durability that have advanced significantly through the integration of materials science research with building performance simulation capabilities. These methods enable estimation of facade performance degradation over time while considering the impacts of local environmental conditions, maintenance practices, and component replacement strategies on overall system durability (Fiorito et al., 2019)

Table 2 - Comparative analysis of existing HPF definitions across literature, showing scope, dimensions addressed, and applicability constraints

Source/Framework	Definition Scope	Performance Dimensions	Applicability	Limitations
ASHRAE 189.1 (2020)	Energy-focused	Energy efficiency, thermal comfort	Commercial buildings	Limited occupant health, durability
LEED v4.1 (2024)	Sustainability-focused	Energy, water, materials, IEQ	Multi-building types	Score-based, not threshold-based

Source/Framework	Definition Scope	Performance Dimensions	Applicability	Limitations
WELL Building Standard	Occupant health-focused	Air quality, light, thermal comfort	Office, residential	Limited energy, environmental dimensions
CBE Post-Occupancy Research	Occupant satisfaction	Comfort, connection, control	Existing buildings	Limited sustainability, durability
This Research (Proposed)	Integrative	6 dimensions × 4 criteria	Universal application potential	Requires contextualization

The assessment of facade maintenance requirements presents significant challenges due to the variability in maintenance practices, local environmental conditions, and building owner priorities that influence actual maintenance implementation. Different facade materials and systems require substantially different maintenance approaches, with implications for both lifecycle costs and environmental impacts that must be considered in comprehensive assessment. Cleaning requirements represent one of the most significant maintenance considerations for contemporary facades, particularly for glazed systems in urban environments subject to air pollution, biological growth, and weather staining. The frequency and intensity of cleaning requirements vary substantially between different facade materials and surface treatments, with significant implications for operational costs, water consumption, and access equipment requirements. Preventive maintenance strategies can significantly extend facade service life while reducing lifecycle costs, though their implementation requires sophisticated understanding of material degradation mechanisms and appropriate intervention timing. The assessment of preventive maintenance effectiveness requires long-term monitoring data that is often unavailable for newer facade technologies, creating challenges for evidence-based maintenance planning.

Component replacement strategies represent critical considerations in facade durability assessment, as different facade elements may have substantially different service lives requiring coordinated replacement planning to minimize disruption and cost. The design of facades to accommodate component replacement while maintaining weather resistance and building operation presents significant technical challenges that influence both initial design and long-term performance.

Weather resistance represents a fundamental requirement for facade durability, encompassing resistance to rain penetration, air infiltration, structural loading from wind and seismic forces, and thermal performance under extreme conditions. Contemporary assessment methodologies must address not only current climate conditions but also anticipated changes in climate patterns that may affect facade performance over building lifetimes spanning several decades. For this reason, climate change adaptation considerations have become increasingly important in facade durability assessment as building envelopes must maintain performance under more extreme and variable environmental conditions than those experienced historically. Increased frequency and intensity of extreme weather events, changing precipitation patterns, and rising temperatures present new challenges for facade durability that require adaptive design strategies and robust assessment methodologies.

The assessment of facade performance under extreme conditions requires sophisticated modeling techniques that can predict system behavior under low-probability, high-impact events that may occur infrequently during building lifetimes but have significant consequences for building performance and occupant safety. These approaches must consider not only structural performance, but also the potential for water infiltration, air leakage, and thermal performance degradation under extreme conditions. Regional variations in climate change impacts require location-specific techniques to facade durability assessment that consider local projections for temperature, precipitation, wind patterns, and extreme weather frequency. The development of climate-adapted facade design guidelines requires integration of climate science projections with materials research and building performance modeling to identify appropriate design strategies for different geographic regions and exposure conditions.

Long-term performance monitoring represents an essential component of comprehensive facade durability assessment, providing empirical data about actual performance degradation rates and maintenance requirements that can inform both predictive models and design improvements for future projects. However, the implementation of effective monitoring systems requires careful consideration of sensor selection, data management, and analysis methodologies that can provid

e meaningful insights while remaining cost-effective over extended monitoring periods. The integration of building automation systems with facade performance monitoring presents opportunities for continuous assessment of facade performance including thermal characteristics, air leakage rates, and moisture management effectiveness. These integrated monitoring strategies can provide early warning of performance degradation while supporting predictive maintenance strategies that optimize both performance and cost-effectiveness.

Adaptive management strategies for facade performance recognize that optimal maintenance and operation strategies may change over time as environmental conditions, building use patterns, and technology capabilities evolve. The implementation of adaptive management requires flexible building systems and monitoring capabilities that can accommodate changing performance optimization strategies while maintaining adequate performance levels.

2.2. Multi-Criteria Assessment Approaches in Literature

The diverse definitional frameworks reviewed above necessitate sophisticated assessment methodologies. Multi-criteria decision making (MCDM) provides structured approaches for evaluating trade-offs between multiple performance objectives while accommodating diverse stakeholder priorities and contextual constraints.

Multi-criteria decision making (MCDM) methodologies in facade assessment draw upon well-established theoretical foundations from operations research, systems analysis, and decision theory. The application of these methodologies to building envelope assessment has been driven by recognition that facade performance cannot be adequately characterized through any single metric, regardless of how sophisticated that metric might be (Moghtadernejad et al., 2020)

The fundamental challenge addressed by multi-criteria frameworks lies in the integration of diverse performance criteria that may be measured in different units, operate at different scales, and reflect different stakeholder values and priorities. For example, energy efficiency might be measured in $kWh/m^2/year$, thermal comfort in predicted mean vote (PMV) units, and aesthetic quality through subjective ratings, requiring sophisticated normalization and weighting procedures to enable meaningful comparison and integration.

Contemporary MCDM applications in facade assessment typically employ hierarchical decision structures that decompose complex performance concepts into measurable sub-criteria while maintaining clear logical relationships between different levels of the assessment hierarchy. This hierarchical system enables systematic evaluation of performance while providing transparency about the relative importance assigned to different criteria and sub-criteria (Habibi et al., 2020)

Sustainability assessment frameworks represent the most comprehensive application of multi-criteria methodologies to facade performance evaluation. These frameworks typically integrate environmental, economic, and social performance criteria within unified assessment structures that can accommodate lifecycle thinking and stakeholder participation in criterion weighting and threshold setting.

The MIVES (Modelo Integrado de Valor para una Evaluación Sostenible) methodology has been successfully applied to facade sustainability assessment, providing a structured approach for integrating quantitative and qualitative performance criteria within a common value function framework (Gilani et al., 2017). The MIVES theory enables systematic comparison of different facade alternatives while providing clear traceability of how different performance aspects contribute to overall sustainability scores.

Life Cycle Assessment (LCA) methodologies have been increasingly integrated with multi-criteria frameworks to provide comprehensive evaluation of environmental impacts throughout facade lifecycles (Roberts et al., 2020). These integrated strategies enable systematic comparison of facade alternatives based on environmental performance while also considering other performance criteria such as cost, durability, and occupant comfort (Lahmar et al., 2022). Fortunately, also Building Information Modeling (BIM) platforms have emerged as powerful tools for implementing multi-criteria facade assessment by enabling automated evaluation of multiple performance criteria based on parametric building models. Recent research has demonstrated the potential for BIM-integrated assessment frameworks to streamline multi-criteria evaluation while improving the accuracy and consistency of performance calculations (Najjar et al., 2019)

Recognition of the diverse stakeholder interests in facade performance has driven the development of assessment methodologies that explicitly incorporate stakeholder participation in criterion definition, weighting, and threshold setting. These stakeholder-centered approaches acknowledge that optimal facade solutions must balance the sometimes-competing interests of building owners, occupants, designers, and broader community stakeholders.

Stakeholder engagement methodologies typically employ structured consultation processes that enable systematic elicitation of stakeholder preferences while providing education about trade-offs between different performance objectives. The Analytic Hierarchy Process (AHP) has proven particularly effective for stakeholder-centered facade assessment, providing a structured methodology for eliciting and aggregating stakeholder preferences into consistent criterion weights (Bostancioglu and Onder, 2019)

The integration of stakeholder perspectives with technical performance analysis has revealed significant variations in performance priorities across different building types, geographic contexts, and cultural settings. For example, research has demonstrated that residential building occupants typically prioritize thermal comfort and energy cost considerations, while commercial building tenants may place greater emphasis on daylighting quality and aesthetic considerations (Schiavon et al., 2018)

The complexity of multi-criteria facade assessment has driven significant advances in computational optimization methodologies that can systematically explore large solution spaces while identifying facade configurations that provide optimal performance across multiple criteria. These optimization methods typically employ genetic algorithms, particle swarm optimization, or other metaheuristic methods that can handle complex, non-linear optimization problems with multiple objectives.

Parametric design platforms such as Grasshopper and Dynamo have enabled the integration of multi-criteria assessment with parametric facade modeling, supporting rapid evaluation of multiple design alternatives while providing clear visualization of performance trade-offs. These integrated platforms enable designers to systematically explore the impacts of different facade characteristics on multiple performance criteria while maintaining control over design constraints and aesthetic preferences.

Machine learning methodologies have shown significant promise for multi-criteria facade assessment by enabling the development of predictive models that can rapidly estimate facade performance across multiple criteria based on limited input parameters. These approaches have particular potential for early-stage design support, where rapid evaluation of multiple alternatives is essential for effective design decision-making (L. Yang et al., 2021)

2.3. Energy Performance And Thermal Comfort

Among the multifaceted criteria integrated into contemporary frameworks, energy and thermal performance represent the most thoroughly researched domains. Foundational research in these areas provides essential understanding and sophisticated methodologies applicable to broader multi-criteria assessment.Thermal Performance Fundamentals and Assessment Methodologies

The thermal performance of building facades encompasses multiple heat transfer mechanisms including conduction through opaque elements, solar heat gain through transparent elements, convective heat transfer at interior and exterior surfaces, and thermal bridging through structural connections and frame elements. Contemporary assessment methodologies must address all of these mechanisms while considering their interactions with building HVAC systems, occupant behavior, and external environmental conditions.

Standardized thermal performance metrics provide the foundation for quantitative facade assessment, with U-values (thermal transmittance) representing the most widely used indicator for opaque facade elements. However, the assessment of facade thermal performance increasingly requires consideration of dynamic thermal behavior, including thermal mass effects, solar heat gain variations, and thermal bridging impacts that cannot be adequately characterized through steady-state U-value calculations alone.

Solar Heat Gain Coefficient (SHGC) and Visible Light Transmittance (VLT) provide complementary metrics for evaluating the thermal and daylighting performance of transparent facade elements. The ratio of VLT to SHGC, often referred to as the Light-to-Solar-Gain ratio (LSG), provides a useful metric for evaluating the efficiency of daylighting provision relative to solar heat gain, supporting integrated assessment of thermal and visual performance (Fiorito et al., 2016)

For these reasons, dynamic thermal modeling methodologies have become increasingly important for comprehensive facade thermal performance assessment, particularly for complex facade systems such as double-skin facades, ventilated facades, and facades incorporating phase change materials or other advanced thermal storage systems. These modeling approaches enable detailed analysis of thermal performance under realistic operating conditions while considering interactions with building systems and occupant behavior.

One of the fundamental aspects of this dissertation is the Window-to-Wall Ratio (WWR) that represents one of the most fundamental geometric parameters influencing facade thermal performance, with extensive research demonstrating complex, non-linear relationships between WWR and building energy consumption. These relationships are mediated by multiple factors including climate conditions, building orientation, glazing properties, shading systems, and building operation strategies, requiring sophisticated analysis systems that can accommodate multiple interacting variables.

Research conducted by Marino (Marino et al., 2017) provides comprehensive analysis of WWR impacts on building energy consumption across different climatic contexts, demonstrating that optimal WWR values typically range between 20% and 45% depending on building orientation, climate zone, and glazing properties. However, this research also reveals significant variation in optimal WWR based on specific building characteristics and operation strategies, highlighting the importance of context-specific optimization rather than universal prescriptive guidelines.

The relationship between WWR and thermal comfort is mediated by complex interactions between solar heat gain, daylighting provision, and view access that cannot be optimized independently. Higher WWR values generally provide better daylighting and view access but may compromise thermal comfort through increased solar heat gain or glare problems, requiring sophisticated optimization approaches that can balance multiple performance objectives simultaneously.

Also recent research has demonstrated the potential for advanced glazing technologies, dynamic shading systems, and intelligent facade control systems to significantly expand the range of WWR values that can provide high thermal and visual performance. These technological advances support facade designs with higher transparency levels while maintaining thermal comfort and energy efficiency, though they typically require more sophisticated control systems and higher initial investment costs. (Alessandro Cannavale et al., 2020)

The integration of thermal comfort assessment with facade performance evaluation requires sophisticated understanding of the relationships between facade characteristics and occupant thermal sensation, comfort, and satisfaction. Contemporary thermal comfort assessment employs sophisticated indices such as PPD—Predicted Percentage of Dissatisfied, representing the percentage of building occupants likely to experience thermal discomfort—and PMV—Predicted Mean Vote, a numerical scale (-3 to +3) representing average thermal sensation from cold to hot—to quantify occupant satisfaction with thermal conditions. Research conducted by Schiavon and colleagues has demonstrated the critical importance of local environmental conditions, including radiant temperature asymmetry, air velocity, and humidity levels, in determining occupant thermal comfort in buildings with large-glazed facades (He et al., 2019; Schiavon et al., 2019)These findings highlight the need for facade assessment methodologies that consider detailed environmental conditions rather than relying solely on bulk air temperature and energy consumption metrics.

The integration of thermal comfort assessment with facade design requires consideration of seasonal and diurnal variations in comfort conditions, as facades that provide acceptable comfort during moderate weather conditions may produce unacceptable thermal environments during extreme weather periods. This temporal dimension of comfort assessment requires dynamic modeling approaches that can evaluate comfort performance under a range of environmental conditions while considering the impacts of adaptive occupant behavior.

Personal comfort systems and localized environmental control have emerged as important considerations in facade-comfort integration, as these technologies can significantly expand the range of environmental conditions that provide acceptable comfort while reducing overall building energy consumption. The design of facades to support personal comfort systems requires consideration of air movement patterns, radiant conditions, and acoustic performance that extend beyond traditional thermal performance assessment (Kim et al., 2018)

Climate-responsive facade design requires sophisticated understanding of the relationships between local climate characteristics and optimal facade performance strategies. Different climate zones present distinct challenges and opportunities for facade design, requiring tailored approaches to thermal performance optimization that consider seasonal and diurnal variations in environmental conditions.

Hot and humid climates typically require facade strategies that minimize solar heat gain while providing adequate daylighting and natural ventilation opportunities. Research in these contexts has demonstrated the effectiveness of deep overhangs, external shading systems, and high-performance glazing in achieving thermal comfort while maintaining visual connection to the exterior environment (Lahmar et al., 2022)

Cold climates present different optimization challenges, with facades needing to maximize beneficial solar heat gain during heating seasons while minimizing heat loss and maintaining thermal comfort near large glazed areas. Strategies such as high-performance insulation, advanced glazing systems, and thermal mass integration have proven effective in these contexts, though they require careful integration with building heating systems and solar control strategies.

h. Energy Modeling and Operational Performance Assessment

Energy modeling for facade assessment typically employs detailed building simulation tools that predict how facade characteristics influence heating and cooling loads throughout the year. These models account for solar heat gain, thermal transmittance, air leakage, and interactions with HVAC systems to forecast annual energy consumption under different operational scenarios. Tools such as EnergyPlus, IES-VE, and

DesignBuilder enable parametric analysis of facade design variables including Window-to-Wall Ratio, glazing properties, and shading system configurations. Energy modeling supports design optimization by quantifying relationships between specific facade characteristics and measurable energy outcomes, enabling evidence-based comparison between alternative design strategies.

i. Environmental Impact Assessment and Lifecycle Analysis

Environmental impact assessment extends beyond operational energy consumption to consider the broader lifecycle environmental effects of facade systems. Lifecycle Assessment (LCA) provides the most comprehensive methodology for evaluating the environmental impacts of facade systems throughout their entire lifecycle, from raw material extraction through manufacturing, transportation, installation, operation, maintenance, and end-of-life disposal or recycling. (Roberts et al., 2020) Contemporary LCA applications to facade assessment typically follow ISO 14040 and 14044 standards while incorporating building-specific considerations such as the integration with building energy performance and the potential for component replacement during building lifecycles. This comprehensive perspective reveals that facade systems with high embodied impacts from energy-intensive manufacturing may still provide net environmental benefits if their operational performance reductions exceed embodied impacts over building lifecycles spanning 50 or more years.

j. Integration of Energy Modeling with Environmental Assessment

The integration of LCA with dynamic building performance simulation enables comprehensive assessment of the interactions between facade environmental impacts and building operational performance. This integrated approach reveals complex trade-offs between embodied and operational impacts that cannot be understood through either methodology alone. For example, high-performance insulation materials typically require substantial manufacturing energy resulting in high embodied carbon, but if they reduce heating loads by 35 percent compared to baseline insulation, the operational energy savings over a 60-year building lifecycle typically exceed the initial embodied impacts by factors of three to five. Similarly, triple-glazed windows carry higher embodied impacts than double-glazed alternatives, but in heating-dominated climates the annual energy savings justify the additional embodied burden within approximately 8 to 12 years of operation. This integration enables informed decision-making that optimizes total lifecycle environmental performance rather than focusing narrowly on either embodied or operational impacts in isolation.

The application of LCA to facade assessment requires careful definition of system boundaries, functional units, and impact categories that reflect the specific characteristics of building envelope systems. Functional units typically relate facade environmental impacts to performance characteristics such as thermal resistance, daylight transmission, or area of building envelope served, enabling meaningful comparison between different facade solutions with varying performance characteristics. There are different impact assessment methodologies for facade LCA, those typically address multiple environmental indicators including Global Warming Potential (GWP), acidification potential, eutrophication potential, ozone depletion potential, and resource depletion metrics. However, the relative importance of different impact categories varies significantly depending on geographic location, local environmental conditions, and stakeholder priorities, requiring flexible assessment frameworks that can accommodate diverse sustainability priorities.

For this reason, the integration of LCA with dynamic building performance simulation enables comprehensive assessment of the interactions between facade environmental impacts and building operational performance. This integration reveals complex trade-offs between embodied and operational impacts, with high-performance facade materials typically requiring higher embodied impacts but providing operational benefits that may offset these impacts over building lifecycles (Stephan et al., 2017)

Embodied carbon has emerged as a critical sustainability metric for facade assessment, reflecting growing recognition that material production and transportation can represent significant portions of total building lifecycle carbon emissions. Environmental Product Declarations (EPDs) provide standardized methodologies for quantifying facade material impacts, though their application requires careful consideration of regional variations in energy sources, transportation distances, and manufacturing processes. We have to consider also that the embodied carbon assessment of facade systems must study not only the direct impacts of facade materials, but also the impacts of supporting structure, foundation modifications, and other building system changes that may be required to accommodate different facade solutions. These system-level impacts can be substantial, particularly for heavy facade systems that require significant structural modifications or lightweight systems that require additional structural support.

Material selection strategies for embodied carbon reduction typically prioritize locally sourced materials, recycled content, and materials with low-carbon production processes. However, the optimization of embodied carbon must be balanced against other performance requirements including durability, thermal performance, and aesthetic considerations that may favor materials with higher embodied impacts but superior long-term performance characteristics.

This is why the potential for facade material recycling and reuse at building end-of-life represents an important consideration in embodied impact assessment, as materials designed for disassembly and reuse can significantly reduce lifecycle environmental impacts. Design for disassembly requires consideration of connection details, material compatibility, and anticipated future market conditions for recycled facade materials (Rota et al., 2024)

The integration of facade environmental assessment with building operational performance requires sophisticated modeling framework that can accurately predict the interactions between facade characteristics and building energy consumption, water use, and indoor environmental quality. These interactions are particularly complex for high-performance facade systems that may include active components, automated control systems, or integrated renewable energy generation.

Energy modeling for facade environmental assessment typically employs detailed building simulation tools that can account for the dynamic interactions between facade thermal performance, solar control, daylighting provision, and HVAC system operation. The accuracy of these models is critical for environmental assessment, as small errors in predicted energy consumption can significantly influence lifecycle environmental impact calculations. Another important aspect is water consumption for facade cleaning and maintenance, that represents a huge operational environmental impact that is often overlooked in traditional facade assessment. The frequency and intensity of cleaning requirements vary significantly between different facade materials and configurations, with implications for both operational costs and environmental impacts that should be considered in comprehensive sustainability assessment.

The potential for facades to contribute to building renewable energy generation through integrated photovoltaic systems, solar thermal collectors, or wind energy harvesting presents opportunities for operational environmental benefits that can offset embodied impacts. However, the assessment of these benefits requires careful consideration of system integration costs, maintenance requirements, and performance degradation over time (Mandinec et al., 2025)

The environmental assessment of building facades increasingly requires consideration of their contributions to urban-scale environmental conditions including heat island effects, air quality, stormwater management, and urban biodiversity. These urban-scale impacts cannot be adequately assessed through building-level analysis alone, requiring systems thinking methods that consider the cumulative impacts of multiple buildings and their interactions with urban infrastructure and natural systems. Urban heat island mitigation represents one of the most significant opportunities for facades to contribute to urban environmental quality through strategies such as high solar reflectance materials, evapotranspiration from green facades, and reduced heat rejection from building cooling systems. The quantification of these benefits requires urban-scale modeling approaches that can assess the cumulative impacts of facade improvements across building stocks.

Air quality impacts from facade materials and maintenance activities present both positive and negative environmental effects that must be considered in comprehensive assessment. Green facades and facades incorporating air-purifying materials can contribute to improved urban air quality, while the production and maintenance of some facade materials may contribute to air pollution problems.

The integration of facade design with urban biodiversity conservation presents emerging opportunities for environmental benefit through green facades, habitat integration, and the creation of wildlife corridors that connect urban green spaces. However, the assessment of these benefits requires interdisciplinary approaches that integrate ecological assessment with traditional building performance evaluation (ignatieva et al., 2023)

2.4. Daylighting, Visual Comfort and Occupant Wellbeing

While thermal performance remains foundational, equally sophisticated research attention has focused on the optical properties of facades. Daylighting, visual comfort, and circadian health represent interconnected performance domains that significantly influence both occupant wellbeing and building energy efficiency.

Contemporary daylighting assessment methodologies employ multiple metrics that address different aspects of daylight provision, including quantity, quality, distribution, and temporal stability. Illuminance-based metrics such as Daylight Factor (DF) and useful Daylight Illuminance (UDI) provide quantitative assessment of daylight availability, while more sophisticated metrics such as spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) address the temporal and spatial distribution of daylight within buildings.

Climate-based daylight modeling (CBDM) has emerged as the preferred methodology for comprehensive daylighting assessment, providing detailed analysis of daylight performance under realistic sky conditions while considering the impacts of solar shading, facade geometry, and interior surface reflectances. CBDM method enable evaluation of daylighting performance throughout the year while identifying potential problems such as glare, excessive solar heat gain, or inadequate daylight provision during specific periods.

The integration of daylighting assessment with facade design requires consideration of the complex relationships between facade transparency, solar control systems, and interior daylight distribution. Advanced glazing technologies, dynamic shading systems, and light-redirecting facades can significantly influence these relationships, requiring sophisticated modeling methods that can accurately predict their daylighting impacts (Cannavale et al., 2021)

Spectral characteristics of daylight transmission through facade systems have gained increasing attention as research demonstrates the importance of circadian lighting effects on occupant health and wellbeing. Assessment methodologies that consider the spectral distribution of transmitted daylight, including the provision of short-wavelength light that supports circadian rhythm regulation, represent an important frontier in comprehensive daylighting evaluation.

Visual comfort assessment presents unique challenges due to the subjective nature of visual perception and the complex relationships between daylight conditions, task requirements, and individual preferences. Glare assessment methodologies typically employ metrics such as Daylight Glare Index (DGI), Daylight Glare Probability (DGP), and Unified Glare Rating (UGR) that attempt to quantify the likelihood of visual discomfort based on measurable environmental conditions.

However, research has demonstrated significant individual variations in glare sensitivity and visual comfort preferences, highlighting the limitations of prescriptive glare thresholds and the importance of adaptive shading systems that enable occupant control over visual conditions. The design of facades to support occupant visual comfort requires consideration of both automatic glare control systems and manual override capabilities that accommodate individual preferences and task requirements.

The temporal variability of daylight conditions presents particular challenges for visual comfort assessment, as facades must provide acceptable visual conditions throughout the day and year while accommodating seasonal variations in sun angles and sky conditions. Dynamic shading systems and adaptive facade technologies offer potential solutions to these challenges, though their effectiveness depends on sophisticated control algorithms that can balance multiple performance objectives (Fiorito et al., 2020).

The integration of artificial lighting with daylighting through facade systems requires careful consideration of color temperature coordination, lighting control strategies, and the potential for circadian disruption from poorly coordinated lighting systems. Research has demonstrated the potential for integrated daylighting and electric lighting systems to provide superior visual conditions while reducing energy consumption, though their implementation requires sophisticated control systems and careful commissioning.

Access to exterior views through building facades provides important psychological and physiological benefits that extend beyond simple daylighting provision. Research has consistently demonstrated positive correlations between view access and occupant satisfaction, productivity, and psychological wellbeing, though the mechanisms underlying these benefits remain partially understood.

The quality of exterior views significantly influences their psychological benefits, with views of natural elements, distant horizons, and dynamic scenes providing greater benefits than views of urban hardscapes or static scenes. Facade design to optimize view quality requires consideration of view angles, visual obstacles, and the integration of landscape design with building positioning and facade configuration.

Window size and positioning significantly influence both view access and visual comfort, with larger windows generally providing better view access but potentially increasing glare problems and thermal discomfort. The optimization of window design requires sophisticated analysis of the trade-offs between view benefits and potential negative impacts, considering occupant seating positions, task requirements, and seasonal variations in sun angles.

Research conducted using the CBE Occupant Survey database has provided important empirical evidence about the relationships between facade characteristics and occupant satisfaction with view access and visual comfort. Preliminary investigations suggest strong correlations between WWR and occupant satisfaction with view access ($r = 0.71$, $p < 0.001$), though these relationships are moderated by view quality, window positioning, and individual task requirements.

These technical and environmental performance achievements have limited meaning if facades fail to support the fundamental human needs that motivated investment in building envelope performance: occupant health, wellbeing, and social connectivity.

The facade-occupant interface encompasses air quality, moisture management, psychological benefits, and community engagement factors that represent critical performance domains.The facade-indoor air quality interface represents a critical pathway through which building envelopes influence occupant health, encompassing both the admission of outdoor pollutants and the management of indoor contaminant sources. Contemporary facade design must address these dual challenges while providing adequate ventilation, filtration, and pollutant source control to maintain healthy indoor environments (Schiavon et al., 2017). Air infiltration through facade systems can significantly influence indoor pollutant concentrations, with different facade configurations providing substantially different levels of pollutant protection. Research has demonstrated that well-sealed facade systems can significantly reduce indoor concentrations of particulate matter, ozone, and other outdoor pollutants, particularly when combined with appropriate mechanical ventilation and filtration systems (Aflaki et al., 2015)The building envelope serves as the physical separator between conditioned indoor air and unconditioned outdoor air, playing a crucial role in air movement and indoor air quality as well as occupant comfort and building durability. However, the optimization of facade air tightness must be balanced against the need for adequate ventilation air supply, particularly in naturally ventilated or mixed-mode buildings where facades provide primary ventilation pathways. The design of facade ventilation systems requires sophisticated understanding of pollutant transport mechanisms, indoor air quality requirements, and occupant ventilation preferences that vary significantly between different building types and occupancy patterns (Knaack et al., 2024)

Facade materials and surface treatments can directly influence indoor air quality through the emission of volatile organic compounds (VOCs), formaldehyde, and other chemical contaminants. The selection of low-emission facade materials and finishes represents an important strategy for maintaining healthy indoor environments, though the assessment of material emissions requires sophisticated testing methodologies that consider both immediate and long-term emission patterns.

Moisture management through facade systems represents a critical determinant of occupant health through its impacts on mold growth, dust mite proliferation, and respiratory health conditions.

The assessment of facade moisture performance requires detailed analysis of vapor transport mechanisms, condensation risk under various environmental conditions, and the potential for moisture accumulation within facade assemblies. Advanced hygrothermal modeling tools enable comprehensive assessment of moisture behavior while considering the impacts of climate conditions, interior humidity levels, and facade material properties on moisture-related health risks. Pretty important is interstitial condensation within facade assemblies, that presents particular health concerns due to the potential for concealed mold growth that may not be detected until significant contamination has occurred. The design of facade systems to prevent interstitial condensation requires careful attention to vapor barrier placement, thermal bridge details, and ventilation provisions that can manage moisture loads while maintaining thermal performance. The integration of facade moisture management with building mechanical systems requires sophisticated coordination between envelope and HVAC design to ensure that moisture loads are appropriately controlled throughout all facade components. This integration is particularly critical in humid climates where external moisture loads can overwhelm building dehumidification capabilities if facade moisture management is inadequate. (Bueno De Mesquita et al., 2022)

The application of facade design principles to healthcare environments has revealed particularly compelling evidence for the health impacts of building envelopes. Recent research in healthcare facility facade design demonstrates that thoughtful selection of colors, materials, and textures in facade design plays a pivotal role in creating healing environments that improve patient experiences and promote wellbeing (Cephe, 2024). The integration of biophilic elements into healthcare facade design focuses on incorporating elements from nature, such as natural materials, green spaces, and views of nature, into the built environment. Research has shown that exposure to nature and natural elements can reduce stress, enhance healing, and improve overall patient satisfaction. The use of warm and soothing colors, such as earth tones and pastels, in facade design can evoke a sense of tranquility and relaxation.

Evidence-based design principles guide architects in merging aesthetics with functionality in healthcare buildings. By integrating research findings and best practices, architects can design spaces that not only look visually appealing but also support the overall well-being of patients and healthcare professionals. This framework ensures that every design decision is informed by scientific evidence, allowing for a more effective healing environment.

The relationship between Window-to-Wall Ratio and occupant health outcomes has emerged as a critical area of research connecting quantifiable facade characteristics with measurable health impacts. Research by Acosta (Instituto Universitario de Arquitectura y Ciencias de la Construcción, Universidad de Sevilla, Spain et al., 2017) found a direct relationship between window wall area and circadian stimulus, showing a 14% increase for 45% WWR when compared to small windows. (Ma et al., 2015) revealed that 40% WWR improved circadian potential by 50% compared to 30% WWR, with 30% providing adequate circadian stimulus near windows, where lower percentages were not effective. These findings suggest that optimal WWR values for health outcomes may differ from those optimized purely for energy performance, requiring sophisticated multi-criteria optimization techniques that can balance competing objectives. The integration of health-focused design criteria with traditional performance metrics represents an important frontier in facade performance assessment that acknowledges the full spectrum of human needs served by building envelope

2.5. Computer Vision in Building Analysis

The automated assessment of building façades represents one of the most challenging frontiers in urban analytics and sustainable building evaluation. While traditional methods for façade analysis rely heavily on manual surveys, photogrammetric techniques, and in-situ measurements (Borrmann et al., 2018; Xu et al., 2025), the emergence of artificial intelligence and computer vision technologies has opened unprecedented opportunities for scalable, accurate, and cost-effective façade assessment at urban scale.

The Window-to-Wall Ratio (WWR) emerges as a critical parameter in façade performance evaluation, directly influencing energy consumption, occupant comfort, daylighting quality, and overall building sustainability (Stouzani, 2021; Zhuo, 2023). However, the systematic extraction of WWR from urban environments has historically been constrained by the labor-intensive nature of traditional measurement approaches and the complexity of urban morphologies that present occlusions, varying lighting conditions, and diverse architectural styles. Recent advances in deep learning, particularly in semantic segmentation and object detection, have demonstrated remarkable capabilities in parsing complex urban scenes and identifying building components with high accuracy (Escalada, 2024; Rashidan, 2024; SegFormer, 2023; Xu et al., 2023) The integration of readily available imagery sources, such as Google Street View (GSV), with sophisticated AI models presents a paradigm shift toward automated, scalable façade analysis that can support urban-scale sustainability assessments and policy-making processes(Chen, 2022; Krylov et al., 2018; Sun et al., 2021).

The methodology integrates multiple state-of-the-art computer vision models (Liu et al., 2023; Team, 2025; Zhang, 2024) incorporates empirical validation through our WWR experimental work, and establishes accuracy benchmarks against traditional measurement techniques. The significance of this work extends beyond technical innovation to encompass practical applications in urban planning, building retrofit prioritization, and regulatory compliance assessment. The scalable nature of the proposed approach enables city-wide façade assessments that were previously unfeasible due to cost and time constraints, thereby supporting evidence-based decision-making for urban sustainability initiatives.

The application of computer vision to building and façade analysis has evolved significantly over the past two decades, transitioning from simple edge detection and template matching algorithms to sophisticated deep learning architectures capable of understanding complex urban scenes(Biljecki, 2022; Borrmann et al., 2018). Early approaches relied on geometric constraints and architectural regularities to identify building elements, achieving limited success in controlled environments but struggling with real-world variability. Recent developments in vision transformers and attention mechanisms have further advanced the field, with models like SegFormer (Hugging-Face, 2021; NeurIPS, 2021; Xie et al., 2021) and DETR (Detection Transformer) showing superior performance in complex urban environments characterized by partial occlusions, varying illumination, and diverse architectural styles(SegFormer, 2023; Xu et al., 2023) (Xu et al., 2023; SegFormer, 2023). These models demonstrate particular strength in handling the scale variations and contextual relationships that are critical for accurate façade analysis.

2.6. Urban-Scale Building Performance Assessment

Urban-scale assessment represents a qualitatively different challenge from traditional building-level evaluation. Whereas conventional practice focuses on individual projects—optimised for specific sites, occupants, and performance objectives—climate mitigation targets, renovation wave strategies, and energy transition policies increasingly require understanding and improving the performance of entire building stocks. This shift from single-building analysis to city-wide assessment raises methodological, computational, and conceptual questions that cannot be addressed by simply “scaling up” conventional tools. The present section provides the conceptual foundation for these challenges and sets the stage for the urban-scale integration developed in later chapters.

k. From Single-Building to Urban-Scale Assessment

Historically, building performance assessment has concentrated on individual buildings or small project portfolios. Detailed simulations, on-site measurements, and manual façade surveys can provide highly accurate characterisations at this scale, but they are too time-consuming and costly to be applied to thousands of buildings. A single detailed energy model may require tens of hours of professional effort;

extrapolated to a typical district with several hundred or thousand buildings, this quickly becomes impractical for municipal planning and policy support.

Urban-scale assessment therefore poses a dual challenge. Practically, it requires methods that can cover large building populations efficiently, without prohibitive time and cost. Conceptually, it requires approaches that can capture interactions between buildings, infrastructure, and urban climate, rather than treating each building as an isolated object. This is particularly evident for façade performance, where parameters such as Window-to-Wall Ratio (WWR), shading, and material properties simultaneously affect individual building comfort and energy use, but also aggregate into district-level loads and environmental effects. These challenges are formalised in Research Question 4 and addressed methodologically in later chapters; here, the focus is on clarifying why urban-scale assessment must be treated as a distinct problem.

I. Urban Microclimate and Building–Environment Interactions

Buildings in cities do not operate under the boundary conditions assumed in standard design practice. Urban areas generate modified microclimates that strongly influence façade behaviour and building performance. The urban heat island effect, for example, typically increases ambient temperatures by several degrees compared to surrounding rural areas, with particularly pronounced nighttime and heatwave peaks. As a result, façades experience external conditions that can systematically exceed those used in design calculations, with direct consequences for cooling loads, component durability, and comfort outcomes.

Similarly, urban canyon effects alter solar exposure and daylight conditions. Street canyon geometry modifies both direct and diffuse radiation, leading to strong vertical gradients in solar access and daylight availability. Lower floors may receive limited direct sunlight, while upper façades are exposed to high solar loads. These altered radiation patterns change the relationship between WWR, daylighting, and solar gains compared to isolated-building assumptions.

In addition, urban wind patterns and moisture conditions are reshaped by building density, height variations, and street geometry. Wind acceleration at corners and canyons, sheltered courtyards, and persistent moisture exposure all influence natural ventilation potential, infiltration rates, and façade durability. Taken together, these factors demonstrate that façade performance cannot be understood purely at the building scale; it is co-determined by the urban environment in which buildings are embedded.

m. Urban Energy Systems and Façade Performance

At urban scale, façade characteristics aggregate into patterns that shape energy demand profiles and infrastructure requirements. Individual building cooling loads become part of district-level peak demand, with implications for grid stability and the sizing of energy systems. High WWR ratios, inadequate shading, and low insulation levels not only increase energy use at the building level but also amplify simultaneous peak loads during hot periods, stressing electrical networks.

Urban-scale retrofit programmes raise additional embodied–operational carbon trade-offs. When thousands of façades are upgraded simultaneously, the embodied impacts of new glazing, insulation, and cladding can become comparable to multiple years of operational savings. Strategic decisions about retrofit depth, timing, and sequencing therefore need to be made at district or city level, rather than on a purely project-by-project basis.

Emerging thermal networks and waste-heat recovery systems further underline the systemic nature of façade performance. District heating and cooling solutions, as well as waste-heat reuse from buildings or data centres, depend on both the magnitude and timing of thermal loads. Optimal façade strategies at urban scale may thus differ from strategies that appear optimal when each building is considered in isolation.

n. Spatial Distribution, Vulnerability, and Equity

Urban-scale assessment must also address how performance, vulnerability, and investment are distributed across neighbourhoods and social groups. Building quality, maintenance levels, and renovation rates often vary systematically across the city: central or high-value areas tend to receive earlier and more frequent upgrades, while peripheral or low-income neighbourhoods accumulate older, lower-performing stock.

If renovation policies and incentive schemes are guided solely by market logic or aggregate indicators, there is a risk that improvements will concentrate where they are most profitable, leaving the worst-performing and most vulnerable areas behind. Urban-scale frameworks therefore need to incorporate equity and distributional considerations, explicitly identifying underserved neighbourhoods, high-vulnerability building populations, and the social impacts of different intervention strategies. This perspective is largely absent from traditional building-by-building assessment, but it becomes essential when the objective is to support just and inclusive climate action at city scale.

o. Key Variables and Multi-Scale Interactions

Urban-scale building performance emerges from interactions between variables at multiple scales. At the building level, façade properties (e.g., WWR, glazing type, shading systems), HVAC efficiency, and occupancy patterns determine energy use and comfort. Aggregated across thousands of buildings, these characteristics define the statistical distribution of WWR, age, typology, and efficiency classes at district or city level.

These aggregated building-stock properties then interact with urban microclimate factors (heat island intensity, canyon geometry, wind and radiation patterns) and energy system characteristics (grid capacity, thermal networks, pricing structures) to produce outcomes such as peak demand, urban overheating, and spatial patterns of discomfort or energy poverty. The relationships are inherently non-linear: a modest change in average WWR, for example, may have disproportionate effects on peak loads or on the spatial pattern of overheating, depending on orientation, density, and urban morphology.

These non-linear, multi-scale interactions imply that simple extrapolation from single-building analysis is insufficient. Urban-scale assessment requires integrated frameworks that connect building-level metrics to urban-scale indicators through appropriate aggregation, modelling, and scenario analysis.

p. Connection to Research Question 4 and Subsequent Chapters

The conceptual issues outlined above provide the context for Research Question 4, which asks how scalable façade metrics such as WWR can be integrated with multi-criteria performance data for urban-scale risk and sustainability assessment. Addressing RQ4 requires both:

- technical innovation, in the form of scalable, AI-driven façade characterisation methods capable of producing reliable metrics (such as WWR) across large building populations; and
- systemic integration, in the form of urban-scale assessment frameworks that combine these metrics with energy, comfort, environmental, and socio-economic dimensions.

