BETWEEN DESIGN INTUITION AND SIMULATIONS

A Standards informed Parametric Decision-Support Tool for Early-Stage Envelope Decision making.

Development and Application of Armadillo with in the LionCity II Case Study.

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Acknowledgements

We would like to express our sincere gratitude to Professor Gabriel Masera for his guidance and supervision throughout the development of this thesis. We are also grateful to the faculty members, students, and questionnaire respondents who contributed during the early stages of the research through their feedback, discussions, and technical input. Finally, we acknowledge the support of the university facilities, particularly the library resources and access to international standards, which provided an important foundation for the technical development of this work.

Declaration of Originality

We declare that this thesis is our own original work and that all sources, references, data, images, diagrams, and materials used in its preparation have been appropriately acknowledged and cited. We confirm that no part of this thesis has been submitted previously for another degree or academic qualification, unless clearly stated. Any external contributions, feedback, or support received during the development of this work have been properly recognised.

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Abstract

This thesis investigates decision-making in early-stage building-envelope design. It begins from the problem that many decisions with strong influence on building performance are made while the design is still flexible, whereas detailed analytical tools are often introduced only after the project has become more defined. Through a literature review and the development of the LionCity II case study in Brussels, the thesis identifies the point in the design workflow where envelope alternatives require faster, clearer, and more integrated comparative support.

The research develops Armadillo, a parametric, standards-informed decision-support tool for early-stage envelope design. The minimum viable prototype developed in this thesis focuses on opaque external wall assemblies. It supports the definition of materials, layers, and assemblies, and evaluates preliminary thermal, dynamic thermal, hygrothermal, cost, and embodied-carbon indicators. The calculation basis includes ISO 6946 for steady-state thermal performance, ISO 13786 for dynamic thermal behaviour, and ISO 13788 for surface humidity and condensation-risk screening. Armadillo does not replace detailed energy simulation, regulatory compliance, transient hygrothermal modelling, LCA platforms, or BIM workflows. Instead, it operates between design intuition and advanced simulation, helping designers compare, interpret, and refine envelope alternatives while decisions remain open. The thesis demonstrates the missing links with in existing workflows and how a parametric decision-support tool, that is Armadillo can make early-stage envelope options more legible, comparable, and performance-informed before detailed technical development, enabling faster preliminary decisions while reducing computational effort prior to formal verification of the selected option.

Sinossi

Questa tesi indaga il processo decisionale nelle fasi iniziali della progettazione dell'involucro edilizio. Parte dal problema che molte decisioni con una forte influenza sulle prestazioni dell'edificio vengono prese quando il progetto è ancora flessibile, mentre strumenti analitici dettagliati vengono spesso introdotti solo quando il progetto è più definito. Attraverso una revisione della letteratura e lo sviluppo del caso di studio LionCity II a Bruxelles, la tesi individua il punto del flusso di lavoro progettuale in cui le alternative per l'involucro richiedono un supporto comparativo più rapido, chiaro e integrato.

La ricerca sviluppa Armadillo, uno strumento parametrico di supporto alle decisioni, basato su standard, per la progettazione dell'involucro nelle fasi iniziali. Il prototipo minimo funzionante (MVP) sviluppato in questa tesi si concentra su assemblaggi di pareti esterne opache. Supporta la definizione di materiali, strati e assemblaggi e valuta indicatori preliminari termici, termodinamici, igrotermici, di costo e di carbonio incorporato. La base di calcolo include ISO 6946 per le prestazioni termiche in regime stazionario, ISO 13786 per il comportamento termico dinamico e ISO 13788 per l'umidità superficiale e la valutazione del rischio di condensa. Armadillo non sostituisce la simulazione energetica dettagliata, la conformità normativa, la modellazione igrotermica transitoria, le piattaforme LCA o i flussi di lavoro BIM. Si colloca piuttosto tra l'intuizione progettuale e la simulazione avanzata, aiutando i progettisti a confrontare, interpretare e perfezionare le alternative di involucro edilizio mentre le decisioni rimangono aperte. La tesi dimostra le lacune presenti nei flussi di lavoro esistenti e come uno strumento parametrico di supporto alle decisioni, ovvero Armadillo, possa rendere le opzioni di involucro edilizio nelle fasi iniziali più leggibili, comparabili e basate sulle prestazioni prima dello sviluppo tecnico dettagliato, consentendo decisioni

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List of Abbreviations & Acronyms

Acronym	Meaning
ACH	Air Changes per Hour
AEC	Architecture, Engineering and Construction
ADE	Armadillo Decision Engine
AI	Artificial Intelligence
ASE	Annual Sunlight Exposure
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building Energy Modelling
BIM	Building Information Modelling
BIM-LCA	Building Information Modelling–Life Cycle Assessment
C40	C40 Cities Climate Leadership Group
CEN	European Committee for Standardization
CIRIA	Construction Industry Research and Information Association
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalent
DA	Daylight Autonomy
DEMATEL	Decision-Making Trial and Evaluation Laboratory
DF	Daylight Factor
DOAS	Dedicated Outdoor Air System
E2BA	Energy Efficient Buildings Association
EN	European Norm
EN ISO	European adoption of International Organization for Standardization standards
EPB	Energy Performance of Buildings
EPBD	Energy Performance of Buildings Directive
EPD	Environmental Product Declaration
EPW	EnergyPlus Weather File
EU	European Union
EUI	Energy Use Intensity
GFRC	Glass Fibre Reinforced Concrete
GFA	Gross Floor Area
GHG	Greenhouse Gas
GH	Grasshopper
GIS	Geographic Information System
GSHP	Ground Source Heat Pump
GWP	Global Warming Potential
HB	Honeybee
HBJSON	Honeybee JavaScript Object Notation
HVAC	Heating, Ventilation and Air Conditioning
IBPSA	International Building Performance Simulation Association
IEQ	Indoor Environmental Quality
IEA	International Energy Agency
IMM	Integrated Modification Methodology
ISO	International Organization for Standardization
ISO/TR	International Organization for Standardization Technical Report
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LEED	Leadership in Energy and Environmental Design
MEP	Mechanical, Electrical and Plumbing
ML	Machine Learning
MMC	Modern Methods of Construction
MOO	Multi-Objective Optimisation
MVP	Minimum Viable Product
MW	Mineral Wool
NPS*	Tecnostrutture prefabricated steel–concrete composite structural system
NV	Natural Ventilation
OSB	Oriented Strand Board
PB	Plasterboard
PEB	Performance Énergétique des Bâtiments / Energy Performance of Buildings regulation
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
PRAS	Plan Régional d'Affectation du Sol / Regional Land Use Plan
PV	Photovoltaic
QGIS	Geographic Information System software used for spatial analysis
RH	Relative Humidity
RQ	Research Question
RRU	Règlement Régional d'Urbanisme / Regional Urban Development Regulation
sDA	Spatial Daylight Autonomy
SFS	Steel Framing System
SHGC	Solar Heat Gain Coefficient
SuDS	Sustainable Drainage Systems
SWOT	Strengths, Weaknesses, Opportunities and Threats
TOWS	Threats, Opportunities, Weaknesses and Strengths
TOTEM	Tool to Optimise the Total Environmental impact of Materials
UDI	Useful Daylight Illuminance
UNEP	United Nations Environment Programme
VAV	Variable Air Volume
VT	Visible Transmittance
WLC	Whole-Life Carbon
WUFI	Wärme Und Feuchte Instationär / transient hygrothermal simulation software
WWR	Window-to-Wall Ratio
ZEB	Zero-Emission Building
ZEMU	Zone d'Entreprises en Milieu Urbain / Urban Enterprise Zone

Symbol / Term	Meaning
A1–A3	Product stage modules in life-cycle assessment
C	Specific heat capacity
df / f	Decrement factor
fRsi	Internal surface temperature factor
g-value	Solar energy transmittance of glazing
$kgCO_2e$	Kilograms of carbon dioxide equivalent
kWh	Kilowatt-hour
kWh/m^2·year	Annual energy use per square metre
R-value	Thermal resistance
Rse	External surface heat-transfer resistance
Rsi	Internal surface heat-transfer resistance
R_T	Total thermal resistance
sd	Vapour-diffusion-equivalent air-layer thickness
U-value	Thermal transmittance
W/K	Heat-loss coefficient unit
W/m^2K	Thermal transmittance unit
W/mK	Thermal conductivity unit
Y11	Internal thermal admittance
Y12	Periodic thermal transmittance
Δt	Time shift / phase shift
λ	Thermal conductivity
μ	Water-vapour diffusion resistance factor
ρ	Density
ρs	Areal mass

Glossary of Technical Terms

Term	Definition
Active Conditioning	Mechanical heating, cooling, ventilation, and air-conditioning strategies used to maintain indoor comfort when passive design measures are insufficient.
Armadillo	The parametric, standards-informed decision-support tool developed in this thesis to support early-stage comparison of opaque external wall assemblies. It helps designers evaluate, gate, score, rank, and interpret envelope options before detailed simulation.
Brownfield Site	Previously developed land that may contain industrial remains, soil contamination, or infrastructure constraints. LionCity II is treated as a brownfield redevelopment site.
Daylight Autonomy	A daylight metric describing how often a space receives sufficient daylight during occupied hours without relying on artificial lighting.
Decision-Support Tool	A tool that helps users compare, interpret, and prioritize design options. It does not replace professional judgement, but makes performance implications clearer.
Decrement Factor	A dynamic thermal indicator showing how much an external temperature fluctuation is dampened as it passes through an envelope assembly. A lower value indicates stronger thermal damping.
Dominance Filtering	A decision-support step that removes alternatives that are equalled or outperformed by another option across all selected criteria.
Drying Potential	The capacity of an assembly to release accumulated moisture over time. It is important for moisture safety and durability.
Dynamic Thermal Behaviour	The way an envelope assembly responds to changing outdoor temperatures over time, considering thermal mass, heat storage, time shift, and damping.
Energy Use Intensity	Annual energy use divided by floor area, usually expressed in kWh/m²·year. It allows comparison between buildings or design scenarios of different sizes.
EnergyPlus	A building energy simulation engine used through workflows such as Honeybee to calculate heating, cooling, loads, and annual energy performance.
Envelope Gating	A pass/fail filtering process where an assembly that fails a critical target, such as moisture safety or maximum U-value, is excluded from ranking.
Envelope Ranking	The ordering of assembly options according to normalized performance scores and weighting priorities.
Glaser Method	A simplified steady-state method for screening interstitial condensation risk by comparing vapour-pressure and saturation-pressure profiles through an assembly.
HBJSON Export	A Honeybee-compatible data format used to transfer model or construction information toward simulation workflows.
Ideal Air System	A simplified HVAC assumption used in energy simulation to estimate heating and cooling loads without modelling a specific mechanical system in detail.
Natural Ventilation	Ventilation driven by wind pressure, buoyancy, or openings rather than mechanical fans. It is used as a passive strategy during suitable outdoor conditions.
Normalized Scoring	The conversion of different performance indicators into a common score range, allowing them to be compared and combined in the decision-support process.
Parametric Design	A design method where geometry, data, and performance outputs are linked through adjustable parameters, allowing rapid testing of alternatives.
Performance Indicator	A measurable value used to evaluate design performance, such as U-value, R-value, EUI, decrement factor, time shift, condensation risk, or embodied carbon.
Performance Target	A desired threshold or benchmark used to assess whether an assembly or design option meets the project's required level of performance.
Periodic Thermal Transmittance	A dynamic thermal property describing how periodic external temperature variations are transmitted through an envelope assembly.
Ranking Stability	A check of whether the preferred option remains the same when weighting assumptions change. It helps evaluate decision robustness.
Steady-State Thermal Performance	Thermal behaviour calculated under constant temperature conditions, mainly represented by thermal resistance and U-value.
Surface Humidity Screening	A simplified check used to identify whether internal surface conditions may create mould or condensation risk.
Trade-Off Analysis	The comparison of strengths and weaknesses between options, showing where an assembly performs well and where it may create risk or compromise.
Transparent Envelope	Glazed or transparent façade elements, including windows and curtain walls. These are acknowledged in the thesis as important future extensions for Armadillo.
Weighted Geometric Mean	A ranking method used in Armadillo to combine multiple category scores while penalizing severe weakness in any single performance area.

01

FOUNDATION

Chapter 1 introduces the research context, objectives, and methodology of the thesis. It examines the role of early-stage design decisions in shaping building performance, identifies the building envelope as a key area of intervention, and reviews the limitations of fragmented assessment workflows in architectural practice. The chapter concludes by defining the research gap and positioning Armadillo as an early-stage decision-support tool for envelope selection.

1.1 Introduction

Background and Motivation

High-performance buildings are shaped most decisively before they are fully defined. In the earliest stages of a project, decisions about massing, orientation, structure, material strategy, and envelope configuration establish the performance potential of the building long before detailed verification is possible. This early stage is therefore not only a conceptual phase; it is the moment when design decisions have the greatest capacity to influence energy demand, comfort, durability, construction cost, and long-term environmental impact. The importance of this moment is reinforced by project-delivery theory, which shows that the ability to influence performance is highest at the beginning of design, while the cost of change increases as the project progresses.[1]

Among these early decisions, the building envelope is especially consequential. The envelope is the primary interface between indoor and outdoor conditions, regulating heat transfer, solar gain, air infiltration, moisture migration, daylight admission, condensation risk, and the durability of construction layers. Because it mediates these exchanges continuously throughout the building's life, the envelope has a major influence on operational energy demand, indoor environmental quality, maintenance requirements, and cost. Yet envelope choices are commonly made at a stage when the design is still fluid and the information required for advanced simulation is incomplete.

This creates a persistent workflow problem. In conventional practice, envelope selection often relies on general guidelines, precedent, heuristic judgment, manual comparison of material properties, and disconnected calculations. More rigorous performance assessment is typically introduced later, when envelope systems have already been formalized and coordinated with the wider design disciplines. As a result, practitioners may commit to wall build-ups, insulation strategies, material layers, facade systems, and moisture-control approaches before receiving adequate feedback on their thermal efficiency, dynamic behavior, condensation risk, or cost implications. The problem is therefore not simply a lack of simulation, but a mismatch between the timing of consequential design decisions and the availability of accessible performance feedback.

This thesis responds to that mismatch through the development of Armadillo, a Grasshopper-based decision-support tool for early-stage building envelope selection. Armadillo is proposed as a lightweight, standards-informed, and design-accessible workflow that helps practitioners compare envelope options before the design becomes fixed. Rather than replacing detailed simulation, professional judgment, or architectural intuition, the tool provides early comparative feedback on thermal transmittance, thermal resistance, dynamic thermal behavior, decrement factor, time lag, condensation risk, and cost-related logic. Its purpose is to help practitioners make well informed envelope decisions during conceptual and schematic design, reducing the need for disruptive revisions later in the process.

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reliance on heuristic judgment, fragmented toolchains, manual comparison, and late-stage performance verification.

- To identify the envelope performance parameters that can be meaningfully assessed during conceptual and schematic design without requiring a fully resolved building model.
- To develop Armadillo as a parametric decision-support tool within the Rhino/Grasshopper environment, integrating layered assembly comparison, thermal performance calculation, dynamic behavior assessment, condensation-risk logic, and cost-related comparison.To apply the proposed workflow to the selected case study in order to demonstrate how early-stage envelope evaluation can inform architectural decision-making within a real design context.

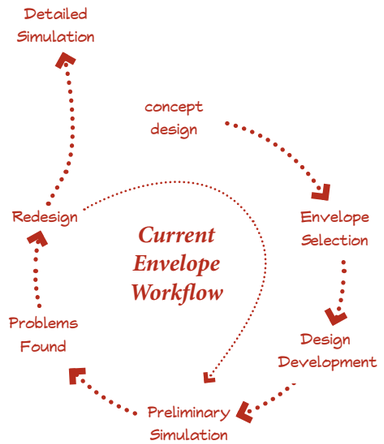


Fig 1.01 *Fragmented Early-Stage Envelope Design Process in Contemporary Architectural Practice*

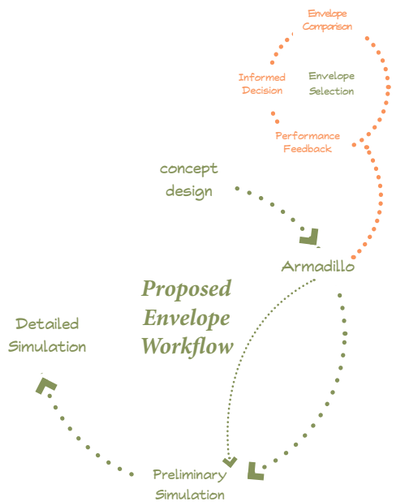


Fig 1.02 *Proposed Armadillo-Supported Workflow for Early-Stage Envelope Performance Evaluation*

- To position Armadillo as a complementary early-stage instrument rather than a replacement for detailed simulation, professional judgment, or later technical verification.

Research Questions

This thesis is organized around three research questions that move from the methodological problem, to the technical development of the tool, to its applied demonstration through a design case study.

RQ1. How can early-stage building envelope selection be supported by digital decision-support tools without disrupting the pace, openness, and creative agency of architectural design?

RQ2. Which envelope performance indicators can be meaningfully evaluated during conceptual and schematic design, and how can they be integrated into a parametric, standards-informed Grasshopper workflow?

RQ3. How can the proposed Armadillo workflow be applied to the LionCity II case study in Brussels to demonstrate early-stage envelope comparison and support performance-informed architectural decision-making?

These questions define the structure of the thesis. The first question establishes the methodological and disciplinary problem. The second question defines the technical and computational scope of the tool. The third question tests the workflow through the applied architectural case study.

Significance of the Study

The significance of this research operates at four interconnected levels: environmental, methodological, technical, and applied.

At the environmental level, the study responds to the urgent need to improve the performance of buildings from the earliest stages of design. Achieving net-zero and low-carbon targets requires more than efficient technologies added later in the process. It requires design methodologies that reduce energy demand, avoid poor material decisions, and improve passive performance before the project becomes technically locked in. Since the envelope has a major influence on heat transfer, durability, comfort, and operational demand, early envelope decisions are a critical part of this transition.

At the methodological level, the research contributes to the ongoing shift from late-stage performance

during conceptual and schematic design, reducing the need for disruptive revisions later in the process.

The current practices and methodologies will be demonstrated through the development of LionCity II case study in Brussels to further demonstrate the mismatch highlighted. The site provides a meaningful testing ground because it combines urban complexity, environmental ambition, regulatory constraints, and a mixed-use architectural program. Located at 50–56 Rue Osseghem, the 6,243 m^2 brownfield plot is planned for redevelopment, including housing, commercial spaces, and the future Cité du Cirque for UP Circus and Performing Arts.[2] Within this context, Armadillo is proposed not as an abstract computational exercise, but as part of a design methodology for testing envelope decisions in relation to climate, performance intent, and architectural development.

The broader relevance of this thesis lies in the environmental urgency of the built environment. Buildings and construction remain major contributors to the climate crisis, consuming up to 32% of global energy and contributing approximately 34% of global CO_2 emissions.1 The sector is not yet on track for net zero by mid-century, and global floor-area growth continues to offset efficiency improvements and decarbonization efforts.[3]

These conditions make early design methodology increasingly important. If buildings lock in patterns of energy demand, material use, and climate vulnerability for decades, then performance cannot remain a late-stage verification exercise. It must become part of the way design decisions are structured from the beginning.

Parametric design environments create an opportunity to support this shift. Rhino and Grasshopper allow designers to generate, compare, and revise alternatives within a flexible computational workflow, while tools such as Ladybug and Honeybee have already expanded environmental analysis within parametric design practice.[4] However, a practical gap remains between powerful simulation ecosystems and the specific task of early-stage envelope selection. Designers still often move between multiple platforms, spreadsheets, material databases, manual calculations, and specialist tools. Armadillo is positioned within this gap: not as a replacement for established simulation platforms, but as an early-stage instrument that brings envelope comparison into the same environment where design alternatives are being explored.

Problem Statement

The problem addressed by this thesis is not simply that building envelope performance is difficult to evaluate. It is that the in-depth evaluation of envelope options often occurs after the most consequential envelope decisions have already been made. During conceptual and schematic design, architects must select building envelope build-ups, insulation strategies, material layers, facade systems, and moisture-control approaches while the project is still fluid. Yet the tools capable of assessing these choices are frequently too detailed, too fragmented, or too disconnected from the design environment to support rapid early-stage comparison.

This creates a methodological gap in the design process. Envelope performance is often inferred through precedent, general guidance, manual calculations, or isolated material properties rather than assessed through a coherent comparative workflow. As a result, decisions that strongly affect energy demand, comfort, durability, and cost may be fixed before their implications are sufficiently understood. Later simulations can then become corrective rather than exploratory, leading to revisions, or re-evaluation of the proposed solutions, that might have been avoided if performance feedback had been available earlier.

The specific problem is therefore how to support early-stage envelope selection with a lightweight, interpretable, and design-integrated method of performance comparison. Such a method must be simple enough to operate during conceptual design, but rigorous enough to provide meaningful feedback on the relative performance of different envelope assemblies. This thesis addresses that problem through Armadillo, a Grasshopper-based decision-support workflow that integrates envelope selection, simplified performance analysis, and comparative feedback within the architect's parametric design environment.

Aim and Objectives

The aim of this thesis is to propose and develop an early-stage, Grasshopper-based decision-support workflow for building envelope selection, enabling architects to select and compare envelope options through simplified but meaningful performance indicators before detailed simulation and late-stage optimization become necessary.

- To achieve this aim, the thesis pursues the following objectives:
- To establish the importance of early-stage envelope decisions within high-performance building design and to clarify why these decisions have long-term consequences for energy demand, comfort, durability, and cost.
- To examine the limitations of existing envelope selection workflows, particularly their

Several limitations must be acknowledged. First, Armadillo is developed as a research prototype rather than a validated professional compliance tool. Its outputs should be understood as comparative indicators, not certified performance results. Second, the thesis does not include post-occupancy evaluation, since the project remains at proposal stage. Third, the work does not conduct exhaustive benchmarking against all existing simulation platforms. Fourth, while the case study engages with broader issues such as structural coordination, urban regeneration, and Modern Methods of Construction, the primary research contribution remains the early-stage envelope selection workflow.

These limitations do not reduce the relevance of the research. Rather, they clarify its position. The thesis addresses the stage before detailed verification: the stage where architectural decisions are still open, where performance direction is established, and where a lightweight, integrated decision-support tool can have the greatest design value.

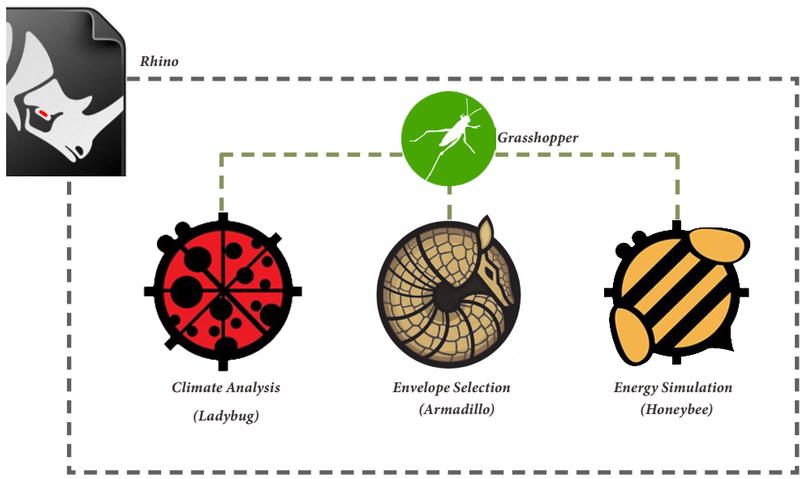


Fig 1.03 *Positioning of Armadillo within the Early-Stage Building Performance Design Ecosystem: Bridging Climate Analysis, Envelope Evaluation, and Detailed Simulation Workflows.*

verification toward early-stage performance-led design. Existing literature has repeatedly argued that simulation and environmental feedback should be introduced earlier in the design process.[6] However, the practical workflows available to architects often remain too fragmented, too slow, or too complex for routine use during concept development. This thesis contributes by framing early-stage envelope selection as a decision-support problem rather than only a simulation problem.

At the technical level, the thesis contributes the development of Armadillo, a parametric Grasshopper-based prototype conceived specifically for early-stage envelope evaluation. Its contribution lies in translating key envelope performance indicators into a design-accessible workflow. Instead of requiring the designer to move between disconnected workflows, manual calculations, and late-stage simulation platforms, Armadillo brings comparative envelope feedback into the parametric modeling environment. This allows envelope assemblies to be assessed while the design is still open to change, and maintaining the parametric workflow for faster response.

At the applied level, the research is grounded in the LionCity II site in Molenbeek-Saint-Jean, Brussels. The site provides a meaningful testbed because it combines urban complexity, environmental ambition, regulatory constraints, and a mixed-use architectural program. Located at 50–56 Rue Osseghem, the 6,243 m^2 brownfield plot acquired by citydev.brussels in 2020 is planned for redevelopment including housing, commercial spaces, and the future Cité du Cirque for UP Circus and Performing Arts.[2] Its context within the Brussels Region's Urban Revitalization Zone, together with the performance expectations of contemporary European building practice, makes it an appropriate case through which to test a performance-informed early-stage envelope methodology.

The study is therefore significant not because it claims to replace established simulation tools, but because it addresses the earlier decision-making gap that often determines whether those later tools are used for refinement or for damage control. By helping designers compare envelope options before design commitment, the research supports a more coherent relationship between architectural intention, environmental performance, and technical development.

Scope and Limitations

The scope of this thesis is defined by its disciplinary, technical, computational, and geographical boundaries.

The disciplinary scope lies at the intersection of architectural design, building engineering, environmental design, and computational design methodology. The thesis does not claim to provide a complete mechanical, structural, or construction-engineering solution. Instead, it focuses on how early-stage architectural decision-making can be strengthened through accessible envelope performance feedback. Structural coordination, Modern Methods of Construction, and broader building systems are acknowledged where they affect the case study, but they are not treated as independent fields of detailed technical design.

The technical scope is centered on the building envelope, with particular attention to multi-layer wall assemblies and their respective development. The main performance indicators considered are thermal transmittance, thermal resistance, dynamic thermal behavior, decrement factor, time lag, surface and interstitial condensation risk, and cost-related comparison. These indicators are selected because they are relevant to early-stage passive performance and can be evaluated before a fully detailed building model is available.

The computational scope is limited to the development and use of Armadillo within the Rhino/Grasshopper environment. The tool is conceived as a research prototype and decision-support instrument. It is not intended to replace certified energy modeling software, hygrothermal simulation tools, professional engineering judgment, or regulatory compliance procedures. Instead, it provides comparative feedback on envelope performance indicators to support early design choices and to guide which options should proceed to more detailed analysis.

The geographical and regulatory scope is anchored to the LionCity II case study in Brussels, Belgium. The design application is therefore situated within the climate, policy, and urban conditions of the Brussels Capital Region, including its temperate oceanic climate and relevant planning and energy-performance frameworks. While the method is intended to be transferable to other locations, the case-study results and design implications are calibrated to the Brussels context.

Limitations

1.2 Literature Review

The proposition underlying this thesis is that the most consequential moment in sustainable building design is the early stages of conceptual and schematic design, when fundamental decisions about urban configuration, site strategy, building form, and envelope composition are made under conditions of incomplete information and intense time pressure. This literature review traces the evidence supporting this premise, from the urban fabric through site conditions to the building envelope, and into the practices encompassing early-stage design, digital tools implemented, and methodologies that currently mediate or fail to mediate between design intuition and performance consequences.

This review is structured to build a clear argument rather than merely survey the field. It first examines the interdependence of decisions across the urban, site and building scales, and how early-stage choices influence sustainable performance. It then reviews the roles of digital tools used in the architecture, Engineering, and construction sector, hereinafter referred to as AEC, addressing both their contributions and limitations. A comparative review of precedents in parametric decision support follows a critical assessment of current methodological gaps. Net-zero building performance is then framed as the key design target. The literature is therefore evaluated against one question: do existing tools and methods help designers make informed decisions on envelope options early enough, quickly enough, and clearly enough to support informed architectural judgment?