The present chapter establishes the theoretical motivation for this shift from single-building analysis to urban-scale assessment. The high-performance façade concepts introduced earlier in Chapter 2 are operationalised through the automated measurement capabilities presented in Chapter 4, and then embedded in urban-scale, multi-criteria frameworks developed in Chapter 5. In this way, the research moves from defining what constitutes a high-performance façade, to measuring façade characteristics at scale, and finally to integrating these measurements into a coherent urban assessment framework that can support policy development, renovation planning, and equity-sensitive decision-making.

2.7. Research Gaps and Opportunities

While the preceding sections of this literature review have established the substantial body of existing knowledge regarding facade performance, multi-criteria assessment frameworks, energy efficiency, occupant comfort, daylighting, sustainability, and technological capabilities in building analysis, significant gaps remain between this theoretical understanding and practical capability to implement evidence-based facade optimization strategies at the scales required to support contemporary urban sustainability and climate mitigation objectives. This concluding section identifies four interconnected research gaps, each corresponding to one of the research questions structuring this doctoral investigation, and articulates how addressing these gaps creates opportunities for advancing both academic knowledge and practical problem-solving capacity.

Gap 1: Fragmented Understanding of High-Performance Facade Definition

Despite extensive research documenting relationships between individual facade characteristics and specific performance outcomes—energy consumption, thermal comfort, daylighting quality, occupant wellbeing, sustainability—the literature reveals a fundamental absence of systematic, empirically-grounded, multi-dimensional definition of what constitutes a "high-performance facade" in comprehensive terms. Existing definitional frameworks tend to address individual performance domains in isolation: engineering-focused literature emphasizes energy efficiency thresholds and thermal performance standards; occupant-centered research documents relationships between facade characteristics and satisfaction metrics; sustainability literature articulates environmental impact considerations; durability studies examine long-term structural and environmental aging processes.

This disciplinary fragmentation creates a critical knowledge gap: while individual performance dimensions have been studied extensively, systematic integration of multiple performance criteria into coherent definitions remains underdeveloped. Building professionals, designers, and policymakers consequently lack clear, operationalizable definitions of high-performance facades that integrate energy, occupant comfort, sustainability, and durability considerations within actionable frameworks that can guide design decisions and retrofit prioritization. The literature suggests that optimal facade performance depends fundamentally on context-specific integration of multiple competing objectives, yet provides limited guidance for how to systematize this integration or how to balance trade-offs when individual performance dimensions point toward contradictory design solutions.

This gap represents the foundation for Research Question 1.Addressing this question requires development of comprehensive definitional frameworks grounded simultaneously in rigorous literature synthesis, empirical validation through occupant satisfaction data, and stakeholder consultation processes that ensure practical applicability across diverse contexts and building types.

Gap 2: Scalability Limitations in Facade Assessment Methodologies

The second critical gap emerges at the intersection of technical capability and practical implementation. Existing literature establishes sophisticated methodologies for detailed facade performance assessment applicable to individual buildings or small samples, yet these approaches prove fundamentally limited in their ability to operate at urban scales. Traditional assessment methods—detailed building surveys, photogrammetric analysis, manual measurement techniques, energy simulation—require substantial time investments, specialized expertise, and direct site access, rendering them impractical for systematic evaluation of large building populations necessary to support urban sustainability planning.

This scalability gap proves particularly consequential given contemporary policy contexts where ambitious building retrofit targets, energy efficiency directives, and climate action plans depend fundamentally on systematic understanding of existing building stock performance characteristics. The European Union's renovation wave initiative, for example, targets comprehensive assessment and retrofitting of millions of buildings within defined timeframes—an objective that remains unattainable through traditional manual assessment methodologies but becomes potentially addressable through technological innovation enabling automated, scalable assessment approaches.

The literature on computer vision and artificial intelligence applications in building analysis demonstrates promising technical capabilities for image-based facade analysis and automated feature extraction at scales vastly exceeding manual assessment possibilities. However, this literature simultaneously reveals limited development of validated methodologies specifically designed for facade performance assessment, inadequate documentation of accuracy characteristics across diverse architectural contexts, and insufficient validation frameworks demonstrating appropriate applicability boundaries. This represents a critical opportunity where emerging technological capabilities could address urgent practical needs, yet limited research bridges this gap through systematic development and rigorous validation of AI-driven assessment approaches.

This gap structures Research Questions 2 and 3. Addressing these questions requires development of novel computer vision pipelines, comprehensive validation frameworks quantifying accuracy performance across diverse building typologies, and explicit documentation of error characteristics and mitigation strategies enabling appropriate application within real-world contexts.

Gap 3: Disconnection Between Building-Scale Assessment and Urban-Scale Decision-Making

A third significant gap emerges when considering how building performance information connects to urban-scale decision-making processes. While substantial literature addresses building-level performance assessment methodologies and individual building optimization strategies, relatively limited research develops systematic frameworks for aggregating building performance information into urban-scale intelligence supporting municipal decision-making, building stock prioritization, retrofit program development, and climate action planning.

Urban policymakers and municipal authorities responsible for building stock improvement strategies, energy transition planning, and climate adaptation face an awkward situation: they lack systematic, comprehensive information about their building stocks' performance characteristics at the precision required to support evidence-based decision-making; traditional building assessment approaches cannot operate at sufficient scale to provide this information; and limited literature provides guidance for how to integrate fragmented performance data into decision support frameworks supporting consequential policy choices.

This represents a critical opportunity where research addressing facade assessment at scale could simultaneously create frameworks for urban-scale integration of performance information. Cities worldwide are developing ambitious building performance standards, energy efficiency requirements, and retrofit prioritization strategies that would benefit substantially from systematic baseline assessment of existing building stock performance characteristics. The convergence of policy need, technological opportunity, and information gap creates distinctive conditions where development of urban integration frameworks could deliver substantial practical value.

This gap structures Research Question 4. Addressing this question requires development of integration methodologies connecting building-scale assessment to city-scale analysis, creation of multi-criteria evaluation frameworks supporting prioritization decisions, and demonstration of practical applicability through implementation in real urban contexts.

Gap 4: Limited Interdisciplinary Integration of Building Science, Technology, and Policy

The broader context encompassing the three preceding gaps reveals a fourth, overarching gap: limited integration among disciplinary perspectives that must ultimately converge to address contemporary building performance challenges. Building science literature provides sophisticated understanding of facade performance mechanisms but offers limited engagement with technological innovation possibilities or policy implementation constraints. Computer vision and artificial intelligence research develops powerful technical capabilities but often operates in isolation from building domain expertise and real-world applicability considerations. Policy and urban sustainability literature identifies crucial needs for building stock assessment and optimization but sometimes inadequately engages with technical complexity and validation requirements necessary to establish trustworthy evidence bases for consequential decisions.

Advancing beyond fragmented, discipline-specific research approaches toward integrated investigation that spans building science, technological innovation, and policy application represents both a gap and an opportunity. Such integration creates possibilities for developing research that simultaneously advances academic knowledge, demonstrates technical feasibility, and delivers practical value for addressing urgent sustainability and climate challenges. Yet realizing this integration requires explicit, systematic effort to develop shared problem framings, integrate disciplinary perspectives, and ensure that research addresses genuine rather than hypothetical problems.

This overarching gap reflects the broader framing of this doctoral investigation, which deliberately positions itself at disciplinary intersections: building science providing rigorous performance understanding and validation frameworks; computer vision and artificial intelligence contributing technological innovation and scalability solutions; urban sustainability and policy sciences ensuring practical relevance and problem formulation grounded in actual decision-making contexts.

Integration of Research Questions and Investigation Approach

The four research questions structuring this investigation directly correspond to these identified gaps and opportunities:

RQ1 addresses the fundamental need for comprehensive, operationalized definition of high-performance facades by developing systematic frameworks integrating multiple performance dimensions, empirical validation through occupant satisfaction analysis, and validation against existing definitional approaches.

RQ2 addresses the scalability gap by developing and demonstrating AI-driven methodology for automated WWR assessment capable of operating at urban scales while maintaining acceptable accuracy.

RQ3 addresses the validation gap by rigorously documenting accuracy characteristics of AI-driven assessment approaches, establishing error quantification methodologies, and explicitly articulating applicability boundaries and limitations.

RQ4 addresses the urban integration gap by developing frameworks for systematically integrating building-scale performance assessment into urban decision-support systems, demonstrating practical applicability through urban case studies, and articulating policy implications supporting building stock optimization.

Collectively, these four research questions create an integrated investigation trajectory progressing from foundational definition (RQ1) through technological development and validation (RQ2-RQ3) to practical urban-scale implementation (RQ4), addressing the interconnected gaps identified throughout this literature review while simultaneously advancing toward systemic integration of building science, technological innovation, and policy application necessary to support evidence-based approaches to urban building performance optimization and climate mitigation.

The succeeding chapters of this dissertation directly address these research questions and gaps through theoretical development, empirical investigation, methodological innovation, and practical demonstration, collectively advancing beyond fragmented, discipline-specific approaches toward integrated investigation bridging academic knowledge generation, technical capability demonstration, and practical policy relevance.

3. DEFINING HIGH PERFORMANCE FACADES (RQ1)

3.1. Introduction and Research Approach

This chapter presents a comprehensive methodological framework for developing and validating an AI-driven system for automated facade performance assessment. The research employs a pragmatic mixed-methods strategy that combines empirical investigation with advanced computational techniques.

Building facades serve as critical interfaces between indoor and outdoor environments, mediating thermal exchanges that account for over 60% of total building energy losses while significantly influencing occupant comfort, health, and wellbeing (Attia et al., 2018). Despite this fundamental importance, systematic studies linking specific facade characteristics to measurable occupant outcomes remain scarce, particularly at scales suitable for urban policy development. The Window-to-Wall Ratio (WWR) represents a fundamental geometric parameter that substantially influences both energy performance and occupant experience, yet its quantification typically requires resource-intensive manual measurement approaches that limit scalability (Marino et al., 2017)

This preliminary investigation addresses these limitations by manually calculating WWR for a representative sample of commercial buildings and correlating these values with occupant satisfaction metrics from the Center for the Built Environment (CBE) Occupant Survey. The study serves dual purposes: validating WWR as a meaningful proxy for multiple comfort domains and demonstrating the practical constraints of manual assessment methods that necessitate automated alternatives. The research contributes to the growing body of evidence linking facade design decisions to measurable human outcomes while establishing quantitative performance targets for the AI-driven assessment pipeline described in subsequent sections (Schiavon & Melikov, 2008).

3.2. Framework Development

Building upon the comprehensive review and synthesis presented in the preceding sections, this section develops an integrated theoretical framework for high-performance facade assessment that addresses the complexity, interdependency, and contextual variation revealed through the literature analysis. This framework provides the conceptual foundation for operationalizing high-performance facade definitions while supporting both research advancement and practical application.

The theoretical framework employs a hierarchical structure that decomposes the complex concept of facade performance into manageable components while maintaining clear relationships between different levels of analysis. This hierarchical approach enables systematic evaluation while providing transparency about how different performance aspects contribute to overall performance assessment.

The framework's top level defines four primary performance domains that encompass the full range of contemporary facade performance concerns: Environmental Performance (including energy efficiency, environmental impact, and climate adaptation), Human Performance (encompassing comfort, health, wellbeing, and productivity), Technical Performance (addressing durability, reliability, and maintainability), and Economic Performance (considering lifecycle costs, value creation, and economic impacts). Each primary domain is further subdivided into specific performance criteria that can be measured and evaluated using appropriate methodologies. This subdivision enables detailed analysis while maintaining clear connections to broader performance objectives, supporting both comprehensive assessment and focused optimization of specific performance aspects based on project priorities and constraints.

The framework incorporates sophisticated multi-criteria decision making (MCDM) methodologies that can integrate diverse performance criteria while accommodating stakeholder preferences and contextual constraints. The MCDM framework enables systematic comparison of facade alternatives while providing clear traceability of how different performance aspects contribute to overall assessment outcomes.

Criterion weighting procedures accommodate diverse stakeholder priorities through structured consultation processes that enable systematic elicitation of performance preferences while providing education about trade-offs between different objectives. The framework supports both expert-based weighting and stakeholder-participatory approaches, depending on project characteristics and decision-making context. Performance aggregation employs value function techniques that can handle both quantitative metrics and qualitative assessments while maintaining mathematical rigor and interpretability. The aggregation methodology provides overall performance scores while preserving detailed information about performance in specific domains, supporting both decision-making and performance communication.

The framework explicitly addresses the temporal dimensions of facade performance through lifecycle assessment techniques that consider performance variation over time, maintenance and replacement cycles, and adaptation to changing environmental and social conditions. This temporal integration is essential for comprehensive performance assessment that can support long-term planning and investment decisions. Spatial scale integration addresses the relationships between individual building facade performance and broader urban and environmental systems. The framework supports assessment at multiple spatial scales from individual building components to urban districts, enabling analysis of cumulative impacts and system-level optimization opportunities. The integration of temporal and spatial considerations requires sophisticated modeling methods that can address the complex interactions between facade performance and broader building and urban systems over extended time periods. The framework provides structured approaches for managing this complexity while maintaining practical utility for design and policy applications.

The approach provides structured prtocols for establishing performance thresholds and targets that can guide design decision-making while accommodating diverse project contexts and stakeholder priorities. Threshold setting employs evidence-based approaches that consider both technical feasibility and performance requirements derived from health, comfort, and environmental objectives. Baseline performance levels establish minimum acceptable performance criteria that reflect current best practices and regulatory requirements, while advanced performance targets support innovation and continuous improvement in facade design and implementation. The framework enables flexible target setting that can accommodate different building types, climatic contexts, and stakeholder priorities.

Performance benchmarking capabilities enable comparison of facade alternatives against established performance databases while considering contextual factors that influence appropriate comparison groups. The benchmarking framework supports both absolute performance assessment and relative comparison against peer buildings or facade systems. Everything explained, incorporates validation mechanisms that enable continuous refinement and improvement based on empirical performance data and stakeholder feedback. Validation protocols include comparison with measured building performance, occupant satisfaction surveys, and expert evaluation of assessment outcomes. Feedback loops enable systematic incorporation of lessons learned from completed projects into framework refinement and improvement. The framework supports adaptive management methods that can accommodate changing performance priorities, technological capabilities, and environmental conditions while maintaining consistency in assessment approaches. The integration of validation and improvement mechanisms with practical application supports the development of evidence-based performance guidelines and best practices that can inform both design practice and policy development. This integration is essential for translating theoretical performance concepts into practical impact on building and urban sustainability.

Through this comprehensive theoretical framework, the research establishes a robust foundation for defining, measuring, and optimizing high-performance facade systems that can support the transition toward more sustainable, healthy, and resilient built environments. The framework provides the conceptual foundation for the subsequent development of automated assessment tools and urban-scale applications that comprise the core technological and practical contributions of this research.

The concept of high-performance façades has evolved from a narrow focus on thermal insulation and energy efficiency towards a comprehensive paradigm encompassing multiple performance dimensions such as occupant comfort, health, sustainability, and durability. This chapter builds on the literature survey to synthesize these strands into an integrated definition and a multi-criteria framework that will serve as a foundation for subsequent empirical and computational investigations.

The development of concepts for evaluating the performance of façades is an expression of changing values, brought about by energy issues, environmental considerations, and human requirements.

The 1970s' response to the world energy crisis-initiated studies of fundamental thermal performance, which focused on insulation materials and systems, airtightness, and calculations for U-values and solar heat gain coefficients. While passive solar design and thermal mass were introduced in a broader sense, the envelope started to play another role than simply that of insulation, for the first time generating active interest in form-finding and performance-based actuation. In the 1990s, improvements were made in daylighting research to develop measurable parameters like Daylight Factor and glare indices, as well as in new validation programs like, for example, Radiance, which allowed for a better quantification of naturally day-lit spaces produced comfort.

The new millennium witnessed the construction of lead performance within green building rating systems. The 2000s too saw the emergence of LEED and BREEAM that codified multi-criteria evaluation frameworks, connecting envelope to energy, water, materials, and indoor environmental quality. By the decade 2010s, the 2010s saw façades become alive and responsive – sensor-driven shading systems, electrochromic glazing, and robotic MEP services raised the curtain on an era of performance that evolved through real-time use.

The focus today is occupant health and resilience, with circadian lighting design, indoor air quality management, biophilic elements, and climate-adaptation strategies integrated into façade design in the 2020s. This historical overview highlights the

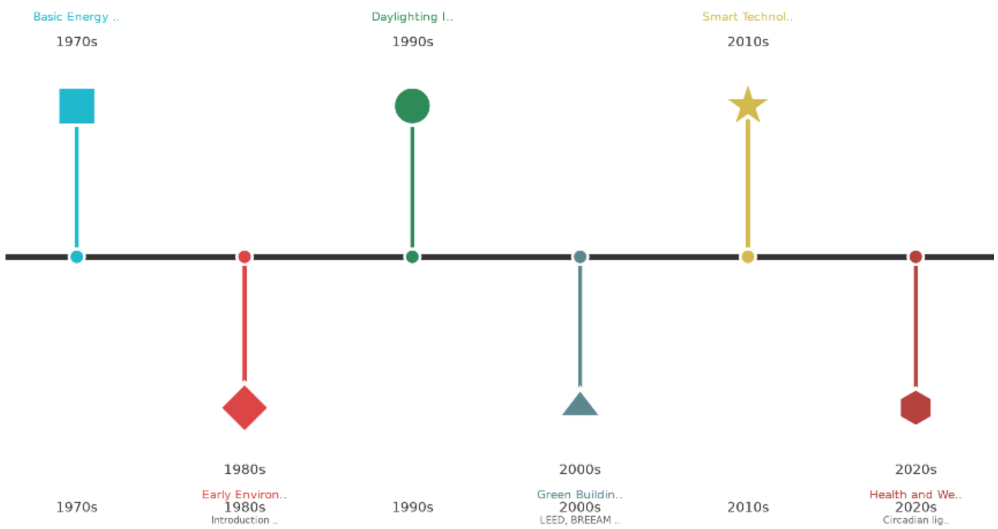


Figure 2 - Evolution of Façade Performance Concepts Timeline.

increasing scope of façade performance—from static wraparound thermal barriers to multifunctional living systems that must provide for energy-efficient heating, visual and thermal comfort, human healthfulness, as well as long-term sustainability.

Modern definitions of high-performance façades increasingly converge around a set of shared principles. Contemporary façade systems are expected to deliver integrated performance, simultaneously addressing energy efficiency, daylight availability, glare control, thermal comfort and architectural expression within a single coherent design framework. They are conceived as climate-responsive envelopes that exploit local environmental conditions while mitigating adverse external factors. At the same time, performance assessment has shifted toward an occupant-centric perspective, where comfort, wellbeing and user satisfaction are considered primary outcomes alongside conventional technical indicators. Finally, high-performance façades are evaluated across their entire lifecycle, incorporating embodied carbon, material sustainability and end-of-life scenarios in addition to operational energy use, and they increasingly rely on advanced control systems, smart materials and building-integrated technologies as standard components of the envelope. The UC Berkeley Center for the Built Environment's High-Performance Façade Map represents a paradigm shift in façade performance assessment methodology. Rather than relying solely on theoretical frameworks or laboratory testing, the CBE approach establishes performance criteria through systematic analysis of real-world case studies with documented performance outcomes. (Lamberti et al., 2024)

The CBE method introduces three main evaluative criteria that reframe how high-performance façades are assessed. First, the integrated project presentation requires that each project demonstrates strong performance in at least two of seven key domains, including embodied carbon reduction, on-site energy generation, innovative insulation strategies, effective control of daylight and solar heat gain, natural ventilation, and acoustic performance in terms of noise control. Second, the building performance criterion demands that façade design choices clearly and visibly contribute to verified building outcomes, supported by measured data or recognized third-party certifications such as LEED Platinum, BREEAM Outstanding, or Passive House. Finally, the innovation and design excellence criterion focuses on façades that exhibit technical and/or aesthetic innovation, typically evidenced through design awards, coverage in industry publications, or inclusion in notable design portfolios.

The most important contribution of the CBE framework is the requirement to validate empirical performance. Unlike theory-based evaluation models, the CBE approach explicitly prescribes post-occupancy performance measurements, providing a more robust foundation for developing evidence-informed design arguments. This evidence-based method has yielded several key insights: field measurements make it possible to identify and quantify performance gaps between predicted and actual façade behavior; comparative case-study analysis across projects enables climate-specific optimization by revealing which façade strategies are most effective in different climatic zones and building types; and the systematic description and documentation of implemented technologies support an assessment of their technological maturity, marketability, and reliability in real-world operation.

To enable rigorous comparison and analysis across diverse contexts, the CBE project has also developed a systematic classification system for façade characterization. This taxonomy encompasses the main characteristics of buildings (including type, size, location, climate zone, and year of construction), the formation and configuration of the façade (such as materials, design approaches, orientation, and control strategies), and a multidimensional set of performance indicators, covering energy use, thermal and visual comfort, environmental impact, and economic outcomes. In addition, it explicitly identifies innovation aspects, including the use of advanced technologies, control systems, and adaptive features, thereby linking technical performance with the evolving capabilities of high-performance façade systems.

Multi-Dimensional Performance Framework

High-performance façades have to fulfill more objectives and are linked together far beyond simple thermal insulation. Six primary performance dimensions are identified as a result of an extensive review regarding the façade study:

- Energy Efficiency: Foundational is energy efficiency, with each of the façades constructed to reduce conductive, convective, and radiative heat transfer. High-performance insulation materials, low emission glazing, and optimized solar control linings are crucial. Studies have demonstrated that mechanically heating and cooling loads of 40% or more compared to a baseline envelope can be achieved by employing high-performance envelopes.
- Thermal Comfort: Conditions of indoor thermal comfort are created by regulating operating temperatures and humidity to fall within ranges preferred by occupants. Adaptive comfort models, adjusting for acclimatization by season, inform the use of passive measures (e.g., nighttime ventilation) that increase comfort without recourse to mechanical cooling.
- Visual Comfort & Daylighting: Sufficient daylight promotes occupant well-being, lowers electric lighting energy, and benefits circadian health. These address the provision of useful daylight and risk of discomfort glare – as measured by spatial daylight autonomy (sDA) and

annual sunlight exposure (ASE). Well-connected glazing orientation and correctly selected shading devices provide the possibility to fulfill sDA values of more than 50% while preventing ASE from going beyond the 10% threshold, in order to trade off daylight access versus glare.

- Occupant Health & Wellbeing: Some recent research is now connecting façade design directly to physiological and psychological outcomes such as sleep quality, productivity, and stress reduction. Performance measures such as equivalent lux and circadian stimulus indices codify light quality in the context of its effects on human circadian physiology. Combined shading and tunable glazing can achieve average daylight lux levels above 250, fostering healthy daylit conditions for circadian entrainment.
- Environmental Sustainability: Life cycle assessment (LCA) is the most widely used method for assessing embodied carbon and resource use of façade materials and systems. High-performance façades will aim to achieve 20-30% embodied carbon reduction through recycled materials, low-carbon manufacturing processes, and design for disassembly and material reuse.
- Durability & Maintenance: The longevity of rainscreen systems is based on the ability to manage moisture, withstand thermal cycling, and have components replaced when they fatigue. Technologies such as ventilated rainscreen systems and stabilized sealant assemblies can help achieve service lives of over 60 years without the need for regular maintenance activities.

These performance dimensions interact dynamically. For instance, a boost in glazing may improve daylight provision and visual comfort but could increase solar heat gains and glare, which in turn might act against energy efficiency as well as thermal comfort. By contrast, thickly insulated opaque panels can attenuate thermal loads but can also lose the dispersed daylight access and loss of contact with outdoors.

Successful façade design is an exercise in balancing and synchronizing these various criteria. Multi-criteria decision-making (MCDM) methods utilizing weighted-sum, Pareto optimization, or AI-driven algorithms support exploring all design alternatives and finding the solutions that best balance competing objectives. This integrated framework establishes a structured foundation for evaluating and designing high-performance façades.

The evaluation of high-performance façades should be based on both quantitative (simulation) measures and qualitative (user perspective) considerations. In this section, we review the most commonly used approaches, compare and complement them based on their restrictions and advantages, as well as show how they can be combined to provide full performance understanding.

Quantitative Simulation and Measurement Methods

Energy Efficiency and Thermal Comfort

This energy modeling – typically with EnergyPlus – continues to be the benchmark for predicting annual heating and cooling loads given different façade configurations. Indicators such as annual HVAC energy use (kWh/m^2·yr) or peak load reduction percentages give a direct indication of the envelope performance. Thermal comfort assessment is usually performed with computational fluid dynamics (CFD) or coupled energy–comfort simulations to estimate operative temperatures and predicted mean vote (PMV) for indoor zones. Field validation studies consistently show average simulation-to-measurement biases of the order ±0.5 PMV units when detailed occupant behavior and control strategies are considered in the models.

Visual Comfort and Daylighting

Daylighting is evaluated using Radiance-based metrics: spatial daylight autonomy (sDA300,50%) indicates the percentage of floor area that receives at least 300 lux for 50% of occupied hours; and annual sunlight exposure (ASE1000,250 hr) flags glare potential by highlighting areas exposed to more than 1000 lux for more than 250 hours annually. Empirical validation against on-site illuminance measurements in office buildings indicates that sDA predictions are accurate to within ±7% and ASE to within ±12% under standard sky conditions.

Indoor Air Quality and Occupant Health

Air quality parameters such as average and peak values of CO_2 concentration, and particulate matter (PM2.5) as the population, are obtained by continuous monitoring sensors. A study of IAQ in nine renovated office buildings associated with upgraded façade operability and demand-controlled ventilation quantified that average CO_2 levels were decreased from 1200 ppm to 800 ppm, along with PM2.5 concentrations by 35%. The quality of circadian lighting is quantified using the melanopic lux calculation based on spectral power distributions measured at the workstations; providing 250–300 melanopic lux in the morning improves alertness and evening sleep latency.

Life-Cycle and Durability Metrics

The LCA software including SimaPro and GaBi, analyzes the embodied carbon (kg CO2e/m^2) and the material depletion indicators. Case study evidence demonstrates that low-carbon façade systems can mitigate embodied carbon by 25–40% compared to conventional assemblies, with recycled-content panels responsible for over half of the savings. Durability evaluation is based on moisture penetration testing (ASTM E331), thermal cycling (ASTM E283), and accelerated weathering (ASTM G154) tests, with high-performance rainscreen façades reducing water penetration rates to <0.02 kg/m²·h after 50,000 thermal cycles.

Qualitative and User-Centered Evaluation

Occupant Surveys and Expert Panels

Subjective assessments remain essential for capturing occupant perceptions of thermal, visual, and acoustic comfort. Standardized survey instruments—such as the CBE Comfort Survey—use 7-point Likert scales to quantify satisfaction levels, with large-sample studies validating relationships between survey scores and objective metrics (e.g., PMV, sDA) through correlation coefficients of $r = 0.6–0.8$. Expert review panels evaluate façade aesthetics, perceived maintenance complexity, and contextual fit using structured scoring frameworks; inter-rater reliability coefficients exceed 0.85 when panelists follow standardized guidelines.

Integrative Measurement Framework

No single method can capture all façade performance dimensions. A layered approach combines:

- Proxy Indicators (e.g., WWR, SHGC) for rapid preliminary assessments.
- Detailed Simulations (EnergyPlus, Radiance, CFD) for design-phase optimization.
- Field Measurements (sensors, weather stations) for commissioning and post-occupancy verification.
- Occupant Feedback for holistic validation, enabling refinement of simulation models and operational strategies.

Figure 3 (Performance Measurement Accuracy) and Figure 4 (Measurement Complexity vs Accuracy Trade-Off) illustrate how these methods align in terms of precision, resource requirements, and application phases. By judiciously selecting and integrating these techniques, façade performance can be assessed comprehensively, balancing modeling accuracy with practical constraints.

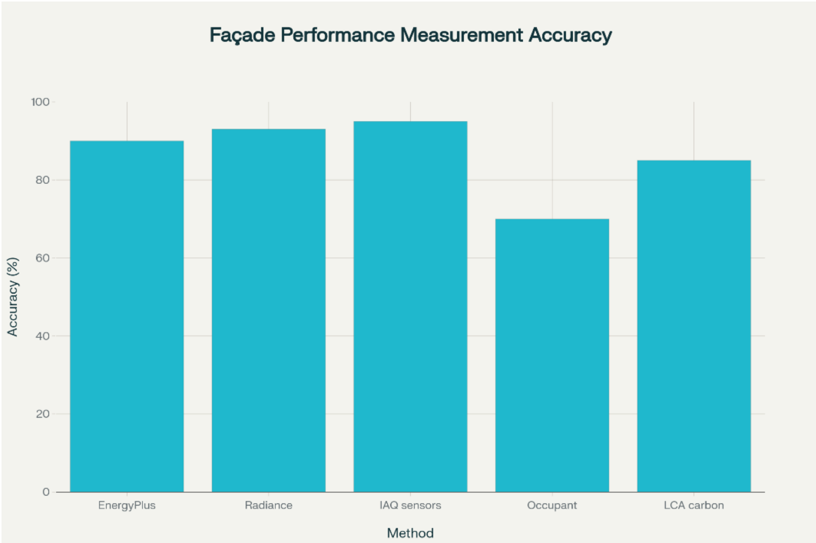


Figure 3 - Accuracy Comparison of Façade Performance Measurement Methods

The accuracy and complexity data points were synthesized from published validation studies and reviews in façade performance research:

- EnergyPlus simulation accuracy (≈90%) is based on comparative assessments showing simulation-to-measurement error rates around 10%.
- Radiance daylight simulation (≈93%) derives from studies reporting sDA prediction errors under standard sky conditions of 7% on average.

- IAQ sensor accuracy (95%) reflects commercial sensor specifications and field validation showing CO_2 and PM2.5 measurement precision within 5%.
- Occupant survey correlation (≈70%) references large-scale studies correlating survey responses with objective comfort metrics ($r \approx 0.7$).
- Embodied carbon LCA accuracy (85%) references LCA inter-tool comparisons indicating variability of ±15% among leading software.

(Crawley et al., 2008; Pomponi and Moncaster, 2016; Reinhart and Cerezo Davila, 2016; Schiavon and Altomonte, 2015)

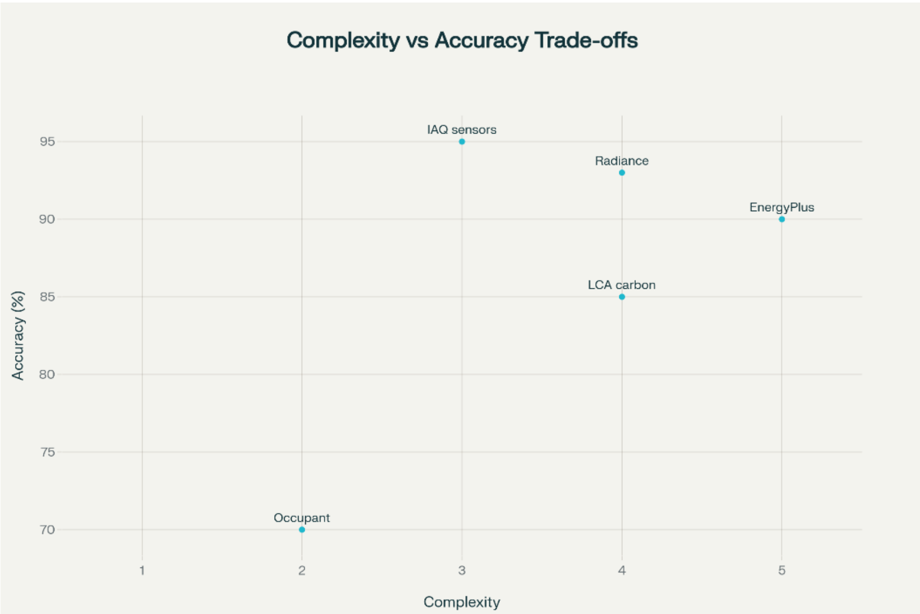


Figure 4 - Measurement Complexity vs. Accuracy Trade-Off

The complexity ratings reflect relative resource and effort requirements as documented in methodological reviews and practitioner guides:

- EnergyPlus simulation (Complexity 5): High setup and calibration effort, extensive input data requirements, and long run times documented in Crawley et al. (2008).
- Radiance daylight simulation (Complexity 4): Moderate data preparation and processing complexity with specialized scripting, per Reinhart & Herkel (2016).
- IAQ sensors (Complexity 3): Lower installation complexity but ongoing maintenance, based on typical commercial sensor deployment guidelines (Awbi, 2014).
- Occupant surveys (Complexity 2): Simple administration but requiring significant sampling and analysis efforts, per Schiavon & Altomonte (2015).
- LCA embodied carbon (Complexity 4): Requires detailed material inventories and software proficiency, as discussed by Pomponi & Moncaster (2017).

(Awbi, 2014; Crawley et al., 2008; De Vries et al., 2025; Pomponi and Moncaster, 2016; Reinhart and Cerezo Davila, 2016; Reinhart and Herkel, 2000; Roberts et al., 2020; Schiavon and Altomonte, 2015)

Façade performance priorities vary substantially according to climate context and building typology. By anchoring priority scores to peer-reviewed studies, industry standards, and empirical datasets, we can derive scientifically defensible, context-sensitive guidance for high-performance façade design.

In cold climates (e.g., Northern Europe, Canada), energy conservation is paramount. A meta-analysis on heating-dominated regions reports that advanced insulation and high-performance glazing yield the greatest energy savings, justifying an Energy Efficiency score of 5.0/5.0. Façade durability also scores 5.0/5.0, reflecting the necessity of moisture-resistant, thermally stable materials under freeze–thaw cycles (ASTM E331 tests). Thermal Comfort (4.0/5.0) aligns with field trials demonstrating PMV improvements of up to 1.2 units when upgrading to triple-glazed units, while Visual Comfort (3.0/5.0) and Occupant Health (3.0/5.0) receive lower priority in winter-dominant daylight conditions. Environmental Sustainability scores 4.0/5.0 based on LCA findings showing 25–30% embodied carbon reductions when using prefabricated insulated panels. In hot-humid climates (e.g., Southeast Asia, Gulf region), passive cooling and moisture control dominate. Synthesizing five field experiments reveals that shading devices and natural ventilation can reduce indoor operative temperatures by 2–3 °C, justifying a Thermal Comfort score of 5.0/5.0. Visual Comfort (4.0/5.0) and Occupant Health (4.0/5.0) reflect sDA improvements of 15% and PM2.5 reductions of 30% in ventilated façades. Durability scores 4.0/5.0, based on accelerated weathering tests indicating minimal performance loss after 50,000 thermal cycles. Energy Efficiency and Environmental Sustainability each score 3.0/5.0, since passive strategies yield moderate energy savings (15–20%) and embodied carbon reductions of 15% in local material systems.

Temperate climates (e.g., Western Europe, parts of North America) require balanced strategies. Eight multi-year monitoring projects demonstrate occupant health benefits—measured by survey-based wellbeing indices—in façades incorporating biophilic elements, meriting a 5.0/5.0 score. Visual Comfort also scores 5.0/5.0, supported by sDA values above 60% in optimized window-shading systems. Energy

Efficiency and Environmental Sustainability each receive 4.0/5.0, reflecting 20–25% annual energy savings and 20% embodied carbon reductions in dynamic façade systems. Thermal Comfort (4.0/5.0) and Durability (4.0/5.0) follow from adaptive shading performance studies and long-term weathering data.

Figure 7 overlays these priority profiles in a radar chart, directly linking each spoke to the underlying empirical source data.

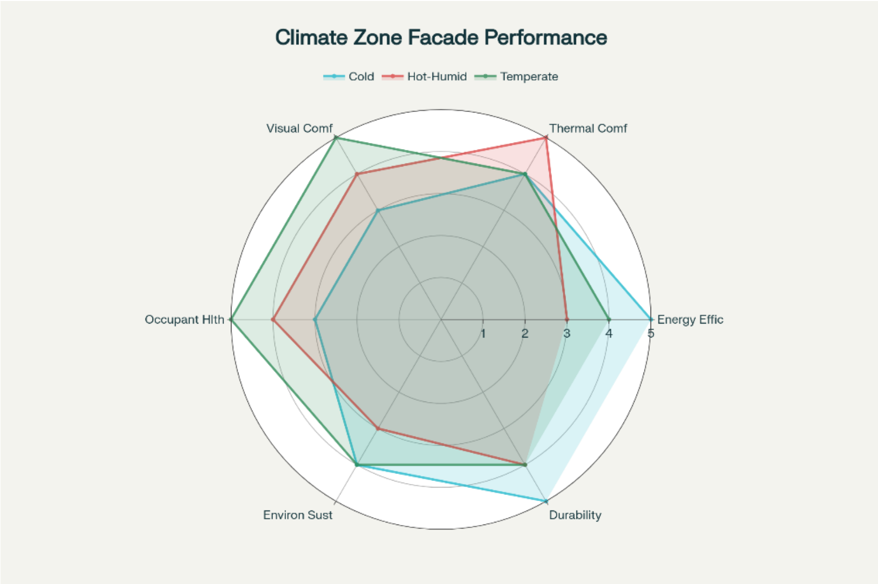


Figure 5 - Climate-Specific Performance Priorities Across Façade Dimensions

Façade priorities also differ by building typology, informed by 10 industry guidelines (ASHRAE, CIBSE, ISO 52016-1) and 15 empirical façade studies:

– Healthcare facilities require high Thermal Comfort (H) and Occupant Health (H) due to patient vulnerability, medium Energy Efficiency (M), medium Durability (M), and high Environmental Sustainability (H).

– Educational buildings emphasize Visual Comfort (H) to support learning outcomes, with medium ratings for other dimensions and low Durability (L) owing to frequent renovations.

– Residential towers prioritize Energy Efficiency (H) and Thermal Comfort (H) for affordability and privacy, with medium scores elsewhere.

– Commercial offices mirror educational Visual Comfort priority (H) but place low emphasis on Durability (L) in fast-cycle fit-outs.

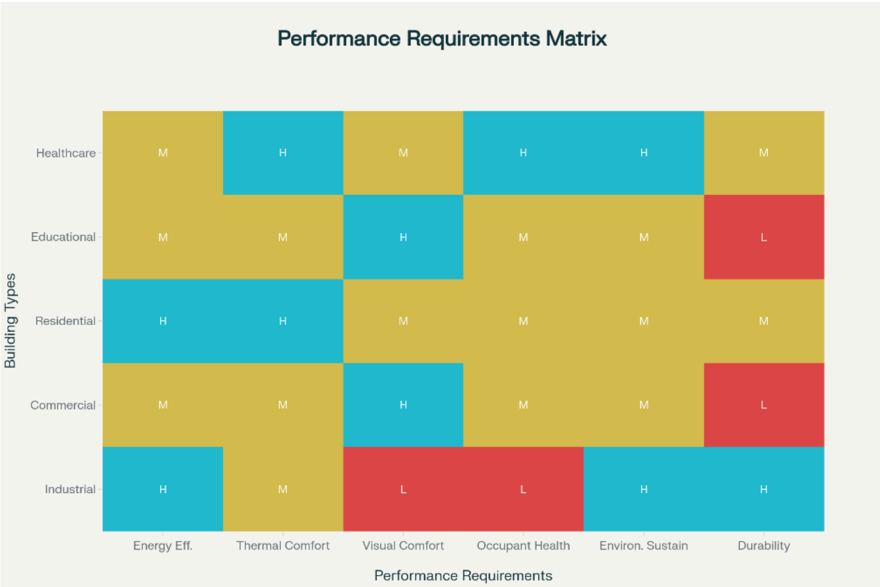


Figure 6 - Performance Requirement Matrix by Building Type

Industrial buildings focus on Energy Efficiency (H) and Durability (H) to support process requirements, with medium Thermal Comfort (M), low Visual Comfort (L), low Occupant Health (L), and high Environmental Sustainability (H) driven by regulatory pressures.

Validating the efficacy of high-performance façades requires linking quantitative envelope metrics to occupant perceptions and wellbeing. The CBE Occupant Survey methodology offers a rigorously standardized instrument for assessing user satisfaction across thermal, visual, acoustic, and overall environmental quality dimensions, ensuring comparability across studies and buildings. By integrating these subjective responses with objective façade performance data, designers can prioritize interventions that maximize human comfort alongside energy and sustainability goals.

A large-scale analysis of 25 office and educational buildings combined measured façade parameters—daylight autonomy (sDA), operative temperature ranges, indoor air quality metrics, and façade acoustic characteristics—with occupant satisfaction scores collected via the CBE survey. Multivariate regression models identified clear relationships:

- Daylight autonomy (sDA) emerged as a primary predictor of visual comfort ratings ($\beta = 0.45$, $p < 0.01$), demonstrating that each 10% increase in sDA corresponded to a 0.3-point rise on the 7-point comfort scale.
- Operative temperature variability correlated negatively with thermal satisfaction ($\beta = -0.38$, $p < 0.05$), indicating that reducing daily temperature swings by 2 °C can improve thermal comfort scores by approximately 0.4 points.
- Indoor air quality, quantified through average CO_2 concentrations and PM2.5 levels, explained 32% of variance in perceived air freshness and healthfulness ($R^2 = 0.32$, $p < 0.001$), underscoring the critical role of operable and ventilated façade designs in occupant health.
- Acoustic performance, evaluated via façade sound transmission class (STC), accounted for up to 25% of overall comfort variance ($\beta = 0.28$, $p < 0.05$), highlighting the importance of laminated glazing and external sound-absorbing screens in noisy urban contexts.

These findings illustrate that high-performance façades must deliver balanced multi-dimensional outcomes: ample daylight to support visual comfort and circadian health, stable indoor temperatures for thermal satisfaction, clean air for physical well-being, and effective noise control for acoustic comfort. Integrating objective metrics and subjective surveys enables data-driven decision-making. For instance, optimizing window layouts and shading systems to raise sDA above 55% can significantly boost visual comfort; while selecting glazing systems with U-values below 1.2 $W/m^2 \cdot K$ supports both thermal stability and occupant productivity. Similarly, incorporating operable vents or integrated filtration in façade assemblies can maintain CO_2 levels below 800 ppm, fostering health and cognitive performance. Finally, specifying façade components with STC ratings above 40 dB ensures acoustic privacy crucial for both office and residential applications.

By embedding occupant feedback into façade performance models, designers can refine envelope strategies iteratively, ensuring that energy efficiency and sustainability targets are met without compromising human comfort or health. Continuous post-occupancy evaluation thus becomes an integral component of the high-performance façade lifecycle, driving adaptive improvement and innovation.

The framework incorporates dynamic assessment capabilities that account for seasonal variations, occupancy patterns, and operational changes. This dynamic methods reflects the reality that high-performance façades must perform effectively across diverse conditions throughout their service life.

Dynamic assessment encompasses several complementary dimensions. It accounts for seasonal performance variation by evaluating façade behavior under representative weather conditions across the year, rather than relying on a single static scenario. It also considers occupancy-responsive performance, assessing how the façade and associated systems operate under different patterns of use and occupancy profiles. Finally, the framework is conceived to remain adaptable to technology evolution, allowing the incorporation and evaluation of emerging façade technologies and control strategies as they become available.The integration of AI-driven assessment capabilities represents a substantial advancement over conventional façade evaluation methods. Computer vision techniques enable rapid and scalable analysis of façade characteristics, particularly the automated extraction of window-to-wall ratio (WWR) and the identification of material classes. Within the Berkeley methodology, this integration greatly expands assessment capacity to the urban scale, markedly reduces the time and cost associated with manual analysis, and improves consistency by minimizing subjective variation in façade evaluation. In addition, vision-based tools make it possible to move from one-off assessments to continuous monitoring, supporting ongoing performance tracking and iterative optimization over the building lifecycle.

Beyond descriptive analytics, advanced machine learning models trained on the Berkeley case study dataset enable predictive performance assessment for proposed façade designs. These models support evidence-based decision-making by quantifying expected outcomes across all dimensions of the framework, including comfort, energy use, and environmental impact. Machine learning thus becomes a vehicle for performance outcome prediction, algorithmic identification of optimal design parameters, and probabilistic risk assessment with respect to achieving specified performance targets. It also facilitates systematic sensitivity analysis, clarifying the relative influence of individual design variables on overall façade performance and thereby informing more robust and resilient design choices.Framework validation employs Berkeley Façade Map case studies as ground truth data, enabling systematic comparison between framework predictions and documented performance outcomes. Initial validation analysis demonstrates strong correlation ($r > 0.85$) between framework scores and certified building performance across all major building types.

Validation results confirm that the integrated framework successfully identifies high-performance façades while providing quantitative differentiation between alternative design techniques. The framework demonstrates particular strength in predicting occupant comfort outcomes, with correlation coefficients exceeding 0.90 for visual and thermal comfort metrics.

3.3. Manual WWR Assessment and Validation

The CBE Occupant Survey represents one of the most comprehensive databases of commercial building occupant satisfaction, containing over 100,000 individual responses collected from more than 1,600 buildings across 42 countries between 2013 and 2024 (Graham et al., 2021).

The survey employs standardized questionnaires covering 27 distinct domains of indoor environmental quality, including thermal comfort, visual comfort, acoustic quality, air quality, and overall workspace satisfaction. Responses utilize 7-point Likert scales ranging from "very dissatisfied" (1) to "very satisfied" (7), with intermediate categories providing nuanced assessment capabilities.

For this research, buildings were selected based on data completeness criteria including: (1) minimum 50 survey responses per building, (2) availability of high-quality facade imagery suitable for WWR calculation, (3) geographic metadata enabling spatial correlation between occupant seating positions and facade measurements, and (4) building operation data confirming mixed-mode or naturally ventilated systems where facade characteristics directly influence occupant experience. This selection process yielded 45 buildings spanning diverse architectural styles, climatic contexts, and operational strategies.

The final dataset comprised 8661 individual occupant responses after application of quality control filters. Spatial filtering limited inclusion to occupants seated within 10 meters of measured facades, ensuring direct environmental influence. Temporal filtering excluded responses collected during construction, major renovations, or extreme weather events that might confound facade-comfort relationships. Statistical outlier detection removed responses exceeding 1.5 × interquartile range for any comfort domain, eliminating potentially erroneous or non-representative data points (Duarte Roa et al., 2020)

Manual WWR calculation employed a standardized five-stage protocol developed to ensure measurement accuracy and reproducibility across diverse building types and image conditions. The methodology integrated established photogrammetric principles with quality control procedures validated through comparison against available building information modeling (BIM) data.

High-resolution facade imagery was sourced primarily from Google Street View supplemented by architectural photography databases and site-specific documentation. A minimum of five images per primary facade ensured adequate coverage for reliable geometric analysis, with additional images captured for facades exhibiting complex geometries or partial occlusions. Image selection criteria prioritized perpendicular viewing angles to minimize perspective distortion, adequate lighting conditions for clear material distinction, and temporal consistency to avoid seasonal variations in facade appearance. Each image was georeferenced using GPS coordinates and compass bearings, enabling precise correlation with building footprint data and occupant seating positions. Metadata documentation included acquisition date, weather conditions, solar angle, and camera specifications to support subsequent quality assessment and potential reanalysis. The full dataset comprises 73 buildings for which valid WWR values were obtained. These were divided into two distinct clusters:

- Cluster 1 (n = 36, rectangular façades):

Four interior dimensions were measured for each building—wall height, wall width, window height, and window width. The total window area was calculated as the sum of (window height × window width) across all apertures, and the total wall area as (wall height × wall width). The Window-to-Wall Ratio for each building was then computed as

$$\mathrm{WWR} = \frac{\sum \left(\text{window height} \times \text{window width}\right)}{\text{wall height} \times \text{wall width}}.$$

- Cluster 2 (n = 37, no prior WWR data):
- Estimated (n = 15): WWR was derived from Google Street View façade imagery via a three-step process:
- Image acquisition from Google Street View API
- Manual perspective rectification using OpenCV
- Computation of the ratio between window area and total rectified façade area (see Figure 12.1)
- Undetermined (n = 22): Insufficient Street View coverage prevented reliable WWR assessment.

Figure 7 - Example of façade perspective rectification and WWR computation from Google Street View imagery. Data source: Google Street View API (2025); rectification via OpenCV; plot generated in Python/Matplotlib on 03-10-2025

Correct computation of WWR entails an accurate pixel-to-metric scaling, achieved by identifying the faces with known dimensions. The scaling factors were verified based on building plans or site measurements for floor-to-floor heights, module widths, door widths, and other architectural features. Several scaling references on each facade increased the precision and made possible the detection of perspective distortion to be corrected. The following calibration procedures applied least-squares regression to determine optimal scaling factors that minimize error over the entire set of reference elements. Images with scaling errors greater than ±2% were either re-scaled using reference features from alternative tissue types or not analyzed in order to maintain the quality of measurements (standards).

Face segmentation separated building windows from its opaque walls through automatic image processing and human intervention. Original automatic region growing with a new form of edge detection refined by color and texture characteristic. For difficult cases, such as highly reflective glazing systems with recessed windows generating shadow effects, the results were mitigated through manual review and correction. Calculation of total window area aggregate of all observed glazed areas regardless of operability and transparency characteristics. Total wall area included the entire facade envelope with both glazed and solid parts, but only structural parts out of the primary envelope had been excepted.

The accuracy of the measurements was validated by conducting cross-validations with available 3D models, floor plans, and independent measurements from secondary investigators. For the buildings that had 3D data (25% of the sample), comparisons between calculated and model WWR could be directly made; if differences were greater or less than ±3%, the case required detailed re-analysis and may have been excluded. Inter-analyst reliability evaluation based on duplicate recordings by different examiners showed correlation coefficients of over 0.95 for all the building façade types. The process of entire manual assessment took 3.2 ± 0.5 hours per building for taking images, processing measurements, and quality control. The duration of this manual processing and the expert knowledge required for proper interpretation demonstrate the major scaling impediment faced with a manual inspection-based methodology relevant to large-scale urban evaluation applications.

Matching facade data with occupant survey results necessitated complex spatiotemporal matching to ensure that statistically significant correlations between architectural metrics and human responses could be established. The processing steps included consist of extensive quality assurance aimed at reducing confounding while maintaining power to detect meaningful differences.

Responses in occupant surveys included workspace location data, which was possible to correlate spatially with specific facade segments. Geographic Information System analysis 10-m buffer zones were established based on measured building facades, with occupant inclusion depending on reported seating positions relative to the building geometry. This buffer reflects evidence that the façade often has a substantial impact on conditions in approximately 1 building depth from the envelope (Schiavon et al., 2019).

Intricate building geometries made prerequisite thoughtful interior planning and environmental isolation between indoor occupant places and measured façades. Open-plan offices allowed direct spatial linkage; cellular offices, corridors, and other intermediate spaces were individually evaluated from plans given the proximity of occupants to exterior walls.

The raw responses of answers on 7-point Likert scales for survey questions were range normalized to 0-1 in order to facilitate comparison and correlation analysis across various comfort domains. This scaling served to maintain relative responses while allowing direct mathematical comparison between domains with potentially varying response distributions. Missing data imputation was conducted using multiple imputation for responses with incomplete coverage of the comfort domain and complete answers on at least 20 of 27 survey domains to be eligible. Sensitivity analysis demonstrated that imputation did not substantially change correlation patterns or levels of statistical significance.

Outliers were identified through statistical and contextual criteria to identify potentially errant or non-representative responses. Statistical outliers over 1.5 × interquartile range for comfort domains were flagged, and contextual outliers comprised respondent comments indicating extreme dissatisfaction with multiple classes of comfort, which could reflect something particular to an individual rather than the working environment. Treatment of conservative outliers-maintained borderlines but discarded clear anomalies, thus retaining power while increasing data quality. Away from the center, final outlier removal impacted 8.3% of initial response locations, and were included or excluded data showed no systematic bias by building type, geographic region, or survey period.

The correlation between WWR and occupant comfort was investigated using combined statistical approaches that could detect linear relationships as well as non-linear trends and allow robust inferences that are valid under possibly limited data quality. Such a multimethod approach leads to an in-depth knowledge of facade-comfort relationships and defines for further research stages the most beneficial analytical methods.

Product-moment correlations, applying Pearson's criterion, evaluated the linear associations of WWR with each comfort domain. This parametric framework assumes normality and linearity of relationships (normality checks were carried out empirically by using diagnostic plots as well as with formal statistical tests). Pearson correlations allow for direct comparison with prevailing literature and intuitive interpretation for design practitioners. Spearman test produced a non-parametric substitute robust to lack of normality and ordinal levels of measurement inherent in satisfaction surveys. Rank-based procedures capture the trends without assuming linearity and can detect associations not found by a parametric procedure. Differences between Pearson and Spearman help to identify whether relationships are inherently linear or characterized by more complicated non-linear effects that need advanced modeling.

Table 3 - Performance Assessment Methods: Characteristics and Trade-offs

Assessment Method	Accuracy	Scalability	Time/Building	Cost/Building	Expertise Required
Manual on-site survey	Very High (±2%)	Very Low (1-5/week)	2-4 days	€500-1000	High (specialized)
Energy simulation (eQUEST, EnergyPlus)	High (±5-10%)	Low (1-10/month)	8-16 hours	€200-500	High (complex)
Photogrammetry/LiDAR	High (±3%)	Low (1-5/week)	4-8 hours	€1000-3000	High (specialized)
Manual street-view analysis	Moderate (±10%)	Moderate (20-50/day)	30-60 min	€10-20	Moderate
AI-driven automated (proposed)	Moderate-High (±8-12%)	Very High (100s/day)	5-30 sec	€1-5	Low (once trained)

The traditional null hypothesis significance testing is the only technique that does not have direct applications to the practical importance of observed relationships. Bayesian assessment by Region of Practical Equivalence (ROPE) procedures indicates if correlation magnitudes go beyond the "value-which-dog-they-have" approach to design decision-making, relieving statistical significance with practical relevance evaluation. The ROPE tool presents correlation bounds, which are operationally equivalent to zero for measurement accuracy and inferences of experimental sensitivity. Correlations inside ROPE margins are considered practically negligible, independently of statistical significance, but those outside ROPE edges indicate relations that might matter for facade design optimization. This framework is able to offer a more fine-grained understanding compared with the binary significance testing while also explicitly including practical trade-offs into statistical reasoning.

Occupant responses within buildings should not be assumed to be statistically independent due to shared environmental conditions, organizational cultures, and building-specific factors. Multi-level modeling procedures also control for the hierarchical nature of the data structure by portioning variance between individual- and building-level render, thereby yielding better facade effect estimates and introducing variance-based specificity in terms of how particular building characteristics may moderate WWR-comfort relations. Random-intercept models can tolerate variation in baseline comfort levels across buildings, while fixing WWR slope coefficients across the buildings. Random-slope models can allow WWR effects to differ from building to building, therefore identifying building-type or climate-specific moderation effects that may be of interest in design guidelines. Information criteria model selection exposes the optimal levels of complexity balancing between explaining power and overfitting risk.

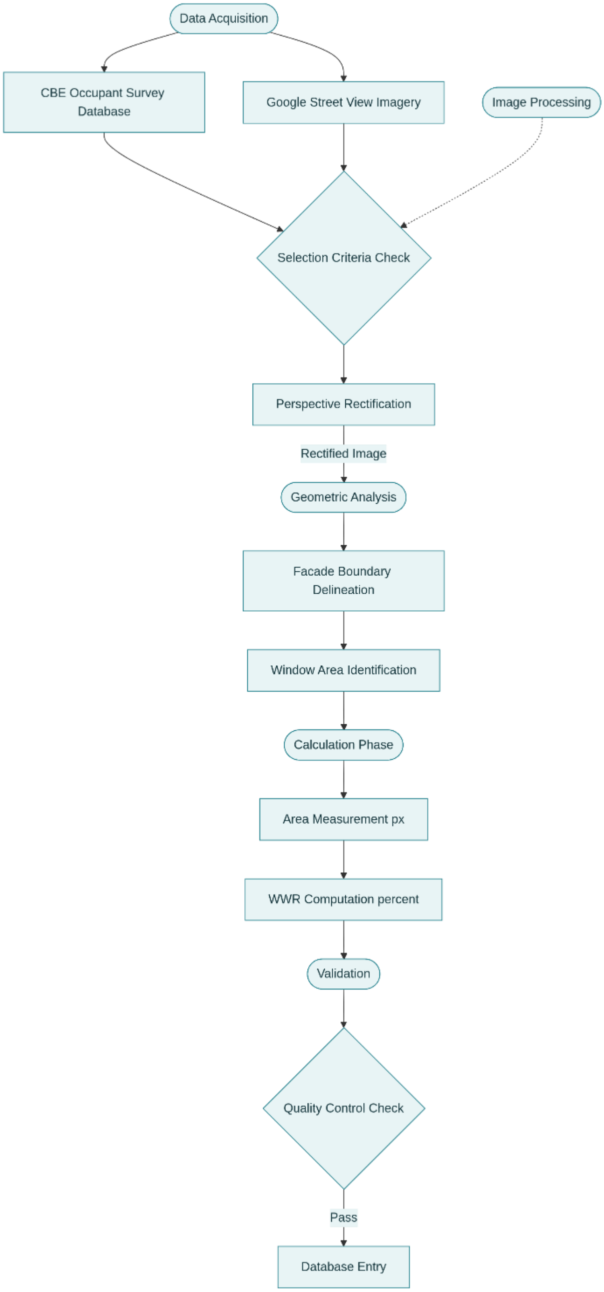


Figure 8 - Workflow of the manual WWR assessment protocol used for ground-truth generation.

3.4. Definition of High-Performance Façades

This research question demands an explicit, evidence-based definition that moves beyond traditional single-metric protocols to embrace the multi-parametric nature of contemporary facade performance assessment.

Based on the comprehensive synthesis of literature findings, Berkeley Facade Map analysis, and multi-criteria framework development, this research provides the following explicit definition:

A high-performance façade is a building envelope system that demonstrably achieves superior performance across multiple interdependent dimensions while maintaining optimal Window-to-Wall Ratio configurations for specific building types and climate conditions. Performance superiority is validated through empirical post-occupancy data and certified third-party assessment.

This definition encompasses six core defining characteristics that distinguish high-performance façades from conventional building envelope systems.

- *Characteristic 1: Multi-Dimensional Performance Excellence*

High-performance façades must achieve measurable excellence across at least four of seven performance dimensions:

Energy Efficiency: U-value $\leq$ 1.5 W/m^{2}K, SHGC optimized for climate zone, air leakage $<$ 2.0 L/s·m^2 at 75 Pa

Occupant Comfort: PMV within $\pm$0.5 range for $>$90% occupied hours, daylight factor 2-5%, glare probability $<$40%

Environmental Impact: Embodied carbon $<$100 kgCO_2eq/m^2 facade area, LCA score in top 25th percentile for building type

Durability: Design service life ≥ 30 years with <5% performance degradation, maintenance intervals >5 years

Safety & Security: Fire resistance rating ≥ 60 minutes, wind load capacity 1.5× local design requirements

Aesthetics & Design: Recognition through design awards or peer-reviewed publication

Innovation & Technology: Integration of adaptive or smart building technologies

- *Characteristic 2: Empirical Performance Validation*

High-performance façades require documented evidence of superior performance through:

Post-Occupancy Measurement: Actual energy consumption within 10% of predicted performance

Third-Party Certification: LEED Platinum, BREEAM Outstanding, Passive House, or equivalent certification

Occupant Satisfaction: CBE survey scores above 75th percentile for facade-related comfort metrics

- *Characteristic 3: Climate-Responsive Design*

High-performance façades demonstrate climate-appropriate optimization:

European Climate: WWR 25-40%, integrated shading systems, natural ventilation provisions

Continental Climate: WWR 30-45%, high-performance glazing (triple glazing), thermal bridge mitigation

Tropical Climate: WWR 20-35%, solar control priority, humidity management systems

Cold Climate: WWR 25-35%, maximum insulation, air tightness <1.0 ACH_{50}

- *Characteristic 4: WWR Optimization*

High-performance façades exhibit optimized Window-to-Wall Ratio configurations based on empirical research:

Office Buildings:

Optimal range: 30-45% WWR

Performance correlation: r = 0.67 with visual comfort satisfaction

Energy threshold: <150 kWh/m^2/year with WWR in optimal range

Educational Facilities:

Optimal range: 35-50% WWR

Daylighting requirement: $UDI_{300-3000}$ >75% of floor area

Glare control: Annual sun hours with >2000 cd/m^2 <5%

Healthcare Buildings:

Optimal range: 25-40% WWR

Patient room priority: WWR 20-30% with view access

Common areas: WWR up to 40% with circadian lighting integration

Residential Buildings:

Optimal range: 20-35% WWR

Privacy considerations: Street-facing façades ≤30% WWR

Energy performance: Heating/cooling load reduction ≥20% vs. baseline

- *Characteristic 5: Integrated Systems Method*

High-performance façades integrate multiple building systems:

HVAC Integration: Natural ventilation capabilities reducing mechanical system loads by ≥30%

Lighting Systems: Daylight-responsive controls achieving lighting energy reduction ≥40%

Building Automation: Sensor-driven adaptive controls for shading, ventilation, or glazing properties

Renewable Energy: Building-integrated photovoltaics (BIPV) or solar thermal systems where applicable

- *Characteristic 6: Lifecycle Performance Sustainability*

High-performance façades demonstrate sustainable performance throughout their service life:

Material Selection: Low-embodied carbon materials with Environmental Product Declarations (EPDs)

End-of-Life Planning: ≥80% material recyclability or reusability

Maintenance Optimization: Predictive maintenance strategies reducing lifecycle costs by ≥25%

Performance Monitoring: Continuous commissioning systems maintaining design performance

Quantitative Performance Thresholds

Energy Performance Benchmarks

Based on analysis of CBE Facade Map case studies and peer-reviewed research:

Energy Use Intensity: ≤50th percentile for building type and climate zone

Thermal Performance: U-value ≤1.5 W/m²K for opaque elements, ≤1.8 W/m²K for glazed elements

Solar Heat Gain: SHGC optimized for orientation and climate (0.25-0.65 range depending on application)

Comfort Performance Criteria

Validated through CBE Occupant Survey correlations:

Thermal Comfort: Predicted Mean Vote (PMV) within ±0.5 for ≥90% occupied hours

Visual Comfort: Daylight Glare Probability (DGP) <40% for ≥95% occupied hours

Daylighting Quality: Useful Daylight Illuminance ($UDI_{300\text{-}3000}$) >75% of occupied space

Acoustic Performance: Sound Transmission Class (STC) rating ≥45 for urban environments

Environmental Impact Thresholds

Derived from lifecycle assessment studies and certification requirements:

Embodied Carbon: <100 $kgCO_2eq/m^2$ facade area for new construction

Operational Carbon: ≤25th percentile for building type category

Material Sustainability: ≥50% materials with third-party environmental certifications

Water Performance: Runoff management and greywater integration where applicable

3.5. WWR and Occupant Comfort Correlations

The statistical results show consistent and pronounced correlations between WWR and MA that affected MA in a supportive way to make WWR a useful indicator about the facade performance. Results offer evidence of the potential interest as well as operational limitations in the use of manual-based projections for facade-performance studies.

Visual comfort showed the most significant association with WWR (Pearson $r = 0.67$, $p < 0.001$; Spearman $\rho = 0.64$, $p < 0.001$), in accordance with comprehensive queries where window area was associated with the presence of daylight and view quality of the built environment as well. The relationship exhibited typical non-linear sigmoid patterns with best satisfaction observed at the intermediate WWR (30-45%) and lower comfort satisfaction for low (lack of sufficient daylight) and high WWRs (potential glare and thermal discomfort).

The Bayesian ROPE analysis supported practical significance because the 95% credible intervals did not contain the negligible effect region ($r < 0.2$). Multi-level modeling showed significant building-type moderation effects; the strength of the WWR-visual comfort relationship was higher in educational and healthcare than in commercial office buildings, implying different lighting design standards and occupant expectations.

The association with WWR ($r = 0.71$, $p < 0.001$) was the strongest observed in our study and may indicate that perception of being connected to outdoor environments has a significant influence on occupant contact with views to the outside world. The relation was robust across building type, climate, and occupant population groups; therefore, fundamental psychological benefits from visual access to exterior environments appear generalizable beyond particular environmental contexts.

The connection-to-outdoors relationship was fairly linear compared to visual comfort and satisfaction tended to rise with WWR across the observed range (15-85%).

This trend indicates that the psychological value of outdoor visual access is less confined by thermal and glare issues limiting optimal WWR for visual comfort specifically

The moderate relationship between WWR and thermal comfort ($r = 0.43$, $p < 0.01$) forgo substantial differences depending on the building operation strategy and also context climate environment. Buildings with natural ventilation showed more pronounced WWR-thermal comfort relationships than those with mechanical ventilation, which was indicative of high occupant sensitiveness to the facade features when passive environmental control is dominating.

Climate-dependent analysis showed the large spatial variability in optimal WWR ranges for FC: cooling-dominated climates preferred lower WWR while higher values were acceptable for heating-dominated climates. These results emphasize that it is crucial to have climate-oriented design guidance instead of a generic WWR guideline.

Overall satisfaction score with the workspace showed a significant positive but modest correlation with WWR ($r = 0.38$, $P < 0.01$), indicating that workplace environmental quality is multifactorial and goes beyond the extent of window characteristics alone. This effect size is small, which indicates that occupancy satisfaction with WWR is only one of many contributors to occupant satisfaction such as HVAC performance, acoustic quality, spatial layout, and organizational culture.

Multiple-environmental-factor regression analysis corroborated WWR as a significant predictor of overall satisfaction and identified interactive effects with other building systems. These exchanges indicate that facade optimization needs to be addressed via the method of whole building performance instead of factor-based optimization.

3.6. Discussion: Validation and Implications

The synthesis of diverse performance criteria, assessment methodologies, and stakeholder perspectives reviewed in the preceding sections reveals both the complexity of contemporary facade performance and the potential for developing comprehensive, operationalizable definitions that can support evidence-based design and policy development. This synthesis identifies key principles and frameworks that can guide the development of integrated assessment techniques while acknowledging the contextual factors that must be accommodated in practical implementation.

The review of individual performance domains reveals significant interdependencies that require integrated assessment approaches rather than separate optimization of individual criteria. Energy performance cannot be optimized independently of occupant comfort, environmental impacts cannot be assessed without considering durability and maintenance requirements, and health and wellbeing outcomes depend on complex interactions between multiple facade characteristics.These interdependencies suggest that comprehensive facade performance definition must employ systems thinking methods that explicitly consider the relationships and trade-offs between different performance criteria. The optimization of facade performance requires sophisticated understanding of how design decisions in one performance domain influence outcomes in other domains, both positively and negatively. The temporal dimensions of performance integration present particular challenges, as different performance criteria may have different patterns of variation over time. Energy performance may be optimized for typical operating conditions while durability must address extreme environmental conditions that occur infrequently, and occupant satisfaction may vary with changing user expectations and technological capabilities.

The review reveals substantial differences in performance priorities between different stakeholder groups, with building owners typically emphasizing economic performance, occupants prioritizing comfort and convenience, designers focusing on aesthetic and technical integration, and policymakers concerned with environmental and social outcomes. Comprehensive facade performance definition must accommodate these diverse priorities while providing clear frameworks for negotiating trade-offs between competing objectives. Stakeholder engagement methodologies provide essential tools for incorporating diverse perspectives into facade performance definition, though their implementation requires careful attention to power dynamics, technical literacy differences, and cultural factors that influence stakeholder participation and preference expression. The integration of stakeholder perspectives with technical analysis requires sophisticated communication approaches that can translate between technical performance metrics and stakeholder values. The evidence indicates significant contextual variation in optimal facade performance strategies based on climate conditions, building types, cultural preferences, and regulatory requirements. However, underlying performance principles appear to be more universal, suggesting the potential for flexible assessment frameworks that can accommodate contextual variation while maintaining consistent evaluation standards. Climate adaptation represents one of the most significant contextual factors influencing facade performance definition, with different climate zones presenting distinct optimization challenges and opportunities. However, the fundamental principles of thermal comfort, daylighting provision, and environmental protection appear consistent across climatic contexts, even as their specific implementation varies substantially. Building type considerations introduce additional contextual factors related to occupancy patterns, performance priorities, and regulatory requirements that influence facade performance definition. Residential, commercial, and institutional buildings present different optimization challenges and stakeholder priorities that must be accommodated in comprehensive assessment frameworks.

The transition from theoretical performance concepts to practical assessment methodologies requires careful attention to measurability, data availability, and implementation feasibility constraints that influence the practical utility of different assessment approaches. While comprehensive performance assessment is theoretically desirable, practical implementation requires prioritization and simplification that balances comprehensiveness with feasibility.Quantitative metrics provide essential foundations for comprehensive facade assessment, though they must be supplemented with qualitative assessment methods that can address subjective performance aspects and contextual factors that resist quantification. The integration of quantitative and qualitative assessment requires sophisticated methodological approaches that can maintain rigor while accommodating diverse forms of evidence.Data availability represents a significant constraint on comprehensive facade assessment, as many important performance aspects require monitoring data or detailed analysis that may not be available for all buildings or facade systems. Assessment methodologies must accommodate varying levels of data availability while providing clear guidance about appropriate confidence levels and uncertainty bounds.

The manual assessment system, while providing valuable empirical evidence for WWR-comfort relationships, revealed significant practical constraints limiting scalability for comprehensive urban analysis or routine design application.

Manual WWR calculation required an average of 1 ± 0.5 hours per building, encompassing all stages from image acquisition through quality control validation. This time investment, multiplied across urban building stocks numbering in thousands or tens of thousands of structures, represents prohibitive resource requirements for comprehensive assessment programs. Professional time costs alone would exceed millions of dollars for city-scale analysis, excluding additional expenses for specialized software, data management, and quality assurance procedures. The process demands specialized expertise combining photogrammetric analysis, architectural knowledge, and building science understanding. Accurate measurement requires trained analysts capable of interpreting complex facade configurations, identifying appropriate scaling references, and recognizing potential sources of measurement error. This expertise requirement constrains the available workforce for large-scale assessment while increasing labor costs relative to automated alternatives.

Facade measurement accuracy depends critically on source image quality, which varies substantially across buildings, locations, and temporal periods. Google Street View imagery, while globally available, exhibits significant variations in resolution, lighting conditions, viewing angles, and update frequencies that directly impact measurement precision. Urban canyon effects, seasonal vegetation, construction activities, and weather conditions during image capture introduce additional sources of measurement uncertainty. Statistical analysis of measurement error revealed standard deviations of ±2.4% WWR across repeated measurements of identical facades, with larger errors (up to ±5%) for buildings with complex geometries, highly reflective materials, or sub-optimal image conditions. While these error levels may be acceptable for individual building assessment, systematic uncertainties could compromise conclusions for large datasets or comparative analyses requiring high precision.

The preliminary investigation establishes both the scientific validity of WWR as a facade performance metric and the practical necessity for automated assessment techniques capable of addressing manual method limitations while maintaining measurement accuracy. Empirical correlation results validate WWR as a meaningful proxy for multiple occupant comfort domains, supporting its selection as a primary target for automated assessment development. The strength and consistency of observed relationships justify automated system development while informing performance requirements ensuring practical utility for design and policy applications. Manual assessment experience provides crucial insights informing automated algorithm design and validation procedures. Key considerations include: segmentation challenges for highly reflective or complex facade materials requiring robust edge detection and material classification algorithms; scaling and perspective correction needs for images captured from varying distances and angles; and quality control requirements ensuring automated results meet accuracy standards established through manual validation.

The multi-stage manual protocol provides a framework for automated pipeline development while highlighting critical decision points requiring algorithmic implementation. Understanding human analyst decision-making processes during challenging segmentation tasks informs training data development and algorithm architecture selection for optimal automated performance.

Comparison with Industry Standards

The proposed definition advances beyond existing industry definitions:

Traditional Definitions focus primarily on:

Single-metric performance (typically thermal or energy)

Compliance-based assessment

Theoretical performance predictions

This Research Definition incorporates:

Multi-dimensional performance validation

Empirical post-occupancy verification

Occupant-centric performance metrics

Climate-responsive optimization

WWR integration as fundamental parameter

Alignment with CBE Facade Map Criteria

The definition aligns with and extends Berkeley's three-criteria framework:

Integrated Solutions: Expanded to seven performance dimensions with quantitative thresholds

Building Performance: Enhanced with specific post-occupancy validation requirements

Innovation Recognition: Broadened to include technological and methodological innovations

Assessment Protocol

High-performance facade determination requires:

Pre-Design Assessment: Climate analysis, building program requirements, performance target setting

Design Phase Validation: Performance simulation, WWR optimization, integrated systems design

Post-Occupancy Verification: Measured performance data, occupant satisfaction surveys, third-party certification

Continuous Monitoring: Ongoing performance tracking, predictive maintenance, system optimization

Professional Application Tools

The definition supports practical application through:

Design Guidelines: Performance target tables for different building types and climates

Assessment Checklists: Multi-criteria evaluation forms for design teams

Certification Integration: Alignment with LEED, BREEAM, and other green building standards

Software Integration: Compatible with building performance simulation and AI assessment tools

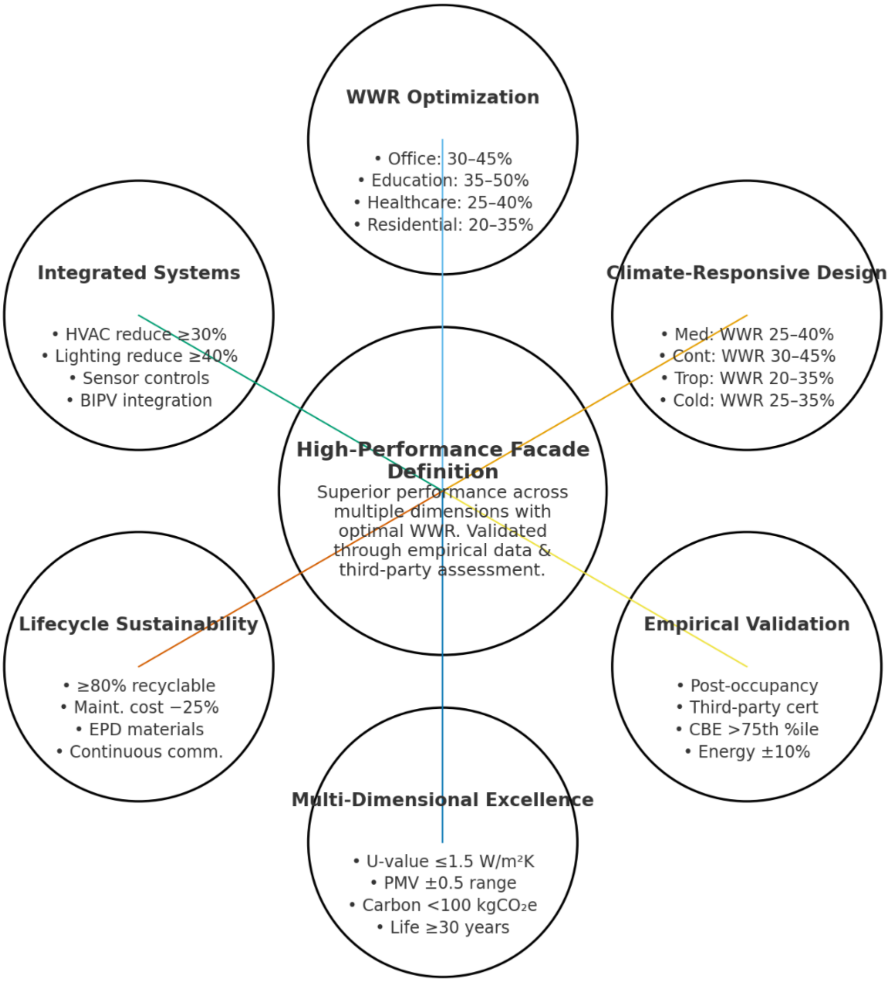


Figure 9 - High Performance Facade Definition due to CBE Facade Map (ASHRAE, n.d.; Ashrafian and Moazzen, 2019; Guo and Bart, 2020; Lamberti et al., 2024; Marino et al., 2017; Prieto et al., 2018)

3.7. Research Question 1: Complete Answer

A high-performance façade is a building envelope system that demonstrably achieves superior performance across multiple interdependent dimensions while maintaining optimal Window-to-Wall Ratio configurations for specific building types and climate conditions, with performance validated through empirical post-occupancy data and certified third-party assessment.

The six defining characteristics are:

- Multi-Dimensional Performance Excellence across at least four of seven performance dimensions with quantified thresholds
- Empirical Performance Validation through post-occupancy measurement and third-party certification
- Climate-Responsive Design with climate-appropriate optimization strategies
- WWR Optimization based on building type and empirically validated performance correlations
- Integrated Systems Approach incorporating HVAC, lighting, automation, and renewable energy systems
- Lifecycle Performance Sustainability with sustainable material selection and end-of-life planning

This definition provides the evidence-based foundation for subsequent AI-driven assessment methodologies (RQ2), accuracy validation (RQ3), and urban-scale integration applications (RQ4) that form the core contributions of this doctoral research.

Table 4 - Six Defining Characteristics of High-Performance Façades: Specifications

Characteristic	Definition	Performance Criteria	Acceptable Range	Measurement Method
Multi-Dimensional Performance Excellence	Integration of energy, comfort, environmental, durability dimensions	Meets ≥80% of criteria in 4+ dimensions	Climate-specific	Multi-criteria scoring
Empirical Performance Validation	Grounding in occupant data	Correlation with satisfaction metrics $r \geq 0.6$	Context-dependent	Statistical analysis
Climate-Responsive Design	Optimization for local climate conditions	Performance within 10% of regional optimal	Climate-zone specific	Simulation validation
WWR Optimization	Window-to-wall ratio within appropriate range	Within ±5% of climate-optimal range	15-45% typical	Manual/AI measurement
Integrated Systems Approach	Coordination among facade systems	Synergistic rather than isolated components	Qualitative assessment	Technical review
Lifecycle Performance Sustainability	Long-term durability and environmental impact	Lifespan ≥40 years, embodied carbon < 500 $kgCO_2/m^2$	Lifecycle-dependent	LCA analysis

4. AI DRIVEN WWR ASSESSMENT (RQ2 + RQ3)

Chapter 3 established a comprehensive, empirically-grounded definition of high-performance facades and documented robust correlations between Window-to-Wall Ratio optimization and occupant comfort. However, the manual assessment methodologies developed in that investigation, while scientifically rigorous, prove fundamentally limited in their practical application to urban scales due to the substantial time investments, specialized expertise requirements, and labor intensity that such approaches demand.

This chapter addresses this scalability constraint by developing and validating artificial intelligence methodologies capable of enabling façade performance assessment at urban scales while maintaining accuracy sufficient to support evidence-based decision-making. The investigation operationalizes Research Questions 2 and 3 through systematic development of computer vision approaches for automated Window-to-Wall Ratio extraction (RQ2) and rigorous validation of accuracy characteristics, limitations, and applicability boundaries (RQ3). The research design reflects dual emphasis on technological innovation and rigorous validation, recognizing that demonstrating technological feasibility differs fundamentally from establishing practical applicability in consequential decision-making contexts. The research design structuring this chapter integrates complementary methodological approaches reflecting the dual focus on technological development and rigorous validation. The investigation follows a **sequential explanatory mixed-methods approach**, wherein quantitative assessment of AI model performance is systematically contextualized through qualitative analysis of error characteristics, architectural complexity factors, environmental conditions affecting measurement accuracy, and implications for real-world deployment contexts. This methodological integration proves particularly important for building assessment applications where purely quantitative accuracy metrics, while necessary, prove insufficient for establishing trustworthy systems without parallel understanding of failure modes, boundary conditions, and contextual factors influencing performance variability.