Early-Stage Design Decision-Making

Design decisions are not equally consequential across the project timeline. Paulson's work, later reflected in the widely used MacLeamy curve (Fig1.04), establishes that the capacity to influence project outcomes is greatest at the beginning of the design phase. In contrast, the cost of change increases as the project advances.[5] Subsequent research supports the same overall pattern: early design choices account for a substantial share of long-term operational costs and environmental impacts, yet many building performance tools remain suited for late-stage evaluation, compliance, and quality control rather than proactively guiding the conceptual design phase.[6] As a result, sustainability-oriented methods are often introduced only after the most consequential design choices have already constrained the design space.

This temporal asymmetry is particularly important because early-stage decisions are not merely formal or organizational; they determine the physical conditions under which all subsequent optimization must proceed. Design variables such as building orientation, shape, aspect ratio, window-to-wall ratio, shading, and floor-to-floor height have already been identified as influential in the early design stage, with direct implications for life-cycle environmental performance. Later interventions can refine these outcomes, but they generally operate within constraints set by earlier choices .[7] The early stage is not merely a creative or speculative phase, but the point of highest design leverage. The literature reviewed below provides evidence that this principle holds consistently, from urban morphology through site analysis to envelope assembly selection.

At Urban Scale: Liveable Communities and the Performance Consequences of Urban Form

Urban-scale decisions made before individual buildings are designed establish the environmental and mobility conditions within which those buildings must later perform. Urban morphology, through street geometry, density, building height, spacing, orientation, and open-space distribution, shapes solar access, ventilation potential, outdoor thermal comfort, and building energy demand at the neighbourhood scale.[8,9] Urban morphology, therefore, does not merely organise forms visually; it conditions the performance boundaries of buildings and public space alike.

Within this context, the liveable community should be understood not only as a social objective but also as a performance framework. Gehl's human-scale approach argues that successful cities are planned around pedestrians, cyclists, and public life rather than around vehicular speed, linking urban quality to cities that are lively, safe, sustainable, and healthy[10]. Later review evidence strengthens this position by showing that greater walkability is associated with improved physical activity and health outcomes. At the same time, the accessibility and design of public space can support social interaction and social cohesion.[11,12] The 15-minute city translates these principles into a proximity-based planning model: Moreno et al. define it around access to daily needs within a short walk or cycle, structured through proximity, density, diversity, and digitalisation, and as an example, Paris has pursued this agenda as the ville du quart d'heure since 2020 under Anne Hidalgo's administration.[13,14] Shoina et al. (2024) show how these principles can be assessed at the district scale in Thessaloniki, making the approach methodologically relevant for regeneration contexts such as LionCity/ Delhaize.[15]

However, the 15-minute city has also been criticised, especially from a social-justice perspective. Mahmoudpour and Shirazi (2025a) argue that proximity-led urban improvement can reproduce rather than reduce inequality when it is associated with gentrification, displacement, segregation, exclusion, weak participation, and non-inclusive mobility[16]. Khavarian-Garmsir, Sharifi, and Sadeghi (2022) make a similar point from a broader review perspective, noting that the concept has been criticised for physical determinism and one-size-fits-all thinking, even as it offers important sustainability potential[17]. For this thesis, the implication is that urban-scale decisions shape the ambient conditions within which buildings must perform, so the relevance of these critiques is methodological rather than dismissive. They show that proximity-based planning is useful only when it is treated as context-sensitive, socially grounded, and institutionally inclusive, rather than as a universal spatial formula. The urban scale must therefore be evaluated not only through accessibility metrics, but also through questions of equity, participation, and local urban character.

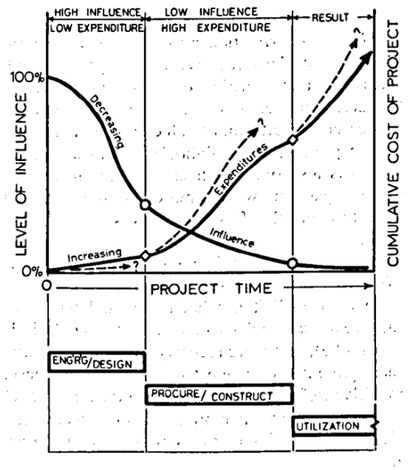


Fig 1.04 *The MacLeamy curve*

The Brussels Capital Region provides a particularly instructive context for this thesis, bringing together two issues central to the study. ZEMU, introduced in the 2013 revision of the PRAS, institutionalised the coexistence of housing and productive activities within specific urban zones.[18,19] Ryckewaert, Zaman, and De Boeck (2021) complement this institutional framework by showing how recent Brussels projects negotiate the spatial coexistence of productive, residential, and other functions, and how conflicts between these uses are mediated in practice.[20] At the same time, studies also show that social disadvantage overlaps with environmental pressures related to green infrastructure, housing, and mobility, which means that urban renewal must be assessed through environmental equity as well as spatial and energy performance. This is directly relevant to the LionCity/ Delhaize case, where the transformation of a former industrial site into a mixed-use neighbourhood raises linked questions of work–housing coexistence, climate vulnerability, and social inclusion.

At Site Scale: Holistic Sustainability and the Bridge Between Urban and Building Performance

If urban-scale decisions set the broad environmental context, site-scale analysis translates that context into project-specific constraints and opportunities. In the EU Level(s) framework, sustainability assessment begins at the conceptual design stage. It already includes comfort, acoustics, climate resilience, and flood risk, indicating that site conditions are part of early performance definition rather than a later technical check.[21] Firrone et al. (2024) also make the same point more directly: environmental analysis at the site scale requires investigation of geographic location, solar radiation, temperature, air speed, humidity, lighting, and noise before design strategies are selected.[22] At this scale, the site becomes the bridge between the urban context and building form, as local microclimate and surrounding morphology affect outdoor comfort and building performance, thereby shaping how climate-responsive the final design can be.

Site-scale solar analysis helps identify how orientation, surrounding buildings, and vegetation affect solar access, shading, and facade exposure, which in turn informs early decisions on glazing and shading strategy. The IEA notes that solar design is inherently site-specific and should account for neighbouring buildings and trees, while Shirinyan, Stefanov, and Petrova-Antonova (2025) present 3D solar studies showing that the inclusion of urban trees can significantly affect solar study results.[23] Wind analysis is equally site dependent. Reiter (2010) shows that local wind speeds and solar radiation are the microclimatic parameters most strongly influenced by urban geometry and relevant to pedestrian comfort and the natural-ventilation potential of buildings. These assessments, therefore, need to be carried out at the site stage, because later corrective measures are generally less effective than early decisions on building shape, size, position, and orientation, which ultimately define the design's passive performance potential.[24]

The idea of conclusive sustainability in this thesis is expressed at the site scale through an integrated reading of ecology, microclimate, local context, and social use. Ayoobi, Inceoğlu, and Inceoğlu (2024) identify 23 sustainability indicators across global sustainable-building studies and assessment methods, then propose a more holistic model built around seven core indicators: Sites & Ecology, Energy, Materials & Resources, Indoor Environmental Quality, Water, Vernacular Principles, and Social–Culture. Their DEMATEL (fig…) analysis further shows that Sites & Ecology had the strongest positive causal role in the model, indicating that site intelligence is not merely a preliminary checklist item but a foundational condition that influences other sustainability dimensions.[25] This builds on the work of this thesis by supporting a site-based understanding of sustainability that encompasses not only energy and materials but also cultural and social dimensions.

Site conditions define the passive opportunities available to the building. Wind-driven rain exposure shapes facade detailing, material durability, and moisture control[26], while the effectiveness of thermal mass depends on local diurnal temperature variation and night-time cooling potential. Natural ventilation and daylighting also depend on site-specific wind patterns, surrounding geometry, and local daylight availability.[27,28] In the European frameworks, these issues are formally part of conceptual design and should be considered from the outset.[21] However, research on early-stage performance tools shows that in conventional workflows, this analysis is often too shallow or too weakly connected to key form and envelope decisions to shape them effectively.[29,30] This thesis addresses that gap by treating site intelligence not as a checklist exercise, but as a design input that must directly inform early building and envelope decisions.

At Building Scale: The Building Envelope as High-Impact Design System

Once site conditions have defined the building's passive opportunities and constraints, those potentials are materialised at the building scale through the envelope, which acts as the primary interface between climate, context, and indoor performance. The building envelope is one of the highest-leverage systems in sustainable building design, aligning with Brunoro (2024). It governs heat exchange and strongly affects airtightness, moisture protection, daylight transmission, acoustic performance, and indoor comfort. According to the Energy Efficient Buildings Association (E2BA, 2012), the envelope accounts for about half of a building's overall energy balance and roughly 57% of thermal loads.[31,32] As operational energy is reduced in high-efficiency buildings, material-related emissions become increasingly important, and envelope material

choices can significantly affect upfront carbon emissions; case-study evidence from Bologna shows that low-carbon facade specifications can reduce facade emissions by up to 30%. The envelope should therefore be treated as a whole-life, multi-criteria system rather than a purely thermal one.

Leccese, Salvadori, and Bisegna (2024) show that dynamic thermal behaviour cannot be reduced to the U-value alone, because the decrement factor and time lag depend on how resistance and capacity are distributed through the wall assembly and are further influenced by internal elements such as partitions and slabs.[33] Moisture performance is equally significant. High-performance envelopes often include higher insulation levels and improved airtightness, but these measures can alter vapour movement and the risk of condensation within wall assemblies. EN 15026 distinguishes transient hygrothermal assessment from simplified steady-state approaches, such as the Glaser method in EN ISO 13788, because real moisture behaviour involves storage, transport, liquid flow, and changing boundary conditions. While detailed hygrothermal simulation may be too advanced for early concept design, ignoring the risk of condensation at the envelope selection stage is equally problematic. A decision-support workflow should therefore provide early-warning logic to help designers identify assemblies that require further verification.

Static Daylight factor methods are also insufficient because they do not account for climate, latitude, orientation, or shading behaviours accordingly. Current assessments rely on climate-based metrics such as DA, sDA, ASE, and UDI, which are better suited to understanding annual performance. [34]However, daylight analysis is often handled separately from envelope thermal and moisture assessment. This separation can cause designers to optimize one dimension while undermining another, for example, improving daylight access while increasing solar gains, cooling risk, or facade cost.

Whole-life carbon further complicates envelope selection. More insulation or more complex façade systems may reduce operational energy use, but they can increase embodied carbon and costs. Monteiro, Freire, and Fernández (2020) identify insulation tipping points beyond which additional thickness becomes counterproductive, as embodied impacts rise faster than operational savings fall.[35] The critical and unresolved issue is the timing; it is not the importance of these decisions, but the time at which they are made. Optimal envelope configurations are highly context-dependent, shaped by climate and grid carbon intensity, so both under- and over-investment in envelope-efficiency measures can increase total carbon.[36] These studies support a multi-criteria view of the envelope as a system of trade-offs rather than a single technical target.

The envelope is therefore not simply a thermal barrier. It is a multi-criteria performance system in which thermal resistance, dynamic thermal behaviour, moisture safety, daylight, solar gain, embodied carbon, cost, durability, and constructability interact. This supports the second premise of Armadillo, envelope selection deserves its own early-stage decision-support workflow. Negendahl (2015b) and Østergård, Jensen, and Maagaard (2016b) show that early-stage simulation remains poorly aligned with the speed, uncertainty, and iterative nature of concept design.[37,38] This mismatch helps explain why the gap between predicted and actual building performance persists. In their study, Zambrano, Oberegger, and Salvalai (2021) note that the performance gap reported in the literature can vary by a factor of 0.2 to 4, with measured energy use usually higher than predicted.[39]

Literature shows that these trade-offs are still rarely assessed in an integrated way at the stage when envelope decisions are most influential. Instead, evaluation is often fragmented across separate tools, delayed until design development, or mediated through specialist workflows that are too slow and discontinuous for concept design.[36,30,6]. The consequence is not only weaker performance reasoning, but a repetitive back-and-forth process in which envelope choices are repeatedly revised, coordination becomes inefficient, and critical early opportunities for climate-responsive design are lost. What is therefore needed is not simply more analysis, but an integrated early-stage workflow capable of making envelope trade-offs visible across multiple criteria with enough clarity, speed, and contextual sensitivity to support architectural decision-making when it matters most.

Tab 1.01 *Standards-Informed Envelope Performance Indicators for Conceptual and Schematic Design*

Performance category	Indicator	Early-stage evaluation	Main standard/ framework basis
Static thermal performance	Layer thermal resistance, R-value(m^2·K/W)	Yes- high confidence	EN ISO 6946 EN ISO 10456
Static thermal performance	Overall thermal transmittance, U-value(W/m^2·K)	Yes- high confidence	EN ISO 6946 EN ISO 10456
Static thermal performance	Area-weighted envelope U-value(W/m^2·K)	Yes- high confidence	ISO/TR 52018-2 ISO 52003-1
Thermal bridge risk	Linear thermal bridge risk / approximate ψ-value(W/m·K)	Partly- medium to low confidence	ISO 10211 ISO/TR 52018-2
Dynamic thermal behaviour	Areal heat capacity (kJ/ m^2·K)	Yes- medium confidence	EN ISO 13786 EN ISO 10456
Dynamic thermal behaviour	Periodic thermal transmittance(W/m^2·K)	Yes- medium confidence	EN ISO 13786
Dynamic thermal behaviour	Decrement factor	Yes - medium confidence	EN ISO 13786
Dynamic thermal behaviour	Time shift/phase shift in (hours (h)	Yes - medium confidence	EN ISO 13786
Surface moisture risk	Internal surface temperature factor, fRsi	Yes - medium confidence	EN ISO 13788
Surface moisture risk	Critical surface humidity / mould-risk screening (% RH or pass/fail)	Yes - medium confidence	EN ISO 13788
Interstitial moisture risk	Interstitial condensation risk (kg/m^2)	Yes - screening only	EN ISO 13788 ISO 9346
Drying behaviour	Drying potential (kg/m^2/ year)	Partly - screening only	EN ISO 13788
Transparent envelope	Window / curtain-wall U-value (W/m^2·K)	Yes - high confidence if product values exist	EN ISO 10077-1 EN ISO 10077-2 Passive House Institute criteria
Transparent envelope	Window-to-wall ratio, WWR (%)	Yes - high confidence	Geometry-based LEED/daylight practice
Solar control	g-value / SHGC	Yes - medium confidence	EN ISO 52022-1 ISO/TR 52018-2 ASHRAE 90.1
Solar control	Shading effectiveness	Yes - medium confidence	EN ISO 52022-1 ISO/TR 52018-2
Daylight potential	Visible transmittance/ daylight proxy (%)	Partly - medium to low confidence	EN 17037 LEED daylight credit framework
Overheating tendency	Summer overheating risk proxy (°C·h)	Partly - medium confidence	ISO/TR 52018-2 Passive House summer comfort
Airtightness	Airtightness target/ infiltration sensitivity (ACH, h^{-1})	Partly - scenario-based	ISO 9972 Passive House airtightness criterion
Envelope energy proxy	Transmission heat-loss coefficient (W/K)	Yes - medium confidence	EN ISO 13789 ISO 52016-1
Envelope energy proxy	Heating demand proxy (kWh/m^2/year)	Partly - medium confidence	ISO 52016-1 ISO 15927-6 Passive House heating demand
Envelope energy proxy	Cooling demand proxy (kWh/m^2/year)	Partly - medium confidence	ISO 52016-1 ISO/TR 52018-2
Embodied carbon	Embodied carbon per m^2 of assembly ($kgCO_2e/m^2$)	Yes - medium confidence	EN 15804 EN 15978 Level(s) framework LEED life-cycle assessment credit framework
Cost	Cost per m^2 of assembly (€/ m^2)	Yes - medium confidence	ISO 15686-5
Durability/resilience	Durability and maintenance score (years)	Partly - qualitative to semi-quantitative	ISO 15686-1 ISO 15686-8 EN 15804

Label	Meaning
Yes - high confidence	Can be reliably calculated during the conceptual design phase using basic available inputs. Suitable for direct comparison between options.
Yes - medium confidence	Can be evaluated during the conceptual design, but the result depends on assumptions such as indoor humidity, occupancy, climate simplification, or material defaults. Suitable for screening and comparison, not final compliance.
Partly - medium to low confidence	Can be estimated as a proxy, but accuracy is limited because some important design details are not yet known. Useful for identifying tendencies and risks.
Screening only	Useful as an early-warning check. Failed or risky results should be verified with a more detailed method.