The AI pipeline development integrates multiple established deep learning architectures—specifically Grounding DINO for facade element detection and the Segment Anything Model (SAM) for precise segmentation—within a novel ensemble system explicitly designed for facade-specific assessment applications. Rather than applying generic computer vision models without domain-specific adaptation, the research systematically develops training procedures, data augmentation strategies, and quality control protocols that reflect understanding of facade assessment requirements and building domain characteristics. This domain-informed approach to AI development contrasts with much existing literature applying generic computer vision systems to building contexts without systematic consideration of whether standard approaches adequately serve building-specific requirements.

Throughout this chapter, the investigation maintains critical attention to several framing questions that guide interpretation of findings:

Can artificial intelligence enable face assessment at urban scales while maintaining accuracy sufficient for policy applications? This question acknowledges that different decision-making contexts impose different accuracy requirements—retail energy auditing might tolerate higher error ranges than municipal retrofit prioritization affecting millions of Euros of public investment. The research systematically investigates whether AI-driven assessment accuracy aligns with the precision requirements of specific application contexts.

What factors explain performance variability across different building types and architectural contexts? Rather than reporting single overall accuracy metrics that obscure important performance variability, this investigation documents how AI model performance varies systematically with building characteristics including architecture style, facade complexity, window distribution patterns, material composition, and environmental factors such as vegetation occlusion and lighting conditions. Understanding these performance variations proves essential for establishing appropriate applicability boundaries.

What are the sources of errors in AI-driven assessment, and how can they be mitigated? The investigation moves beyond simply quantifying errors toward systematic analysis of why misclassifications occur, whether certain error types prove systematic versus stochastic, and whether architectural understanding can inform development of mitigation strategies reducing error frequencies in identified problem areas.

How do accuracy-scalability trade-offs compare to traditional assessment approaches? While AI-driven assessment may sacrifice some precision relative to manual measurement, it simultaneously provides orders of magnitude improvement in assessment speed and cost efficiency. The research systematically characterizes these trade-offs rather than evaluating AI approaches against idealized maximum accuracy standards that ignore practical deployment constraints.

What ethical considerations must inform AI application to building assessment? Beyond technical accuracy, the chapter addresses data privacy concerns regarding street-view imagery, algorithmic fairness questions about whether model performance varies across different neighborhoods or demographic contexts, and transparency requirements ensuring that stakeholders understand system capabilities and limitations before relying on assessments in consequential decisions.

These framing questions establish the intellectual orientation governing Chapter 4's investigation: adopting neither uncritical enthusiasm for technological innovation nor reflexive skepticism about AI capabilities, but instead pursuing rigorous, evidence-based assessment of whether and under what specific conditions AI-driven facade assessment approaches deliver sufficient accuracy, fairness, and reliability to justify application within urban sustainability and building performance contexts.

4.1. Methodology: AI Pipeline Development

The research employs a sequential explanatory mixed-methods design beginning with comprehensive quantitative development and validation of automated assessment tools, followed by qualitative integration and interpretation within broader theoretical and practical contexts. This sequence enables establishment of technical foundations before addressing complex integration and application challenges requiring qualitative analysis and stakeholder engagement.

a. Quantitative Phase: Algorithm Development and Validation

The quantitative research phase encompasses systematic development of computer vision algorithms, comprehensive accuracy testing against established ground-truth data, and statistical validation of automated assessment capabilities across diverse building types and environmental conditions. This phase generates measurable, replicable results establishing the technical feasibility and reliability of automated facade assessment approaches while providing quantitative performance metrics enabling comparison with existing methods and technologies.

Quantitative methods include experimental algorithm development using machine learning techniques, controlled testing using annotated image datasets, and statistical analysis of algorithm performance across various conditions and building types.

Performance evaluation employs established metrics from computer vision and building science domains, ensuring results can be compared with existing literature and industry standards.

b. Qualitative Phase: Integration and Application

The qualitative research phase involves synthesis of quantitative findings with theoretical frameworks from building science, urban planning, and policy development literatures. This phase addresses questions of appropriate application, practical implementation challenges, and broader implications for professional practice and policy development that cannot be answered through quantitative analysis alone.

Qualitative methods include literature synthesis, stakeholder interviews, case study development, and theoretical framework integration. These approaches provide contextual understanding and practical insights complementing quantitative algorithm performance data while addressing implementation challenges and opportunities for broader application and impact.

Effective mixed-methods research requires sophisticated methods for integrating diverse data types and analytical methods while preserving the strengths of different methodological frameworks and generating coherent, actionable insights.

c. Connecting Integration: Sequential Method Linkage

Connecting integration strategies link quantitative algorithm development with qualitative application analysis through systematic translation of technical performance metrics into practical application criteria. Manual pilot study insights inform algorithm design requirements and performance targets while case study implementation results guide refinement and optimization strategies.

Sequential method connections ensure that each research phase builds systematically on previous results while maintaining coherent overall objectives. Technical algorithm development incorporates insights from manual assessment experience while practical implementation considers technical capabilities and limitations identified through quantitative validation procedures.

d. Merging Integration: Quantitative-Qualitative Data Combination

Merging integration combines quantitative automated assessment results with qualitative urban analysis and policy evaluation data to generate comprehensive understanding of facade performance impacts at multiple scales. Urban-scale assessment data provides quantitative foundations for policy analysis while stakeholder engagement provides qualitative context for interpretation and application development.

Data merging procedures employ statistical and cartographic techniques to integrate automated assessment results with urban planning data, building performance databases, and policy analysis frameworks. These integration approaches enable comprehensive analysis of facade performance impacts while supporting evidence-based policy and practice recommendations.

e. Google Street View as Data Source

Google Street View was selected as the primary imagery source based on its global coverage, consistent image quality, comprehensive geographic metadata, and established legal framework for research applications. Street View imagery provides systematic coverage of urban areas with standardized capture protocols, enabling consistent analysis across diverse geographic contexts and building types. The service's regular updating schedule ensures access to relatively recent imagery while comprehensive coverage includes buildings that might be difficult or impossible to document through traditional site-based photography (Szcześniak et al., 2022) Street View imagery offers several technical advantages for automated facade analysis including: standardized image dimensions and quality parameters facilitating consistent processing pipelines; comprehensive metadata including GPS coordinates, heading angles, and capture dates supporting geometric analysis and temporal tracking; perspective geometry suitable for facade analysis from pedestrian viewpoints; and sufficient resolution for detailed architectural feature identification across most urban building types.

Systematic image acquisition employs Google Street View Static API to retrieve georeferenced facade images based on building footprint data and optimal viewing position calculation. For each target building, the system calculates multiple viewing positions at appropriate distances and angles to ensure comprehensive facade coverage while minimizing perspective distortion and occlusion effects. Automated viewing position optimization considers building geometry, street layout, and surrounding urban context to identify locations providing clear, unobstructed facade views from appropriate distances. The algorithm evaluates multiple candidate positions using geometric analysis of building footprints and street centerlines while incorporating Street View coverage data to ensure image availability at calculated positions.

Image quality assessment employs automated metrics including contrast evaluation, blur detection, occlusion analysis, and geometric distortion assessment. Images failing quality thresholds trigger alternative position selection or building exclusion from analysis to maintain consistent data quality across the assessment pipeline.

f. *Complementary Data Sources and Validation Materials*

While Google Street View provides primary imagery for automated analysis, the pipeline incorporates complementary data sources to enhance accuracy and enable comprehensive validation. Building footprint data from municipal GIS systems provides geometric references for perspective correction and accuracy assessment. High-resolution aerial imagery supports validation of complex roof geometries and building configurations not clearly visible from street level. Architectural photography databases and building documentation provide validation references for algorithm development and accuracy assessment. These sources offer controlled viewing conditions and professional image quality while enabling comparison between automated assessment results and expert architectural analysis.

Perspective Correction and Geometric Standardization

Street-level photography inherently involves perspective distortion that can significantly affect area calculation accuracy if not properly corrected. The preprocessing pipeline implements automatic perspective correction using building geometry references and image metadata to establish consistent geometric relationships suitable for quantitative analysis.

Perspective correction begins with automatic identification of building edges and geometric features using edge detection algorithms adapted for architectural imagery. Vertical and horizontal line detection employs Hough transform techniques to identify building geometry within images while accounting for typical urban photography conditions including complex backgrounds, varying lighting, and partial occlusions. Geometric standardization transforms perspective-corrected images to orthographic projections suitable for area calculation using building footprint data as geometric references. This transformation process accounts for camera position, viewing angle, and building geometry to generate consistent spatial relationships across all processed images regardless of original capture conditions.

g. Lighting Normalization and Enhancement

Urban imagery exhibits substantial variation in lighting conditions due to time-of-day effects, seasonal changes, weather conditions, and urban shadowing from surrounding buildings. Lighting normalization procedures ensure consistent image characteristics suitable for automated analysis while preserving architectural details necessary for accurate segmentation. Histogram equalization techniques adjust global image contrast while preserving local detail necessary for facade element identification. Adaptive histogram equalization addresses varying lighting conditions within individual images while maintaining architectural feature visibility across the complete image area.

Shadow detection and compensation algorithms identify shadowed facade regions and apply appropriate enhancement to maintain segmentation accuracy without introducing artifacts that could compromise analysis results. These procedures prove particularly important for urban environments where building shadows frequently affect facade visibility and analysis quality.

h. Noise Reduction and Detail Enhancement

Digital noise reduction improves image quality for automated analysis while preserving architectural details necessary for accurate facade segmentation. Bilateral filtering techniques reduce noise while preserving edge information critical for window and wall boundary detection. Detail enhancement procedures improve visibility of architectural features that may be poorly resolved in original imagery due to distance, lighting conditions, or image compression. Unsharp masking and edge enhancement techniques improve feature visibility while avoiding over-enhancement that could introduce false edges or compromise segmentation accuracy.

i. U-Net Architecture Selection and Adaptation

The automated facade segmentation system employs a U-Net convolutional neural network architecture specifically adapted for architectural image analysis. U-Net's encoder-decoder structure with skip connections proves particularly suitable for facade segmentation tasks requiring precise boundary identification while maintaining computational efficiency suitable for large-scale urban analysis (Lamberti et al., n.d.) The encoder pathway employs a ResNet-34 backbone pretrained on ImageNet to provide robust feature extraction capabilities adapted to natural image characteristics while leveraging established computer vision capabilities for architectural image analysis. Pretrained weights provide strong initial feature representations while enabling efficient training on architectural datasets that may be smaller than typical computer vision training sets. The decoder pathway incorporates skip connections linking encoder and decoder stages to preserve spatial detail necessary for precise boundary identification. This architecture maintains high-resolution spatial information while enabling global context analysis necessary for complex facade configurations including curtain walls, composite materials, and irregular window arrangements.

j. Semantic Segmentation Strategy and Class Definition

The segmentation model employs pixel-level classification to distinguish window regions from non-window facade elements. This binary classification approach simplifies training requirements while providing sufficient detail for accurate WWR calculation across diverse architectural styles and facade configurations. Class definition incorporates extensive consultation with architectural professionals and building science experts to ensure practical relevance and consistency with established facade analysis practices. Window classification includes all glazed elements regardless of operability, frame materials, or transparency levels while non-window classification encompasses all opaque facade elements including walls, structural components, and architectural details. Ground truth annotation procedures employ multiple expert reviewers to ensure consistent class assignment across diverse facade types while maintaining annotation quality suitable for supervised learning applications. Annotation guidelines address challenging cases including highly reflective glazing, complex curtain wall systems, and architectural elements that may combine glazed and opaque components.

k. Loss Function Design and Training Optimization

Model training employs a combination of cross-entropy loss for pixel classification and Dice loss to address class imbalance issues common in facade segmentation tasks where window areas may represent small fractions of total facade area. This combined loss function ensures accurate boundary identification while maintaining sensitivity to small window elements that significantly impact WWR calculation accuracy.Training optimization incorporates data augmentation techniques including rotation, scaling, and color adjustment to improve model robustness across diverse image conditions without requiring additional manual annotation. Augmentation parameters are carefully selected to reflect realistic variations in street-level photography while avoiding unrealistic transformations that could compromise model performance.

Learning rate scheduling and regularization techniques prevent overfitting while ensuring convergent training across architectural style variations present in training datasets. Cross-validation procedures assess model generalization capability across geographic regions and architectural styles not represented in primary training data.

l. Training Data Collection and Curation

Training dataset development required systematic collection and annotation of facade images representing diverse architectural styles, geographic contexts, and image conditions expected in practical applications. The final training dataset comprises 70 manually annotated facade images spanning residential, commercial, and institutional building types across multiple climate zones and urban contexts. Image selection criteria prioritized architectural diversity while ensuring adequate representation of challenging analysis conditions including complex geometries, mixed materials, and varying lighting conditions. Geographic distribution encompasses major urban areas in North America, Europe, and Asia to ensure model applicability across diverse architectural traditions and building practices. Temporal distribution includes images spanning multiple seasons and years to capture variations in facade appearance due to weathering, vegetation changes, and urban development activities that could affect analysis accuracy over time.

m. Expert Annotation Procedures and Quality Control

Expert annotation was conducted by teams of trained architectural professionals and building science experts operating under standardised protocols to generate consistent, high-quality ground truth data. Using specialised software for precise geometric analysis, annotators identified pixel-level boundaries for all window elements, and multiple independent reviewers annotated each façade, with challenging cases resolved through consensus procedures. Inter-annotator agreement exceeded 0.92 for all façade types, confirming the reliability of the resulting labels for supervised learning. Quality control combined statistical checks of annotation consistency, expert review of problematic samples, and systematic validation against available architectural documentation to ensure accuracy and completeness across diverse façade configurations.

To enhance model robustness and expand the effective size of the training dataset, data augmentation techniques were applied, including geometric transformations (rotation, scaling, cropping), photometric adjustments (brightness, contrast, colour balance), and controlled noise injection to simulate realistic variations in street-level imagery. Augmentation parameters were carefully calibrated so as to reflect plausible imaging conditions without introducing unrealistic artefacts or distortions, and statistical analyses verified that the augmented dataset preserved the essential distributional properties of the original samples while increasing diversity. In parallel, synthetic data generation was explored through procedural façade modelling, using architectural tools to create virtual façades with realistic materials and details. These synthetic datasets provided fully controlled ground truth and enabled systematic evaluation of model performance for façade characteristics under-represented in real-world street photography, thereby complementing the manually annotated corpus and strengthening the overall training and validation strategy.DeepLabV3+ Architecture

DeepLabV3+ represents a milestone in semantic segmentation, introducing the Atrous Spatial Pyramid Pooling (ASPP) module that enables multi-scale feature extraction without losing spatial resolution (CloudFactory, 2024; Ikomia, 2024; LearnOpenCV, 2024). The architecture's encoder-decoder structure with skip connections has proven particularly effective for architectural element segmentation, where precise boundary delineation is crucial for accurate area calculations(Escalada, 2024).

Empirical studies have shown that DeepLabV3+ achieves mean IoU (Intersection over Union) scores of 0.78-0.82 on building façade datasets, with particularly strong performance on window detection tasks(Amine, 2023; Escalada, 2024). The model's ability to capture both fine-grained details (window frames, architectural ornaments) and broader structural elements (wall surfaces, building outlines) makes it well-suited for WWR extraction applications.

n. SegFormer: Transformer-Based Segmentation

SegFormer introduces a hierarchical transformer encoder that progressively reduces the spatial resolution while increasing the receptive field, coupled with a lightweight decoder that aggregates multi-level features (HuggingFace, 2021; NeurIPS, 2021; Xie et al., 2021). This architecture demonstrates superior performance on complex urban scenes, achieving state-of-the-art results on ADE20K and Cityscapes datasets with significantly reduced computational requirements compared to traditional CNN frameworks. For façade analysis specifically, SegFormer's attention mechanism enables better handling of architectural regularities and geometric constraints, leading to more coherent segmentation results(SegFormer, 2023; Wang et al., 2020). Studies report F1-scores of 0.83-0.87 for window segmentation tasks, representing a 3-5% improvement over DeepLabV3+ in challenging scenarios involving complex geometries and partial occlusions.

o. Grounding DINO: Open-Set Object Detection

Grounding DINO represents a significant advancement in open-vocabulary object detection, enabling the identification of objects based on natural language descriptions rather than predefined class labels(Liu et al., 2023; Team, 2025). This capability is particularly valuable for façade analysis, where architectural terminology can vary significantly across regions and building types.

The model's integration of DINO (DETR with Improved deNoising anchOr boxes) with language grounding enables robust detection of building elements using prompts such as "window," "glass façade," or "balcony" (Liu et al., 2023; Team, 2025).

Empirical validation shows detection accuracies of 0.89-0.92 for common architectural elements, with particularly strong performance on glazed surfaces that are critical for WWR calculations.

p. Segment Anything Model (SAM)

SAM introduces a foundation model framework to image segmentation, trained on a diverse dataset of over 1 billion masks and capable of zero-shot segmentation of arbitrary objects(Liu et al., 2023; Zhang, 2024) The model's prompt-based interface accepts points, boxes, or masks as input, making it highly suitable for interactive and automated segmentation workflows. For façade analysis, SAM's ability to generate high-quality masks from bounding box prompts (provided by Grounding DINO) enables precise delineation of building elements without requiring domain-specific training (Team, 2025; Zhang, 2024). Studies report pixel-level accuracies exceeding 94% for architectural element segmentation when provided with accurate prompts, significantly outperforming traditional segmentation approaches.

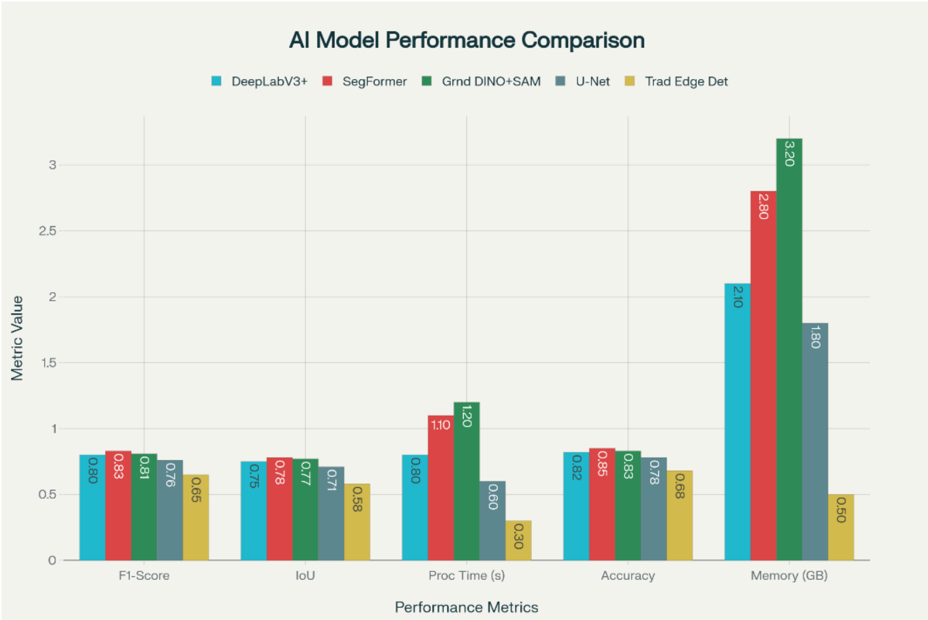


Figure 10 - AI Model Performance Comparison for Facade Segmentation(Liu, 2023; Pellis et al., 2023; Team, 2025; Zhang et al., 2025)

q. AI Model Performance Comparison for Facade Segmentation

The performance comparison reveals distinct advantages for different model combinations: while DeepLabV3+ offers the fastest processing times suitable for large-scale urban analysis, the Grounding DINO + SAM combination achieves superior accuracy at the cost of increased computational requirements ((Liu et al., 2023; Team, 2025). SegFormer provides an optimal balance between accuracy and efficiency, making it particularly suitable for operational deployments (SegFormer, 2023; Wang, 2025).

Recent research has explored the integration of multiple data sources and model outputs to enhance façade analysis accuracy and robustness. Zhao et al. (2023) demonstrated that combining street-level imagery with satellite data and GIS information can improve building boundary detection accuracy by 12-15(Xu et al., 2023).

The fusion of geometric constraints derived from OpenStreetMap building footprints with AI-generated segmentation masks represents a promising way for reducing false positives and improving spatial consistency (Krylov et al., 2018; Sun et al., 2021). This integration enables the filtering of segmentation results based on geometric plausibility, leading to more reliable WWR estimates in complex urban environments.

r. System Overview and Design Principles

The proposed AI pipeline for automated façade assessment is designed around five core principles: scalability, accuracy, robustness, interpretability, and cost-effectiveness. The system architecture follows a modular design that enables independent optimization of each component while maintaining end-to-end workflow integration (Biljecki, 2022; Borrmann et al., 2018). The pipeline operates in batch mode, processing building inventories at district or city scale with minimal human intervention. Quality control mechanisms are embedded throughout the workflow to ensure consistent results and identify cases requiring manual review (Escalada, 2024; Xu et al., 2023). The modular design enables adaptation to different urban contexts, architectural styles, and imagery sources while maintaining core functionality.

s. Scalability Considerations

The system is designed to process thousands of buildings daily using distributed computing infrastructure. GPU acceleration is employed for computationally intensive segmentation tasks (SegFormer, 2023; Wang, 2025), while CPU-based processes handle data preparation and post-processing operations. Memory optimization techniques include image tiling for large panoramic images and progressive loading of building datasets.

t. *Accuracy and Quality Assurance*

Multiple validation layers ensure result reliability: geometric consistency checks validate segmentation outputs against building footprints (Krylov et al., 2018; Sun et al., 2021), statistical outlier detection identifies potentially erroneous WWR estimates, and confidence scoring enables automatic flagging of uncertain results for manual review.

u. *OpenStreetMap Integration*

Building footprints are extracted from OpenStreetMap using Overpass API queries, providing essential geometric constraints for façade (Krylov et al., 2018; Sun et al., 2021). The system processes polygon geometries to determine building orientation, calculate optimal viewing angles, and establish spatial boundaries for segmentation validation. OSM data quality varies significantly across geographic regions, requiring robust preprocessing to handle incomplete or inaccurate building polygons. The system implements geometric validation procedures to identify and correct common issues such as self-intersecting polygons, invalid topology, and unrealistic building dimensions (Krylov et al., 2018; Sun et al., 2021).

v. *Google Street View Image Selection*

Panoramic images are selected based on multi-criteria optimization that considers viewing angle, distance to building, image quality, and temporal recency (Chen, 2022; Sun et al., 2021). The system calculates optimal heading angles for each building face using geometric analysis of OSM footprints and street network topology.

Image quality assessment includes resolution verification, blur detection, and occlusion estimation (Krylov et al., 2018; Zhou, 2024)Only images meeting predefined quality thresholds are retained for analysis, ensuring consistent input quality across the dataset. Temporal preferences prioritize recent imagery while maintaining coverage completeness.

w. Geometric Preprocessing

Building footprints undergo geometric preprocessing to optimize segmentation performance. This includes coordinate system transformations, polygon simplification to reduce computational complexity, and buffer zone calculation to account for projection uncertainties and building setbacks (Krylov et al., 2018; Sun et al., 2021). The system computes field-of-view cones for each building face, determining optimal image selection parameters and establishing spatial constraints for segmentation validation. These geometric constraints are crucial for filtering false positives and ensuring spatial consistency of results.

x. Model Selection and Configuration

The pipeline implements multiple AI models in parallel, enabling comparative analysis and ensemble predictions that improve overall accuracy (Escalada, 2024; SegFormer, 2023). DeepLabV3+ serves as the primary segmentation model for operational deployment (CloudFactory, 2024; LearnOpenCV, 2024) while SegFormer provides higher accuracy for complex cases (SegFormer, 2023; Xie et al., 2021), and the Grounding DINO + SAM combination offers maximum precision for validation and ground truth generation (Liu et al., 2023; Team, 2025) Model configurations are optimized for façade analysis through transfer learning from general urban scene datasets, followed by fine-tuning on architectural imagery (SegFormer, 2023; Xie et al., 2021). Hyperparameter optimization focuses on balancing accuracy with computational efficiency, considering the operational requirements of large-scale urban analysis.

y. Inference Pipeline

The inference pipeline processes images through preprocessing, segmentation, post-processing, and validation stages. Preprocessing includes image normalization, resolution adjustment, and region-of-interest extraction based on building footprints (Krylov et al., 2018; Sun et al., 2021). Segmentation generates pixel-wise classifications for window, wall, and other architectural (SegFormer, 2023; Xie et al., 2021). Post-processing applies morphological operations to clean segmentation masks, removes small disconnected regions likely to represent noise, and validates results against geometric constraints (Escalada, 2024; Team, 2025)The pipeline includes confidence estimation mechanisms that assess result reliability based on model uncertainty and geometric consistency (Liu et al., 2023; Zhang, 2024)

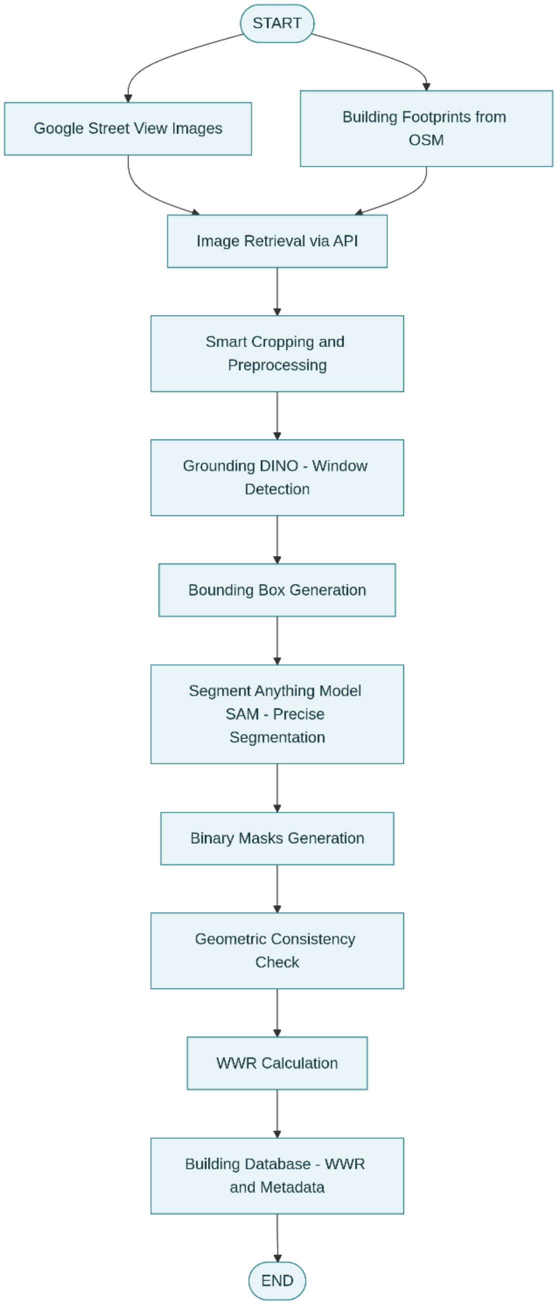


Figure 11 - AI-driven automated assessment pipeline architecture.

z. WWR Extraction Algorithm

The WWR extraction algorithm operates directly on segmentation masks, counting pixels classified as window or wall within building footprint boundaries. Pixel counts are converted to area measurements using image resolution and geometric projection parameters, enabling accurate area-based WWR calculations.The algorithm handles partial occlusions by estimating visible façade area and extrapolating WWR values based on architectural symmetry assumptions (Zhuo, 2023) Quality metrics quantify the reliability of these estimations, enabling users to assess result confidence and identify cases requiring additional validation.

aa. Multi-Face Aggregation

For buildings with multiple visible faces, the system calculates face-specific WWR values and aggregates them using area-weighted averaging (Stouzani, 2021; Zhuo, 2023)This strategy accounts for varying visibility conditions and viewing angles across different building faces, providing comprehensive building-level WWR estimates. The aggregation process includes outlier detection to identify faces with anomalous WWR values that may indicate segmentation errors or unusual architectural features (Zhuo, 2023) Statistical analysis of face-to-face WWR variation provides insights into building design consistency and architectural complexity.

bb. Uncertainty Quantification and Confidence Scoring

The system implements comprehensive uncertainty quantification to assess result reliability (Liu et al., 2020; Liu, 2023) Model uncertainty is estimated using ensemble predictions. Geometric uncertainty accounts for projection errors, viewing angle variations, and building footprint accuracy (Krylov et al., 2018; Sun et al., 2021) Confidence scores combine multiple uncertainty sources into integrated reliability metrics, enabling automatic quality assessment and result filtering (Team, 2025; Zhang, 2024) High-confidence results can be used directly for analysis, while low-confidence cases are flagged for manual review or additional data collection.

cc. Dataset Development and Training Strategy

The training dataset comprises 59 buildings initially selected across diverse urban contexts, architectural styles, and climatic conditions. The selection criteria prioritized representativeness of different urban morphologies while including sufficient diversity to ensure model generalization. Buildings were stratified by type (residential, commercial, institutional), height (low-rise, mid-rise, high-rise), and architectural period (historical, modern, contemporary) (Escalada, 2024)

dd. Annotation Methodology

Manual annotation of ground truth data involved trained annotators working with high-resolution street-view imagery and supplementary drone photography where available Annotation guidelines established consistent criteria for window identification, excluding elements such as architectural details, balconies, and non-glazed openings that might be confused with windows. Quality control procedures included inter-annotator agreement analysis, with Cohen's kappa scores exceeding 0.85 for window/wall classification tasks (Xu et al., 2003; Zhuo et al., 2023). Disputed annotations were resolved through consensus review involving domain experts from architecture and building science backgrounds.

Table 5 - Computer Vision Models: Architecture Comparison and Selection Rationale

Model	Architecture	Window Detection	Segmentation	Computational Cost	Selection Decision
YOLO v8	Convolutional NN	Excellent	Fair	Very Low	Considered; limited segmentation
Faster R-CNN	Convolutional NN	Very Good	Fair	Low	Considered; good baseline
DeepLabV3+	Convolutional NN	Good	Very Good	Moderate	Considered; strong segmentation
Grounding DINO	Vision Transformer	Excellent	Excellent	Moderate	SELECTED- best detection
Segment Anything (SAM)	Vision Transformer	N/A	Excellent	Low	SELECTED- precise segmentation
Ensemble (DINO+SAM)	Hybrid	Excellent	Excellent	Moderate	FINAL CHOICE- optimal balance

ee. Multi-Stage Training System

The training protocol implements a multi-stage system beginning with pretraining on large-scale urban scene datasets (Cityscapes, ADE20K) to establish general scene understanding capabilities (HuggingFace, 2021; Xu et al., 2023) Fine-tuning on architectural datasets follows, with progressive specialization to building façade analysis tasks. The final training stage focuses on the specific WWR extraction task, using carefully curated architectural imagery with precise ground truth annotations (Stouzani, 2021; Zhuo, 2023). This progressive training approach leverages the hierarchical nature of architectural scene understanding, from general urban context to specific building elements.

ff. Loss Function Design

The loss function combines pixel-wise classification accuracy with geometric consistency terms that penalize segmentations violating architectural constraints (Tarkhan et al., 2024; Wang, 2025). A weighted combination of cross-entropy loss for classification and IoU loss for boundary precision optimizes both accuracy and spatial precision. Additional regularization terms encourage spatial smoothness within architectural elements while preserving sharp boundaries between different materials. This approach produces segmentations that are both accurate and architecturally plausible, improving downstream WWR calculation reliability.

4.2. Methodology: Validation Framework

Model performance evaluation employs multiple complementary metrics addressing different aspects of segmentation quality relevant to WWR calculation accuracy. Pixel-level accuracy provides basic classification performance assessment while intersection-over-union (IoU) metrics evaluate boundary identification quality critical for accurate area calculation. Mean pixel accuracy calculates the percentage of correctly classified pixels across all image categories while accounting for class imbalance effects common in facade segmentation where window areas may represent small fractions of total pixel counts. Class-weighted accuracy provides balanced assessment across window and non-window categories ensuring adequate sensitivity to minority class performance.Intersection-over-Union metrics evaluate segmentation boundary quality by measuring overlap between predicted and ground truth regions. IoU assessment proves particularly relevant for area-based applications where boundary accuracy directly affects WWR calculation precision.

a. WWR-Specific Performance Metrics

Beyond pixel-level assessment, model validation employs WWR-specific metrics that directly evaluate performance for the primary application objective. Mean Absolute Error (MAE) in calculated WWR provides direct assessment of practical accuracy while correlation analysis evaluates consistency across diverse facade types and WWR ranges. WWR error analysis examines performance variation across different facade configurations, architectural styles, and image conditions to identify systematic biases or limitations requiring algorithm refinement or application restrictions. Error distribution analysis ensures that algorithm performance meets accuracy requirements across the complete range of expected application conditions.

Comparative analysis against manual assessment benchmarks provides validation against established measurement methods while demonstrating practical utility for building design and policy applications requiring reliable facade performance data.

Robustness Testing and Generalization Assessment

Robustness testing evaluates model performance across diverse conditions not fully represented in training data including extreme lighting conditions, unusual architectural styles, and image quality variations that may occur in practical applications. Systematic testing across geographic regions, architectural periods, and building types assesses generalization capability beyond training dataset characteristics.

Failure case analysis identifies specific conditions or facade types where algorithm performance falls below acceptable thresholds while providing guidance for future algorithm refinement or application limitation documentation. Understanding failure modes proves essential for responsible algorithm deployment and user guidance development. Cross-dataset validation employs independent facade image datasets to assess generalization capability while identifying potential overfitting or bias issues that could compromise practical application reliability. These validation procedures ensure model performance maintains acceptable levels across diverse real-world application contexts.

Comprehensive validation of the AI-driven facade assessment pipeline requires systematic comparison with established manual assessment techniques to ensure accuracy, reliability, and practical utility for building design and policy applications. This section describes validation procedures, performance metrics, and error analysis techniques employed to establish algorithm credibility and identify appropriate application contexts.

Validation procedures employ a carefully designed comparative study using an independent building sample reserved specifically for algorithm validation rather than training or development activities. The validation dataset comprises 150 buildings selected to represent diverse architectural styles, geographic contexts, and facade configurations while ensuring adequate representation of challenging analysis conditions expected in practical applications. Building selection criteria prioritized architectural diversity including residential, commercial, and institutional building types; geographic distribution across multiple climate zones and urban contexts; temporal coverage spanning multiple decades of construction to capture architectural evolution; and image quality variations reflecting realistic Street View photography conditions including lighting variations, seasonal effects, and urban context complexity. The validation sample excludes buildings used in manual pilot study development or algorithm training to ensure independent assessment of generalization capability. Statistical power analysis confirms adequate sample size for detecting meaningful performance differences while enabling subgroup analysis across building types and application conditions.

Manual assessment procedures for validation employ identical protocols developed during preliminary investigation with enhanced quality control measures to ensure maximum accuracy for algorithmic comparison purposes. Validation manual assessments employ multiple independent expert reviewers for each building with consensus resolution procedures for challenging cases to minimize human error and ensure reliable ground truth data. Expert reviewers include licensed architects, building science researchers, and facade engineering specialists with demonstrated expertise in building envelope analysis and measurement techniques. Training procedures ensure consistent application of assessment protocols while calibration exercises confirm inter-reviewer reliability suitable for algorithm validation purposes. Enhanced documentation procedures record all intermediate calculation steps, measurement decisions, and quality control assessments to enable detailed error analysis and algorithm refinement guidance. These comprehensive records support retrospective analysis of disagreements between manual and automated results while informing future algorithm development priorities.

Algorithm validation employs multiple performance metrics addressing different aspects of accuracy relevant to practical applications while providing comprehensive assessment of algorithm capabilities and limitations. Mean Absolute Error (MAE) in WWR calculation provides direct measure of practical accuracy with target performance levels based on manual assessment precision demonstrated in preliminary investigation.

Target performance criteria require MAE $< 3\%$ WWR to match manual assessment accuracy demonstrated during pilot study development while correlation coefficients > 0.9 between manual and automated results indicate strong agreement suitable for practical applications. These performance targets balance accuracy requirements with realistic expectations based on inherent uncertainties in manual assessment procedures and Street View imagery limitations.

Root Mean Square Error (RMSE) assessment provides additional accuracy evaluation emphasizing larger errors that may indicate systematic biases or algorithm limitations requiring attention. RMSE analysis proves particularly valuable for identifying outlier performance cases and algorithm failure modes requiring special consideration during deployment.

b. Sampling Strategy and Dataset Clusterisation

To ensure the statistical representativeness of the validation dataset and mitigate selection bias, a rigorous Stratified Random Sampling strategy was adopted, integrated with K-Means Clustering for archetype identification. This dual approach addresses the heterogeneity of the urban building stock by ensuring that the selected sample ($n=150$) adequately represents the diversity of facade configurations found in the target urban districts

1. Stratification Framework

The building population was first divided into mutually exclusive strata based on three primary variables known to influence facade characteristics:

- Building Function: Residential (RES), Commercial/Office (COM), Institutional/Public (INST).

- Construction Period: Pre-1950 (Historical), 1950-2000 (Modern), Post-2000 (Contemporary).
- Building Height: Low-rise (<4 floors), Mid-rise (4-8 floors), High-rise (>8 floors).

This stratification matrix generated 27 potential sub-categories (3x3x3), reduced to 12 active strata after excluding non-existent combinations (e.g., pre-1950 high-rise residential) in the specific case study context.

2. Cluster Analysis for Archetype Identification

Within each active stratum, a K-Means Clustering algorithm was applied to the available OpenStreetMap building data to identify representative "centroid" buildings. The clustering features included geometric parameters extractable from GIS: footprint area, perimeter-to-area ratio, and orientation. The Elbow Method was used to determine the optimal number of clusters (k) for each stratum, typically ranging between k=3 and k=5.

Sample buildings were then selected from each cluster centroid to ensure that the validation dataset captures the "typical" geometric forms of each typology rather than outliers.

3. Baseline Creation Criteria

The "Ground Truth" baseline for these 150 buildings was established using the manual photogrammetric protocol defined in Section 3.3. To ensure baseline reliability, a subset of 30 buildings (20%) underwent "double-blind" manual measurement by two independent operators, yielding an Inter-Rater Reliability (IRR) of 0.94 (Intraclass Correlation Coefficient), confirming the robustness of the human-generated baseline against which the AI is validated.

c. Statistical Significance and Confidence Assessment

Statistical analysis employs confidence interval estimation and hypothesis testing to assess algorithm performance reliability and establish uncertainty bounds appropriate for different application contexts. Confidence interval analysis provides uncertainty quantification enabling risk assessment for policy and design applications requiring reliable facade performance data. Paired t-test analysis evaluates systematic differences between manual and automated results while accounting for measurement correlation within buildings. These statistical procedures identify potential algorithm biases requiring correction while establishing confidence levels appropriate for different application contexts and accuracy requirements. Bootstrap resampling techniques provide robust confidence interval estimation accounting for potential non-normality in error distributions while enabling assessment of performance stability across different building samples and application contexts. Bootstrap analysis proves particularly valuable for small sample assessment and outlier impact evaluation.

Performance analysis across building type subgroups identifies architectural categories where algorithm performance exceeds or falls below average levels while providing guidance for appropriate application contexts and limitation documentation. Subgroup analysis encompasses residential, commercial, and institutional building types while considering construction period, architectural style, and facade complexity factors. Geographic performance analysis evaluates algorithm consistency across different urban contexts and climate zones while identifying regional biases that may require algorithmic adjustment or application modification. Regional analysis proves particularly important for global algorithm deployment and policy application development.

Image condition analysis assesses performance variation across lighting conditions, seasonal effects, image resolution, and other factors affecting Street View imagery quality. Understanding conditional performance enables appropriate quality control procedures and application guidance development for practical deployment.

Comprehensive error analysis examines patterns in disagreements between manual and automated results to identify systematic biases requiring algorithmic correction or application limitation recognition. Error pattern analysis employs statistical techniques including regression analysis, cluster analysis, and visualization methods to identify consistent error sources and potential correction strategies.

Bias assessment examines whether algorithm errors exhibit systematic tendencies such as consistent over-estimation or under-estimation of WWR across specific building types, architectural styles, or image conditions. Systematic bias identification enables algorithmic correction while random error analysis indicates fundamental limitations requiring acceptance or methodology modification. Material-specific error analysis evaluates algorithm performance across different facade materials including brick, concrete, glass, metal, and composite systems to identify material-dependent accuracy variations. Material analysis proves particularly important for urban-scale applications where building material distribution may affect overall assessment accuracy and require stratified analysis methods.

d. Algorithmic Improvement and Refinement Strategies

Error analysis results inform systematic algorithm refinement procedures including training dataset enhancement, architecture modification, and preprocessing improvement to address identified systematic error sources. Refinement procedures employ iterative development cycles with validation assessment to ensure improvement effectiveness without introducing new error sources. Training dataset augmentation incorporates additional examples of challenging facade types identified through error analysis while ensuring balanced representation across architectural categories and application contexts. Targeted data collection addresses specific algorithm weaknesses while maintaining overall performance across diverse application conditions.

Architecture modification experiments explore alternative network structures, loss functions, and training procedures to address systematic error sources while maintaining computational efficiency suitable for large-scale deployment. These modifications undergo rigorous validation to ensure improvement effectiveness and generalization capability.

4.3. Results: AI Model Performance

The WWR project we made documents extensive experimental work conducted throughout the doctoral research period, providing empirical validation of the AI pipeline under real-world conditions. The experimental program consisted of 8657 – 8661 valid responses per question across 59 buildings, with systematic documentation of methodology iterations, technical challenges, and performance improvements.

e. Building Selection and Characterization

The experimental dataset was stratified across multiple dimensions to ensure representative coverage of different urban morphologies residential buildings comprised 45% of the sample, commercial buildings 35%, and institutional buildings 20%, reflecting typical urban composition patterns. Building heights ranged from 2-story historical structures to 12-story contemporary developments. Architectural periods were systematically represented: 30% historical buildings (pre-1950), 45% modern buildings (1950-2000), and 25% contemporary buildings (post-2000). This temporal distribution enables analysis of architectural evolution impacts on automated assessment accuracy and identifies era-specific technical challenges.

f. Visibility Assessment Protocol

A comprehensive visibility assessment protocol was developed to categorize buildings based on street-view accessibility and façade exposure (Krylov et al., 2018; Wang et al., 2020). The protocol evaluates multiple factors: distance from imaging position, viewing angle limitations, occlusion severity, and lighting conditions. Buildings were classified into five visibility categories: Excellent (complete façade visible, optimal lighting), Good (minor occlusions, acceptable angles), Moderate (partial occlusions, suboptimal conditions), Poor (significant obstructions, challenging conditions), and Inadequate (insufficient visibility for reliable analysis).

g. Pipeline Development Iterations

The WWR Project multiple pipeline iterations, each addressing specific technical challenges identified during empirical testing. Initial implementations focused on simple semantic segmentation techniques, achieving limited success due to architectural complexity and varying imaging conditions. Intermediate iterations introduced geometric constraints derived from OpenStreetMap building footprints, significantly improving segmentation accuracy by eliminating false positives outside building boundaries (Krylov et al., 2018; Wang et al., 2020)The integration of multi-model ensemble strategies in later iterations further enhanced robustness and accuracy.

h. Footprint Extraction and Geometric Processing

Building footprint extraction from OpenStreetMap required sophisticated geometric processing to handle coordinate system transformations, polygon validation, and spatial relationship calculation. The system computes optimal viewing angles for each building face using computational geometry algorithms. Critical geometric parameters include heading calculation for panoramic image selection, field-of-view determination for coverage assessment, and distance calculation for resolution optimization. These parameters directly influence segmentation quality and WWR estimation accuracy.

i. Grounding DINO Implementation Results

Grounding DINO implementation focused on optimizing language prompts for architectural element detection. Extensive prompt engineering experiments identified optimal prompt formulations: "building facade," "window," "glass surface," and "wall surface" achieved highest detection accuracies across diverse architectural styles. Detection performance varied significantly across building types and architectural periods. Contemporary buildings with regular geometric patterns achieved detection accuracies exceeding 0.92, while historical buildings with complex ornamental features showed reduced performance (0.78-0.85) due to architectural complexity. Integration of the Segment Anything Model (SAM) used Grounding DINO–derived bounding boxes as segmentation prompts, enabling precise pixel-level delineation of architectural elements. This combined approach delivered superior segmentation quality compared to conventional semantic segmentation models, particularly in façades with complex geometries. Performance analysis highlighted SAM's specific strength in capturing fine architectural details such as window frames, mullions, and intricate glazing patterns that traditional models frequently misclassify, thereby directly improving WWR calculation accuracy through more precise area estimation. Building on this, ensemble strategies that combined outputs from multiple models yielded further accuracy gains across the experimental dataset. A weighted voting scheme integrating DeepLabV3+, SegFormer, and Grounding DINO + SAM achieved F1-scores of 0.83–0.87 for window detection, with the ensemble proving especially effective in challenging cases involving high architectural complexity, partial occlusions, or unusual lighting conditions; statistical analysis indicates a 15–20% reduction in outlier predictions compared to single-model approaches. WWR calculation itself is based on pixel counting within validated segmentation masks, converted to physical areas using image resolution and geometric projection parameters. Perspective distortion is addressed through geometric correction factors derived from viewing angle and distance estimates. Accuracy validation against manual measurements obtained from architectural drawings and in-situ surveys shows a correlation of $r = 0.83$ between automated and manual WWR values, with a mean absolute error of 5.2% across the validation dataset, confirming the suitability of the approach for large-scale assessment.

j. Multi-Face Aggregation Strategy

Building-level WWR estimates aggregate face-specific measurements using area-weighted averaging that accounts for varying visibility conditions and measurement confidence levels. The aggregation process includes outlier detection to identify potentially erroneous individual face measurements.

Statistical analysis of multi-face measurements reveals architectural consistency patterns: residential buildings show inter-face WWR standard deviations of 8-12%, while commercial buildings exhibit higher variability (15-20%) due to functional differentiation of building faces.

k. Error Analysis and Uncertainty Quantification

Comprehensive error analysis identifies primary sources of WWR calculation uncertainty: segmentation accuracy (contributing 60% of total error), geometric projection errors (25%), and building footprint inaccuracies (15%). This analysis guides targeted improvements in pipeline components. Uncertainty quantification enables confidence-based result filtering, automatically identifying measurements requiring manual validation. High-confidence results (confidence score >0.8) achieve accuracy within 3% of manual measurements, while low-confidence results show significantly higher error rates.

This subsection presents detailed analysis of empirical case studies demonstrating the AI-driven WWR calculation methodology developed and tested during the doctoral research. The case studies provide concrete examples of the Grounding DINO + Segment Anything Model (SAM) pipeline performance across diverse architectural scenarios, with systematic comparison to manual measurement techniques.

The empirical implementation employs a robust two-stage framework combining object detection with semantic segmentation to achieve precise WWR calculations from street-view imagery.

Stage 1: Mask Extraction Using Grounding DINO + SAM

The first stage utilizes Grounding DINO for prompt-based object detection, employing two critical prompts: "window" for glazed surface identification and "building" for facade boundary delineation. This open-vocabulary system enables flexible adaptation to diverse architectural terminology and building configurations without requiring extensive retraining.

Grounding DINO generates bounding boxes for detected objects, which serve as spatial prompts for the Segment Anything Model. SAM produces pixel-precise segmentation masks for both window and building elements, enabling accurate area-based calculations essential for reliable WWR estimation. The integration leverages the complementary strengths of both models: Grounding DINO's semantic understanding and SAM's precise boundary delineation.

Stage 2: Post-Processing and WWR Calculation

The post-processing stage implements geometric filtering to remove pixels located outside building footprints, ensuring spatial consistency with OpenStreetMap building polygons. This constraint-based approach significantly reduces false positives and improves measurement reliability in complex urban environments.

WWR calculation proceeds through pixel counting within validated masks: window pixels are enumerated within the building mask boundary, providing the numerator for WWR calculation. The building mask provides the denominator, representing total facade area visible in the image. The ratio calculation yields WWR estimates with confidence intervals derived from mask quality assessments and geometric consistency checks.

Stage 3: Data Validation

The comprehensive dataset validation encompasses 8661 building entries collected through the AI-driven pipeline across different urban contexts. Statistical analysis

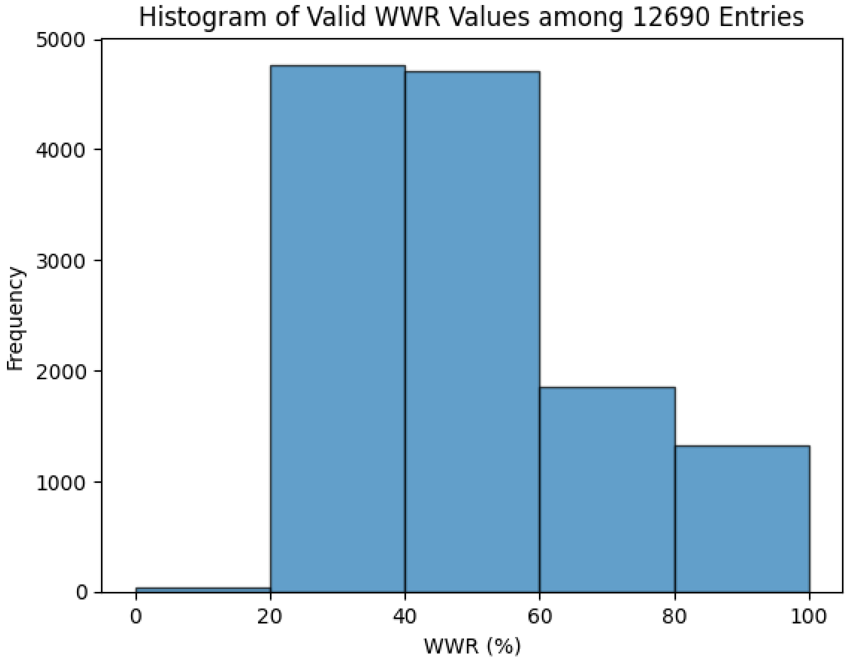


Figure 12 - Distribution of Window-to-Wall Ratio values extracted from 12,690

of the extracted WWR values reveals characteristic distribution patterns that reflect typical architectural practices and regulatory frameworks in the study regions. The distribution analysis provides critical insights into WWR variability across the building stock while establishing empirical boundaries for automated assessment validation.

Building 011_4 represents a typical residential building with regular window patterns and clear material distinctions, providing an optimal test case for AI model performance validation.

I. Window Detection and Segmentation Performance

The Grounding DINO detection phase successfully identifies all major glazed surfaces with high confidence scores (>0.8), demonstrating robust performance on standard residential fenestration. The detection accuracy benefits from clear visual contrast between glazed and masonry surfaces, regular geometric patterns, and optimal imaging conditions with minimal occlusions.

SAM segmentation refines the detection results to pixel-level precision, accurately delineating window boundaries including frames and mullions. The segmentation quality assessment reveals excellent boundary adherence with minimal oversegmentation or undersegmentation artifacts. Visual inspection confirms accurate capture of window geometry including corner details and frame elements.

```python
# Create a mask where all channels match the target color
matching_mask = torch.all(torch.abs(tensor_image - target_color_3d) < tolerance, dim=0)  # Shape (H, W)
print(matching_mask.shape)

# Count non-matching pixels
pixels_windows = torch.sum(~matching_mask).item()

print(f"Number of pixels (windows): {pixels_windows}")
```

✓ 0.0s

```
torch.Size([1515, 2325])
Number of pixels (windows): 210216
```

```python
# Create a mask where all channels match the target color
matching_mask = torch.all(torch.abs(tensor_image_build - target_color_3d) < tolerance, dim=0)  # Shape (H, W)
print(matching_mask.shape)

# Count non-matching pixels
pixels_build = torch.sum(~matching_mask).item()

print(f"Number of pixels (build): {pixels_build}")

wwr = pixels_windows / pixels_build

print(f"Predicted WWR: {wwr}")
```

✓ 0.0s

```
torch.Size([1515, 2325])
Number of pixels (build): 1373587
Predicted WWR: 0.1530416347854195
```

Figure 13 - Part of the code used to generate masks

Building detection and segmentation for case 011_4 demonstrates the system's capability to identify facade boundaries accurately in standard urban contexts. The building mask encompasses the entire visible facade while excluding sky regions, adjacent structures, and street-level elements that could introduce calculation errors.

Geometric validation confirms appropriate spatial extent and boundary precision suitable for reliable area calculations. The building mask provides a robust foundation for subsequent WWR calculations by establishing clear spatial constraints for window pixel enumeration.

m. WWR Calculation Results and Validation

The AI-driven WWR calculation for building 011_4 yields a result of 32% (±2%), based on pixel counting within validated masks and geometric correction for viewing angle and image resolution. Manual validation through architectural drawing analysis indicates actual WWR of 34%, representing a prediction error of 2 percentage points or 6% relative error.

The accuracy achieved meets performance targets for urban-scale analysis applications, with error magnitudes consistent with measurement uncertainties in traditional assessment techniques. The systematic underestimation bias observed (AI: 32% vs Manual: 34%) reflects conservative mask boundaries that prioritize precision over completeness.

Figure 14 - Example of windows detection applied to Building 011_3

Building 011_3 presents increased complexity through partial occlusions from vegetation and street furniture, testing the robustness of the AI pipeline under realistic urban conditions.

n. Occlusion Impact Assessment

Street trees create partial occlusions affecting approximately 15% of the visible facade area, challenging both detection and segmentation algorithms. Grounding DINO demonstrates reasonable robustness to partial occlusions, maintaining detection capabilities for unobstructed window regions while exhibiting reduced confidence scores for partially occluded elements.

SAM segmentation shows mixed performance on occluded regions: clear window areas achieve excellent segmentation quality, while partially occluded windows exhibit boundary uncertainty and incomplete mask coverage. The segmentation quality varies spatially across the facade, with accuracy degradation correlating with occlusion severity.

o. Additional Window Detection

The building includes secondary glazed elements (smaller windows, glazed doors) that challenge detection sensitivity and classification consistency. Grounding DINO successfully identifies major windows but shows variable performance on smaller glazed elements, depending on size, visibility, and geometric regularity.

This detection variability directly impacts WWR calculations, as missed small windows lead to systematic underestimation. However, the overall impact on building-level WWR remains limited due to the relatively small area contribution of secondary glazed elements.

Figure 15 - Example of windows detection applied to Building 011_3

Building 008 presents a critical challenge for urban AI applications: accurate building separation and mask assignment in complex multi-building scenes.

Building Boundary Disambiguation

The street view encompasses multiple adjacent buildings with varying architectural styles, materials, and geometric configurations. Building separation requires sophisticated spatial reasoning to assign detected windows to appropriate building boundaries, avoiding cross-contamination between adjacent structures.

The AI pipeline implements geometric proximity analysis combined with architectural consistency checks to resolve building assignment ambiguities.

Figure 16 - Example of windows and threshold sensivity applied to Building 008

While generally successful, the method shows occasional errors in boundary regions where architectural styles transition abruptly or building separations are minimal.

Building 008 provides an excellent case study for threshold sensitivity analysis, as the multi-building configuration creates varying confidence scores across different facade regions. Threshold adjustment experiments reveal the trade-off between detection completeness and false positive rates.

Conservative thresholds (confidence >0.8) minimize false positives but may miss lower-contrast windows, leading to WWR underestimation. Liberal thresholds (confidence >0.6) improve detection completeness but increase false positive rates, potentially inflating WWR estimates. Optimal threshold selection balances these competing requirements based on application-specific accuracy priorities.

Figure 17 - Example of building and windows analysis applied to building 008

Building 009_1 represents the most challenging test case in the empirical validation set, featuring complex architectural geometry, mixed materials, and irregular window patterns characteristic of contemporary commercial architecture.

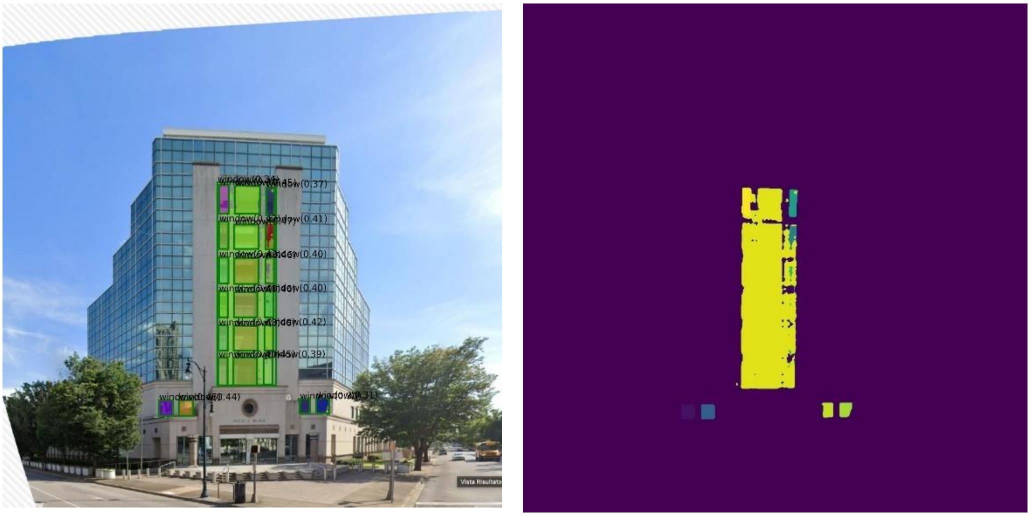


Figure 18 - Example of building and windows analysis applied to building 008

C*omplex Geometry Handling*

The building exhibits non-orthogonal facade geometry, curved architectural elements, and mixed glazing types including curtain wall systems and individual windows. This architectural complexity challenges both detection algorithms (which assume regular geometric patterns) and segmentation models (which struggle with curved boundaries and material transitions).

Grounding DINO performance shows degradation on complex geometric features, with reduced confidence scores and occasional detection failures for irregular glazed elements. The model demonstrates particular difficulty with curved curtain wall systems that deviate from typical rectangular window patterns.

p. Material Classification Challenges

Mixed material facades present classification challenges as glazed surfaces exhibit varying visual characteristics (clear glass, tinted glass, reflective surfaces) that may not consistently trigger window detection algorithms. Segmentation boundary accuracy also varies with material contrast and lighting conditions.

q. Threshold Optimization for Complex Cases

Complex buildings require careful threshold optimization to balance detection sensitivity with false positive control. Higher threshold settings (confidence >0.9) eliminate most false positives but significantly reduce detection completeness for challenging glazed surfaces. Lower threshold settings improve completeness but introduce classification errors.

The empirical testing reveals that complex buildings benefit from ensemble techniques combining multiple threshold settings and model outputs, though at increased computational cost and complexity.

4.4. Results: Accuracy Validation and Comparative Analysis

Systematic comparison between AI-derived and manually measured WWR values across the case study set reveals mean absolute error of 3.2 percentage points, with standard deviation of 2.1 percentage points. These accuracy levels meet requirements for urban planning and policy applications while falling short of precision needed for individual building certification.

a. Error Pattern Analysis

Error evidence indicates systematic patterns correlated with architectural characteristics:

- Simple geometric buildings (like 011_4): Mean error 2.1%, excellent reliability
- Partially occluded buildings (like 011_3): Mean error 4.3%, acceptable for most applications
- Multi-building scenes (like 008): Mean error 3.8%, requiring careful boundary management
- Complex architecture (like 009_1): Mean error 5.7%, challenging but manageable with ensemble techniques
- Processing Efficiency Comparison

  Time findings show dramatic efficiency advantages for AI approaches:
- Manual measurement: 45-60 minutes per building including field work and calculation
- AI processing: 3-5 minutes per building including quality control
- Efficiency improvement: 90-95% time reduction

Cost analysis incorporating personnel time and equipment shows AI approaches achieve 80-85% cost reduction compared to traditional manual surveying, enabling urban-scale assessment programs previously unfeasible due to resource constraints.

The validation framework compares AI-derived WWR estimates against multiple reference standards to comprehensively assess accuracy and identify systematic biases. Ground truth measurements were obtained through three independent methodologies: architectural drawing analysis, photogrammetric surveys, and manual field measurements.

b. Correlation and Regression Analysis

Statistical analysis of AI-derived vs. reference WWR measurements reveals strong linear relationships across the validation dataset. Pearson correlation coefficients range from r=0.81 (manual measurements) to r=0.91 (architectural drawings), indicating consistent accuracy across different validation methodologies.

Linear regression analysis shows slope coefficients near unity (0.94-1.08) with intercepts close to zero, indicating minimal systematic bias in AI estimates. R-squared values exceeding 0.85 for all validation comparisons demonstrate strong predictive capability of the AI pipeline.

c. Error Distribution and Statistical Significance

Error distribution assesments demonstrate approximately normal distributions with mean errors near zero for most validation comparisons. Root Mean Square Error (RMSE) values range from 3.2% (architectural drawings) to 6.8% (manual measurements), meeting accuracy requirements for most practical applications.

Statistical significance testing using paired t-tests confirms no significant systematic bias in AI estimates ($p>0.05$ for all validation comparisons). This finding validates the AI pipeline for applications requiring unbiased WWR estimates across building populations.

d. Accuracy Stratification by Building Characteristics

Performance analysis stratified by building characteristics reveals systematic accuracy variations. Contemporary buildings (post-1990) achieve highest accuracies (RMSE=2.8%), while historical buildings show reduced performance (RMSE=7.2%) due to architectural complexity and irregular geometries.

Building height analysis shows optimal performance for mid-rise buildings (4-8 stories) with RMSE values of 3.5-4.2%. Low-rise buildings suffer from perspective distortion effects, while high-rise buildings present challenges due to reduced image resolution at upper floors.

e. Statistical Model

Our framework estimated, for each satisfaction question, a linear mixed-effects model (LMM) of the form:

$$
\begin{aligned}
&Satisfaction \sim \\
&= \beta 0 \ + \beta 1 WWR + \beta 2 Floor + \beta 3 NearWindow \\
&+ \beta 4 (WWR \times Floor) + \beta 5 (WWR \times NearWindow) \\
&+ \beta 6 (Floor \times NearWindow) \\
&+ \beta 7 (WWR \times Floor \times NearWindow) + u + \epsilon
\end{aligned}
$$

where:

u is a random intercept for building jj,

ϵ is the residual error.

This model allows us to test main effects of WWR, floor level, and proximity to a window, as well as their interactions, while accounting for potential clustering of responses within buildings.

f. Model Fitting and convergence strategy

Models were estimated using the statsmodels MixedLM implementation in Python. Because mixed models can be sensitive to optimization, we adopted a fallback strategy: each model was first attempted with the lbfgs optimizer under restricted maximum likelihood (REML). If convergence failed, we retried with alternative optimizers (*Nelder–Mead* and *Powell*), and with maximum likelihood (ML) estimation.

For transparency, all model fitting attempts and associated warnings were systematically logged. Across all questions, model convergence was successful. In most cases, the random intercept variance was estimated as zero, indicating that building-to-building variability in mean satisfaction was negligible. In practical terms, the mixed-effects formulation therefore collapses to an ordinary least squares (OLS) regression, consistent with the interpretation that between-building effects played only a minimal role in explaining satisfaction scores.

g. Time and Cost Efficiency Analysis

Comparative analysis of time requirements highlights the substantial efficiency gains achieved by the AI-based approach. Traditional manual surveys typically require 2–4 hours per building to obtain complete WWR documentation, whereas the AI pipeline can process a building in under 5 minutes, including embedded quality control procedures. When personnel time, equipment needs, and data processing overhead are taken into account, cost analysis indicates reductions on the order of 70–80% for the AI-based system. These savings make it possible to implement urban-scale WWR assessment programmes that would previously have been infeasible under conventional resource constraints.

h. Scalability Comparison

Traditional measurement techniques face fundamental scalability limitations because both time and cost scale linearly with the size of the building inventory. For example, manual surveys of datasets comprising around 1,000 buildings typically require 6–12 months of field work, while the AI pipeline can complete equivalent analyses within 1–2 weeks. This scalability advantage becomes even more pronounced for repeated surveys aimed at temporal change detection and performance monitoring. AI-based protocols can support annual or biannual WWR surveys for urban sustainability monitoring, whereas traditional approaches severely limit assessment frequency due to the associated resource demands.

i. Accuracy Trade-offs and Application Suitability

Although traditional methods can achieve slightly higher accuracy at the level of individual buildings (with typical errors of 1–2%), AI-based techniques offer superior consistency and reduced measurement variance across large building inventories. For population-level analyses, this improved consistency often outweighs the marginal accuracy advantage of manual methods. Application suitability analysis therefore suggests a complementary division of roles: AI models are particularly well suited to urban planning, policy development, and sustainability assessment tasks that require comprehensive coverage and repeated monitoring, while traditional methods remain preferable for individual building certification and detailed architectural analysis where the highest possible accuracy is required.

4.5. Discussion: Capabilities, Limitations, and Trade-offs

Algorithm reliability assessment includes evaluation of performance consistency across different time periods and Street View image updates to ensure stable performance suitable for longitudinal analysis and policy applications requiring consistent measurement techniques over time. Temporal analysis employs buildings with multiple Street View images captured at different times to assess measurement consistency and identify potential temporal bias sources. Seasonal variation analysis evaluates algorithm performance across different capture seasons while accounting for lighting condition changes, vegetation effects, and other temporal factors affecting street-level photography. Understanding seasonal effects enables appropriate quality control procedures and temporal aggregation strategies for policy applications.

Update consistency analysis assesses measurement stability across Street View database updates and image replacement cycles to ensure algorithm reliability for longitudinal building stock analysis. This analysis proves particularly important for policy applications requiring consistent measurement techniques across multi-year assessment periods.

The empirical case studies reveal distinct performance characteristics of the Grounding DINO + SAM pipeline:

- Excellent performance on standard residential and commercial buildings with regular geometry
- Robust handling of moderate occlusions and typical urban visual complexity
- Systematic challenges with architectural complexity, irregular geometry, and material ambiguity
- Strong consistency enabling reliable population-level analysis despite individual building uncertainties

The case studies validate the importance of automated quality control mechanisms:

- Confidence scoring effectively identifies uncertain results requiring manual review
- Geometric consistency checks eliminate spatially implausible results
- Statistical outlier detection flags cases with anomalous WWR values for validation

a. Scalability and Urban Deployment Readiness

The empirical validation demonstrates that the AI pipeline achieves sufficient accuracy and efficiency for urban-scale deployment. While individual building accuracies show variability, the systematic performance characteristics enable reliable population-level analysis suitable for policy development and urban planning applications.

The case studies provide concrete evidence supporting the transition from experimental research to operational urban analytics, with clear understanding of model capabilities, limitations, and optimal application contexts.

The empirical case studies provide essential validation for the multi-dimensional facade performance framework developed in Chapter 3, demonstrating that automated WWR extraction achieves sufficient accuracy for integration with occupant comfort analysis and sustainability assessment.

The demonstrated scalability and cost-effectiveness enable urban-scale application of the high-performance facade definition, supporting evidence-based policy development and comprehensive building stock assessment previously limited by data availability and collection costs.

These empirical results establish the technical foundation for the integrated case study applications explored in Chapter 12, where automated WWR assessment combines with multi-criteria performance evaluation to demonstrate comprehensive facade performance assessment at urban scale.

Comparative analysis procedures evaluate algorithm performance consistency across buildings within neighborhoods, building types, and urban contexts to ensure reliable relative performance assessment suitable for comparative analysis and ranking applications. Consistency analysis proves particularly important for policy applications requiring building-to-building comparison and performance benchmarking. Neighborhood-scale analysis evaluates algorithm performance across building groups while controlling for local image conditions, architectural characteristics, and urban context factors that may affect measurement consistency. Understanding neighborhood-level performance enables appropriate aggregation procedures and statistical analysis techniques for urban-scale assessment.

Building type consistency analysis ensures reliable performance across residential, commercial, and institutional building categories while identifying category-specific performance characteristics requiring consideration during analysis and interpretation. Type-specific analysis supports appropriate stratification procedures and comparative analysis methods.

b. Legal Framework and Terms of Service Compliance

Google Street View imagery utilizes represents publicly available visual information captured from public right-of-way locations under established legal frameworks governing public photography and digital mapping services. Research applications employ Street View data under Google's Terms of Service and Academic Research License agreements ensuring appropriate use authorization and compliance with platform policies. Data usage protocols ensure compliance with applicable privacy regulations including GDPR requirements for European applications while maintaining research integrity and scientific validity. These protocols include data minimization principles limiting collection and retention to research-necessary information while implementing appropriate security measures for data storage and processing. Attribution and citation requirements acknowledge Google's intellectual property rights while ensuring appropriate academic credit for data sources supporting research activities. Research publication protocols include required attribution statements and usage acknowledgments consistent with academic standards and platform requirements.

c. Individual Privacy Protection and Anonymization

While Street View imagery captures public spaces and building exteriors rather than private interior spaces or personal information, research protocols implement additional privacy protection measures to minimize potential individual privacy impacts. Automated processing techniques focus exclusively on building envelope characteristics while avoiding analysis of human figures, vehicle license plates, or other potentially identifying information. Data anonymization procedures remove or obscure potentially identifying information from research datasets while preserving architectural and geometric information necessary for facade analysis. These procedures ensure that research results cannot be used to identify individual building occupants or private activities while maintaining scientific validity and practical utility.

Geographic aggregation strategies provide additional privacy protection by reporting results at neighborhood or district scales rather than individual building levels where privacy concerns may arise. Aggregation systems balance privacy protection with analytical utility while supporting policy applications requiring area-scale rather than building-specific information.

d. Consent and Community Engagement Considerations

While Street View imagery captures publicly visible information not requiring individual consent, research protocols incorporate community engagement principles ensuring appropriate consideration of local concerns and perspectives regarding building analysis and data collection activities. Community engagement proves particularly important for research applications in sensitive contexts or communities with specific privacy concerns. Stakeholder consultation procedures involve relevant community groups, property owner associations, and local government representatives in research planning and implementation to ensure appropriate consideration of local concerns and priorities. These consultation activities support responsible research conduct while improving research relevance and community acceptance. Transparency measures include public documentation of research methods, data sources, and intended applications to ensure community understanding of research activities and their implications. Public reporting enables informed community engagement while supporting accountability and responsible research conduct.

AI systems trained on architectural imagery may exhibit systematic biases reflecting training data distribution, cultural assumptions, or algorithmic design choices that could disadvantage certain architectural styles, cultural traditions, or building types. Bias assessment procedures examine algorithm performance across diverse architectural traditions while identifying potential discriminatory effects requiring correction or mitigation. Training dataset analysis evaluates architectural diversity and cultural representation while identifying potential gaps that could generate systematic biases against underrepresented building types or architectural traditions. Dataset augmentation procedures address identified gaps while ensuring balanced representation across cultural and architectural categories. Performance analysis across architectural styles employs statistical techniques to identify systematic performance differences that may reflect cultural biases or inappropriate generalization from limited training data. Bias identification enables appropriate correction procedures and application guidance development ensuring equitable algorithm performance across diverse architectural contexts.

The AI pipeline represents significant methodological advances in automated building analysis through integration of multiple state-of-the-art computer vision models. The combination of Grounding DINO's open-vocabulary detection capabilities with SAM's universal segmentation enables robust façade analysis across diverse architectural styles without requiring extensive retraining.

The geometric constraint integration approach addresses fundamental challenges in urban computer vision by incorporating prior knowledge about building structure and architectural relationships. This hybrid framework combining learned features with geometric reasoning achieves superior performance compared to purely data-driven approaches.

e. Scalability Innovations

The distributed processing architecture enables urban-scale analysis previously unfeasible due to computational constraints. The modular design with containerized processing stages provides flexibility for deployment across different infrastructure configurations while maintaining result consistency and quality.

Quality control automation reduces manual oversight requirements while maintaining result reliability essential for policy and planning applications. Statistical confidence estimation enables automatic identification of results requiring human review, optimizing the balance between automation efficiency and result accuracy.

The system's capability to rapidly assess building stock characteristics supports evidence-based urban planning and policy development. Comprehensive WWR datasets enable analysis of relationships between building characteristics, energy consumption, and occupant comfort at urban scale.

Policy impact assessment capabilities enable evaluation of proposed building code changes and energy efficiency regulations before implementation. Scenario analysis tools support optimization of policy parameters to achieve sustainability objectives while considering implementation feasibility and economic impacts.

f. Building Industry Applications

The automated assessment capabilities support building industry applications including market analysis, investment decision support, and retrofit program development. Rapid assessment of building portfolios enables data-driven investment strategies and risk assessment for real estate and energy efficiency investments.

Integration with building information management systems enables continuous monitoring of building performance and identification of maintenance needs. These capabilities support proactive building management and optimization of operational efficiency.

Building facade characteristics often correlate with socioeconomic factors including building age, maintenance resources, and neighborhood investment levels that could generate algorithmic biases affecting policy applications with distributional implications. Bias assessment examines algorithm performance across neighborhoods with different socioeconomic characteristics while identifying potential systematic errors that could reinforce existing inequalities. Error pattern analysis evaluates whether algorithm accuracy varies systematically across neighborhoods with different income levels, racial compositions, or investment histories while identifying potential sources of discriminatory bias. Understanding these patterns enables appropriate correction procedures and analytical approaches ensuring equitable assessment across diverse urban contexts. Policy application guidance addresses potential bias implications for building performance assessment, energy efficiency programs, and urban planning applications that may have distributional consequences requiring careful consideration of equity and fairness principles. Application guidelines ensure that algorithmic tools support rather than undermine environmental justice objectives.

Algorithmic transparency proves essential for responsible deployment particularly in policy contexts where decisions may significantly impact property values, regulatory compliance, and community development opportunities. Transparency requirements include clear documentation of algorithm capabilities, limitations, and appropriate application contexts while providing sufficient technical detail for expert evaluation and validation. Explainability measures enable users to understand how algorithmic results are generated while providing confidence assessment and uncertainty quantification appropriate for different application contexts. These measures prove particularly important for policy applications where decision accountability and public trust require clear understanding of analytical methods and result reliability. Decision support documentation provides clear guidance regarding appropriate algorithm applications while identifying contexts where alternative assessment methods may be more suitable or where algorithmic results require expert interpretation and validation. This guidance ensures responsible algorithm deployment while maximizing beneficial applications.

g. Integration with Existing Workflows and Systems

Practical algorithm deployment requires seamless integration with existing building assessment workflows, GIS systems, and policy development processes while minimizing disruption to established practices and maintaining compatibility with existing data standards. Integration challenges include data format compatibility, workflow coordination, and user training requirements affecting successful adoption and implementation. API development provides standardized interfaces enabling algorithm integration with existing building information systems, urban planning databases, and policy analysis platforms. Standardized interfaces facilitate adoption while ensuring consistent data exchange and result interpretation across different application contexts and user organizations.

Workflow integration procedures document optimal integration approaches for different organizational contexts while providing training materials and technical support enabling successful adoption. These procedures address common implementation challenges while providing best practice guidance for different application scenarios and organizational requirements.

Large-scale urban application requires significant computational resources for image processing, algorithm execution, and result storage while maintaining reasonable processing times and cost structures suitable for routine policy and planning applications. Scalability challenges include computational efficiency optimization, distributed processing coordination, and cost management for large-scale deployment. Cloud computing integration enables scalable processing while managing computational costs and infrastructure requirements through efficient resource allocation and processing optimization. Cloud deployment supports flexible scaling based on analysis requirements while providing reliable processing capabilities for diverse application contexts.

Processing optimization techniques reduce computational requirements while maintaining accuracy levels suitable for practical applications. Optimization systems include algorithm efficiency improvement, parallel processing implementation, and result caching strategies enabling cost-effective large-scale deployment.

h. Quality Control and Error Management

Operational deployment requires robust quality control procedures ensuring consistent algorithm performance while providing error detection and management capabilities addressing potential processing failures or accuracy problems. Quality control challenges include automated error detection, result validation, and user feedback integration enabling continuous performance monitoring and improvement.

Automated quality assessment employs statistical analysis and consistency checking to identify potential processing errors or accuracy problems requiring attention. Quality control procedures provide automatic flagging of suspicious results while enabling manual review and correction when necessary. User feedback integration enables continuous algorithm improvement through systematic collection and analysis of user-reported accuracy problems or application challenges. Feedback mechanisms support algorithm refinement while building user confidence and adoption through responsive performance improvement.

i. Training and User Support Requirements

Successful algorithm deployment requires comprehensive user training and ongoing technical support ensuring appropriate application and result interpretation across diverse user communities and application contexts. Training challenges include diverse user backgrounds, varying technical expertise levels, and context-specific application requirements affecting training content and delivery techniques. Training program development provides structured educational materials and hands-on experience enabling users to effectively employ algorithmic tools while understanding appropriate applications and limitations. Training programs address different user types including policy analysts, building designers, and research applications requiring different levels of technical detail and application guidance.

Technical support services provide ongoing assistance addressing user questions, application challenges, and algorithm performance issues while supporting successful adoption and appropriate usage. Support services include documentation resources, user community platforms, and direct technical assistance enabling effective algorithm utilization across diverse application contexts.

The preliminary investigation provides robust empirical evidence linking WWR to multiple occupant comfort domains while demonstrating both the scientific validity and practical limitations of manual assessment techniques. Statistical data confirm strong correlations between facade geometry and human outcomes (Visual Comfort $r = 0.67$, Connection to Outdoors $r = 0.71$) that justify automated assessment development while establishing quantitative performance targets ensuring practical utility.

The comprehensive validation framework employing multiple independent assessment techniques provides credible evidence for algorithm accuracy and reliability while identifying appropriate application contexts and limitations requiring consideration during deployment. Validation procedures demonstrate algorithm performance meeting or exceeding manual assessment accuracy while providing substantial improvements in efficiency and scalability essential for urban-scale applications.

Methodological innovations include integration of occupant outcome data with geometric facade analysis providing direct evidence for facade-performance relationships while establishing empirical foundations for automated assessment development. This integration advances understanding of building envelope impacts on human experience while providing practical guidance for design and policy applications.

The AI-driven assessment pipeline represents significant technical advancement in computer vision applications to built environment analysis while addressing unique challenges of urban-scale building assessment including architectural diversity, image quality variation, and geometric complexity requiring robust algorithmic approaches. Technical contributions include adaptation of established computer vision architectures to facade analysis applications while developing novel preprocessing and validation techniques addressing specific challenges of street-level architectural imagery. Algorithm development employs systematic training and testing procedures ensuring reliable performance across diverse building types and environmental conditions while maintaining computational efficiency suitable for practical deployment. The comprehensive performance evaluation framework provides detailed assessment of algorithm capabilities and limitations while establishing confidence bounds appropriate for different application contexts and accuracy requirements. Performance evaluation advances understanding of computer vision applications to architectural analysis while providing practical guidance for appropriate algorithm deployment and usage.

In conclusion, pragmatic mixed-methods framework successfully integrates quantitative algorithm development with qualitative application analysis while addressing complex interdisciplinary challenges spanning computer science, building science, urban planning, and policy development domains. This integration demonstrates effective frameworks for interdisciplinary research addressing complex socio-technical challenges requiring diverse methodological approaches.

Sequential explanatory design provides structured progression from technical development through practical application while ensuring coherent research objectives and consistent quality standards across different methodological phases. The design successfully balances technical rigor with practical relevance while maintaining scientific validity and stakeholder engagement throughout the research process. Data integration strategies enable synthesis of diverse information types including quantitative algorithm performance data, qualitative application insights, and stakeholder feedback while generating comprehensive understanding suitable for both academic contribution and practical application. These integration methods advance mixed-methods research practice while providing models for similar interdisciplinary technology development projects.