Static Daylight factor methods are also insufficient because they do not account for climate, latitude, orientation, or shading behaviours accordingly. Current assessments rely on climate-based metrics such as DA, sDA, ASE, and UDI, which are better suited to understanding annual performance.[34] However, daylight analysis is often handled separately from envelope thermal and moisture assessment. This separation can cause designers to optimize one dimension while undermining another, for example, improving daylight access while increasing solar gains, cooling risk, or facade cost.

Whole-life carbon further complicates envelope selection. More insulation or more complex façade systems may reduce operational energy use, but they can increase embodied carbon and costs. Monteiro, Freire, and Fernández (2020) identify insulation tipping points beyond which additional thickness becomes counterproductive, as embodied impacts rise faster than operational savings fall.[35] The critical and unresolved issue is the timing; it is not the importance of these decisions, but the time at which they are made. Optimal envelope configurations are highly context-dependent, shaped by climate and grid carbon intensity, so both under- and over-investment in envelope-efficiency measures can increase total carbon.[36] These studies support a multi-criteria view of the envelope as a system of trade-offs rather than a single technical target.

The envelope is therefore not simply a thermal barrier. It is a multi-criteria performance system in which thermal resistance, dynamic thermal behaviour, moisture safety, daylight, solar gain, embodied carbon, cost, durability, and constructability interact. This supports the second premise of Armadillo, envelope selection deserves its own early-stage decision-support workflow. Negendahl (2015b) and Østergård, Jensen, and Maagaard (2016b) show that early-stage simulation remains poorly aligned with the speed, uncertainty, and iterative nature of concept design.[37,38] This mismatch helps explain why the gap between predicted and actual building performance persists. In their study, Zambrano, Oberegger, and Salvalai (2021) note that the performance gap reported in the literature can vary by a factor of 0.2 to 4, with measured energy use usually higher than predicted.[40]

Literature shows that these trade-offs are still rarely assessed in an integrated way at the stage when envelope decisions are most influential. Instead, evaluation is often fragmented across separate tools, delayed until design development, or mediated through specialist workflows that are too slow and discontinuous for concept design[36,30,6]. The consequence is not only weaker performance reasoning, but a repetitive back-and-forth process in which envelope choices are repeatedly revised, coordination becomes inefficient, and critical early opportunities for climate-responsive design are lost. What is therefore needed is not simply more analysis, but an integrated early-stage workflow capable of making envelope trade-offs visible across multiple criteria with enough clarity, speed, and contextual sensitivity to support architectural decision-making when it matters most.

Digital Tools and Decision-Making in Architectural Practice

Digital tools now mediate a large share of architectural decision-making. Still, as established in the preceding sub-chapters, their analytical strength remains poorly matched to the stages where decisions matter most. Many tools used in early design cannot provide reliable feedback while remaining flexible enough for rapidly changing concepts. In contrast, simulations are still used only to a limited extent in the early phases, even though those phases have the greatest influence on performance and cost.[6,31]

Within the broader scope of Digital tools adopted in the construction industry, BIM workflows are now institutionally embedded in European construction through public-sector digitalisation initiatives and the growing regulatory emphasis on whole-life carbon assessment. The EU BIM Task Group presents BIM as a major instrument for transforming construction delivery, while the revised EPBD introduces life-cycle carbon calculation requirements for new buildings. Yet the performance promise of BIM remains only partially realised. Jung, Häkkinen, and Rekola (2018) show that energy, environmental quality, lighting, and acoustics are typically assessed after the main architectural phases and passed to engineers during technical design, while Burgess et al. (2026) report from interviews across eleven European countries that BIM is still used chiefly for coordination and process management rather than to improve resource efficiency.[40,41]

In Parametric environments, performance feedback is closely linked to the geometry, particularly in facade and environmental design workflows. Grasshopper-based facade studies now combine thermal, daylight, glare, ventilation, environmental, and cost objectives within early-stage exploration. Yet this capability has not translated into broad professional uptake, especially given the slight differences in the design of the global building envelope. Mahmoud, Kamara, and Burford (2020) report that early-stage use of building energy performance simulation remains limited in practice, partly because architects experience these tools as knowledge-intensive, time-consuming, or detached from their design process.[4243]

Multi-objective optimisation is now mature in parametric design workflows and effectively supports decision-making by generating and comparing high-performing alternatives across multiple criteria. Common MOO studies use Pareto-based workflows to balance energy, daylight, thermal discomfort, ventilation, environmental impact, and cost, allowing practitioners to explore trade-offs across multiple variables within a limited timeframe.[44] Additionally, Wang et al. (2024) investigate the adoption of machine-learning surrogates, showing that repeated simulations in early-stage optimisation can be replaced with near-instant evaluations with low prediction error, which is particularly valuable in concept design, where information remains flexible, and decisions must be made quickly.[45] However, these methods primarily improve the speed and breadth of option generation rather than the act of selection itself. Pareto-optimal sets make efficient trade-offs visible, but they do not rank alternatives or determine which option is most appropriate for a given design intent. For that reason, multi-objective optimisation and decision support should be understood as related but distinct steps: the former structures the solution space, while the latter supports the designer in interpreting and selecting among the alternatives produced.

The main barriers to performance analysis in early design are not only technical but organisational and cultural. Purup and Petersen (2020), drawing on Danish practice, identify five recurring obstacles: performance is often treated as secondary to form-giving, measurable criteria are feared to displace architectural judgement, workflows between architects and engineers do not align, existing tools remain poorly suited to design practice, and early-stage fees rarely support detailed analysis. Tool improvement, therefore, matters, but interface simplification alone cannot resolve the decision-support gap.[45] Another difficulty is that authority over performance-relevant envelope decisions is fragmented across stakeholders with different priorities. Architects, contractors, subcontractors, and clients do not value the same criteria, architects prioritise performance and appearance. In contrast, contractors and subcontractors give greater weight to delivery time, ease of installation, system simplicity, and coordination. This divergence creates a predictable tension between design intent and delivery priorities.

Lifecycle assessment has entered digital workflows, but its integration remains structurally late. Bolognesi et al. (2025) find that the dominant BIM-LCA workflow still exports quantities from BIM into external LCA tools rather than embedding carbon feedback directly in design modelling.[46] Huang et al. (2024) show that many BIM-based embodied-carbon frameworks still rely on project-delivery documents or construction-stage data, which limits early design optimisation and decision support.[47] In practice, whole-life carbon assessment is increasingly possible, but it often remains reactive rather than generative.

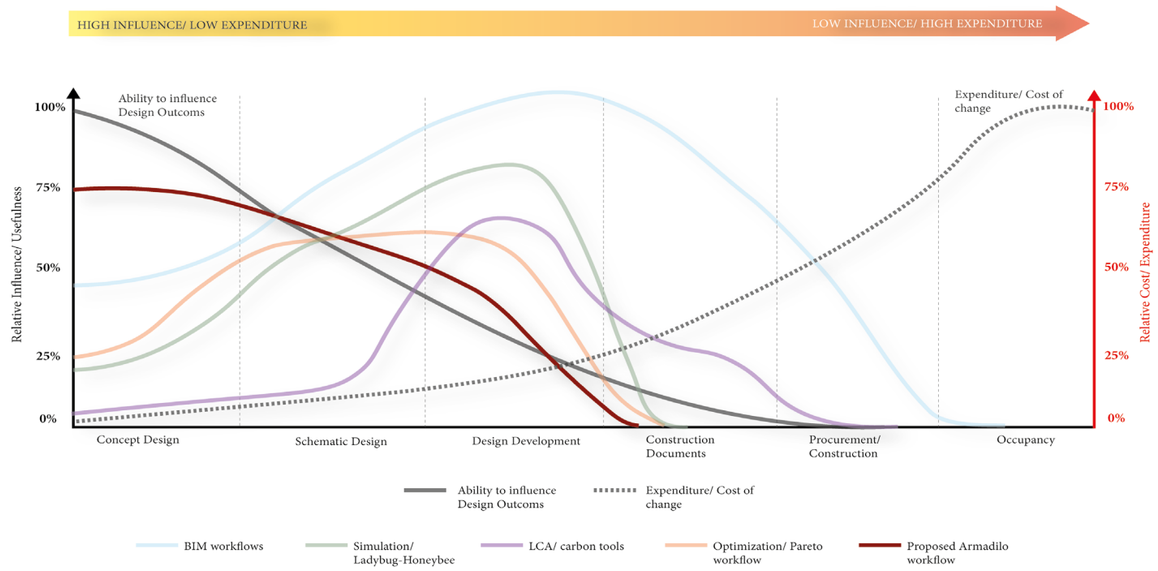
Across the literature, the problem is not the absence of digital tools but the misalignment between analytical capability, workflow integration, and decision timing. Although simulation, optimisation, BIM, and LCA platforms have significantly expanded the capacity to evaluate design performance, they remain too fragmented, too specialist-dependent, or too weakly embedded in concept design to guide the decisions during the stage that matters most. The consequence is not only a decision-support gap but also a process inefficiency: when early-stage guidance is limited, design development can become a repetitive back-and-forth workflow of revisions, reassessments, and late adjustments that consume time, disrupt coordination between disciplines, and place added pressure on the project's critical path. What remains missing is not more analytical power, but an early-stage decision-support framework that is comparative, accessible, multi-criteria, and directly usable within the architect's iterative design process.

The comparative reading shows that existing tools are not irrelevant; they are essential parts of contemporary practice. The problem is that they do not fully converge around the specific task required by this thesis: rapid, interpretable, early-stage comparison of layered envelope assemblies across thermal, dynamic, moisture, cost, and environmental criteria inside the architect's parametric design environment.

Tab 1.02 Comparative reading of current digital tool categories against the thesis problem

Tool/workflow family	Primary contribution	Early-stage strength	Limitation for envelope assembly selection	Implication for Armadillo
BIM workflows	Information coordination, quantities, documentation, model-based collaboration	Strong once geometry and specifications stabilize	Often too late or too detailed for conceptual envelope comparison	Armadillo should operate before full BIM resolution
Building performance simulation	Detailed energy, comfort, and compliance evaluation	High analytical depth	Input-heavy, specialist-dependent, and often applied after key decisions	Armadillo should provide earlier comparative feedback
Ladybug/Honeybee workflows	Climate, daylight, and energy analysis inside Grasshopper	Connects environmental feedback to parametric design	Powerful, but can be complex for rapid layered assembly comparison	Armadillo should simplify the envelope-specific decision layer
LCA and carbon tools	Embodied carbon and life-cycle impact assessment	Increasingly important under net-zero and EPBD frameworks	Often external to design modelling or dependent on stable quantities	Armadillo should expose carbon/cost-related data earlier, where possible
Optimization / Pareto workflows	Generation of high-performing alternatives across competing objectives	Useful for exploring trade-off spaces	Can produce option overload without selection guidance	Armadillo should support both interpretation, and guidance, not only generation

Fig 1.05 The conceptual modified Macleamy curve / Paulson diagram comparing current workflow families and proposed Armadillo decision-support position



Gaps in Current Workflows

The most critical gap identified in the literature is fragmentation. Energy simulation, daylight analysis, hygrothermal assessment, cost comparison, embodied-carbon calculation, and material selection are often distributed across separate tools and disciplinary workflows. This separation turns what should be one envelope decision into several disconnected analyses. The designer may compare U-values in a spreadsheet, check climate in Ladybug, prepare a detailed energy model elsewhere, estimate carbon through an LCA platform, and discuss cost through a separate quantity or supplier workflow. Each transfer increases time, introduces possible information loss, and weakens the continuity between design intention and performance reasoning.

Interoperability research confirms that the problem is not only organisational but also technical. Porsani et al. (2021) show that BIM-to-BEM transfer can produce geometry reduction, loss of envelope elements, and major divergences in output between open-schema workflows.[48] This matters for early-stage envelope selection because designers require fast iteration, not repeated model repair. If every performance question requires exporting, cleaning, remodelling, or reassigning data, the workflow discourages exploratory testing precisely when it is most valuable.

Lifecycle assessment workflows show a similar pattern. Bolognesi et al. find that BIM-LCA integration often still depends on extracting quantities from BIM and sending them into external assessment environments.[46] Huang et al. (2024) further show that many embodied-carbon frameworks rely on information that becomes reliable only later in the project, limiting their usefulness during early design.[47] This creates a contradiction: whole-life carbon targets require early material decisions, but many assessment workflows depend on late-stage data.