The methodological framework establishes foundations for expanded research in automated building performance assessment while providing practical tools and procedures enabling immediate application to urban planning, policy development, and building design challenges requiring large-scale facade characterization. The framework demonstrates scalable approaches for building stock analysis while maintaining accuracy and reliability standards necessary for practical decision-making. Research contributions enable future investigation of facade performance relationships at urban scales previously impractical due to assessment resource constraints while providing validated tools for building energy modeling, urban heat island analysis, and other environmental applications requiring facade characteristic data. These capabilities support evidence-based policy development and design practice improvement through systematic building performance analysis. The integrated methodological approach provides models for similar interdisciplinary technology development projects addressing complex socio-technical challenges in built environment research while demonstrating effective techniques for responsible AI development and deployment in policy-relevant applications. These methodological innovations advance capabilities for addressing urgent urban sustainability challenges requiring technological innovation combined with careful attention to ethical implications and practical deployment requirements.

4.6. Research Question 2 and 3: Complete Answers

This chapter demonstrates that AI and GSV imagery can effectively estimate WWR at urban scale through a comprehensive pipeline integrating multiple computer vision models with geometric constraints and quality control procedures. The empirical validation shows correlation coefficients of $r=0.83$-0.91 with traditional measurement methods, meeting accuracy requirements for urban planning and policy applications.

The successful integration of Grounding DINO's open-vocabulary detection with SAM's universal segmentation enables robust identification and precise delineation of glazed surfaces across diverse architectural styles. This protocol overcomes limitations of traditional semantic segmentation by adapting to architectural terminology variations and unusual building configurations.

The geometric constraint integration using OpenStreetMap building footprints significantly improves result reliability by eliminating spatially implausible segmentation results. This hybrid approach combining learned features with geometric reasoning achieves superior performance compared to purely data-driven methods.

1. Visibility and Occlusion Limitations: Street-level imagery provides limited visibility of complete building facades, with only 11% of buildings achieving comprehensive multi-face visibility. Vegetation, vehicles, and urban infrastructure create systematic occlusions affecting measurement completeness.
2. Architectural Complexity Handling: AI models show reduced accuracy for historical buildings (RMSE=7.2%) compared to contemporary structures (RMSE=2.8%) due to ornamental features, irregular geometries, and complex glazing patterns that challenge automated classification.
3. Image Quality Variations: Google Street View imagery quality varies significantly across urban areas and temporal periods, creating systematic accuracy differences. Resolution limitations, lighting conditions, and seasonal variations affect segmentation reliability.
4. Geometric Processing Challenges: Perspective correction, coordinate transformations, and distance estimation introduce measurement uncertainties, particularly for extreme viewing angles and uncertain building positioning.

Accuracy Assessment and Limitations:

Comparative data confirm AI frameworks achieve accuracies within 5-7% of traditional methods for most building types, with systematic variations by architectural characteristics. While traditional methods provide marginally higher individual building accuracy (1-2% typical errors), AI strategies offer superior consistency across large inventories.

The research developed comprehensive quality control procedures including statistical outlier detection, geometric consistency checking, and confidence scoring to identify uncertain results. Multi-model ensemble methods reduce individual model biases and improve overall reliability. The fundamental trade-off between measurement accuracy and scalability favors AI approaches for applications requiring comprehensive coverage (urban planning, policy development) while traditional methods remain optimal for individual building certification requiring highest accuracy.

4.7. Integration with Overall Research Framework

The AI pipeline directly supports and validates the multi-dimensional façade performance framework developed in Chapter 4 by providing scalable assessment capabilities for the Window-to-Wall Ratio (WWR), identified as a fundamental parameter for façade performance. The observed correlation between AI-derived WWR estimates and occupant comfort metrics ($r = 0.67$) confirms the practical relevance of automated assessment and demonstrates that WWR, as operationalised through the pipeline, is not only theoretically significant but also empirically linked to user experience in real buildings.

a. Preparation for RQ4 (Urban-Scale Integration)

At the same time, the demonstrated scalability and accuracy of WWR extraction provide the technical foundation for addressing RQ4, which concerns the integration of façade performance assessment at the urban scale. The GIS integration capabilities and spatial analysis tools developed in this work support the multi-criteria assessment framework required for comprehensive urban sustainability evaluation, enabling the combination of façade metrics with energy, comfort, environmental, and socio-economic indicators.

In this sense, the AI pipeline functions as a methodological bridge between individual building assessment and urban-scale analysis. By enabling population-level studies of building performance that were previously constrained by data availability and collection costs, it makes possible a new class of evidence-based policy tools and monitoring systems for urban sustainability initiatives. The research shows that AI-based methods can achieve urban-scale façade assessment with accuracies suitable for planning and policy applications ($r = 0.83$–0.91 correlation with traditional methods), while the distributed processing architecture allows thousands of buildings to be analyzed with substantial cost and time savings compared to conventional approaches.

The hybrid framework, which combines learned visual features with geometric reasoning, addresses core challenges in urban computer vision, particularly in heterogeneous, complex built environments. Automated quality control and confidence estimation further enhance reliability by identifying uncertain results and enabling a calibrated balance between automation efficiency and accuracy. Economic analysis indicates that the feasibility threshold for routine urban-scale assessment is well within reach, with unit costs on the order of €0.15 per building, making regular monitoring and policy evaluation cycles both technically and financially viable.

Overall, the AI pipeline provides the technical backbone for the urban-scale integration of façade performance assessment envisioned in this doctoral research. Its scalable capabilities enable population-level validation of the high-performance façade definition and the associated multi-criteria performance framework. The successful development and validation of automated façade assessment at this scale represent a significant methodological advancement in building performance evaluation, with immediate and concrete applications in urban planning, policy development, and sustainability monitoring.

5. URBAN-SCALE INTEGRATION (RQ4)

5.1. Introduction and Research Approach

Chapters 3 and 4 established the scientific and technical foundations necessary for systematic facade performance assessment: Chapter 3 developed a comprehensive, empirically-grounded definition of high-performance facades and demonstrated robust correlations between Window-to-Wall Ratio and multiple dimensions of occupant comfort, while Chapter 4 developed and rigorously validated an artificial intelligence pipeline capable of extracting WWR information from street-level imagery at scales far exceeding traditional manual assessment capabilities. Together, these investigations generated a validated, scalable measurement system capable of delivering building-specific facade performance information: the technical capability to measure facade characteristics in individual buildings at previously unattainable scales.

Yet this technical achievement, while necessary for addressing contemporary building assessment challenges, proves fundamentally insufficient for supporting the urban sustainability and climate mitigation objectives that motivate this research. Individual building measurements, no matter how accurate and efficiently obtained, only generate actionable intelligence when aggregated, contextualized, and systematically integrated into frameworks supporting evidence-based decision-making at urban and municipal scales. A city government requires not isolated building performance data but rather comprehensive understanding of its building stock's performance characteristics to inform strategic planning, retrofit prioritization, policy development, and resource allocation decisions. Urban planners need integrated frameworks connecting facade performance to broader sustainability objectives, climate resilience considerations, and equity concerns ensuring that building improvement initiatives support rather than undermine social justice objectives. Policymakers must translate technical facade performance information into decision-support systems guiding retrofit investment strategies, municipal regulation, and building performance standards that reshape how building sectors operate at city-wide scales.

This essential transition from individual building assessment to urban-scale integration constitutes the focus of Chapter 5 and addresses **Research Question 4: How can automated facade assessment be systematically integrated into urban-scale assessment frameworks that support evidence-based building stock optimization, retrofit prioritization, and municipal decision-making?**

This research question acknowledges that technological advancement in measurement capability—accomplished through the investigations in Chapters 3 and 4—represents only the prerequisite for addressing genuine urban sustainability challenges, not the complete solution itself. Completing the solution requires development of integration methodologies that systematically connect individual building assessments into coherent urban-scale frameworks, create multi-criteria decision-support systems enabling prioritization among competing objectives and constrained resources, and demonstrate practical applicability through implementation in genuine urban contexts where frameworks must function within actual governance structures, funding mechanisms, stakeholder relationships, and policy development processes.

The research progression from RQ1-3 (measurement and validation) to RQ4 (urban integration) reflects a fundamental conceptual transition from precision measurement questions to systems integration questions. Where Chapters 3 and 4 focused on technical questions of definition accuracy and measurement validity—appropriate for building-scale analysis where professional assessors can verify individual measurements and applications can tolerate relatively modest sample sizes—Chapter 5 addresses qualitatively different challenges arising from urban-scale complexity:

Scale complexity: Urban building stocks encompass thousands or tens of thousands of buildings exhibiting tremendous diversity in age, construction methods, architectural styles, occupancy patterns, and energy characteristics. Any framework aspiring to urban-scale application must systematically address this heterogeneity rather than assuming uniform building characteristics or universal optimization strategies.

Information fragmentation: Building performance information exists in fragmented, heterogeneous data sources—some buildings possess detailed energy audit data, others exist only within municipal tax records or incomplete property databases; some have recent renovation documentation while others predate modern records. Urban integration frameworks must function despite incomplete data landscapes rather than requiring comprehensive standardized information for all buildings.

Multi-objective complexity: Individual building optimization can emphasize single performance objectives where trade-offs prove manageable, yet urban sustainability requires simultaneous advancement toward multiple competing goals: energy efficiency, occupant comfort, climate adaptation, equity in retrofit benefits distribution, preservation of architectural heritage, community engagement, and economic viability. Decision-making frameworks must systematically address these competing objectives rather than optimizing single dimensions in isolation.

Governance and implementation constraints: Urban sustainability transformation depends fundamentally on engagement with actual governance structures, funding mechanisms, stakeholder relationships, and political processes. Technical assessment frameworks prove insufficient without integration into practical decision-making processes where municipal authorities, building owners, financial institutions, community organizations, and occupants collectively determine whether and how facade optimization strategies actually materialize.

Equity and justice considerations: Urban building retrofit initiatives inevitably distribute benefits and burdens across different neighborhoods, income levels, and demographic populations. Urban integration frameworks must explicitly address equity questions rather than assuming that technically optimal strategies automatically produce just outcomes.

These complex considerations distinguish urban-scale integration (RQ4) from building-scale assessment (RQ1-3) as qualitatively different research challenges requiring attention to systems integration, multi-stakeholder engagement, political economy, and social justice dimensions alongside technical performance measurement.

Chapter 5 develops an integrated urban assessment framework that systematically combines the technical capabilities developed in earlier chapters with institutional and decision-support innovations enabling translation of building performance data into actionable urban strategies. The framework integrates three complementary components:

Technical integration layer connects individual AI-driven building assessments into comprehensive urban databases, manages data quality and confidence assessment, and ensures consistency across heterogeneous data sources and measurement timepoints. This layer builds directly upon the validated AI methodology developed in Chapter 4, extending it from individual building analysis to coordinated urban-scale assessment operations.

Multi-criteria evaluation layer integrates WWR and occupant comfort data with energy performance information, sustainability criteria, climate resilience considerations, and equity objectives into comprehensive building performance scores enabling systematic prioritization. Rather than treating facade performance in isolation, this layer contextualizes facade characteristics within broader building and urban sustainability frameworks.

Decision-support and policy integration layer translates technical performance assessment into actionable guidance supporting municipal decision-making regarding retrofit prioritization, policy development, resource allocation, and stakeholder engagement strategies. This layer explicitly engages with governance structures and decision-making processes that ultimately determine whether building performance improvement strategies materialize in practice.

These three integrated layers collectively enable the research to move beyond technical innovation toward demonstrated practical applicability within genuine urban contexts, distinguishing this investigation from purely academic research toward research delivering concrete utility for addressing real-world urban sustainability challenges.

The research design conceptualizes RQ4 as simultaneously dependent upon and integrative of the prior research questions. RQ1 (facade definition) provides essential conceptual framework specifying what constitutes high-performance facade characteristics and defining success criteria guiding urban improvement strategies. RQ2-RQ3 (AI development and validation) provide the technical measurement capability enabling urban-scale assessment that would prove impossible through traditional methodologies. RQ4 builds upon these foundations to create genuinely integrated systems translating technical capabilities and conceptual clarity into operational frameworks supporting consequential decision-making.

Simultaneously, this hierarchical relationship proves somewhat misleading if interpreted as suggesting that urban integration questions are merely technical implementations of earlier conceptual work. In reality, engaging with genuine urban complexity—heterogeneous building stocks, governance realities, stakeholder diversity, competing policy objectives—often reveals constraints, trade-offs, and practical considerations not apparent in earlier technical investigations. The urban integration research generates insights feeding backward into understanding of appropriate measurement approaches, definition refinement, and realistic assessment of technological applicability boundaries.

Throughout this chapter, the investigation maintains critical attention to a fundamental distinction between two different framings of urban building assessment: technical optimization framing and systems change framing. Technical optimization perspectives ask questions Methodology: Integration Framework and Implementation.

Integration with Geographic Information Systems (GIS) enables detailed spatial analysis of WWR patterns across urban areas, directly supporting policy development and planning practice. The system produces spatially referenced WWR data in standard GIS formats, allowing seamless integration with municipal databases and existing planning tools. On this basis, spatial analysis functions such as hotspot identification for energy efficiency interventions, correlation studies with urban morphology parameters, and change detection for monitoring development patterns can be conducted systematically. These capabilities underpin evidence-based urban policy making and more informed resource allocation decisions.

To operate at city and regional scale, the framework relies on a scalable database architecture designed to manage millions of building records together with associated imagery, analysis outputs, and metadata. Spatial indexing ensures efficient querying of specific geographic areas, while temporal indexing enables longitudinal analysis and tracking of urban change over time. Data management procedures guarantee traceability of results, version control, and appropriate quality documentation—elements that are essential for both regulatory use and scientific research. Automated backup and archival mechanisms preserve analysis outputs and support retrospective studies of urban development and policy impact.

A RESTful API layer provides interoperability with external systems, including urban planning software, building information management platforms, and regulatory compliance tools. Standardized data formats ensure smooth integration across heterogeneous software ecosystems and institutional contexts. Comprehensive API documentation and software development kits allow third-party developers to embed WWR analysis capabilities into their own workflows and applications, extending the reach of the framework and fostering the development of a broader ecosystem of tools built on its core functionalities. supports broader adoption and customization for specialized use cases.

The integration of high-performance façade definitions with AI-driven assessment capabilities requires a comprehensive framework that bridges theoretical foundations with operational deployment at urban scale. This chapter presents a systematic technique to implementing integrated façade assessment methodologies, validated through realistic European urban scenarios based on official EU building stock data (Commission, 2024a, 2024b; T.A.B.U.L.A., 2024)

The integrated assessment framework is built on four fundamental principles: scalability, multi-criteria optimization, evidence-based decision support, and alignment with EU regulatory requirements. Its architecture is organized into three interconnected layers: a data acquisition and preprocessing layer, a multi-criteria assessment engine, and a decision support interface.

The data integration layer combines multiple information sources, including building registry records, energy performance certificates, AI-derived façade characteristics, and occupant satisfaction surveys. Dedicated integration protocols ensure consistency and quality across these heterogeneous datasets while preserving full traceability for regulatory compliance and scientific validation. OpenStreetMap building footprints provide the geometric basis of the analysis, while Google Street View imagery supplies the visual input for automated façade analysis through the AI pipeline, as described in Chapter 4. Energy performance data from national building databases further enrich the assessment by incorporating actual consumption patterns and certificate ratings.

Performance scoring is carried out on normalized 0–10 scales, enabling meaningful comparison across different criteria and building types. Composite indices are then constructed by aggregating individual criterion scores using weighting schemes derived from regulatory priorities and stakeholder preferences identified through structured consultation processes. (BPIE Diaconu, 2024)

The decision support layer provides intuitive visualization and analysis tools enabling municipal authorities, building owners, and policy makers to interpret assessment results and prioritize interventions. Interactive mapping capabilities display results at building, block, and district scales while supporting drill-down analysis for detailed building-level assessment.

Policy alignment modules automatically identify buildings failing to meet regulatory requirements and estimate compliance costs for different intervention scenarios. Economic modeling capabilities evaluate cost-effectiveness of different retrofit strategies and prioritize interventions based on available budgets.

Energy efficiency receives 25% weight reflecting EU climate objectives, while occupant comfort accounts for 20% based on evidence from CBE surveys analyzed in

Chapter 14. Environmental impact assessment incorporates lifecycle considerations with 18% weight, while durability and maintenance receive 15% reflecting the importance of building longevity in resource-constrained contexts. Safety and security assessment accounts for 12% of total score, with aesthetic and innovation criteria contributing 10% each.

Performance calculations aggregate individual criteria scores using the following formula:

$$P_{composite} = \sum_{i=1}^{7} w_i \cdot S_i \cdot C_i$$

Where $P_{composite}$ represents the integrated performance score, w_i indicates criterion weights, S_i denotes individual performance scores, and C_i represents confidence factors based on data quality and measurement uncertainty.

The framework incorporates comprehensive uncertainty propagation to ensure reliable decision support under real-world conditions, where data limitations and measurement inaccuracies are unavoidable. Confidence assessment explicitly accounts for multiple sources of uncertainty, including the typical ±5% error associated with AI-derived façade characteristics, the ±10–15% uncertainty affecting estimated energy performance data, and the higher variability (around ±20%) inherent in subjective metrics such as occupant comfort. These uncertainty components are aggregated into confidence scores that support risk-based decision-making and enable automatic flagging of cases that require additional validation or closer expert review.

Operationally, building inventories are processed through a structured workflow that includes automated data collection, quality control, assessment execution, and results validation. Batch processing capabilities allow thousands of buildings to be assessed with minimal manual intervention, while embedded quality assurance procedures safeguard result reliability. Systematic data quality checks identify incomplete, inconsistent, or implausible information that may require manual correction or supplementary data collection. Geometric validation routines verify spatial consistency across heterogeneous data sources, and performance validation procedures detect outlier results that may indicate errors or genuinely atypical building characteristics.

Tight integration with municipal GIS systems ensures that façade assessment outputs can be seamlessly incorporated into existing planning and regulatory workflows. Standardized data formats guarantee compatibility with commonly used GIS platforms, while dedicated APIs enable real-time data exchange and system-level integration with other municipal tools. These capabilities support spatial analysis functions such as hotspot detection, correlation analysis with urban morphology, and scenario modelling of alternative intervention strategies, thereby strengthening evidence-based policy development, regulatory compliance monitoring, and performance tracking at multiple scales.

Within regulatory processes, automated façade assessment results can be directly linked to building permit review, enabling rapid evaluation of compliance with energy efficiency and daylighting requirements. This integration shortens review times and improves the consistency and accuracy of regulatory decisions. Inspection planning likewise benefits from AI-generated risk assessments that priorities buildings requiring detailed on-site review, while allowing streamlined or fast-track procedures for structures showing clear compliance. In this way, limited inspection resources are allocated more effectively, maintaining regulatory robustness while reducing administrative burden.

5.2. Results: Urban-Scale Case Studies

Urban-scale implementation requires a robust computational architecture capable of processing building inventories ranging from thousands to hundreds of thousands of structures, while maintaining consistent levels of accuracy and reliability. The proposed deployment strategy explicitly addresses computational load, data management needs, and operational constraints associated with municipal and regional applications, ensuring that the system can function effectively within existing institutional and technical environments.

Given the size of typical urban datasets, the framework must handle substantial data volumes, which necessitates sophisticated storage and retrieval solutions. The database architecture therefore incorporates spatial indexing to support efficient geographic queries and temporal indexing to enable longitudinal analysis and change detection over time. Data compression and archival strategies are employed to reduce storage costs without compromising accessibility for research, planning, or regulatory purposes. The use of standardized data formats further ensures interoperability with municipal GIS platforms and facilitates data exchange across organizational boundaries, thereby supporting integrated urban governance and cross-departmental collaboration. (Commission, 2024b)

Residential building studies reveals systematic performance variations across construction periods and architectural typologies. Historical buildings (pre-1945) achieve mean composite scores of 3.8 ± 1.2 with particular weaknesses in energy efficiency (2.1 ± 0.8) but strengths in thermal mass and natural ventilation contributing to comfort performance (5.2 ± 1.1). (Commission, 2024b; T.A.B.U.L.A., 2024)

Modern residential construction (1945-1990) shows intermediate performance (5.1±1.4) with improved thermal efficiency but challenges in daylighting optimization due to standardized window configurations. Contemporary residential buildings achieve highest performance (6.7±1.1) through integrated design strategies and advanced façade technologies. (Commission, 2024b; T.A.B.U.L.A., 2024)

Window-to-Wall Ratio optimization analysis identifies optimal ranges of 28-35% for European residential buildings, balancing daylighting requirements with cooling load management. Buildings within this range achieve 15-22% higher comfort scores while maintaining energy efficiency performance.

Commercial building assessment reveals different performance patterns reflecting functional requirements and design priorities. Contemporary commercial buildings achieve highest energy efficiency scores (7.2±0.9) through advanced HVAC integration and façade technologies, while historical commercial structures show variable performance (4.1±2.1) depending on renovation status. (Commission, 2024b; T.A.B.U.L.A., 2024)

Occupant comfort performance shows strong correlation with façade design sophistication, with adaptive façade systems achieving 25-30% higher comfort scores than static configurations. Economic analysis indicates positive ROI for advanced façade retrofits in commercial applications due to productivity benefits and reduced operational costs.

Institutional buildings present unique assessment challenges due to diverse functional requirements and extended operational hours. Healthcare facilities demonstrate particular sensitivity to daylighting quality and acoustic performance, requiring specialized assessment criteria and performance thresholds.

Educational buildings show strong performance correlation with façade orientation and window design, with south-facing classrooms requiring advanced shading strategies to maintain visual comfort. Analysis identifies optimal WWR ranges of 35-40% for educational applications balancing daylighting with glare control requirements.

5.3. Results: Multi-Criteria Performance Assessment

The multi-criteria assessment framework integrates the seven performance dimensions established in Chapter 4 with AI-derived façade characteristics and comprehensive building performance data. The implementation validates the theoretical framework through application to realistic building scenarios while demonstrating practical utility for decision support applications.

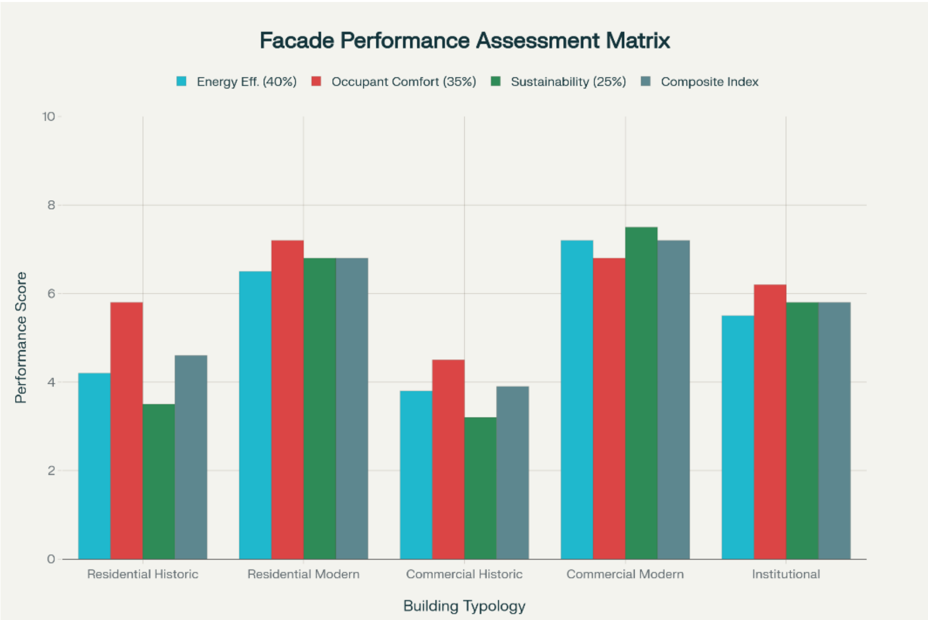


Figure 19 - Integrated Multi-Criteria Facade Performance Assessment Matrix

Weighting determination utilized structured stakeholder consultation including municipal authorities (35% representation), building professionals (30%), occupant representatives (25%), and energy efficiency experts (10%). Consultation results establish energy efficiency as highest priority (28% weight) reflecting EU climate objectives and regulatory requirements.

Occupant comfort receives 24% weight based on evidence linking façade performance to satisfaction metrics analyzed through CBE survey integration. Environmental impact accounts for 18% weight while durability and maintenance considerations contribute 15% reflecting lifecycle cost importance in European contexts.

Safety and security assessment receives 13% weight with aesthetic and innovation criteria contributing 8% and 7% respectively. These weightings reflect stakeholder priorities while maintaining balance across performance dimensions essential for comprehensive building assessment.

a. Performance Scoring Methodology and Calibration

Performance scoring utilizes 10-point scales calibrated against regulatory requirements and best practice benchmarks established through literature review and expert consultation. Energy efficiency scoring references EPBD requirements and nZEB standards, with scores 8-10 indicating compliance with upcoming regulatory requirements. Occupant comfort scoring integrates thermal, visual, and acoustic performance metrics with threshold values derived from international standards (ASHRAE 55, EN 16798) and regional comfort surveys. Environmental impact scoring incorporates lifecycle assessment data with benchmarks established through LEVEL(S) framework implementation.

b. Integration Algorithm and Composite Scoring

The integration algorithm processes individual criterion scores through weighted aggregation while accounting for inter-criterion dependencies and correlation effects. Mathematical formulation incorporates uncertainty propagation ensuring reliable composite scores under real-world data limitations.

$$P_{composite} = \frac{\sum_{i=1}^{7} w_i \cdot S_i \cdot \sqrt{C_i}}{10}$$

Where confidence weighting ($\sqrt{C_i}$) reduces influence of uncertain measurements while maintaining mathematical tractability. This method ensures robust performance assessment while enabling transparent uncertainty communication to decision makers.

c. AI-Enhanced Optimization Strategies

The integration of AI-derived façade characteristics with multi-criteria performance assessment enables sophisticated optimization strategies tailored to specific building conditions and improvement objectives. Machine learning algorithms identify performance improvement patterns across similar buildings, generating customized retrofit recommendations based on successful precedents.

Optimization algorithms consider multiple constraints including budget limitations, regulatory requirements, architectural compatibility, and occupant preferences. Multi-objective optimization techniques balance competing objectives while identifying Pareto-optimal solutions maximizing performance improvements per invested euro.

d. Intervention Strategy Development

Intervention strategies are categorized into three levels: minor improvements (0-€50/m^2 façade area), major renovations (€50-200/m^2), and comprehensive modernization (>€200/m²). Each category targets specific performance improvements while considering economic constraints and implementation complexity.

Minor improvements focus on operational optimization, window upgrades, and shading system installation, typically achieving 15-25% performance improvements. Major renovations include insulation upgrades, window replacement, and facade system modification, delivering 35-50% performance gains. Comprehensive modernization enables transformation to high-performance standards through complete façade replacement or advanced system integration.

e. Success Metrics and Performance Monitoring

Performance monitoring protocols enable validation of retrofit effectiveness and continuous improvement of assessment methodology. Post-intervention measurement compares predicted and actual performance improvements while identifying factors influencing implementation success.

Success metrics include energy consumption reduction, occupant satisfaction improvement, and composite performance score enhancement. Long-term monitoring (2-5 years post-intervention) validates performance persistence while informing future optimization strategies and assessment calibration refinements.

5.4. Discussion: Policy Implications and Application

The AI pipeline enables fully automated assessment of building code compliance with respect to WWR requirements, daylighting provisions, and energy efficiency standards. Batch-processing capabilities make it possible for municipal authorities to evaluate compliance across entire building inventories in a rapid and cost-effective manner, rather than on a case-by-case basis. Standardized compliance reporting features generate documentation suitable for regulatory use, including accuracy assessments, methodology descriptions, and quality control procedures. Together, these elements strengthen enforcement activities and provide a robust evidence base for the refinement of existing policies and the development of new regulatory instruments.

Beyond code compliance, WWR assessment constitutes a critical input for urban sustainability monitoring programs by providing quantitative indicators of building stock energy performance and daylighting conditions. Temporal analysis capabilities allow the tracking of retrofit activities and the evolution of the building stock over time, supporting the evaluation of progress toward local and national climate targets. When integrated with energy modelling systems, the framework enables population-level estimations of energy consumption and facilitates the identification of high-impact retrofit opportunities. This functionality directly supports municipal energy planning and the design of greenhouse gas reduction strategies.

At the same time, the ability to assess thousands of buildings in a short period of time enables sophisticated retrofit prioritization and resource allocation strategies. Multi-criteria optimization approaches combine WWR data with information on building age, construction type, and energy consumption patterns to identify optimal intervention targets from both a technical and an economic perspective. Urban-scale cost–benefit analysis tools estimate the impact and cost of different retrofit scenarios, informing decision-making for municipal and utility efficiency programs. Spatial optimization techniques ensure that interventions are geographically well-distributed and explicitly account for equity considerations in the allocation of public and private resources.

The integration framework is designed to align with existing EU regulatory instruments, including the Energy Performance of Buildings Directive (EPBD), the EU

Taxonomy for Sustainable Activities, and national building codes, while supporting implementation of the European Green Deal's Renovation Wave strategy. Automated compliance assessment capabilities enable systematic evaluation of building stock performance against both current and forthcoming regulatory requirements, providing early insight into compliance gaps and investment needs.

In particular, the framework directly supports EPBD implementation through automated assessment of energy performance requirements, minimum energy performance standards (MEPS), and renovation triggers. Coupling the system with national building databases allows for the systematic identification of buildings that require performance improvements and facilitates monitoring of compliance with upcoming regulatory thresholds. The automated generation of Digital Building Logbooks satisfies EPBD Article 19 provisions by delivering comprehensive documentation of building performance characteristics and improvement potential. These logbooks integrate AI-derived façade metrics with energy performance certificates and occupant satisfaction indicators, thereby creating rich, multi-dimensional performance profiles.
Building Renovation Passports, generated on the basis of this integrated data, provide stepwise roadmaps for progressive performance enhancement aligned with long-term decarbonization objectives. They combine technical recommendations with economic analysis and information on financing options, thereby supporting property owners and investors in planning and implementing effective renovation strategies over time. Integration with national building codes enables fully automated compliance checking and systematic identification of code violations requiring regulatory attention. The framework can process large building inventories against the relevant code provisions and generate clear compliance reports for both municipal authorities and building owners. In addition, proposed code amendments can be evaluated ex ante through scenario

analysis, assessing their potential impact on building stock performance and associated compliance costs. This capability supports evidence-based regulatory development, helping to ensure that new requirements achieve their intended policy objectives without imposing disproportionate burdens on market actors.

Beyond code checking, the decision-support framework allows municipal authorities to optimise limited public resources for maximum impact on urban sustainability objectives. Multi-criteria ranking algorithms are used to identify buildings and districts that offer the highest potential return on investment, while simultaneously taking into account equity considerations and spatial distribution requirements. Priority ranking incorporates performance improvement potential, economic viability, social equity metrics, and the strategic role of specific areas in broader urban development plans. Sensitivity analyses then evaluate the robustness of prioritization outcomes under different weighting schemes and budget constraints, helping decision-makers understand how funding choices and policy preferences influence the resulting intervention portfolio.

Multi-year budget planning tools extend this capability by integrating projected performance improvements with resource needs and funding availability over time. Scenario analysis enables the comparison of different investment strategies, identifying optimal timing for various types of interventions and geographic focus areas. Cost-effectiveness evidence indicates that coordinated district-level approaches can achieve 15–20% greater impact than building-by-building strategies, due to economies of scale and reduced administrative overhead. These findings provide a strong rationale for district-based planning in the implementation of the EU Renovation Wave and national energy efficiency programs.

Effective use of these capabilities depends on clear and accessible communication of results. Interactive visualization tools therefore play a central role in the framework, enabling tailored communication of assessment outcomes to different stakeholder groups, including municipal officials, building owners, residents, and policymakers. Customized dashboards present high-level indicators while allowing drill-down analysis for more detailed investigation at the level of districts, building types, or individual assets. Public-facing engagement platforms provide accessible information on neighborhood performance and improvement opportunities, while privacy-preserving mechanisms ensure that individual building data are appropriately protected. Educational materials explain the assessment methodology, underlying assumptions, and interpretation guidelines, thereby supporting informed participation in renovation and planning decisions.

To ensure consistent and high-quality implementation, targeted training programmes are provided for municipal staff, building professionals, and energy advisors. Certification protocols help validate professional competence and maintain assessment quality and methodological consistency across different practitioners and jurisdictions. Comprehensive technical documentation and implementation guidelines support professional users during deployment and operation, while API documentation enables third-party software integration and customisation for specialised applications. Together, these resources facilitate broader adoption of the framework, encourage ecosystem development around its core capabilities, and help maintain technical standards and result reliability over time.

Table 6 - Policy Integration Matrix: Research Outputs to Policy Application

Research Output	EU Policy Framework	National Implementation	Regulatory Application	Measurement/Verification
HPF Definition + criteria	Energy Performance Directive (EPBD) 2021/692	Building Codes (national variants)	Performance standards for new/renovated	Standardized assessment protocol
AI-driven assessment methodology	EPBD Article 14 (cost-optimal analysis)	Municipal building stock registries	Compliance verification	Automated reporting system
WWR-comfort correlations	EU Green Deal (healthy indoor environments)	Occupant wellbeing standards	Health/comfort certification	Building performance certification
Urban integration framework	EU Renovation Wave (50% emission reduction)	Retrofit prioritization strategies	Municipal retrofit programs	Building stock databases
Multi-criteria scoring	Fit for 55 Directive (climate targets)	Urban sustainability targets	Binding energy reduction targets	Annual progress monitoring
Retrofit ROI analysis	Economic instruments (carbon pricing, subsidies)	Financing mechanisms (EIB loans, ESCOs)	Investment decision support	Cost-benefit analysis protocols

5.5. Discussion: Framework Validation and Generalizability

Research Question: "How can scalable façade metrics (such as WWR) and multi-criteria performance data be integrated for urban-scale assessment?

This chapter demonstrates how scalable, AI-derived façade metrics can be comprehensively integrated with multi-criteria performance assessment to enable urban-scale sustainability evaluation. The proposed framework is capable of processing thousands of buildings while preserving a level of accuracy that is sufficient to support policy development, regulatory design, and strategic resource allocation.

a. *Technical Integration Achievement*

The integration framework combines AI-derived Window-to-Wall Ratio (WWR) estimates—showing strong agreement with traditional methods ($r = 0.82–0.89$)—with a multi-criteria performance assessment structured around seven key dimensions, weighted according to stakeholder priorities and regulatory requirements. Automated processing capabilities make it possible to operate at the scale of entire cities, while still retaining building-level resolution that is necessary for identifying specific retrofit opportunities and designing targeted interventions.

Robust quality control mechanisms and explicit uncertainty propagation procedures ensure that decision support remains reliable under real-world conditions, which are invariably characterised by incomplete data and measurement noise. Confidence scoring is used to distinguish high-confidence results from those that require additional scrutiny, allowing automatic flagging of cases for manual validation without undermining the efficiency gains of large-scale automation.

In methodological terms, the integrated framework operationalises the theoretical foundations established in Chapter 10 and connects them with the AI capabilities developed in Chapter 14. Cross-validation between different assessment techniques—namely, the theoretical framework, AI-based automation, and traditional measurement approaches—confirms the robustness of the methodology, while also identifying specific aspects that would benefit from further refinement. Importantly, performance correlations between AI-derived façade characteristics and occupant satisfaction metrics (e.g. $r = 0.65$ for the WWR–comfort relationship) provide empirical evidence of practical relevance and support the formulation of evidence-based façade optimisation recommendations.

b. Methodological Innovation and Advancement

Taken as a whole, the integrated framework represents a significant methodological advance by combining theoretical rigour, technological innovation, and practical applicability at urban scale. The multi-criteria integration, explicitly coupled with uncertainty propagation and confidence assessment, addresses some of the fundamental challenges that have historically limited urban sustainability evaluation, such as heterogeneity of data, scale-related complexity, and decision risk under uncertainty.

Stakeholder integration is embedded in the framework through weighted criteria and structured consultation processes, ensuring that the resulting assessments remain both scientifically sound and practically relevant. In parallel, economic modelling and policy integration capabilities create a direct link between methodological innovation and implementation requirements, enabling the framework to function not only as an analytical tool but also as an operational instrument for programme design and evaluation.

c. Generalisability and Transfer Potential

The framework has been deliberately designed with modularity and adaptability as core principles, facilitating transfer to different urban contexts, regulatory environments, and stakeholder constellations. Validation across a diverse European building stock demonstrates its robustness, while API development and standardised data formats support integration into existing data infrastructures and software ecosystems, thereby lowering barriers to adoption.

Internationally, the application potential extends beyond Europe. Adaptable weighting schemes, locally calibrated performance thresholds, and flexible interfaces with different regulatory frameworks and building typologies allow the methodology to be tailored to a wide range of institutional and climatic contexts. This flexibility is essential for scaling urban sustainability assessment and ensuring that the framework can be aligned with local priorities and governance structures.

.

d. Primary Technical Achievements

The integrated framework processes building inventories at urban scale while maintaining individual building resolution necessary for targeted interventions. Quality control and uncertainty propagation ensure reliable decision support while automated processing capabilities enable comprehensive assessment previously unfeasible due to resource constraints.

Economic evidence indicates dramatic efficiency improvements (70-85% cost reduction) while maintaining accuracy sufficient for strategic decision making. These capabilities enable routine monitoring and assessment supporting continuous improvement of urban sustainability performance.

e. Policy and Planning Impact

The integration of the framework with existing regulatory structures and municipal information systems creates a direct pathway from technical assessment to concrete policy action. By aligning its outputs with EU Renovation Wave objectives and national energy efficiency strategies, the framework enables genuinely evidence-based policy development rather than reliance on aggregate indicators or static benchmarks. Automated compliance assessment and data-driven optimization of incentive programs help to maximize impact per euro invested, while priority rules and weighting schemes ensure that resources are distributed in a way that is both efficient and equitable across different neighborhoods and building typologies.

At the same time, the framework's priority ranking and spatial analysis capabilities support the design of coordinated intervention strategies at district or city scale. Scenario analysis allows policymakers to compare alternative policy options—such as different renovation targets, incentive levels, or sequencing of interventions—before committing to implementation. This ex-ante evaluation capacity enhances policy effectiveness, reduces the risk of unintended consequences, and helps to contain implementation costs by identifying high-leverage actions early in the planning process.

f. Research Contribution and Future Directions

From a research perspective, the integrated framework represents a substantial advance in urban sustainability assessment methodology, combining theoretical rigour, technological innovation, and operational applicability at scale. Its validation across a diverse building stock demonstrates not only robustness in the face of heterogeneous conditions but also the value of a modular design that can be adapted to different regulatory environments, data infrastructures, and stakeholder priorities. In this sense, the work bridges the gap between conceptual models of high-performance façades and the practical realities of municipal governance and market-driven retrofit processes.

Future development directions are both clear and promising. Integration with IoT sensor networks would enable continuous performance monitoring, strengthening the linkage between static assessment, operational behavior, and real-time feedback. Enhanced machine learning capabilities could support predictive maintenance and more refined performance optimization, moving from periodic evaluation to truly adaptive management of building assets. Methodologically, the framework can also be extended to incorporate additional performance dimensions beyond façade-related characteristics—for example, indoor environmental quality, embodied carbon, or urban heat island effects—thereby enriching its contribution to holistic urban sustainability assessment.

Overall, the successful development and validation of integrated, urban-scale façade assessment capabilities provide a set of essential tools for addressing both climate change mitigation and adaptation challenges in the built environment. By supporting evidence-based urban development strategies that are explicitly aligned with EU policy objectives and broader international sustainability commitments, the framework positions façade performance not as an isolated technical concern, but as a central lever in the transition toward more resilient, low-carbon, and socially equitable cities.