The second gap is specialist dependency. High-fidelity simulation tools can be powerful, but their use often requires expertise in zoning, schedules, boundary conditions, construction libraries, HVAC assumptions, moisture modelling, or simulation settings. This does not make those tools unsuitable; rather, it means their primary role is verification, refinement, or specialist analysis. Early-stage envelope selection requires a different level of tool: one that allows architects to compare alternatives without requiring the full setup of a certified simulation model.

A third gap is decision guidance. Simulation and optimisation tools produce outputs, but outputs are not decisions. Wortmann, Cichocka, and Waibel (2022) show that practitioners value clarity, interactivity, overview, and efficiency in optimization workflows.[49] Osika et al. (2023) make the distinction even clearer by arguing that decision-support methods are needed after Pareto fronts have been generated, because a set of non-dominated alternatives does not, by itself, indicate which option should be selected.[50] For envelope design, this means the comparison needs to be structured around interpretable indicators rather than numerical output alone.

The fourth gap concerns the limited support for comparative analysis of layered envelope assemblies. While existing workflows can evaluate whole-building energy performance, climate exposure, daylight availability, embodied carbon, and cost, they do not consistently enable architects to compare wall assemblies as design alternatives while accounting for the combined performance implications of these assemblies. This methodological gap is the space in which Armadillo is positioned. Rather than replacing existing tools and workflows, Armadillo builds upon them by making early-stage envelope assembly trade-offs visible before detailed analysis becomes the only corrective mechanism. Operating within an already tool-rich parametric environment, it enables designers to modify input data through interactive controls and visualize results almost instantly. This supports a more streamlined and time-efficient design process compared with external workflows, such as spreadsheet-based analysis, where data changes and interpretation of results are often slower and less integrated.

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Precedents in Early-Stage Parametric Decision-Support

Parametric tools have been widely adopted in contemporary design workflows due to their efficient data management and controlled workflows, with the strongest feature being the ability to keep design development, data, and performance feedback within the same computational environment. Therefore, parametric tools are significant not only as modelling platforms but also as ecosystems through which climate analysis, environmental simulation, façade studies, structural exploration, optimisation, visualisation, and BIM exchange can be integrated. The relevance of these precedents lies not only in what they enable but also in the gap they expose: the absence of an early-stage decision-support workflow for building-envelope development, despite the envelope's major role in energy efficiency.

Parametric decision support is distinct from parametric modelling. Parametric modelling produces variations by changing the relationships among inputs. Decision support adds an interpretive layer that helps the designer understand which option or route is preferable, under which criteria, and for what design intention. In concept design, where information is incomplete and decisions remain provisional, the value of a precedent lies not simply in the number of alternatives it can generate but in the clarity with which it connects alternatives to performance consequences.

Ladybug and Honeybee represent two of the most directly relevant environmental precedents within the Grasshopper ecosystem. Ladybug facilitates the integration of climate data, sun-path analysis, radiation studies, comfort visualisation, and environmental mapping into parametric design workflows. At the same time, Honeybee extends these capabilities to daylighting and energy simulation through engines such as Radiance and EnergyPlus .[51] Their significance is primarily methodological, as they demonstrate Grasshopper's capacity to function simultaneously as a design and performance-analysis environment. However, these tools

remain limited in providing material- and envelope-specific decision support. Although they enable broader analysis of envelope assemblies through predefined libraries and customizable assembly options, they do not provide a dedicated framework for evaluating and comparing wall assemblies across static and dynamic thermal performance, hygrothermal behaviour, cost, and material-related climate impacts during the early stages of design.

Facade and massing optimization studies form a second precedent group. These workflows use parametric variation to test relationships among form, orientation, glazing ratio, shading depth, solar exposure, daylight, comfort, energy demand, and cost.[36] These studies move performance feedback upstream, allowing designers to identify promising formal or facade directions before the design is fully fixed. Surrogate modelling strengthens this precedent by reducing the time required for repeated simulations within tools like Lunchbox ML, thereby making rapid early-stage evaluation more feasible.[37] However, these workflows usually operate at the scale of massing, facade variables, or objective functions. They help generate and filter design directions, but they rarely resolve the material assembly question, "Which envelope sets should be selected for further architectural and technical development?"

BIM-LCA and parametric LCA workflows depend heavily on the maturity of design data rather than on geometry alone. In BIM-LCA, environmental impacts are often generated through automated quantity take-off from the BIM model, making the assessment dependent on the accuracy of the modelled quantities, materials, and assemblies at each design stage. This creates a limitation in concept design, where placeholder materials and incomplete specifications can distort embodied-impact results; Hollberg, Genova, and Habert (2019) found that embodied GWP during the design phase was twice as high as the final building result, mainly because provisional materials were later refined[48]. Detailed BIM-LCA workflows require refined BIM data and are often applicable only in advanced design stages, while early-stage approaches rely on simplified and uncertain information. Parametric LCA tools in environments such as Grasshopper improve iteration and comparison, enabling faster parameter updates as the project progresses. However, process-based datasets, restricted geometry inputs, limited real-time visualisation, and the need for technical expertise still constrain existing tools. Therefore, while BIM-LCA and parametric LCA tools are valuable for environmental accounting, their reliability increases only as envelope geometry, material assemblies, and quantity data become more stable.

Optimization and Pareto-based workflows are also relevant precedents because they expose trade-offs that are difficult to see through intuition alone. In facade engineering, Pareto methods can reveal non-dominated alternatives across energy, daylight, comfort, cost, and environmental objectives.[36] This is valuable, but it is not the same as decision support. A Pareto front can show that several options are efficient. Still, it does not determine which option is appropriate for a specific design intent, climate conditions, construction logic, or budget priorities. Research on decision support beyond the Pareto front, therefore, emphasises the need for interpretation, weighting, and contextual judgement after optimisation has produced its solution set.[49]

Overall, these workflows establish a clear pattern. Existing tools are powerful, but their contributions remain distributed. Ladybug and Honeybee support environmental simulation; optimisation workflows generate and filter alternatives; BIM-LCA platforms account for carbon and material impacts; and BIM environments support coordination and documentation. What remains underdeveloped is the decision layer between these capabilities, particularly in layered envelope assemblies. Armadillo is positioned in that space. It does not attempt to replace simulation engines, optimization platforms, or BIM-LCA tools. Instead, it adds a focused parametric decision-support layer, making envelope trade-offs legible before detailed simulation and later-stage verification.

Net-Zero Buildings: Definitions, Frameworks, and Design Implications

The regulatory direction in Europe has shifted from operational energy alone toward life-cycle carbon accountability. The revised EPBD defines a zero-emission building as one with very low energy demand, no on-site fossil-fuel carbon emissions, and zero or very low operational greenhouse-gas emissions; it requires all new buildings to meet this standard from 2030, with earlier application to public buildings from 2028.[52] More importantly for design practice, the EPBD requires life-cycle GWP to be calculated and disclosed in the energy performance certificate from 2028 for new buildings above 1,000 m² and from 2030 for all new buildings. In Belgium, this aligns with the role of TOTEM, developed by the three Belgian regions to assess and compare the environmental impact of building elements and buildings throughout their life cycle, rather than to replace regional EPB energy regulations.[53]

As operational energy decreases, embodied carbon becomes a proportionally greater share of the total. Röck et al. (2019) show that embodied GHG emissions account for roughly 20–25% of life-cycle emissions in buildings that meet current energy regulations, rising to 45–50% in highly energy-efficient buildings and exceeding 90% in extreme cases. [54]Lützkendorf and Balouktsi (2022b) similarly argue that embodied carbon is now a design issue, not only an accounting issue, because upfront emissions can represent more than 60% of total embodied carbon and are released before the building begins operation.[55] This makes envelope decisions critical: insulation thickness, glazing specification, facade build-up, durability, and material substitution affect both operational demand and embodied impact.

This changes the logic of net-zero design. The question is no longer whether an assembly meets a U-value target, but whether its thermal benefit justifies its material, carbon, cost, moisture, and daylight consequences within a specific climate and programme. Echenagucia, Moroseos, and Meek (2022b) show that envelope carbon optimisation depends on local climate and energy-grid conditions, meaning that both under-insulation and over-insulation can increase whole-life carbon.[36] Net-zero design, therefore, requires envelope assessment to move from isolated compliance checks toward comparative, multi-criteria reasoning at the point where assembly choices are still flexible.

These frameworks demonstrate that net-zero design has shifted envelope evaluation from a narrow question of operational energy reduction to a broader life-cycle performance problem. As European regulation increasingly requires life-cycle GWP disclosure, envelope assemblies must be assessed not only for their thermal efficiency but also for their embodied impact, durability, hygrothermal safety, daylighting implications, and cost implications within a specific climate and programme. This reinforces the methodological need for decision-support workflows that can make such trade-offs explicit before envelope assemblies are fixed. Within this context, Armadillo is positioned as an early-stage, performance-led framework to support informed envelope decisions prior to detailed simulation and informal compliance verification.

Summary and Research Gap

The literature reviewed in this chapter establishes that sustainable building performance is shaped most significantly during the early stages of design, when decisions on urban configuration, site response, building form, and envelope composition remain open to adjustment. Paulson's influence-cost logic and subsequent studies on early-stage design demonstrate that the capacity to affect environmental and economic outcomes is greatest before design decisions become technically fixed.[5,6,7] Across the urban, site, and building scales, the reviewed literature shows that early decisions define the conditions within which later optimisation must operate. Urban morphology shapes solar access, ventilation potential, mobility, and outdoor comfort; site analysis translates these wider conditions into project-specific environmental constraints; and the building envelope materialises them through thermal, hygrothermal, daylight, carbon, and cost-related performance.

Within this sequence, the envelope emerges as one of the most consequential systems in sustainable building design. It is not simply a thermal barrier, but a complex performance system with multi-criterial interaction.[31,33,34,35] These criteria are also context-dependent, with the suitability of an envelope assembly varying with the context in which it's set, meaning that both under- and over-investment in envelope efficiency can produce weaker whole-life outcomes.[36] Envelope selection is therefore a decision-support problem rather than a simple technical calculation; designers leverage performance criteria that relate to one another before the envelope strategy becomes fixed.

The review further shows that the AEC sector already contains powerful digital tools for analysing different dimensions of building performance. BIM workflows support coordination and quantity extraction; building performance simulation tools provide detailed energy and comfort analysis; Ladybug and Honeybee integrate climate, daylight, and energy analysis within Grasshopper; LCA tools support embodied-carbon accounting; and optimisation workflows expose trade-offs across compe-

ting objectives[40.41,44,45,51,56]. These tools are essential parts of contemporary practice, but their capabilities remain distributed across separate platforms, specialist domains, and different stages of design. The central issue is therefore not the absence of analytical tools, but the limited continuity between design exploration, performance interpretation, and decision-making at the moment when envelope assemblies are still flexible.

Four connected gaps can be identified from the reviewed literature. The first is a timing gap: detailed simulation, BIM-LCA, and compliance-oriented assessment often become reliable only after geometry, assemblies, and specifications have stabilised.[37,38,46,47] The second is an integration gap: thermal performance, daylight, hygrothermal risk, embodied carbon, and cost are frequently assessed through separate workflows rather than as part of a single envelope decision. The third is a decision-support gap: simulation and optimisation tools can generate outputs, alternatives, or Pareto fronts, but they do not necessarily clarify which option is most appropriate for a specific design intention, climate condition, construction logic, or project constraint [45][46]. The fourth is an envelope-assembly gap: existing workflows do not consistently support the recommendation, modification, evaluation, and comparison of layered envelope assemblies during conceptual and schematic design.

This gap becomes more significant under emerging net-zero and whole-life carbon frameworks. The revised EPBD shifts European building regulation from operational energy reduction toward zero-emission standards and life-cycle GWP disclosure, while TOTEM provides a Belgian framework for assessing the environmental impact of building elements throughout their life cycle.[52,53] As operational energy decreases, embodied carbon becomes proportionally more significant, requiring envelope assemblies to be assessed not only for thermal efficiency but also for material impact, durability, hygrothermal safety, daylighting implications, and cost consequences.[54,55] Net-zero design, therefore, reinforces the need for early-stage workflows that make envelope trade-offs explicit before assemblies are fixed, thereby mitigating excessive time consumption in later stages.

The research gap addressed by this thesis is the limited availability of an integrated, early-stage, parametric decision-support workflow for layered building-envelope selection. Existing tools can analyse climate, simulate energy, calculate carbon, generate alternatives, and support BIM coordination, but they do not fully converge around the specific task of helping architects make informed envelope decisions while design intent is still developing. This thesis addresses that gap through Armadillo: a Grasshopper-based decision-support workflow that supports the recommendation, modification, evaluation, and comparison of envelope assemblies via clear, multi-criteria performance feedback. Its contribution is not to replace detailed simulation, LCA, BIM, or professional judgement, but to provide an intermediate decision-support layer that makes envelope trade-offs legible before detailed simulation and formal compliance verification become necessary.

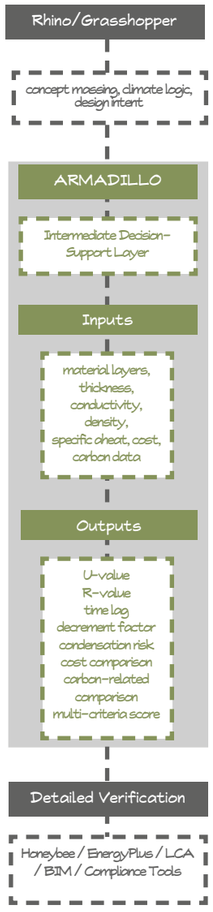


Fig 1.06 positions Armadillo as an intermediate decision-support layer within the early-stage design process. The workflow does not replace detailed simulation, BIM-LCA, or compliance verification, but supports the earlier comparison and shortlisting of envelope assemblies through clear multi-criteria feedback.

1.3 Research Methodology

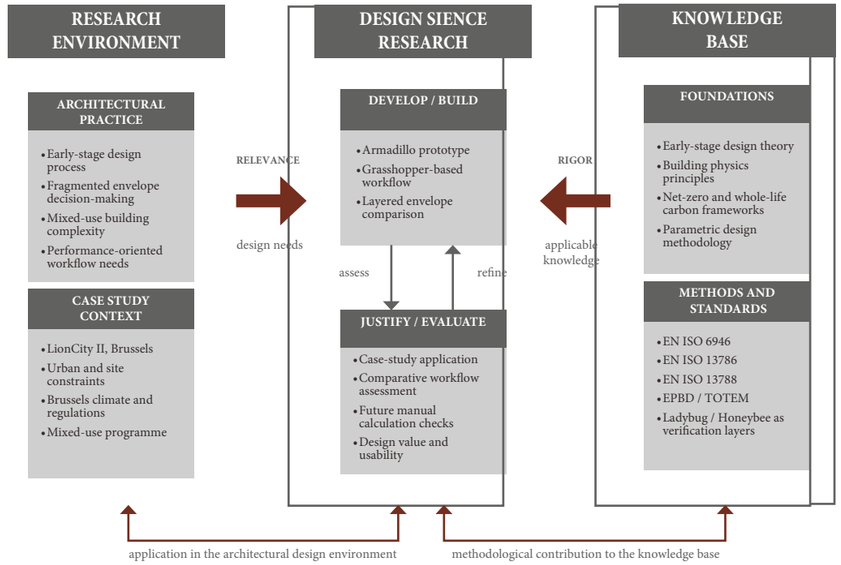


Fig 1.07 Illustrates the adapted Design Science Research Framework, based on Hevner et al. (2004). The framework connects the architectural research environment, including early-stage design practice and the LionCity II case-study context, with the knowledge base of building physics, EN ISO standards, net-zero frameworks, and parametric design methodology. Within this structure, Armadillo is positioned as a research artifact developed, applied, and evaluated as an early-stage decision-support workflow for layered building-envelope selection.

Research Paradigm and Approach

This research is situated within a constructive research paradigm, aligned with the design science tradition as formulated by Hevner et al. (2004), in which the primary output is a tool whose validity is demonstrated through application rather than through controlled experiments.[57]The research is pragmatic and applied: it focuses on developing a methodological contribution that is both technically grounded and architecturally operational. It is neither purely empirical nor purely theoretical; it treats the act of making a useful tool as itself a form of inquiry.

The method combines three linked strands. First, the literature review establishes the research gap and the need for integrated envelope decision support. Second, the LionCity II project is examined through existing design and performance-analysis workflows to identify where current methods are fragmented, delayed, or insufficient. Third, Armadillo is proposed within the Rhino/Grasshopper environment to address these gaps. The case study, therefore, does not constitute final validation of Armadillo. Instead, it acts as a methodological vehicle for assessing the relevance of the proposed workflow, defining its functional requirements, and clarifying how it could support early-stage envelope decision-making in future development.

Data Collection Methods

The research draws on three categories of data. The

first is published literature: peer-reviewed journal articles, conference papers, technical standards, and regulatory documents. Key standards informing the tool development include EN ISO 6946 for thermal resistance and transmittance, EN ISO 13786 for periodic thermal characteristics of building components, and EN ISO 13788 for hygrothermal surface conditions and condensation risk assessment. European regulatory sources include Directive EU/2024/1275 (the recast EPBD) and its transposition into Brussels regional practice through the PEB ordinance and the TOTEM whole-life carbon framework.

The second category is site-specific documentation for the LionCity II project: the Reinventing Cities competition brief and site requirements issued by citydev.brussels, the exploratory urban planning study commissioned by citydev.brussels and perspective.Brussels, the hydrological diagnostic and hydrological strategies reports, the urban study Volet III, and the regulatory provisions of the Regional Urban Development Regulation (RRU) and Regional Land Use Plan (PRAS) applicable to the site.

The third category is computational and performance data generated through the design process itself: EPW climate data for Brussels processed through Ladybug, envelope assembly performance outputs produced by Armadillo across successive design iterations, and broader energy simulation data generated during the architectural development of the LionCity II proposal using Climate Studio and Honeybee as verification layers.

Case Study

LionCity II, located at 50–56 Rue Osseghem in Molenbeek-Saint-Jean, Brussels, is used as the primary case study for this research. The site is a 6,243 m² brownfield plot formerly occupied by a printing facility, acquired by citydev.brussels in March 2020 and later included in the Reinventing Cities competition brief for a mixed-use redevelopment with strong sustainability ambitions.[58]The case study is selected because it brings together the main conditions addressed by the thesis: a demanding Brussels regulatory context, brownfield and hydrological constraints, a complex mixed-use programme, and a strategic urban location within the Brussels Urban Revitalisation Zone near Beekkant metro station and the Gare de l'Ouest district. These conditions require design reasoning that connects urban context, site performance, building form, envelope strategy, and technical coordination.

In this thesis, LionCity II does not serve as a completed building through which Armadillo is fully validated. Instead, it serves as a design vehicle to examine current digital and performance-analysis workflows and to identify where early-stage envelope decisions remain fragmented or insufficiently supported. The case study, therefore, provides the practical basis for positioning Armadillo as a proposed Grasshopper-based decision-support layer within the existing architectural workflow.

Tool Development Methodology

Armadillo is developed according to the design science research framework, in which a tool is proposed to address an identified gap and evaluated in that context. The development proceeds through four stages.

Requirements definition. The functional requirements of Armadillo are derived directly from the research gap identified in Chapter 1.2: the absence of an integrated, standards-informed, early-stage parametric workflow that supports the recommendation, modification, and comparative evaluation of layered building-envelope assemblies across multiple criteria. The tool is to be developed in the Rhino/Grasshopper environment due to its already integrated workflows, and it is to accept only the input data available at the concept stage, produce interpretable comparative output without specialist configuration, and ground its calculations in EN-ISO standards.

Implementation. Armadillo is developed as a Grasshopper-based plugin, with components primarily written in C# and supported by native Grasshopper components and additional plugins such as Ladybug tools, Lunchbox, and One-click LCA. Its calculation logic follows EN ISO 6946 for layer-by-layer thermal resistance and U-value, EN ISO 13786 for periodic thermal transmittance, decrement factor, and time lag, and EN ISO 13788 for simplified condensation risk screening. Material thermal properties are based on EN ISO 10456 and established building physics references.

Iterative refinement. The design process of LionCity II constitutes the primary development context. Each design stage assesses the current practices and workflows to assess the significance of the proposed tool and its relevant architecture. This workflow ensures that Armadillo's significance is

consequential and relevant to current practices, and that the proposal remains calibrated to the actual informational conditions and decision logics of early-stage practice rather than to a theoretical model of the design process.

Scope acknowledgement. Armadillo is framed as an early-stage decision-support prototype rather than a certified compliance or simulation instrument. Its outputs are comparative indicators intended to support envelope reasoning, assembly selection, and design refinement before detailed simulation and formal regulatory verification. This scope defines the tool's methodological position: it supports informed architectural decision-making without replacing specialist analysis, compliance calculations, or professional judgement.

Simulation and Validation Strategy

Armadillo is developed in this thesis as a proposed research prototype for early-stage envelope decision support. Its validation is therefore not treated as the certification of a completed software tool or as a measured comparison against an occupied building. Instead, the thesis proposes a validation framework and uses the LionCity II proposal to examine where such a tool would be relevant within an existing design workflow.

The study first follows the current workflow without Armadillo, using established methods such as climate analysis, envelope studies, simulation tools, and standards-based checks. This allows the thesis to identify where performance feedback is already available, where it becomes fragmented, and where envelope decisions remain insufficiently supported during conceptual and schematic design.

Within this workflow, Armadillo is positioned as a potential decision-support layer rather than a replacement for existing tools. Its proposed value lies in organising envelope assembly data, supporting assembly recommendations and modifications, evaluating key performance indicators, and clarifying trade-offs through comparative and graphical feedback.

The proposed validation strategy operates at two levels. At the calculation level, future versions of Armadillo should be checked against manual calculations based on relevant EN ISO standards. At the application level, its usefulness should be assessed by examining whether its feedback is clear, actionable, and capable of improving envelope-related design decisions.

The validation approach is therefore methodological rather than conclusive. This thesis does not claim full technical validation of Armadillo; instead, it establishes a structured basis for evaluating its relevance, accuracy, and design value in future development.

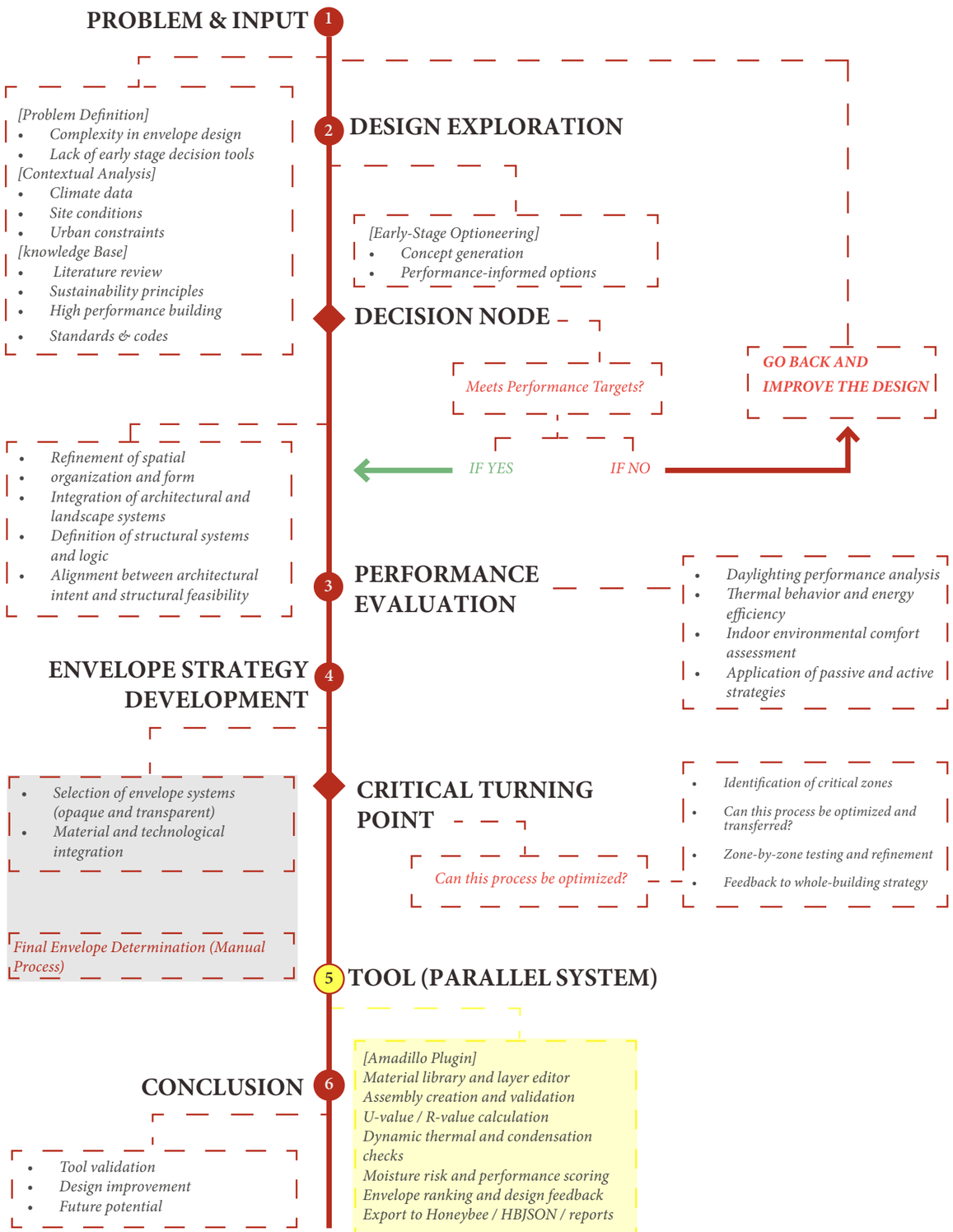
Ethical Considerations

This body of work does not involve human subjects and therefore falls outside the scope of participant-based ethical protocols. Its ethical obligations include academic integrity, disciplinary transparency, and responsible communication for a design tool intended for professional use.

All data sources are cited with full attribution, including regulatory documents, technical standards, and published research. Site documentation provided by citydev.brussels and the Reinventing Cities programme is used in accordance with the thesis's public and academic nature. No confidential or commercially sensitive data has been incorporated, and no proprietary computational methods are used without acknowledgement.

Armadillo is documented with explicit acknowledgement of its scope and the conditions under which its outputs are applicable. It is not presented as a regulatory or certification instrument. The transparency of this framing is treated as an ethical obligation: a tool that enters the design profession without clear communication of its limitations, risks being applied outside its intended context, with potentially adverse consequences for building performance and regulatory compliance. The thesis, therefore, foregrounds Armadillo's prototype status, its EN-ISO grounding, and the boundary between decision-support screening and certified simulation at every stage of its presentation.

General workflow



Endnotes

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02 SITE ANALYSIS

Chapter 2 analyses the LionCity II site in Molenbeek-Saint-Jean, Brussels, through historical, urban, ecological, climatic, and regulatory perspectives. The findings are synthesised using SWOT–TOWS and the Integrated Modification Methodology to identify key opportunities, constraints, and design catalysts. The chapter concludes with a set of design drivers that form the basis for the architectural proposal developed in Chapter 3.