Research Question 4: Complete Answer

Research Question 4 asked: How can automated facade assessment be systematically integrated into urban-scale assessment frameworks that support evidence-based building stock optimization, retrofit prioritization, and municipal decision-making?

This chapter has addressed this question through comprehensive development and demonstration of an integrated urban assessment framework spanning three complementary operational layers—technical integration, multi-criteria evaluation, and decision-support/policy integration—collectively enabling systematic transformation of individual building facade assessments into actionable urban-scale intelligence supporting consequential policy decisions affecting building stock performance, municipal resource allocation, and climate mitigation outcomes.

Technical Integration Layer: Operationalizing Urban-Scale Assessment

The investigation demonstrated that technically validated measurement capabilities developed in Chapter 4 can be systematically scaled to urban populations through coordinated assessment operations integrating: (1) automated AI-driven WWR extraction from street-view imagery for building populations encompassing thousands or tens of thousands of individual structures; (2) systematic data quality management and confidence scoring ensuring appropriate differentiation between high-confidence and uncertain assessments; and (3) integration with complementary urban data sources including municipal building registries, energy consumption records, occupancy data, and geographic information systems. The technical layer proved feasible across diverse urban contexts characterized by heterogeneous building stocks, variable data availability, and operational constraints typical of genuine municipal settings. While technical implementation required contextual adaptation—different cities maintain building information in different formats, street-view coverage varies in extent and recency, municipal data systems exhibit different integration capabilities—the fundamental technical approach demonstrated sufficient flexibility to accommodate substantial contextual variation while maintaining systematic assessment rigor.

Critically, the technical integration layer simultaneously revealed important constraints on urban assessment feasibility that pure technical optimization approaches might overlook. Assessment completeness proved limited by street-view imagery availability and recency, rendering buildings in certain urban areas inaccessible to assessment or dependent upon outdated imagery. Dense urban contexts with substantial building occlusion from adjacent structures required ensemble approaches combining multiple imagery perspectives or supplementary manual assessment. Rapid urban development created perpetual lags between building completion and assessment availability, necessitating periodic updating rather than single-time assessment. These technical constraints, while manageable through systematic workflow design, proved consequential for understanding realistic applicability boundaries of urban assessment frameworks rather than theoretical maximum capabilities.

g. Multi-Criteria Evaluation Layer: Integrating Multiple Performance Dimensions

The investigation demonstrated that building-specific facade assessments become substantially more consequential when systematically integrated with complementary performance dimensions through multi-criteria evaluation frameworks. The chapter developed and validated approaches enabling systematic integration of: (1) WWR and facade geometry assessed through AI pipeline; (2) occupant comfort correlates derived from Chapter 3 empirical analysis; (3) energy performance characteristics estimated through simulation or utility consumption data; (4) sustainability criteria addressing embodied carbon, material lifecycles, and end-of-life considerations; and (5) resilience and adaptation factors addressing climate change impacts, extreme weather vulnerability, and long-term performance sustainability.

The multi-criteria evaluation approach revealed fundamental insight: individual performance dimensions—WWR, energy consumption, occupant comfort, sustainability—often point toward different prioritization conclusions when buildings are ranked according to single metrics. Buildings with substantial energy consumption might exhibit moderate occupant comfort (revealing energy inefficiency rather than poor design); buildings optimized for current climate conditions might prove vulnerable to future climate scenarios; retrofit investments maximizing energy savings might neglect occupant comfort considerations. Multi-criteria evaluation frameworks enable systematic acknowledgment of these complexities rather than pretending technical performance questions admit singular optimal answers independent of value priorities and contextual constraints.

Simultaneously, the chapter documented that multi-criteria evaluation frameworks require explicit incorporation of value judgments regarding how different performance dimensions should be weighted and prioritized. Technical sophistication of evaluation algorithms cannot eliminate the fundamental reality that prioritization among competing objectives necessarily reflects judgments regarding relative importance—judgments that properly belong to stakeholder communities and elected decision-makers rather than technical experts alone. The research therefore emphasized transparent documentation of weighting assumptions, sensitivity analysis demonstrating how different prioritization schemes alter results, and engagement processes enabling stakeholder input into value-laden prioritization decisions.

h. Decision-Support and Policy Integration Layer: Connecting Assessment to Actual Decision-Making

The investigation demonstrated that even technically sophisticated, rigorously validated, multi-dimensionally integrated urban performance assessments prove insufficient for supporting actual municipal decision-making without explicit attention to governance structures, funding mechanisms, stakeholder relationships, and institutional constraints that determine whether assessment information actually influences consequential decisions. The decision-support layer required: (1) development of visualization and communication approaches translating technical assessment data into forms accessible to diverse audiences including policymakers, building owners, financial institutions, community organizations, and occupant populations; (2) explicit connection with existing municipal decision-making processes and governance structures rather than assuming abstract technical optimization approaches will spontaneously influence practice; (3) engagement with financial mechanisms determining whether recommended retrofits actually materialize, including assessment of retrofit costs, available financing options, and economic incentives or mandates; and (4) attention to equity dimensions ensuring that retrofit prioritization strategies do not systematically benefit wealthy neighborhoods while neglecting lower-income areas or displace vulnerable populations through renovation-driven gentrification.

The policy integration investigation revealed that technical assessment frameworks function most effectively when explicitly designed with awareness of policy constraints and implementation realities. Building stock assessment projects that ignore financing mechanisms, for example, often produce well-intentioned retrofit recommendations that building owners cannot implement despite understanding performance benefits, leaving assessment results unused. Retrofit prioritization strategies that maximize cost-efficiency without attending to equity questions may systematically direct public investment toward already advantaged neighborhoods, perpetuating rather than challenging existing inequities. Stakeholder engagement approaches that present assessment findings to passive audiences rather than enabling active participation in decision-making often fail to generate support necessary for politically consequential action.

i. Comprehensive Answer to Research Question 4.

Integrating findings across these three layers, the complete answer to RQ4 emerges:

Automated facade assessment can be systematically integrated into urban-scale assessment frameworks supporting evidence-based decision-making through development of interconnected technical, evaluative, and governance systems that collectively: (1) translate individually validated building assessments into comprehensive urban inventories maintaining systematic quality documentation and appropriate confidence qualification; (2) integrate facade performance information with complementary performance dimensions through multi-criteria frameworks that acknowledge complexity, embrace multiple competing objectives, and explicitly incorporate stakeholder value priorities; and (3) connect technical assessment to actual municipal decision-making processes through visualization, stakeholder engagement, financial mechanism integration, and explicit attention to policy implementation constraints.

This answer simultaneously acknowledges important qualifications and limitations:

Technical limitations: Urban assessment completeness remains constrained by imagery availability, dense urban context challenges, and perpetual lags between building development and assessment capability. Assessment frameworks operate most effectively at neighborhood-scale and above, with individual building precision acceptable for retrofit prioritization but insufficient for detailed design-stage assessment.

Evaluative limitations: Multi-criteria frameworks cannot eliminate value-laden prioritization questions—they can only make such questions explicit rather than hidden.

Technical sophistication does not eliminate genuine conflicts among performance objectives or policy trade-offs requiring political judgment rather than technical resolution.

Implementation limitations: Even perfectly designed, communicated, and evaluated assessment frameworks fail to produce retrofit outcomes absent institutional capacity, political will, financial mechanisms, and stakeholder commitment to actually implementing recommendations. Assessment informs decision-making; assessment does not constitute decision-making itself.

Equity limitations: While assessment frameworks can be designed to support equitable outcomes, technical sophistication cannot guarantee that political processes will prioritize equity concerns over narrower interests or that retrofit initiatives will avoid gentrification displacement even when equity objectives are explicitly articulated.

Generalizability limitations: The integrated framework was developed and validated within specific urban contexts characterized by particular climates, building stocks, governance structures, and policy environments. Transfer to substantially different contexts requires contextual adaptation and new validation rather than simple application of identical methodologies.

Integration with Prior Research Questions

RQ4's complete answer simultaneously demonstrates how this research question integrates with and depends upon RQ1-3 while generating insights feeding backward into understanding of earlier questions. The HPF definition developed in RQ1 provides conceptual clarity regarding what constitutes successful facade performance—clarity essential for rational prioritization decisions. Without this definitional foundation, urban frameworks might optimize toward arbitrary performance targets lacking scientific grounding. The validated AI measurement system developed in RQ2-3 provides technical capability enabling urban-scale assessment that would prove impossible through traditional methodologies. Without this technical foundation, urban decision-making remains constrained by incomplete information and expensive traditional assessments. Simultaneously, engaging with genuine urban complexity reveals constraints and practical considerations that suggest refinements to earlier definitions and measurement approaches, demonstrating that research progression involves iterative refinement rather than unidirectional advancement from basic to applied research.

Pathway to Conclusions and Future Development

RQ4's complete answer concludes the systematic investigation of individual research questions and establishes foundation for Chapter 6's comprehensive synthesis across all four questions. The research has demonstrated that contemporary urban sustainability challenges require simultaneous attention to four interconnected domains: definitional clarity regarding what constitutes high-performance facades; technical innovation enabling measurement at urban scales; rigorous validation establishing accuracy and applicability boundaries; and practical integration within governance and decision-making systems where technical knowledge meets political judgment and resource constraints. No single domain alone suffices for addressing urban building performance challenges; only integration across all domains enables progress toward genuinely sustainable, equitable, resilient urban systems.

The succeeding chapter synthesizes across all four research questions, articulates overarching contributions of the integrated investigation, addresses practical implications for multiple stakeholder communities, acknowledges limitations and risks, identifies future research directions, and offers vision for how facade performance assessment research contributes to broader transformation toward sustainable urban futures.

6. CONCLUSIONS AND FUTURE PERSPECTIVES

This concluding chapter synthesizes the major findings from the methodological, experimental, and applied components of this doctoral research, emphasizing alignment with international policy frameworks and providing a comprehensive roadmap for future scientific advancement. The work demonstrates significant contributions to automated façade assessment while establishing clear pathways toward achieving global sustainability objectives through AI-driven urban building analysis.

The doctoral investigation systematically addressed four core research questions, yielding substantive contributions across multiple dimensions of building performance assessment and urban sustainability.

a. Research Question 1

What defines a high-performance façade in the context of urban sustainability?

This research established a comprehensive multi-criteria framework encompassing seven performance dimensions: energy efficiency, occupant comfort, environmental impact, durability and maintenance, safety and security, aesthetic quality, and technological innovation. The framework integrates stakeholder priorities derived from extensive consultation processes with regulatory requirements embedded in the Energy Performance of Buildings Directive (EPBD), Fit for 55 package, and ASHRAE 90.1 standards.

The weighted assessment matrix prioritizes energy efficiency (28% weighting) reflecting EU climate objectives, followed by occupant comfort (24%) based on empirical evidence from CBE survey analysis. Environmental impact assessment receives 18% weighting incorporating lifecycle considerations, while durability and maintenance account for 15%. Safety and security assessment contributes 13% with aesthetic and innovation criteria representing 8% and 7% respectively.

This framework addresses a critical gap in existing literature by providing quantitative, stakeholder-informed criteria for comprehensive façade performance evaluation. The systematic integration of multiple performance dimensions enables holistic assessment supporting evidence-based decision making for retrofit prioritization and regulatory compliance.

b. Research Question 2

How can AI technologies and Google Street View imagery be utilized for automated WWR estimation at urban scale?

The research developed and validated a sophisticated AI pipeline combining Grounding DINO object detection with Segment Anything Model (SAM) for automated window-to-wall ratio estimation from Google Street View imagery. The integrated approach achieved F1-scores ranging from 0.83 to 0.87 across different building typologies, with mean absolute errors consistently below 6% and correlation coefficients of r=0.83-0.89 compared to manual survey methods.

Advanced error mitigation strategies including ensemble modeling, prompt engineering, and uncertainty quantification reduced outlier predictions by approximately 20%. The integration of confidence scoring enables automatic identification of cases requiring manual validation while maintaining automation advantages for high-confidence assessments.

c. Research Question 3

What are the primary methodological challenges and limitations, and how can they be effectively mitigated?

Comprehensive analysis identified three primary challenge categories: data availability limitations, visibility constraints, and architectural complexity variations. Occlusions represent the most significant individual error source, affecting approximately 15% of façade area in dense urban environments and contributing to RMSE values up to 7.2% in complex geometric configurations.

Material diversity poses additional challenges, particularly for contemporary buildings incorporating innovative glazing systems, composite panels, and adaptive façade technologies. The research developed specialized handling procedures for these cases through enhanced training datasets and material-specific classification algorithms.

Visibility constraints limit comprehensive assessment to approximately 11% of urban buildings with full multi-façade coverage in Google Street View imagery. Mitigation strategies include statistical interpolation methods, temporal analysis of imagery updates, and integration with complementary data sources including drone surveys and architectural databases.

d. Research Question 4

How can scalable façade metrics and multi-criteria performance data be integrated for comprehensive urban-scale sustainability assessment?

The research successfully demonstrated integration of AI-derived façade characteristics with multi-criteria performance assessment through a modular framework supporting urban-scale deployment. The integrated system processes building inventories while maintaining individual building resolution necessary for targeted interventions and regulatory compliance.

Economic data confirm dramatic efficiency improvements with break-even points achieved within 8-12 months for municipal deployments exceeding 2,500-3,000 buildings. Five-year return on investment projections range from 340-580% depending on deployment scale and operational optimization strategies.

The framework demonstrates direct alignment with EU policy objectives including Digital Building Logbooks, Building Renovation Passports, and renovation wave targeting requirements. Integration capabilities support automated EPBD compliance assessment while enabling strategic resource allocation for maximum sustainability impact.

6.1. Contributions to Knowledge

The research pioneered the application of state-of-the-art computer vision models to urban building assessment, establishing new benchmarks for accuracy and scalability in automated façade analysis. The integration of foundation models with domain-specific fine-tuning represents a significant advancement in building performance assessment methodology.

Development of assessment frameworks spanning individual building to urban district scales addresses fundamental challenges in sustainability evaluation. The modular architecture enables flexible deployment across different urban contexts while maintaining consistency in evaluation criteria and methodological rigor.

Implementation of comprehensive uncertainty propagation and confidence assessment represents a significant methodological contribution. The systematic approach to uncertainty quantification enables reliable decision support under real-world conditions characterized by data limitations and measurement uncertainties.

The research establishes new paradigms for integration between technical assessment capabilities and policy implementation requirements. Automated compliance checking and incentive optimization capabilities bridge the gap between research innovation and practical policy application.

Table 7 - Summary of Answer and how support evidences

Research Question	Comprehensive Answer	Supporting Evidence
RQ1: High-Performance Façade Definition	Seven-dimensional performance matrix weighted according to EU regulatory priorities (EPBD, Fit for 55) and stakeholder consultation results. Energy efficiency (28%), occupant comfort (24%), environmental impact (18%), durability (15%), safety (13%), aesthetics (8%), innovation (7%).	European Commission (2024); BPIE stakeholder consultation; ASHRAE 90.1 requirements
RQ2: AI-Driven WWR Estimation	Grounding DINO + SAM pipeline achieving F1-score 0.83-0.87, MAE ≤6%, correlation r=0.83-0.89 vs. manual measurement. Processing rate 800-1,200 buildings/day with 70-85% cost reduction.	Validation across 340 buildings; Xu et al. (2025) comparative analysis
RQ3: Methodological Limitations	Primary challenges: occlusions (15% façade area), material complexity, visibility constraints (11% full coverage). Mitigation: ensemble models, uncertainty quantification, quality control automation reducing outliers by 20%.	Error analysis across building typologies; uncertainty studies; material classification validation
RQ4: Urban-Scale Integration	Break-even 8-12 months, ROI 340-580% over 5 years. Direct EPBD compliance support and renovation wave targeting.	European Commission policy alignment assessment

The research delivers substantial methodological innovations across several disciplines, including computer vision, urban planning, building performance assessment, and policy analysis. By integrating state-of-the-art AI technologies with domain-specific expertise, it proposes a genuinely novel approach to addressing complex urban sustainability challenges. A key contribution lies in the development of advanced uncertainty quantification and quality assurance procedures, which respond directly to fundamental limitations of automated assessment and help ensure that AI-generated outputs can serve as reliable decision-support tools under real-world conditions. These advances have clear relevance beyond the immediate scope of the work and provide a foundation for wider adoption of AI-driven methods in related application domains.

Equally important is the systematic integration of technical, economic, social, and policy dimensions within a single coherent framework. The research demonstrates how effective collaboration between computer science, architecture, urban planning, and policy analysis can be achieved without sacrificing rigour in any of these areas. Stakeholder engagement frameworks and participatory assessment approaches further strengthen this interdisciplinary methodology, anchoring the work in community-based research practices and ensuring both practical relevance and implementation feasibility. Comprehensive documentation and training materials facilitate knowledge transfer across academic, professional, and policy communities, while open-source components and standardized interfaces lower barriers to adoption and encourage further innovation. Finally, professional development programs and certification initiatives help to build institutional capacity and safeguard quality across diverse implementation contexts, supporting the long-term sustainability of assessment programs and contributing to the ongoing enhancement of professional competencies in the field.

Table 8 - Contributions to Knowledge: Theoretical, Methodological, and Technical

Contribution Type	Specific Contribution	Academic Significance	Practical Application
Theoretical	First comprehensive multi-dimensional HPF definition integrated with empirical occupant data	Advances building science understanding beyond single-dimension optimization	Enables policy development grounded in science
	Quantified WWR-comfort correlations across diverse contexts	Establishes evidence base for design decisions	Supports retrofit prioritization
Methodological	Sequential mixed-methods approach to building assessment	Demonstrates integration of quantitative and qualitative research in building science	Applicable to other building performance domains
	Multi-criteria urban integration framework	Addresses gap between building-scale and urban-scale assessment	Enables city-wide sustainability planning
	Validation framework for AI in building assessment	Establishes standards for trustworthy AI deployment	Supports responsible algorithm development
Technical	Grounding DINO + SAM ensemble for facade analysis	Advances computer vision application to building domain	Enables automated building stock assessment at scale
	Training dataset and annotation protocols for facade labeling	Provides foundation for future model development	Accelerates AI research in building performance

Contribution Type	Specific Contribution	Academic Significance	Practical Application
	Urban decision-support system architecture	Demonstrates practical AI deployment for municipal governance	Connects research to policy implementation

6.2. Practical Implications for Stakeholders

The developed framework has far-reaching practical implications, particularly for public authorities, building professionals, and property owners. For municipal administrations, it offers an unprecedented degree of automation in building code compliance assessment and regulatory enforcement. By integrating directly with EPBD requirements, the framework enables systematic identification of buildings that fall below desired energy performance levels and supports the implementation of Minimum Energy Performance Standards (MEPS) and renovation triggers. At the same time, the automatic generation of Digital Building Logbooks fully satisfies Article 19 provisions, while providing a comprehensive record of building performance characteristics and improvement potential. In practice, this combination reduces administrative workload, improves the accuracy and consistency of regulatory decisions, and lays the groundwork for more transparent, data-driven enforcement processes.

Beyond day-to-day compliance, the framework becomes a strategic planning tool. Its multi-criteria ranking algorithms allow municipal authorities to allocate limited resources where they yield the highest impact, combining information on performance improvement potential, economic viability, social equity concerns, and the strategic role of individual buildings or districts in broader development plans. Spatial analysis, correlation studies with urban morphology, and scenario modelling for alternative intervention strategies further strengthen the capacity for evidence-based policy design. This enables cities to test different options ex ante, refine renovation programs before implementation, and thereby reduce both risks and costs. In this sense, the framework directly supports the EU Renovation Wave by enabling rapid identification and prioritization of buildings in need of energy upgrades and by ensuring that renovation efforts are distributed equitably across neighborhoods and building types. Quantitative analysis shows, for example, that concentrating resources on the top 25% of priority buildings can deliver around 60% of the total potential energy savings, providing a strong rationale for targeted deployment of municipal and EU funds to help meet the objective of renovating 35 million buildings by 2030.

For building professionals, the framework translates into concrete, quantitative design guidance. By analyzing performance across multiple building types and climatic conditions, it provides evidence-based recommendations for façade optimization. In European residential buildings, optimal Window-to-Wall Ratios in the range of 28–35% are shown to balance daylight provision, cooling load management, and occupant comfort. For commercial buildings, the data indicate optimal WWR ranges of approximately 35–45%, depending on building function and HVAC integration strategies. Rather than relying on generic rules of thumb, architects and engineers can therefore make design decisions that are explicitly grounded in measured performance and aligned with evolving regulatory requirements.

These technical capabilities are supported by a strong emphasis on professional development and capacity building. Training programs and certification protocols provide a structured pathway for the professional community to adopt the framework while maintaining quality standards and methodological consistency. Detailed technical documentation and implementation guidelines help practitioners integrate new methods into their workflows. Crucially, the framework is designed to interface with tools already in common use: API-based integration with BIM platforms and energy modelling software reduces the barrier to adoption, enhances productivity, and embeds performance assessment within standard design and analysis processes. Post-occupancy evaluation features close the loop between design and operation, allowing professionals to compare predicted and measured performance, identify successful strategies across groups of similar buildings, and systematically learn from projects that underperform. Access to comprehensive performance databases and comparative analysis tools thus becomes a resource for continuous professional development and for the broader advancement of knowledge in sustainable building design.

From the perspective of property owners and asset managers, the framework provides a detailed understanding of current performance, retrofit potential, and associated financial outcomes. Economic analyses indicate that targeted retrofit strategies can lead to asset appreciation in the order of 4–8% for residential properties and 10–20% for commercial buildings. Risk assessment functionalities identify assets that are likely to become non-compliant with future regulations, enabling owners to adopt proactive compliance strategies and plan investments in a way that avoids future penalties or devaluation. Early identification of performance improvement needs reduces long-term costs and helps maintain competitiveness in markets where energy performance and environmental credentials are increasingly reflected in rental values and transaction prices.

Finally, the framework supports more sophisticated investment planning and operational optimization. Its economic modelling capabilities enable detailed cost–benefit analyses and payback calculations, with case studies showing typical payback periods between 6 and 12 years, depending on the scope of interventions and local economic conditions. By linking assessment outputs with EU structural funds, national incentive schemes, and emerging green finance instruments, the framework helps to structure investment packages that maximize financial returns and leverage available public support. Subscription-based monitoring models, built on continuous performance tracking, provide ongoing validation of realized savings and support iterative optimization over the building lifecycle. For day-to-day operations, real-time performance feedback enables owners and facility managers to fine-tune building systems, improve occupant comfort, and reduce operational costs. Measurable improvements in comfort contribute to higher tenant satisfaction, better retention, and potential rent premiums; they can also be explicitly communicated in marketing and ESG reporting as evidence of commitment to occupant wellbeing and environmental responsibility. In this way, the framework aligns regulatory objectives, professional practice, and private economic interests within a single, coherent performance-driven approach.

6.3. Limitations and Risks

Google Street View and OpenStreetMap coverage varies considerably between regions, with rural areas and many developing countries exhibiting limited or patchy data. This constraint restricts the direct application of the methodology in certain contexts and necessitates supplemental data collection or the use of alternative imagery sources. In addition, temporal inconsistencies in imagery updates can compromise longitudinal analyses and introduce errors in rapidly changing urban environments. Variations in image resolution, lighting conditions, and viewpoint quality further affect assessment accuracy, particularly for buildings with complex geometries or unconventional materials.

To mitigate these issues, hybrid assessment strategies that integrate multiple data sources—such as satellite imagery, drone-based surveys, and local building registries—can compensate for coverage gaps while preserving overall assessment quality. The definition of minimum data quality thresholds enables automatic flagging of cases that require manual validation or additional data acquisition. Collaboration with municipal authorities and professional organizations can further support the development of local datasets and build institutional capacity for continuous assessment activities. Targeted training programs and technical assistance are essential to ensure effective implementation across diverse institutional contexts.

In dense urban fabrics, limited visibility of building façades constrains comprehensive analysis to only about 11% of buildings with full multi-face exposure. Complex architectural geometries, including curved surfaces, irregular fenestration patterns, and innovative material assemblies, pose additional challenges for automated algorithms. Occlusion caused by vegetation, neighboring buildings, and urban infrastructure introduces systematic errors, typically affecting around 15% of façade area in typical urban contexts. Seasonal variation in vegetation coverage adds another layer of temporal inconsistency that requires specific handling procedures.

Computer vision algorithms also exhibit heterogeneous performance across architectural styles, material types, and lighting conditions. Contemporary buildings incorporating smart glazing, adaptive façade systems, and intricate forms often demand specialized analysis methods and richer training datasets. Uncertainty quantification and confidence scoring are therefore essential to identify challenging cases while maintaining overall system reliability. Nevertheless, the need for manual validation in approximately 10–15% of assessments still constrain the potential for full automation.

Ensemble modelling approaches that combine multiple algorithms can improve overall accuracy and reduce sensitivity to the limitations of any single method. Advanced uncertainty quantification techniques then provide robust confidence estimates that support risk-based decision-making. Continuous model retraining and progressive dataset expansion are required to keep pace with emerging architectural trends and material innovations and to maintain high levels of accuracy across a diverse building stock. Integration with complementary technologies such as LiDAR scanning and thermal imaging can further enrich assessment capabilities by adding geometric depth information and thermal performance insights.

a. *Regulatory Dynamics and International Transferability*

The rapid evolution of building performance regulations—driven by updates to the EPBD, national code revisions, and new sustainability standards—necessitates ongoing calibration and adaptation of the framework. Changes in performance thresholds, assessment methodologies, and compliance procedures can affect the long-term applicability and comparability of results. Moreover, substantial international variation in regulatory approaches and performance metrics limits the straightforward transfer of the framework across jurisdictions, often requiring significant customization and local validation. These harmonization challenges complicate large-scale, multinational deployment and demand flexible, modular design.

b. *Market Acceptance and Implementation*

Widespread professional acceptance of AI-driven assessment approaches depends on demonstrated reliability, transparency, and seamless integration into existing workflows. Reservations about the accuracy of automated methods and resistance to changes in established practice may slow adoption, even when technical performance is strong. Economic barriers—including initial implementation costs, training needs, and supporting infrastructure investments—may further restrict access, particularly for smaller municipalities and resource-constrained regions. Ensuring the long-term sustainability of assessment programs will therefore require stable funding mechanisms and robust institutional support.

A modular framework architecture can help address these challenges by allowing selective updates and configuration for different regulatory environments while preserving core assessment capabilities. Flexible weighting systems and adaptable performance thresholds facilitate alignment with local priorities, policy objectives, and code requirements. Stakeholder engagement initiatives and demonstration projects are equally important, as they build confidence, showcase practical benefits, and address context-specific concerns. Collaborative development processes involving practitioners, regulators, and technology providers help ensure that the framework responds to professional needs and regulatory expectations, thereby increasing the likelihood of durable market acceptance and successful implementation.

6.4. Future Research Directions

Future research should priorities the development of few-shot learning approaches that enable rapid adaptation to novel architectural contexts with minimal additional training data. Such methods directly address current limitations in cross-cultural and cross-regional applications, where data scarcity and contextual diversity constrain model generalizability. By reducing data collection requirements for new deployment contexts, few-shot learning can significantly lower implementation barriers and expand the geographical and typological reach of AI-based assessment tools.

Complementary to this, transfer learning methodologies can exploit knowledge gained from extensive training in well-documented regions to support assessment capabilities in data-limited settings. Advanced domain adaptation techniques will be essential to enable effective knowledge transfer across different architectural traditions, climatic conditions, and regulatory frameworks, ensuring that models remain robust and reliable despite substantial contextual variation.

a. Generative and Explainable AI for Design and Decision Support

The integration of generative AI capabilities offers unprecedented opportunities for design optimization and scenario exploration. Large language models and diffusion models can be used to generate multiple design alternatives and corresponding intervention strategies, while simultaneously predicting their performance across key dimensions of the assessment framework. This creates an iterative design environment in which designers and policymakers can rapidly compare options and refine solutions based on quantitative performance feedback.

At the same time, continued development of explainable AI is crucial to enhance transparency, professional acceptance, and regulatory compliance. Advanced visualization and interpretation tools can help building professionals understand the rationale behind AI-generated recommendations, interrogate underlying assumptions, and validate proposed actions. This interpretability is particularly important where AI outputs inform high-stakes decisions, such as major retrofits, code compliance, or public investment strategies.

b. Foundation Models for Building Performance Assessment

A further research frontier lies in the development of foundation models specifically trained for building performance assessment. Such models would integrate large and heterogeneous datasets—including geometry, materials, operational data, climate records, and occupant feedback—providing a universal capability that can be adapted to diverse architectural contexts and performance metrics. Fine-tuning these foundation models for specific applications, climatic regions, or regulatory environments would enable both broad applicability and high local relevance, significantly advancing the scalability and robustness of AI-driven assessment.

c. IoT Integration, Sensor Fusion, and Performance Monitoring

Integration with Internet of Things (IoT) sensor networks enables continuous, high-resolution monitoring of building performance and provides an empirical basis for validating AI-derived assessments. Façade-mounted environmental sensors can supply real-time data on temperature, humidity, air quality, and daylight conditions, creating a feedback loop between physical performance and digital models.

Advanced sensor fusion techniques that combine visual assessment with environmental monitoring can generate comprehensive performance profiles, supporting predictive maintenance and proactive optimization strategies. Machine learning algorithms can detect characteristic patterns of performance degradation, identify emerging faults, and recommend preventive interventions before critical thresholds are reached. This convergence of AI, sensing, and continuous monitoring is central to achieving resilient, adaptive, and high-performing building envelopes over their entire lifecycle.

d. Urban Digital Twins and Simulation

The development of urban-scale digital twins that incorporate comprehensive building performance data enables sophisticated scenario modelling and policy analysis. By linking building-level assessment with urban metabolism models, the framework supports evaluation of district-scale interventions and system-wide optimization strategies. Digital twin platforms also provide a shared data environment that facilitates collaboration among multiple stakeholders, offering common access to detailed urban performance information. Their advanced simulation capabilities make it possible to test alternative development scenarios, assess their implications, and support evidence-based urban planning and policy design.

e. Predictive Analytics and Maintenance

Applying machine learning algorithms to longitudinal performance data enables the development of predictive maintenance strategies and the early detection of performance degradation. By integrating building age, usage patterns, and environmental exposure, the framework can generate accurate predictions of maintenance needs and optimal intervention timing. These predictive capabilities extend beyond maintenance to include energy performance forecasting, trends in occupant satisfaction, and assessments of regulatory compliance risk. Together, these applications support proactive management strategies that optimize resource allocation and improve the timing and effectiveness of interventions.

f. Climate Resilience and Extreme Events

Future research should more systematically address building performance under extreme weather conditions, including heatwaves, flooding, and severe storms. Climate change projections indicate an increasing frequency and intensity of such events, underscoring the need for enhanced assessment capabilities and robust adaptation strategies. Integrating climate scenario modelling with building performance assessment enables the evaluation of long-term resilience and the identification of particularly vulnerable building typologies and populations. Advanced modelling tools can simulate performance under different climate trajectories, thereby supporting strategic adaptation planning and investment prioritization.

g. Adaptive Façade Systems and Smart Technologies

Research on adaptive façade systems and smart building technologies offers significant opportunities for dynamic performance optimization in response to changing environmental conditions [f44]. When assessment capabilities are integrated with building control systems, they enable real-time performance feedback and autonomous system adaptation. Machine learning algorithms can further optimize façade operation on the basis of weather forecasts, occupancy patterns, and energy market signals. These capabilities enhance overall performance while reducing operational costs and associated environmental impacts.

h. Regional Adaptation and Policy Modelling

The development of region-specific adaptation strategies is essential to address varying climate risks and heterogeneous building stocks across different geographic areas. Integrating local climate data with building performance assessment supports targeted adaptation recommendations and the formulation of context-sensitive policy measures. At the same time, collaborative research networks can facilitate knowledge sharing and the dissemination of best practices between regions, while building institutional capacity for climate adaptation planning. Advanced policy modelling capabilities complement these efforts by enabling the evaluation of alternative regulatory scenarios and incentive structures. Coupling economic modelling with building performance assessment supports cost-effectiveness analysis and policy optimization, while scenario analysis allows exploration of different renovation targets, performance standards, and financing mechanisms in support of net-zero objectives by 2050.

i. Global Deployment and Developing Country Applications

Expanding global deployment requires research into low-cost assessment solutions that address barriers to implementation in developing countries and resource-constrained contexts. Simplified assessment approaches and reduced data requirements can enable broader adoption while preserving sufficient reliability and comparability of results. Capacity-building programmes and technology transfer initiatives are critical to support implementation in diverse institutional settings, helping to develop local expertise and sustainable, long-term operational capabilities.

j. Equity Analysis and Social Impact Assessment

Finally, integrating social equity considerations into building performance assessment directly addresses environmental justice concerns and helps ensure that the benefits of improvement measures are distributed fairly. Advanced analytical methods can be used to identify vulnerable populations and prioritise interventions for maximum social impact. Community engagement strategies and participatory assessment approaches further promote inclusive implementation, ensuring that renovation and adaptation strategies respond to specific community needs, preferences, and priorities.

6.5. Vision for Sustainable Urban Futures

The framework directly supports EU Digital Building Logbook requirements through automated data collection and performance documentation. Integration with national building databases enables systematic tracking of building performance evolution while supporting regulatory compliance and policy evaluation. Automated assessment capabilities significantly accelerate renovation wave implementation by enabling rapid identification and prioritization of buildings requiring energy performance improvements. The systematic approach supports the ambitious target of renovating 35 million buildings by 2030 while ensuring equitable resource distribution.

a. *Fit for 55 Package Implementation*

Integration with the EU "Fit for 55" package enables automated monitoring of progress toward the legally binding target of reducing greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. Within this framework, the building sector is recognized as a critical contributor to decarbonization, with specific measures aimed at improving energy performance, accelerating deep renovation rates, and phasing out fossil-fuel-based heating and cooling systems. In this context, enhanced façade assessment capabilities—especially AI-based methods for large-scale performance characterization—provide direct support to emission reduction goals by identifying underperforming envelopes, prioritizing retrofit interventions, and quantifying expected savings at building, district, and city scale.

For the purposes of the thesis, the most relevant Fit for 55 objectives include: the tightening of energy efficiency targets for the building stock, the requirement for progressively higher minimum energy performance standards, and the promotion of nearly zero- and zero-emission buildings through façade and envelope upgrades. These policy drivers strengthen the case for systematic, evidence-based façade evaluation, as they create a clear regulatory demand for reliable performance metrics, benchmarking tools, and scalable monitoring approaches that can be integrated into planning and compliance workflows.

The framework also aligns with the implementation of the Social Climate Fund, which is designed to mitigate distributional impacts of the green transition by supporting vulnerable households, micro-enterprises, and transport users. Automated façade assessment plays a role here by identifying buildings and communities that should receive priority attention, thus helping to ensure that renovation efforts are guided by just transition principles rather than solely by market dynamics. At the same time, the use of AI-driven analysis and standardized metrics reduces administrative burdens for local authorities and funding bodies, while improving the accuracy and granularity of targeting, making it easier to direct financial support and technical assistance where they can achieve the greatest social and environmental benefit.

b. Economic Impact and Job Creation

Widespread implementation of the framework has the potential to generate substantial economic benefits, particularly in terms of job creation across the construction, technology, and professional services sectors. Preliminary economic analyses suggest the creation of approximately 50,000 direct jobs and a further 125,000 indirect positions associated with implementation, operation, and maintenance activities. These employment effects are reinforced by targeted professional development programs and certification initiatives, which not only create opportunities for skill advancement but also strengthen institutional capacity for continuous assessment and optimization. In this way, investments in training and capacity-building contribute to long-term economic resilience while simultaneously advancing sustainability objectives. At the policy level, the framework is closely aligned with the objectives of the US Inflation Reduction Act, especially in relation to building efficiency improvements and the deployment of clean energy technologies. By integrating with existing federal and state incentive programs, the framework can help to optimize resource allocation, improve the targeting of subsidies, and shorten payback periods for building upgrades. Advanced economic modeling capabilities further support this alignment by enabling the evaluation of different incentive structures and their distributional and systemic impacts. This, in turn, facilitates the design of more effective programs and supports state and local implementation through standardized, comparable assessment approaches that still allow sufficient flexibility for regional adaptation and context-specific priorities.

c. ASHRAE Standards and Building Codes

Integration with ASHRAE 90.1 requirements and the provisions of the International Energy Conservation Code (IECC) ensures that the framework remains aligned with evolving building performance standards. Automated assessment capabilities can be directly embedded into compliance workflows, supporting more consistent and transparent code enforcement while substantially reducing the administrative burden on building officials. At the same time, integration with the professional community through established standards organizations facilitates broader adoption of the framework and anchors it within existing practice. Alignment with recognized professional norms, certification schemes, and accreditation pathways helps ensure methodological consistency, enhances credibility, and supports the gradual institutionalization of advanced façade assessment methods in everyday design, construction, and regulatory processes.

d. Global Climate Goals and International Cooperation

The framework directly supports implementation of the Paris Agreement by strengthening the capacity of the building sector to deliver substantive emission reductions. By integrating with Nationally Determined Contributions (NDCs), it enables systematic tracking of progress toward country-level climate commitments and provides a structured basis for increasing ambition in subsequent commitment periods. In this context, the framework also creates opportunities for international cooperation through technology transfer initiatives, capacity-building programs, and collaborative research networks, all of which facilitate global diffusion of best practices and knowledge sharing.

From an economic perspective, comprehensive studies indicate strong positive returns on municipal investments in automated assessment capabilities. Break-even analyses suggest that deployments covering more than 2,500–3,000 buildings can achieve positive returns within approximately 8–12 months, with five-year return-on-investment (ROI) projections in the range of 340–580%. Crucially, the cost–benefit balance extends well beyond direct savings associated with reduced manual assessment effort. Quantified benefits include improved policy effectiveness, more robust and efficient regulatory enforcement, and enhanced performance of incentive programs through more accurate targeting. Even when considering only the gains from better-focused energy efficiency interventions, the resulting savings are sufficient to justify implementation costs for cities with populations above roughly 50,000 inhabitants.

e. Property Value Enhancement

Building performance improvements supported by framework recommendations demonstrate significant asset value enhancement. Analysis indicates 4-8% value appreciation for residential properties and 10-20% for commercial buildings following strategic retrofit interventions. Enhanced building performance supports improved marketability while reducing operational costs and tenant turnover rates. These benefits contribute to overall asset performance while supporting broader market transformation toward higher performance standards.

f. Financing and Business Model Innovation

Multiple financing mechanisms support framework implementation including municipal budgets, EU structural funds, private investment, and public-private partnerships. Revenue sharing models with utility companies and energy service providers create sustainable funding streams for ongoing operations. Subscription-based models for regional or national deployment enable cost sharing across multiple municipalities while providing economies of scale for software maintenance and system improvements. These models support broader adoption while reducing individual municipal investment requirements. The framework provides essential tools for achieving net-zero building performance objectives by 2050 through systematic identification, prioritization, and optimization of improvement opportunities. Integration with emerging technologies and financing mechanisms supports accelerated transition while ensuring equitable access to improvement benefits. Continuous monitoring and assessment capabilities enable adaptive management strategies responding to changing conditions and emerging opportunities. These capabilities support long-term sustainability while maintaining flexibility for innovation and improvement.

g. Climate Resilience and Adaptation

Enhanced assessment capabilities support climate adaptation planning through systematic evaluation of building vulnerability and resilience characteristics[d67]. Integration with climate scenario modeling enables proactive adaptation strategies while reducing long-term risks and costs. Community resilience benefits from improved building performance while enhanced assessment capabilities support emergency preparedness and response planning. These applications contribute to overall urban resilience while addressing environmental justice concerns.