2.1 Site History



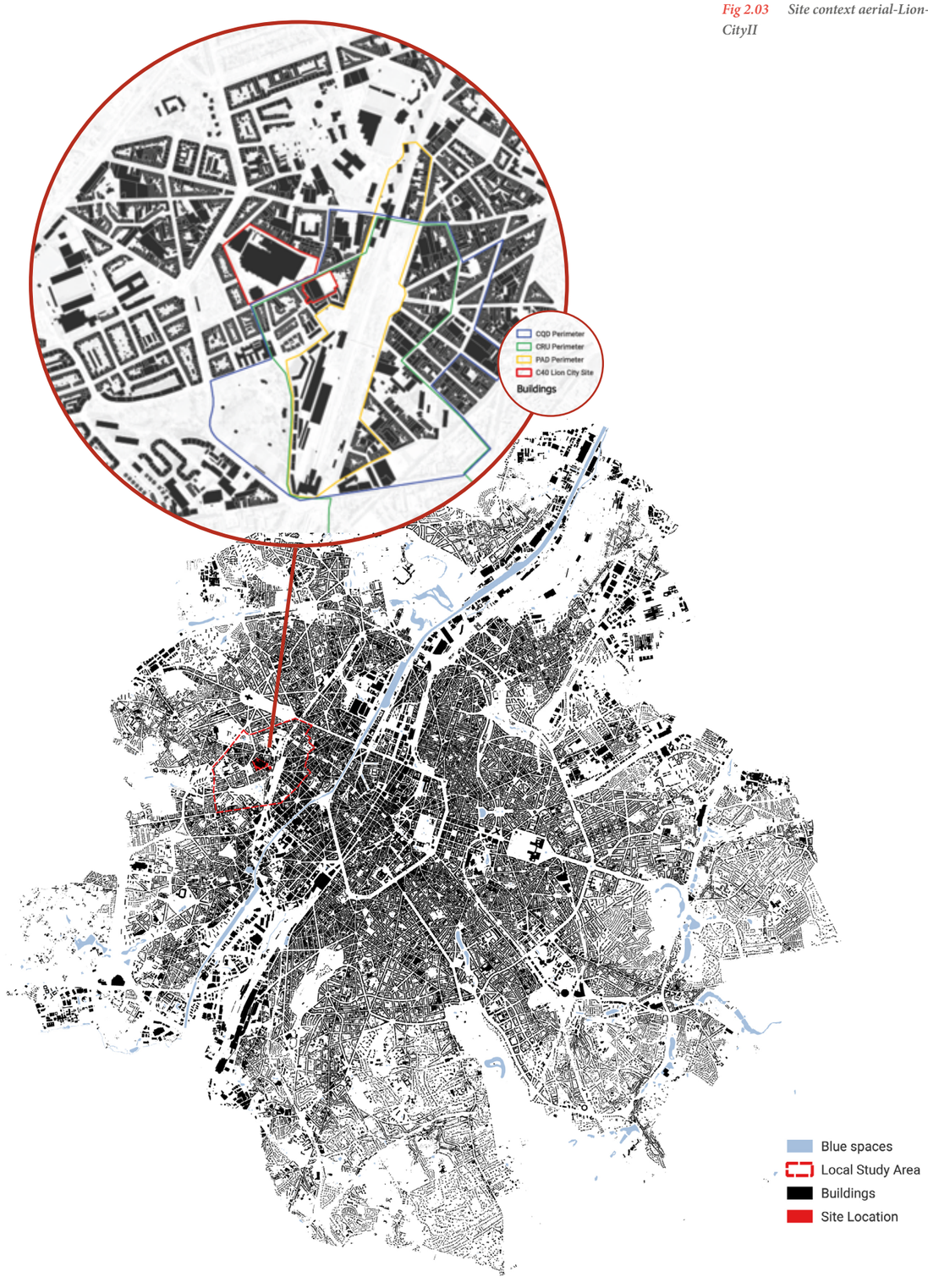
Fig 2.01 *Regional location: the Brussels-Capital Region within Belgium, with Molenbeek-Saint-Jean and the LionCity II site marked.*

Geographical and Location Context

The project site, known as LionCity II, is located at 50-56 Rue Osseghem in the commune of Molenbeek-Saint-Jean, within the Brussels Capital Region of Belgium[1[JN1.1]]. It lies in the heart of the Osseghem district, in the western part of the Brussels urban area and in direct continuity with the historic city Centre (écorce 2019). The site covers approximately 6,243 m² and presently comprises a former printing works of around 3,188 m² and an adjoining car park of around 3,123 m², the latter temporarily occupied by the non-profit organization UP Circus & Performing Arts.[59]

The site directly borders the 13-hectare Gare de l'Ouest railway brownfield, which lies within overlapping Brussels planning and regeneration frameworks, as shown in Figure 2.2: the PAD (Plan d'Aménagement Directeur, Master Development Plan), the CRU (Contrat de Rénovation Urbaine, Urban Renewal Contract), and the CQD (Contrat de Quartier Durable, Sustainable Neighbourhood Contract). The district benefits from strong public-transport accessibility, and a planned pedestrian connection links the site (C40 Lion City site) to the Beekkant metro station via Place Beekkant [1]. The whole area falls within the Brussels Region's Urban Revitalization Zone (Zone de Revitalisation Urbaine), where public investment is concentrated in the most socioeconomically vulnerable neighbourhoods.

Fig 2.02 *Regional location map, PRAS zoning for development*
Fig 2.03 *Site context aerial-Lion-CityII*



2.2 Historical and Heritage Studies

The LionCity II site is not an empty brownfield, but the remnant of a former industrial-logistics landscape. Its present condition — a large enclosed parcel, strong infrastructural edges, deep industrial plots, and remaining architectural fragments — is the result of more than a century of commercial expansion, logistical modernisation, and gradual industrial decline. The historical reading of the site is therefore relevant not only as background information, but as a way to understand the spatial structure that the redevelopment must transform.

Fig 2.04 *Aerial view of the Delhaize "commercial city" in 1900, distinguishing the main construction periods and showing the progressive expansion of the industrial complex.*

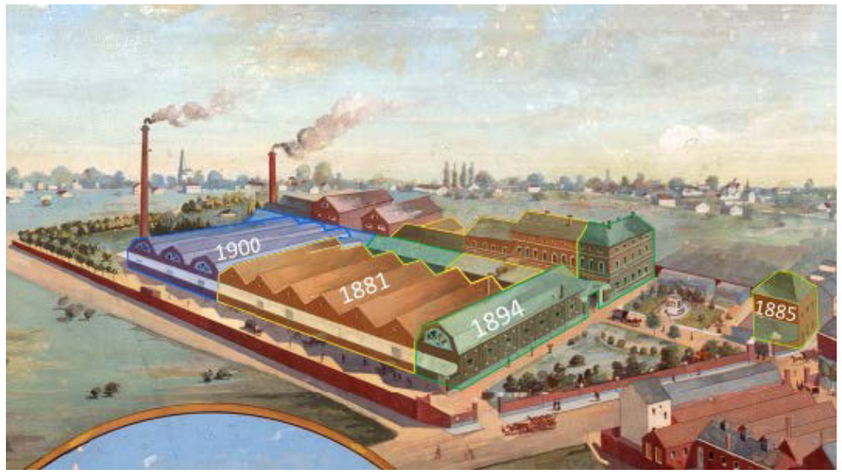
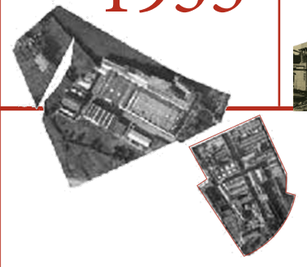


Fig 2.05 *Site history timeline: main phases in the transformation of the Delhaize site from commercial-logistics infrastructure to contemporary redevelopment area.*



Delhaize trucks at the Gare de l'Ouest in 1899. AD, Iconographic Fund.

1935



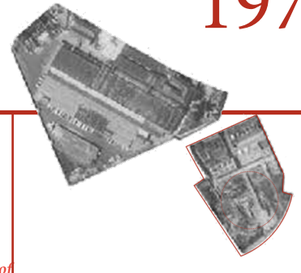
1880: Acquisition of land in Rue Osseghem, Molenbeek, marking the start of Zone 2's development.

1934-1939 : Modernization of warehouses, railway integration, and a Bauhaue.

1958 – Introduction of Belgium's first supermarket, shifting focus from warehousing to retail.

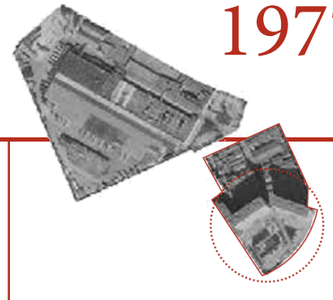


1971



1960-2012 – Gradual decline of industrial use, with logistics moving to Zellik and Ninove.

1977



1971 : Building the first tower in zone 02

1977: Building the second tower in

1960-2012 : Gradual decline of industrial use, with logistics moving to Zellik and Ninove.

1991 : Decommissioning of railway connection



2019



The buildings form part of a chain of buildings that are situated parallel to the west side of the railway. In total, it concerns 800 homes that are managed by 'Le Logement Molenbeekois'. This chain of buildings contributes to the social and physical fault line between the western and eastern parts of the railway.

Fig 2.06 *Historical views of the Delhaize commercial city: (a) overview of the site in 1897 and (b) view of the covered loading street around 1905–1910, showing the internal logistics structure of the industrial compound. Compared to (c) modern day. Sources: AAM, Inventaire; Delhaize Archives, iconographic collection.*

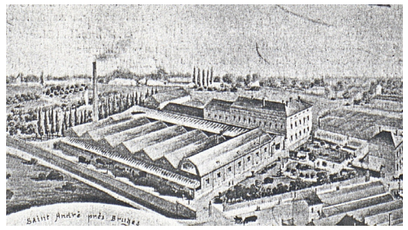






Fig 2.07 *Early twentieth-century front façade of the Delhaize complex, showing the administrative and urban face of the industrial site. Exact date unknown.*

Fig 2.08 *Early twentieth-century front façade of the Delhaize complex, showing the relationship between the industrial compound and the street edge. Exact date unknown.*





Formation of the Delhaize Logistics City (Late 19th Century)

Delhaize Frères was founded in 1867 by Jules and Auguste Delhaize, later joined by their brothers Édouard and Adolphe and their brother-in-law Jules Vieujant. The company expanded through a branch-store model that depended on centralised storage, coordinated supply, and efficient distribution. This led to its relocation to Brussels in 1871, where proximity to the canal and railway infrastructure supported the growth of its logistics network.[59] By 1876, the expansion of the distribution system required larger facilities for storage and handling.[60]

In 1880, Delhaize acquired land on Rue Osseghem in Molenbeek-Saint-Jean, close to the Gare de l'Ouest railway infrastructure.[61] The first warehouses and administrative offices were built in 1881, followed by additional storage halls and an important administrative building between 1894 and 1900.[62] During this period, the site developed as a compact "commercial city": not a single building, but an organised industrial compound combining administration, warehousing, loading, internal streets, and distribution spaces.

Industrial Consolidation and Modernisation (20th Century)

Between 1905 and 1914, Delhaize modernised the site through new halls for sorting, packaging, and distribution.[63] The railway connection became central to the operation of the compound, allowing goods to move more efficiently between production, storage, and retail networks. Between 1911 and 1914, warehouse operations also expanded vertically, increasing storage capacity within the existing site boundaries.[64] This phase explains the large-scale industrial grain that still distinguishes the parcel from the smaller residential fabric around it.From 1934 to 1939, the site underwent further transformation through modernised façades, improved logistics infrastructure, and a direct railway connection to the distribution hub.[65] The introduction of automated conveyor systems positioned Delhaize as an early example of logistics modernisation in Belgium.[66] These changes are important for the thesis because they show that the site's heritage is not limited to isolated façades. its historical value also lies in its spatial logic: enclosure, loading, internal circulation, industrial depth, and connection to infrastructure.

Commercial Transformation and Industrial Decline (20th–21st Century)

The role of the Osseghem site began to change after 1958, when Delhaize introduced Belgium's first supermarket concept.[67] This transformed the company's relationship between storage, distribution, and retail, gradually reducing dependence on the former central logistics site.[68] Between 1960 and 2012, most logistics activities were relocated to Zellik and Ninove, while the Osseghem site retained administrative functions and specialised activities such as coffee roasting and wine bottling.[69]

By 1991, the rail connection to the site had been permanently decommissioned, marking the end of its original industrial role.[70] This shift produced the condition visible today: a large former logistics parcel with residual industrial structures, enclosed edges, underused ground, and a weakened relationship to the surrounding neighbourhood. The site's current urban problem is therefore historical as much as spatial. It was shaped to receive, store, and distribute goods, not to support public permeability, ecological continuity, or mixed urban life.

From Industrial Enclosure to Urban Reintegration (21st Century)

In 2016, Delhaize merged with the Dutch retailer Ahold, further reshaping the company's operational structure and accelerating the departure of remaining central functions from the Osseghem site.[71] In 2019, citydev.brussels acquired the site with the aim of transforming it into a mixed-use urban district integrating housing, productive activities, public functions, and open spaces.[72] Since 2020, the former Delhaize site has become part of wider urban renewal efforts connected to LionCity II and the Gare de l'Ouest district.[73]

For this thesis, the historical significance of the site lies in the design question it creates. LionCity II must not erase the industrial past, but reinterpret it. The redevelopment should transform the former logistics enclosure into a more open urban structure, while selectively retaining the memory of the Delhaize compound through material traces, façade fragments, spatial alignments, and the logic of large covered volumes. In this way, heritage becomes more than preservation; it becomes a design instrument for connecting the new project to the historical formation of the site.



Fig 2.09 *Historical structure and redevelopment implication: Arial views showing the transformation from enclosed logistics compound to mixed-use urban fabric (1977-2020)*

2.3 Urban and Site conditions

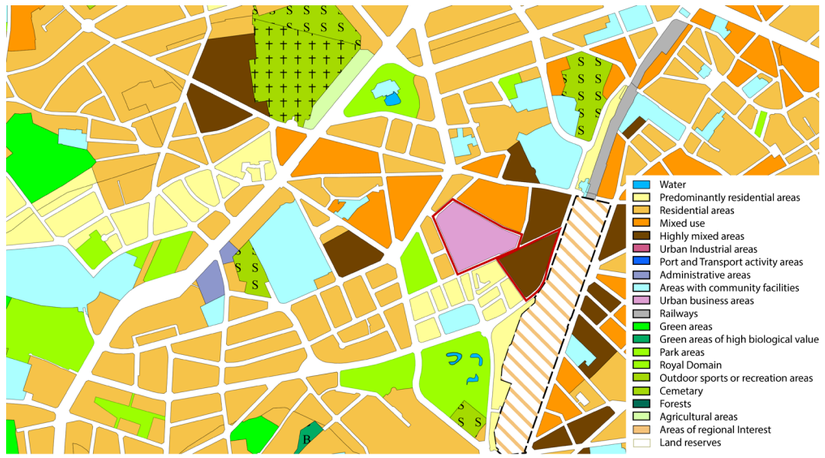


Fig 2.10 *Land use of the 500 m context, General land use divided into parcel and the rail belt reads as void, the residential fabric as continuous solid, and (b) Detailed individual building block*

The LionCity II site occupies a strategic urban region between three contrasting conditions: the rail belt to the west, the fine-grain residential fabric of Osseghem to the east, and the larger-scale Machtens towers to the south.

This position makes the site more than an infill plot. It is a point of transition between infrastructure, housing, industrial memory, and emerging cultural use. The section below therefore focuses on the conditions that directly affect the project strategy: urban grain, identity, movement, public edges, ecology, soil, and the design implications carried forward into the masterplan and envelope approach.