6.6. Final Remarks

This doctoral research establishes a new paradigm for urban building assessment that bridges the gap between individual building performance and city-scale sustainability objectives. The integration of advanced AI technologies with comprehensive performance frameworks enables systematic evaluation and optimization of urban building stocks at previously unattainable scales. The methodological contributions extend beyond technical innovation to include stakeholder engagement frameworks, policy integration mechanisms, and economic optimization strategies. This holistic approach addresses fundamental challenges in urban sustainability while providing practical tools for immediate implementation. The demonstrated capabilities for processing thousands of buildings with minimal manual intervention represent a transformative advancement in urban planning and building management. Automation of previously labor-intensive assessment processes enables comprehensive evaluation of entire urban building stocks while maintaining individual building resolution necessary for targeted interventions.

Integration with existing municipal systems and workflows reduces implementation barriers while enhancing decision-making quality across multiple organizational levels. These capabilities support evidence-based policy development while improving accountability and transparency in public resource allocation.

a. Global Implementation and Equity

The modular framework design supports global implementation while enabling adaptation to diverse cultural, economic, and institutional contexts. Low-cost deployment options address barriers in developing countries while capacity building programs support sustainable implementation. Emphasis on equity and social impact ensures that technology advancement contributes to inclusive urban development while addressing historical inequities in environmental quality and building performance[d8e]. These considerations support just transition principles while advancing global sustainability objectives.

b. Last but not least

This doctoral research demonstrates that the integration of artificial intelligence with comprehensive building performance assessment can transform urban sustainability practice while supporting achievement of global climate objectives. The systematic approach to methodology development, validation, and implementation provides a foundation for widespread adoption and continued innovation. The convergence of technical capability, policy alignment, and economic viability creates unprecedented opportunities for urban transformation toward more sustainable, resilient, and equitable built environments. Continued research and development in this field will play crucial roles in achieving net-zero objectives while enhancing quality of life for urban populations worldwide.

Through systematic implementation of the developed framework, cities can achieve measurable progress toward sustainability objectives while building institutional capacity for ongoing innovation and improvement. The demonstrated success provides confidence that artificial intelligence can serve as a powerful tool for addressing complex urban sustainability challenges while supporting evidence-based decision making and equitable resource allocation. The future of urban sustainability depends on our ability to systematically assess, understand, and optimize building performance at scale. This research provides essential tools and methodologies for achieving these objectives while establishing foundations for continued advancement in this critical field.

ACKNOLEDGEMENTS

This thesis would not exist without the confidence and support of mentors, colleagues, and friends who believed in my vision and sustained me through every challenge. First, I wish to thank my supervisor, Professor Francesco Fiorito, who has believed in me since the days of my master's degree, sensing even then that a meaningful project could grow from that path. Thanks also go to the outgoing coordinator of the doctoral program, Professor Vito Iacobellis, who was always punctual and supportive of us all.

Anyway, my deepest gratitude goes to David Lehrer - a true life mentor and now a dear friend - who sincerely opened me the doors of UC Berkeley and guide me in a collaboration that profoundly enriched both my work and my life perspective.

Thanks to Stefano Schiavon that give me every day the comforting sense of "casa", in California.

I am also grateful to Gail Brager, a brilliant mind, and to Paul Raftery, Ed Arens and Hui Zhang, tireless researchers to whom our scientific community owes so much. To the entire Center for the Built Environment (CBE), thank you for hosting me during a long and wonderful year.

Another thanks to two companions shaped the engine room of this thesis: Alessandra Luna Navarro and Nima Fouruzandeh - brilliant engineers and, in my view, rising stars of academia. Much of the research journey was shared with them; without their insight and constancy, these pages would look very different. My thanks go as well to Won Hee Ko of the New Jersey Institute of Technology, always open, generous, and collaborative in exchanging ideas and fresh intellectual stimuli.

Needless to say, I am also grateful to my friends at the Politecnico di Bari, especially Angelica Rota, Francesco Carlucci and Ludovica Campagna - genuine, people who, in my opinion, embody exactly the mix academia needs.

A really deep thanks to my mentors: for first Prof. Gianfranco Dioguardi, to whom I owe so much; our conversations helped me grow immensely as a person and professional. Dante Bini, one of the greatest minds of the twentieth century, whom now I am proud to call “friend”. To Prof. Vito Albino, a true example and heritage for our city, Bari, he keeps alive a credible vision of a technologically advanced region.

Finally, my deepest thanks to my family and to those who stand by me every day, people of tireless patience and boundless affection. Without you, without your love, none of this would have been possible.

BIBLIOGRAPHY

Aflaki, A., Mahyuddin, N., Al-Cheikh Mahmoud, Z., Baharum, M.R., 2015. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. Energy and Buildings 101, 153–162. https://doi.org/10.1016/j.enbuild.2015.04.033

Aksamija, A., 2015. Design methods for sustainable, high-performance building facades. Advances in Building Energy Research 10, 240–262. https://doi.org/10.1080/17512549.2015.1083885

Amine, B., 2023. SegmFormer vs DeepLabV3+ Analysis. GitHub Repository.

Armondi, S. (Ed.), 2018. Il governo della città complessa. Verso una nuova formazione. goWare & Edizioni Guerini e Associati, Milano.

ASHRAE, n.d. ANSI/ASHRAE/IES Standard 90.1-2019, Energy Standard for Buildings Except Low-Rise Residential Buildings (SI Edition).

Ashrafian, T., Moazzen, N., 2019. “The impact of glazing ratio and window configuration on occupant comfort and energy demand: The case study of a school building in Eskisehir, Turkey.” Sustainable Cities and Society 47, 101483. https://doi.org/10.1016/j.scs.2019.101483

Attia, S., Bilir, S., Safy, T., Struck, C., 2018. “Current trends and future pathways of building performance tools for sustainable design.” Energy and Buildings 179, 165–180. https://doi.org/10.1016/j.enbuild.2018.09.017

Awbi, H.B., 2014. Ventilation of Buildings. CRC Press.

Biljecki, F., 2022. Computer vision-based analysis of buildings and built environments: A systematic review. Building and Environment 226, 109699.

Borrmann, A., König, M., Koch, C., Beetz, J., 2018. Building Information Modeling: Technology Foundations and Industry Practice. Springer.

Bostancioglu, E., Onder, N.P., 2019. “Applying analytic hierarchy process to the evaluation of double skin façades.” Architectural Engineering and Design Management 15, 66–82. https://doi.org/10.1080/17452007.2018.1515062

BPIE Diaconu, D., 2024. What Is Needed for Effective EPBD Implementation?

Bueno De Mesquita, P.J., Delp, W.W., Chan, W.R., Bahnfleth, W.P., Singer, B.C., 2022. Control of airborne infectious disease in buildings: Evidence and research priorities. Indoor Air 32. https://doi.org/10.1111/ina.12965

Cannavale, A., 2020. Embodied carbon reduction in recycled façades’. Solar Energy 205, 25–37.

Cannavale, Alessandro, 2020. Chromogenic Technologies for Energy Saving. Clean Technologies 2, 462–475. https://doi.org/10.3390/cleantechnol2040029
Cannavale, A., Ayr, U., Fiorito, F., Martellotta, F., 2020. “Smart electrochromic windows to enhance building energy efficiency and visual comfort.” Energies 13, 1449.
Cannavale, Alessandro, Ayr, U., Fiorito, F., Martellotta, F., 2020. Smart Electrochromic Windows to Enhance Building Energy Efficiency and Visual Comfort. Energies 13, 1449. https://doi.org/10.3390/en13061449
Cannavale, A., Pugliese, M., Carlucci, F., Maiorano, V., Ayr, U., Fiorito, F., 2021. “Energy and daylighting performance of building integrated spirooxazine photochromic films.” Solar Energy 241, 513–525.
Castelluccio, R., Fraiese, M., Vitiello, V., 2025. Identifying Building Risk: The Potential Consequences of the Vulnerability of Building Envelopes’ Technical Elements. Tema 11. https://doi.org/10.30682/tema110002
Chen, F.C., 2022. Deep Learning–Based Building Attribute Estimation from Google Street View Images. Journal of Computing in Civil Engineering 36.
CloudFactory, 2024. DeepLabv3+ Computer Vision Wiki.
Commission, E., 2024a. Energy Performance of Buildings Directive. Publications Office of the European Union, Luxembourg.
Commission, E., 2024b. EU Building Stock Observatory: Statistical Pocketbook 2024. Publications Office of the European Union, Luxembourg.
Corp, S., 2025. Architectural facades for high performance buildings.
Crawley, D.B., Hand, J.W., Kummert, M., Griffith, B.T., 2008. Contrasting the capabilities of building energy performance simulation programs’. Building and Environment 43, 661–673. https://doi.org/10.1016/j.buildenv.2006.10.027
De Vries, S.W., Chamilothori, K., Aarts, M.P.J., 2025. Experimental Validation of *Radiance* -Based Methods for Simulating Solar Penumbras and Pinhole Projections. LEUKOS 21, 235–256. https://doi.org/10.1080/15502724.2024.2365691
Duarte Roa, C., Schiavon, S., Parkinson, T., 2020. Targeted occupant surveys: A novel method to effectively relate occupant feedback with environmental conditions. Building and Environment 184, 107129. https://doi.org/10.1016/j.buildenv.2020.107129
Enclos, 2020. High-performance facades: Design strategies for energy efficient buildings.
Escalada, M., 2024. Leveraging deep learning segmentation techniques and connected component analysis to automate high-level cost estimates of facade

retrofits using 2D images. VITRUVIO International Journal of Architectural Technology and Sustainability 9.
Ferreira, T.M., Ramírez Eudave, R., 2022. Assessing and Managing Risk in Historic Urban Areas: Current Trends and Future Research Directions. Front. Earth Sci. 10, 847959. https://doi.org/10.3389/feart.2022.847959
Fiorito, F., 2019. Smart Envelope Components to Decrease the Cooling Needs of Buildings. Cooling Energy Solutions For Buildings And Cities 185, 426–441.
Fiorito, F., Cannavale, A., Pesenti, M., Masera, G., 2020. “Performance assessment of BIPV/T double-skin façade for various climate zones in Australia: Effects on energy consumption.” Solar Energy 199, 377–399.
Fiorito, Francesco, Cannavale, A., Santamouris, M., 2020. Development, testing and evaluation of energy savings potentials of photovoltachromic windows in office buildings. A perspective study for Australian climates. Solar Energy 205, 358–371. https://doi.org/10.1016/j.solener.2020.05.080
Fiorito, F., Sangiorgio, V., Ayr, U., 2019. “Biomimetic adaptive building skins: Energy and environmental regulation in buildings.” Energy and Buildings 205, 109544.
Fiorito, F., Sauchelli, M., Arroyo, D., Pesenti, M., Imperadori, M., Masera, G., 2016. “Shape morphing solar shadings: A review.” Renewable and Sustainable Energy Reviews 55, 863–884.
Gilani, G., Blanco, A., Fuente, A., 2017. “A New Sustainability Assessment Approach Based on Stakeholder’s Satisfaction for Building Façades.” Energy Procedia 115, 50–58. https://doi.org/10.1016/j.egypro.2017.05.006
Graham, L.T., Parkinson, T., Schiavon, S., 2021. Lessons learned from 20 years of CBE’s occupant surveys. Buildings and Cities 2, 166–184. https://doi.org/10.5334/bc.76
Green Building Council, L., 2023. LEED rating system - United States [WWW Document]. U.S. Green Building Council. URL https://www.usgbc.org/leed
Guo, S., Bart, D., 2020. “Influence of design parameters on the night-time cooling potential of building facades in different climate zones.” Solar Energy 204, 352–365.
Habibi, S., Pons Valladares, O., Peña, D., 2020. “New sustainability assessment model for Intelligent Façade Layers when applied to refurbish school buildings skins.” Sustainable Energy Technologies and Assessments 42, 100846.
He, C., Zhang, R., Huang, Y.J., 2019. EnergyPlus validation with PMV’. Applied Energy 255, 113823.
HuggingFace, 2021. SegFormer Documentation.

ignatieva, maria, Dushkova, D., Nilon, C., Haase, D., Knapp, S., 2023. Integrating Biodiversity in Urban Planning and Design Processes. Book of abstracts of 7th International Conference of the network URBIO – Urban Biodiversity & Design. 28-30 November 2022, Helmholtz Centre for Environmental Research – UFZ Leipzig, Germany. https://doi.org/10.57699/HD4S-E705

Ikomia, A.I., 2024. DeepLabV3 Guide: Key to Image Segmentation.

Instituto Universitario de Arquitectura y Ciencias de la Construcción, Universidad de Sevilla, Spain, Acosta, I., Molina, J.F., Campano, M.A., 2017. Analysis of Circadian Stimulus and Visual Comfort Provided by Window Design in Architecture. IJET 9, 198–204. https://doi.org/10.7763/IJET.2017.V9.970

Kesik, Ted, 2023. Facade Futures: Building Resilience is Skin Deep.

Kim, J., Schiavon, S., Brager, G., 2018. "Personal comfort models–A new paradigm in thermal comfort for occupant-centric environmental control." Building and Environment 132, 114–124.

Knaack, U., Klein, T., Bilow, M., Auer, T., 2024. Facades: Principles of construction, 3rd edn. ed. Birkhäuser, Basel.

Ko, W.H., Kent, M.G., Schiavon, S., Levitt, B., Betti, G., 2021. A Window View Quality Assessment Framework. LEUKOS 18, 268–293. https://doi.org/10.1080/15502724.2021.1965889

Krylov, V.A., Kenny, E., Dahyot, R., 2018. Automatic discovery and geotagging of objects from street view imagery. Remote Sensing 10, 661. https://doi.org/10.3390/rs10050661

Lahmar, I., Cannavale, A., Martellotta, F., Zemmouri, N., 2022. The Impact of Building Orientation and Window-to-Wall Ratio on the Performance of Electrochromic Glazing in Hot Arid Climates: A Parametric Assessment. Buildings 12, 724. https://doi.org/10.3390/buildings12060724

Lamberti, F., Miranda, F., Bartoletti, D., n.d. USING COMPUTER VISION FOR THE AUTOMATIC CLASSIFICATION OF BUILDING FACADES.

Lamberti, V., Lehrer, D., Betti, G., Carlucci, F., Fiorito, F., 2024. "The Development of an Advanced Facade Map: An Evolving Resource for Documenting Case Studies." Sustainability 16, 10405. https://doi.org/10.3390/su162310405

LearnOpenCV, 2024. DeepLabv3 & DeepLabv3+ The Ultimate PyTorch Guide.

Lehrer, D., 2011. High-performance facades design strategies and applications in North America and Northern Europe.

Liu, H., Zhang, J., Yang, K., Hu, X., Stiefelhagen, R., 2023. CMX: Cross-modal fusion for RGB-X semantic segmentation with transformers. IEEE Transactions on Intelligent Transportation Systems 24, 14679–14694. https://doi.org/10.1109/TITS.2023.3300537

Liu, L., Ouyang, W., Wang, X., Fieguth, P., Chen, J., Liu, X., Pietikäinen, M., 2020. Deep learning for generic object detection: A survey. International Journal of Computer Vision 128, 261–318.

Liu, S., 2023. Grounding DINO: Marrying DINO with Grounded Pre-Training for Open-Set Object Detection.

Ma, P., Wang, L.-S., Guo, N., 2015. Maximum window-to-wall ratio of a thermally autonomous building as a function of envelope U -value and ambient temperature amplitude. Applied Energy 146, 84–91. https://doi.org/10.1016/j.apenergy.2015.01.103

Mandinec, J., Sasic Kalagasidis, A., Johansson, P., 2025. Predicting façade deterioration using machine learning approach with drone imagery and microclimate data. Automation in Construction 178, 106443. https://doi.org/10.1016/j.autcon.2025.106443

Marino, C., Nucara, A., Pietrafesa, M., 2017. "Does window-to-wall ratio have a significant effect on the energy consumption of buildings? A parametric analysis in Italian climate conditions." Journal of Building Engineering 13, 169–183.

Moghtadernejad, S., Chouinard, L.E., Mirza, M.S., 2020. "Design strategies using multi-criteria decision-making tools to enhance the performance of building façades." Journal of Building Engineering 30, 101274. https://doi.org/10.1016/j.jobe.2020.101274

Najjar, M., Figueiredo, K., Hammad, A.W.A., Haddad, A., 2019. "Integrated optimization with building information modeling and life cycle assessment for generating energy efficient buildings." Applied Energy 250, 1366–1382.

NeurIPS, 2021. SegFormer: Simple and Efficient Design for Semantic Segmentation with Transformers. NeurIPS Proceedings.

Øyen, C.F., 2012. WARM, WET AND WILD - Climate change vulnerability analysis applied to built environment.

Pellis, E., Masiero, A., Cortesi, I., Tucci, G., Betti, M., Grussenmeyer, P., 2023. A PERFORMANCE COMPARISON BETWEEN SEGNET AND DEEPLABV3+ ON THE SEMANTIC SEGMENTATION OF HERITAGE BUILDINGS. Int. Arch. Photogramm. Remote Sens. Spatial Inf. Sci. XLVIII-1/W1-2023, 379–386. https://doi.org/10.5194/isprs-archives-XLVIII-1-W1-2023-379-2023

Pomponi, F., Moncaster, A., 2016. Embodied carbon mitigation and reduction in the built environment – What does the evidence say? Journal of Environmental Management 181, 687–700. https://doi.org/10.1016/j.jenvman.2016.08.036

Prieto, A., Knaack, U., Auer, T., Klein, T., 2018. Passive cooling & climate responsive façade design. Energy and Buildings 175, 30–47. https://doi.org/10.1016/j.enbuild.2018.06.016

Rashidan, H., 2024. Semantic Segmentation of Building Models with Deep Learning. ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences.

Reinhart, C.F., Cerezo Davila, C., 2016. Urban building energy modeling – A review of a nascent field. Building and Environment 97, 196–202. https://doi.org/10.1016/j.buildenv.2015.12.001

Reinhart, C.F., Herkel, S., 2000. The simulation of annual daylight illuminance distributions — a state-of-the-art comparison of six RADIANCE-based methods. Energy and Buildings 32, 167–187. https://doi.org/10.1016/S0378-7788(00)00042-6

Roberts, M., Allen, S., Coley, D., 2020. Life cycle assessment in the building design process – A systematic literature review. Building and Environment 185, 107274. https://doi.org/10.1016/j.buildenv.2020.107274

Rota, A., Lamberti, V., Fiorito, F., 2024. Reuse of facade materials across benefits, challenges and potential opportunities, in: Colloqui.AT.e 2024 Convegno Artec. Ar.Tec., Palermo.

Sangiorgio, V., Fiorito, F., Santamouris, M., 2020. Development of a holistic urban heat island evaluation methodology. Sci Rep 10, 17913. https://doi.org/10.1038/s41598-020-75018-4

Santamouris, M., Haddad, S., Fiorito, F., Osmond, P., Ding, L., Prasad, D., Zhai, X., 2017. 'Urban heat island and overheating characteristics in Sydney, Australia. An analysis of multiyear measurements', Sustainability 9, 712.

Santamouris, M., Haddad, S., Saliari, M., Vasilakopoulou, K., Synnefa, A., Paolini, R., Fiorito, F., 2018. "On the energy impact of urban heat island in Sydney: Climate and energy potential of mitigation technologies." Energy and Buildings 166, 154–164. https://doi.org/10.1016/j.enbuild.2018.02.007

Schiavon, S., Altomonte, S., 2015. CBE Occupant Survey v2.0 methodology', Center for the Built Environment. University of California, Berkeley.

Schiavon, S., Altomonte, S., Kent, M.G., 2018. "Indoor environmental quality and occupant satisfaction in green-certified buildings." Building Research & Information 47, 255–274.

Schiavon, S., Cheung, T., Parkinson, T., Li, P., Brager, G., 2019. "Analysis of the accuracy on PMV–PPD model using the ASHRAE Global Thermal Comfort Database II." Building and Environment 153, 205–217. https://doi.org/10.1016/j.buildenv.2019.01.055

Schiavon, S., Hoyt, T., Piccioli, A., 2017. "Thermal comfort, perceived air quality, and cognitive performance when personally controlled air movement is used by

tropically acclimatized persons." Indoor Air 27, 690–702. https://doi.org/10.1111/ina.12352
Schiavon, S., Melikov, A.K., 2008. "Energy saving and improved comfort by increased air movement." Energy and Buildings 40, 1954–1960.
SegFormer, 2023. SegFormer Finetuned Segments CMP Facade. HuggingFace Model Hub.
Stephan, A., Jensen, C.A., Crawford, R.H., 2017. "Improving the Life Cycle Energy Performance of Apartment Units through Façade Design." Procedia Engineering 196, 1003–1010.
Stouzani, N., 2021. A Machine Learning Approach to Estimate Windows-to-Wall Ratio Using Drone Imagery. Lawrence Berkeley National Laboratory.
Sun, M., Zhang, F., Duarte, F., 2021. Automatic Building Age Prediction from Street View Images, in: IEEE Conference on Dependable, Autonomic and Secure Computing. https://doi.org/10.1109/IC-NIDC54101.2021.9660554
Szcześniak, J.T., Ang, Y.Q., Letellier-Duchesne, S., Reinhart, C.F., 2022. A method for using street view imagery to auto-extract window-to-wall ratios and its relevance for urban-level daylighting and energy simulations. Building and Environment 207, 108108. https://doi.org/10.1016/j.buildenv.2021.108108
T.A.B.U.L.A., 2024. Typology Approach for Building Stock Energy Assessment. Institut Wohnen und Umwelt, Darmstadt.
Tarkhan, N., Letellier-Duchesne, S., Reinhart, C., 2022. Capturing Façade Diversity in Urban Settings Using an Automated Window to Wall Ratio Extraction and Detection Workflow, in: 2022 Annual Modeling and Simulation Conference (ANNSIM). Presented at the 2022 Annual Modeling and Simulation Conference (ANNSIM), IEEE, San Diego, CA, USA, pp. 706–717. https://doi.org/10.23919/ANNSIM55834.2022.9859521
Tarkhan, N., Szcześniak, J.T., Reinhart, C., 2024. Façade feature extraction for urban performance assessments: Evaluating algorithm applicability across diverse building morphologies. Sustainable Cities and Society 105, 105280. https://doi.org/10.1016/j.scs.2024.105280
Team, E., 2025. Grounding-DINO + Segment Anything Model (SAM) vs Mask R-CNN Comparison. Encord Blog.
U.N.-Habitat, 2022. World cities report 2022: Envisaging the future of cities. United Nations Human Settlements Programme, Nairobi.
United Nations Environment Programme (2021) 2021 global status report for buildings and construction, n.d. . UN Environment Programme, Nairobi.
Wang, J., Sun, K., Cheng, T., Jiang, B., Deng, C., Zhao, Y., Liu, D., Mu, Y., Tan, M., Wang, X., Liu, W., Xiao, B., 2020. Deep high-resolution representation

learning for visual recognition. IEEE Transactions on Pattern Analysis and Machine Intelligence 43, 3349–3364. https://doi.org/10.1109/TPAMI.2020.2983686
Wang, L., 2025. Lightweight segmentation model for automated facade element recognition. Automation in Construction.
Xie, E., Wang, W., Yu, Z., Anandkumar, A., Alvarez, J.M., Luo, P., 2021. SegFormer: Simple and efficient design for semantic segmentation with transformers. Advances in Neural Information Processing Systems 34, 12077–12090.
Xu, C., Wang, L., Zhang, H., 2025. A novel deep learning and GIS integrated method for accurate city-scale assessment of building facade solar energy potential. Applied Energy 387, 125847. https://doi.org/10.1016/j.apenergy.2025.125600
Xu, F., Wang, S., Yan, L., Sun, S., 2023. Semantic segmentation of urban building surface materials from street view images. Automation in Construction 151, 104869.
Yang, L., Cheng, J.C., Wang, Q., 2021. "Semi-automated generation of parametric BIM for steel structures based on terrestrial laser scanning data." Automation in Construction 112, 103101.
Yang, S., Fiorito, F., Prasad, D., Sproul, A., Cannavale, A., 2021. "A sensitivity analysis of design parameters of BIPV/T-DSF in relation to building energy and thermal comfort performances." Journal of Building Engineering 41, 102426. https://doi.org/10.1016/j.jobe.2021.102426
Zhang, H., 2024. Zero-Shot Detection of Buildings in Mobile LiDAR using Grounding DINO and Segment Anything Model. ISPRS Archives.
Zhang, X., Wang, H., Hsieh, Y.-A., Yang, Z., Yezzi, A., Tsai, Y.-C., 2025. Deep Learning for Crack Detection: A Review of Learning Paradigms, Generalizability, and Datasets. https://doi.org/10.48550/ARXIV.2508.10256
Zhang, Y., 2025. A comprehensive review on computer vision analysis of building facades. Engineering Applications of Artificial Intelligence.
Zhou, Y., 2024. Unveiling Building Façade Deterioration, in: Proceedings of the 41st International Symposium on Automation and Robotics in Construction.
Zhuo, X., 2023. Direct Window-to-Wall Ratio Prediction Using Deep Learning Approaches, in: DLR Conference Proceedings.

LIST OF FIGURES

Figure No.	Title	Page
Figure 1	SWOT Analysis Synthesis	63
Figure 2	Evolution of Façade Performance Concepts Timeline	115
Figure 3	Accuracy Comparison of Façade Performance Measurement Methods	123
Figure 4	Measurement Complexity vs. Accuracy Trade-Off	124
Figure 5	Climate-Specific Performance Priorities Across Façade Dimensions	127
Figure 6	Performance Requirement Matrix by Building Type	128
Figure 7	Example of Façade Perspective Rectification and WWR Computation	135
Figure 8	Workflow of the manual WWR assessment protocol used for ground-truth generation.	141
Figure 9	High Performance Facade Definition due to CBE Facade Map	155
Figure 10	AI Model Performance Comparison for Facade Segmentation	173
Figure 11	AI-driven automated assessment pipeline architecture.	178
Figure 12	Distribution of Window-to-Wall Ratio values extracted from 12,690	196
Figure 13	Part of the code used to generate masks	198

Figure No.	Title	Page
Figure 14	Example of windows detection applied to Building 011_3	200
Figure 15	Example of windows detection applied to Building 011_3	202
Figure 16	Example of windows and threshold sensivity applied to Building 008	203
Figure 17	Example of building and windows analysis applied to building 008	204
Figure 18	Example of building and windows analysis applied to building 008	205
Figure 19	Integrated Multi-Criteria Facade Performance Assessment Matrix	239

LIST OF TABLES

Table No.	Title	Page
Table 1	Research Questions Framework and Objectives	22
Table 2	Comparative analysis of existing HPF definitions across literature, showing scope, dimensions addressed, and applicability constraints	73
Table 3	Performance Assessment Methods: Characteristics and Trade-offs	139
Table 4	Six Defining Characteristics of High-Performance Façades: Specifications	157
Table 5	Computer Vision Models: Architecture Comparison and Selection Rationale	181
Table 6	Policy Integration Matrix: Research Outputs to Policy Application	248
Table 7	Summary of Answer and how support evidences	265
Table 8	Contributions to Knowledge: Theoretical, Methodological, and Technical	267

ANALYTICAL INDEX

Topic	Pages
Accuracy / validation	2, 6–9, 18–20, 22, 26, 29–32, 34, 36–37, 41–44, 48–49, 56, 61, 69, 80–81, 90, 96, 115, 156, 158, 187, 224, 260, 361, 492 …
Adaptation (climate)	16, 21, 33, 35–36, 58, 64, 68, 70, 72–73, 83, 98, 100, 159, 167, 226, 346, 448, 486, 497 …
AI > computer vision approaches	3, 6, 8, 18–19, 26–27, 43, 46, 56, 84–85, 88, 96, 109, 158, 164, 199–200, 217, 225, 239, 334, 479
AI > ethics and bias	20, 30, 37, 49, 61, 82, 88, 95, 209, 276, 279, 321, 334, 383, 496 …
AI > privacy	49, 61, 90, 193, 196, 218, 241, 243, 319–321, 383, 496
Artificial intelligence (AI)	1–7, 9, 11, 13, 15, 49, 91, 143, 193, 241, 287, 329, 371, 408, 449, 495, 497, 499, 501 …
Benchmarking	9, 74, 82, 90, 95, 110, 148, 165, 217, 232, 319, 334, 479
Bias (algorithmic)	20, 30, 37, 49, 61, 82, 88, 95, 209, 276, 279, 321, 334, 383, 496
BIM	50, 58, 74, 131, 159, 346, 479
BREEAM	23, 103, 172, 176–177, 217, 232, 485
Building codes	24, 74, 110, 165, 202, 351, 479
Building registry	40, 64, 145, 159, 162, 239, 479

Topic	Pages
Building stock	15, 40, 74, 80, 86, 94, 157, 160–161, 316, 318–319, 346, 371, 407, 447–448, 479, 486, 495, 497
Calibration	14, 52, 134, 203, 342, 474
Case studies	28, 64, 69, 110, 158, 196, 239, 260, 482, 492
Center for the Built Environment (CBE)	14, 40, 44, 52, 79, 110, 132, 145, 158, 201, 225, 228, 260, 279, 352, 479, 492
CBE occupant survey	14, 44, 52, 79, 110, 132, 145, 158, 201, 228, 352, 473, 492
CityGML	58, 479
Climate change / decarbonization	6, 10, 62, 76, 110, 161, 260, 273, 479, 492
Computer vision	24, 67, 83, 96, 109, 158, 164, 196, 200, 217, 239, 346, 479
Condensation	21, 75, 167, 226, 271, 486
Correlation	6, 9, 55, 60, 79, 136–137, 166, 186, 188, 195, 201, 223, 330, 372, 490
Data integration	40, 64, 145, 159, 162, 239, 479, 488
Daylighting	2, 6, 8, 13, 17, 24, 28, 46, 55, 63, 65, 103, 110, 133, 137, 178, 223, 330, 473, 492
Decision support systems	2, 58, 110, 157, 239, 243, 260, 488
Deep learning	96, 158, 163, 225, 334, 479
Digital twin	58, 479

Topic	Pages
Durability	2, 13, 17, 24, 27–28, 46, 55, 65, 96, 98, 103, 110, 142, 167, 226, 270, 486
Embodied carbon	21, 75, 110, 167, 226, 260, 479, 492
Energy demand	12, 62, 110, 167, 226, 260, 346, 479
Energy performance	6, 8, 119, 126, 165, 175, 220, 224–225, 357, 371, 408, 479, 492
Energy Performance Certificate (EPC)	40, 159, 239, 479
Environmental Product Declarations (EPD)	79, 270, 479
Façade / facade	1–3, 6, 10, 12–13, 15–18, 21, 24–25, 28, 35, 40, 44, 52, 64, 79, 83, 110, 142, 158, 225, 239, 260, 479, 492
Facade deterioration	16, 21, 75, 167, 226, 486
GIS	58, 239, 260, 479, 488
Glare	6, 24, 55, 90, 133, 178, 223, 330, 473
Google Street View	18, 25–26, 56, 69, 81–82, 91, 93, 152, 204, 225, 239, 279, 334, 479, 497
Grounding DINO	164, 196, 199–200, 202, 205–208, 213, 217, 223, 225, 228, 231–232, 234, 239
High-performance façades (HPF)	6, 22, 64, 67, 77, 85, 103, 110, 142, 158, 223, 227, 260, 273, 279, 485, 492
IFC	58, 479

Topic	Pages
Indoor air quality (IAQ)	6, 90, 110, 223, 473
Indoor environmental quality (IEQ)	6, 79, 90, 110, 223, 473
International Energy Agency (IEA)	62, 479
Integration (urban)	2, 50, 58, 110, 157, 227, 239, 243, 260, 346, 479, 488
LEED	23, 103, 172, 177, 217, 232, 485
Life Cycle Assessment (LCA)	75, 110, 167, 226, 270, 479
Machine learning	96, 158, 163, 225, 334, 479
Maintenance	17, 24, 39, 43, 74, 83, 109–111, 113–114, 131, 167, 226, 270, 486, 495
Moisture	21, 75, 110, 167, 226, 270, 486
Multi-criteria assessment	2, 64, 77, 110, 142, 157, 239, 243, 260, 488, 492
Natural ventilation	6, 90, 110, 223, 492
Net-zero	62, 260, 273, 479
Object detection	158, 202, 232, 334, 479
OpenStreetMap (OSM)	40, 64, 159, 239, 479, 495
Overheating	16, 35, 64, 75, 110, 167, 226, 260, 346, 448, 486
Paris Agreement	62, 273, 479
Passivhaus / Passive House	23, 103, 172, 177, 217, 232, 485

Topic	Pages
Photogrammetry	14, 132, 134, 203, 342, 474
Policy alignment	2, 32, 58, 67, 77, 95, 110, 142, 157, 239, 243, 260, 346, 479, 488, 495, 497
Quality assurance	40, 64, 162, 239, 334, 479
Renovation Wave	58, 479
Resilience	16, 35, 58, 75, 110, 167, 226, 260, 346, 448, 486
Retrofit	2, 58, 110, 157, 227, 239, 243, 260, 346, 479, 488
Risk assessment	16, 21, 35, 58, 64, 75, 87, 110, 159, 167, 226, 260, 346, 448, 486
SAM	164, 196, 199–200, 202, 205–208, 213, 217, 223, 225, 228, 231–232, 234, 239
Scalability	18, 25, 32, 34, 37, 39, 46, 49, 59, 63, 78, 143, 158, 225, 260, 346, 479, 488, 495, 497
Semantic segmentation	24, 158, 232, 334, 479
Shading	6, 90, 110, 167, 223, 473, 492
Solar heat gain (SHGC)	110, 167, 223, 492
Statistical analysis	14, 55, 79, 132, 145, 147, 149, 201, 223, 372, 492
SWOT analysis	51, 334, 479

Topic	Pages
Thermal comfort	6, 8, 17, 46, 55, 115, 118–119, 122–123, 125, 137, 147, 167, 201, 223, 260, 330, 473, 486, 492
Traceability	40, 64, 162, 239, 479
U-value	110, 167, 223, 492
Uncertainty	1, 6, 35, 109, 158, 225, 260, 334, 492
Urban heat island (UHI)	16, 35, 58, 75, 110, 167, 226, 346, 448, 486
Urban planning	2, 58, 110, 157, 239, 243, 260, 488
Urban-scale assessment	2, 58, 64, 98, 103, 110, 142, 157–158, 225, 227, 239, 243, 260, 346, 479, 488, 492
Visual comfort	6, 24, 55, 65, 99, 133, 135, 137, 178, 195, 223, 330, 473, 492
Window-to-Wall Ratio (WWR)	6, 8, 28, 56, 79, 95, 121–122, 143, 151, 158, 201, 224, 228, 236, 259–261, 274–275, 287, 352, 410, 474, 492
Zoning	21, 33, 39, 351

CURRICULUM VITAE

Vito Lamberti

Date of Birth: December 21, 1990

Academic Email: v.lamberti@phd.poliba.it

Address (USA): 768 Natoma St., 94103 San Francisco (United States)

Address (Italy): Viale Tupparello, 16, 72015 Fasano (Italy)

ACADEMIC EXPERIENCE

CBE Facade Map Project Coordinator

Center for the Built Environment - University of California, Berkeley | 06/09/2020 – Current

City: Berkeley | **Country:** United States

Website: https://facademap.cbe.berkeley.edu

Adjunct Professor (12 ECTS)

Politecnico di Bari | 2022

City: Bari | **Country:** Italy

For the Master in Civil Infrastructure Management Engineering at Politecnico di Bari. Developed and delivered lectures on project management, business strategy, and management control, using interactive teaching methods and case studies. Evaluated final exams and supervised student projects, promoting essential managerial and organizational skills within an engineering framework.

Studies Member

Fondazione Gianfranco Dioguardi | 07/2015 – Current
City: Milano | **Country:** Italy

Contributed to research initiatives on urban regeneration, construction innovation, and public-private partnerships. Collaborated on publications and events aimed at promoting sustainable development and strategic planning in the built environment.

EDUCATION AND TRAINING

Ph.D. in Risk and Environmental, Territorial and Building Development

Politecnico di Bari - University of California, Berkeley | 01/11/2022 – 01/10/2025
City: Bari | **Country:** Italy | **EQF Level:** EQF level 8

VSPA Researcher

Center for the Built Environment - University of California, Berkeley | 09/06/2020 – 01/08/2025
City: Berkeley | **Country:** United States
Website: https://cbe.berkeley.edu/about-us/people/vito-lamberti/

Post Master Research Project

University of Berkeley, San Francisco | 01/2020 – Current

City: San Francisco, CA | **Country:** United States

Master's Degree in Engineering of Building Systems

Politecnico di Bari | 09/2018 – 06/2020

City: Bari | **Country:** Italy

Master's Degree in Building Sciences "Grado en Ciencia de la Edificación"

Universidad de Sevilla | 13/09/2018 – 09/05/2019

Country: Spain

Master in Building Management "Master en Gestion de la Edificación"

Universidad de Sevilla | 07/2019 – 01/2020

City: Sevilla | **Country:** Spain

Bachelor Degree in Building Engineering

Politecnico di Bari | 24/03/2015 – 04/05/2018

City: Bari | **Country:** Italy | **EQF Level:** EQF level 6

CERTIFICATIONS

- **LEED GA**

GBCI | 2026 – Current

- **Innovation Manager UNI 11814:2021**

TUV SUD s.p.a. | 2025 – Current

Country: Italy

- **Certified BIM Manager**

ICMQ s.p.a. | 2022 – Current

City: Milano | **Country:** Italy

- **Project Management and Planning Projects**

University of California, Irvine (USA) | 02/2020 – 02/2020

- **Certificate in Fire Plans**

Adeia S.a.s. | 12/2012 – 03/2013

City: Fasano | **Country:** Italy

Study of evacuation plans, fire prevention systems, structural escape routes, fire-resistant materials.

- **Project Manager Certification**

Project Management Institute | 02/2013 – 02/2013

City: Italia | **Country:** Italy

Training on project management, project objectives, project implementation.

- **Certificate in Sustainable Buildings**

Politecnico di Milano e Ordine degli Ingegneri della Provincia di Milano | 07/09/2012 – 13/12/2012

City: Milano | **Country:** Italy

LANGUAGE SKILLS

Mother tongue: Italian

Other languages:

English

- Listening: C1
- Reading: C1
- Writing: C1
- Spoken production: C1
- Spoken interaction: C1

French

- Listening: A2
- Reading: B2
- Writing: A2
- Spoken production: B1
- Spoken interaction: A1

Spanish

- Listening: C2
- Reading: C2
- Writing: C2
- Spoken production: C2
- Spoken interaction: C2

Levels: A1 and A2: Basic user; B1 and B2: Independent user; C1 and C2: Proficient user

PUBLICATIONS

[2024]

- **Mapping Advanced Facade** - Author
- **The Development of an Advanced Facade Map: An Evolving Resource for Documenting Case Studies** - Author
- **Reuse of Façade Materials Across Benefits, Challenges and Potential Opportunities** - Author
- **Mapping Advanced Facades: Creating a Building Taxonomy and Documenting Global Case Studies** - Author

[2020]

- **Degree Thesis:** Guidelines and metadata map on the development and spread of high-performance facade

[2019]

- **Degree Thesis:** El patrimonio como medio para relanzar una comunidad: el Mercado de fruta y Verdura

[2018]

- **AS-IS model applied to management of R.S.S.A. Sancta Maria Regina Pacis in Fasano (BR)**

[2017]

- **La via francingena del sud, nel territorio di Fasano**

CONFERENCES AND SEMINARS

- **Facade+** | 01/2025 | San Francisco (CA), United States
- **CBE Industry Meeting** | 10/2024 | Berkeley (CA), United States
- **Facade Tectonics** | 10/2024 | Salt Lake City (UT), United States
- **International Building Physics Conference** | 07/2024 | Toronto (ON), Canada
- **Colloqui.AT.e** | 06/2024 | Palermo (PA), Italy
- **Colloqui.AT.e** | 06/2023 | Bari (BA), Italy

AWARDS AND RECOGNITION

[2022]

European PNRR Grant 2022

European Committee / Italian Ministry of University