Urban Structure and Built Context

Three urban grains meet around the site, each operating at a different scale. The rail belt forms a regional infrastructural void which has remained largely unbuilt. The eastern fabric is smaller, denser, and more continuous, with a 3-5 storey residential area that defines a continuous street wall. The Machtens towers to the south introduces a contrasting modernist scale: two free-standing slabs of approximately forty-nine metres set within residual open space and parking. The site is therefore located at a point where different urban conditions meet and change in scale.

The clearest spatial challenge is the abrupt change in height between the surrounding residential fabric and the taller Machtens towers. The site itself is currently an impermeable plateau of approximately 6,200 m², composed of the former printing works and surface parking. As a result, the site interrupts rather than mediates the surrounding urban fabric. The design response must therefore manage scale transition, restore ground-level continuity, and establish a massing logic that preserves solar access while negotiating the different neighbouring conditions.

Culture, Identity, and Morphology

The identity of Osseghem is defined by layering rather than by a single architectural language. Within walking distance of the site, industrial halls, workers' rowhouses, interwar garden-city fragments, modernist towers, and late twentieth-century sheds coexist without forming a unified image. This heterogeneous condition is important for the project because it discourages a singular stylistic response and instead calls for a design strategy capable of working with memory, contrast, and transition.

The future Cité du Cirque must therefore operate as both a cultural anchor and an urban mediator. Existing civic and cultural facilities are dispersed across the neighborhood, including schools, religious institutions, sports facilities, and the temporary UP Circus presence on site. This dispersed pattern creates an opportunity for the project to consolidate public activity without imposing an isolated landmark. The architectural task is to transform cultural programme into a connective urban device.











Fig 2.11 *eight transition across the site context, showing the contrast between the surrounding residential fabric and the taller Machtens towers*

Fig 2.12 *Five types within one context: a photographic catalogue of the architectural families that coexist within walking distance of the parcel*

Connectivity, Access, and Movement

The site benefits from strong public-transport accessibility but weak local stitching with the Beekkant metro station, lies within approximately 250 m, while the Gare de l'Ouest multimodal hub is within 600 m. The planned improvement of Place Beekkant further strengthens the site's connection to the regional network.[59]

The network centrality analysis reinforces this condition: higher closeness values around the main transit nodes indicate strong overall accessibility, while higher betweenness values along the rail-edge and Beekkant axis show where movement is concentrated through limited crossing points.

Fig 2.13 Strength in transit: walking isochrones around the parcel against the metro, tram, and bus network.

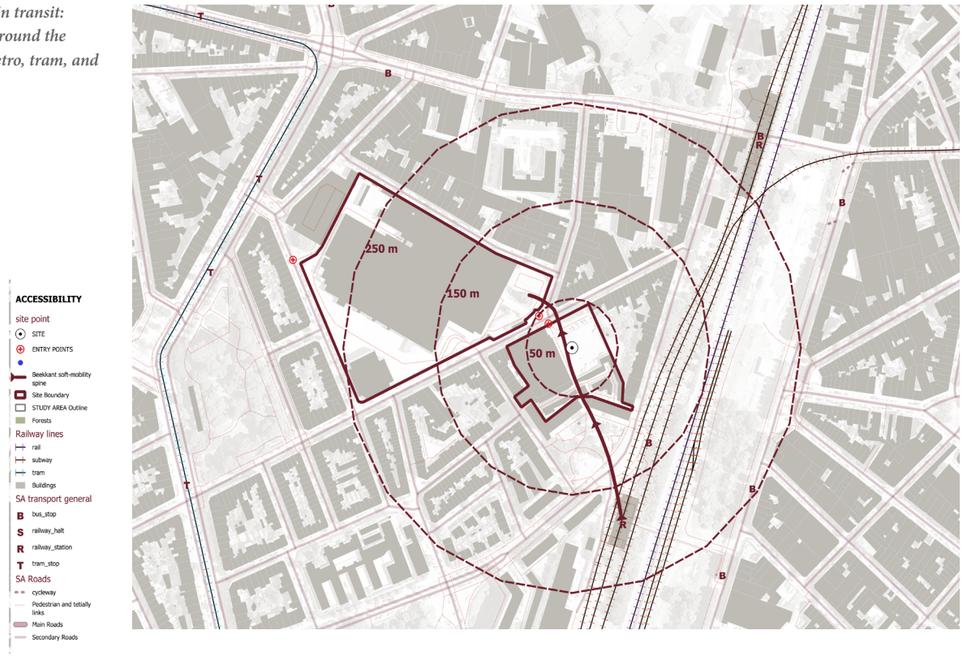
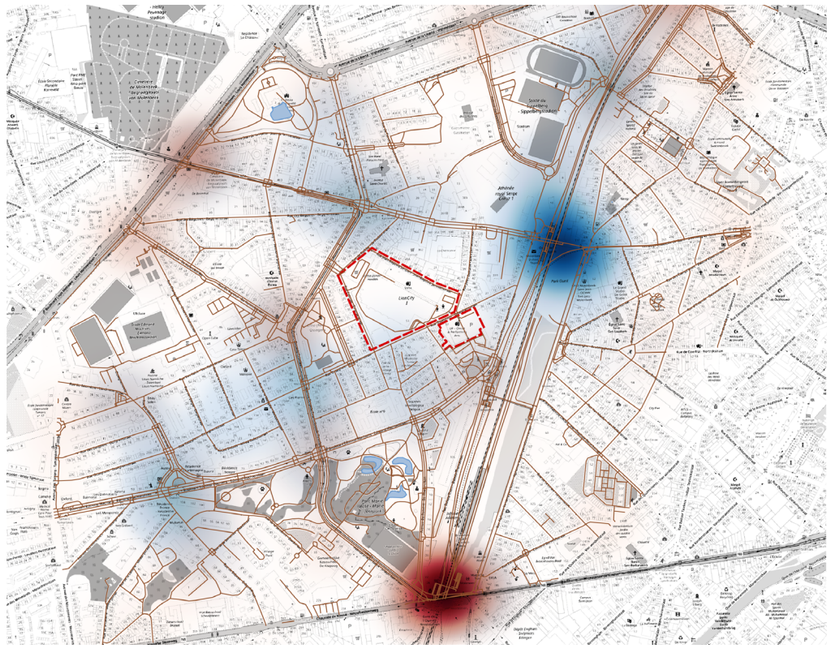


Fig 2.14 Network centrality analysis: closeness and betweenness values around the LionCity II site, showing strong accessibility near Beekkant and Gare de l'Ouest but limited east–west permeability across the rail corridor.



The site's local soft mobility remain limited by the rail corridor to the east, The aerial condition shows that this accessibility is not yet translated into continuous local movement: the railway, service roads, parking areas, and enclosed industrial edges interrupt east–west permeability around the site. The redevelopment should therefore strengthen the Beekkant axis as a soft-mobility route, transforming the former industrial enclosure into a connected threshold between Rue Osseghem, Place Beekkant, the rail edge, and the wider West Station district.

The network centrality analysis reinforces this condition: higher closeness values around the main transit nodes indicate strong overall accessibility, while higher betweenness values along the rail-edge and Beekkant axis show where movement is concentrated through limited crossing points.



Fig 2.15 Street hierarchy and soft-mobility barriers: the rail corridor limits east–west permeability, while the Beekkant axis offers the main opportunity for vehicular, pedestrian and cycling connection.

- Line 28
- 3 stations- Brussels West station, Osseghem, Beekkant
- 4 metro lines- 1, 2, 5, 6.

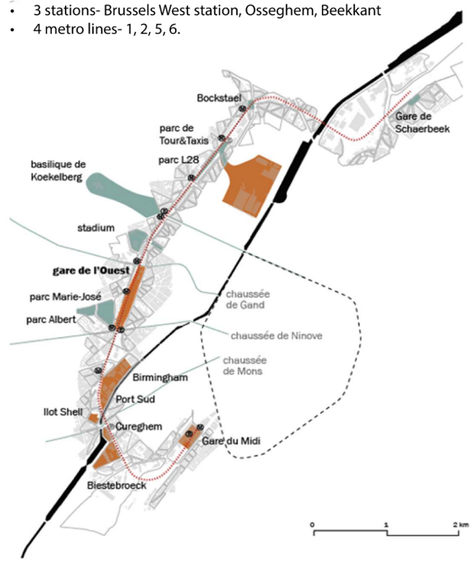


Fig 2.16 *Lion City II_Aerial view: comparative street edges of the north, south, east, and west boundaries of the parcel.*





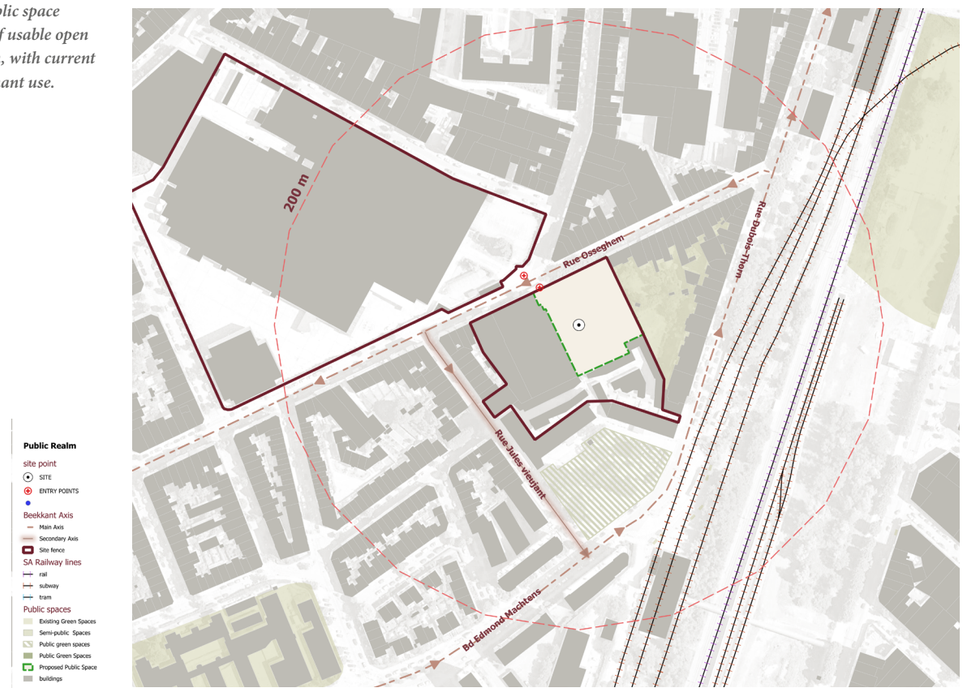


Public Realm and Site Edges

The parcel currently lacks a clear public frontage. Each edge has a different condition, and each requires a distinct response. For this reason, the edge strategy is a primary design issue rather than a late-stage facade question.

Along rue d'Osseghem, the north edge maintains a street alignment but offers little active frontage. To the south, the boundary toward the Machtens block dissolves into parking and service space rather than forming a shared public threshold. The east edge meets the existing fabric through blind party walls and rear gardens, while the west edge turns away from the rail corridor. Place Beekkant is the only significant public space within approximately 200 m and is currently being reconfigured. The project must therefore construct public realm as part of its architectural strategy, using active ground floors, calibrated thresholds, and landscape structure to repair weak edges

Fig 2.17 *What public space remains: inventory of usable open ground within 400 m, with current condition and dominant use.*



Ecological and Vegetation Conditions

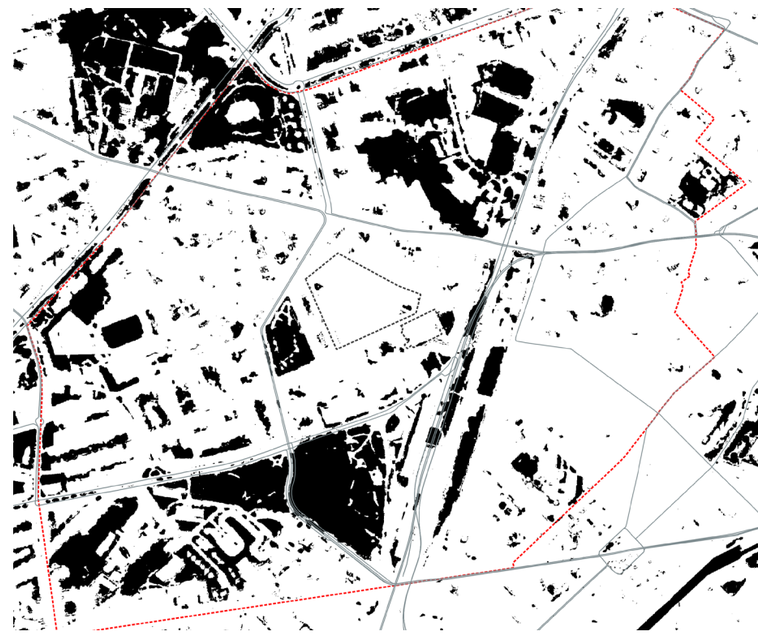
Although limited in size, the LionCity II site has strategic ecological value within a wider urban context where green spaces are unevenly distributed. The Brussels-Capital Region has a substantial vegetation network, with around 54% of its territory covered by open and closed green environments, supporting biodiversity, rainwater infiltration, air-quality improvement, and urban heat-island mitigation[74]. However, this green structure is not evenly accessible across the region. Central and canal-side districts, including parts of Molenbeek, remain more mineral, fragmented, and affected by former industrial land uses and soil pollution.[74]

Fig 2.18 *Green space distribution in the Brussels-Capital Region: accessible green and recreational spaces showing the uneven distribution of vegetation across the region*



At the scale of the site, this condition is clearly visible. The surrounding area is highly impervious, with local imperviousness estimated at 73%, compared with a Brussels regional average of 46%.[60] Vegetation is stronger toward the west, while ecological continuity weakens toward the denser urban fabric to the east. The parcel therefore has the potential to act as a transition point between these conditions, extending green continuity through the site rather than remaining as a sealed industrial surface.

Fig 2.19 *Impervious ground condition: the parcel identified as a large sealed surface within a highly impervious urban context.*



The site also sits near a wider sequence of green and open spaces, including the cemetery landscape, park areas, and the rail-side vegetation corridor. This gives the redevelopment the opportunity to contribute to a broader east–west ecological connection, linking existing green areas to the west with the denser urban fabric toward Beekkant and the West Station district.

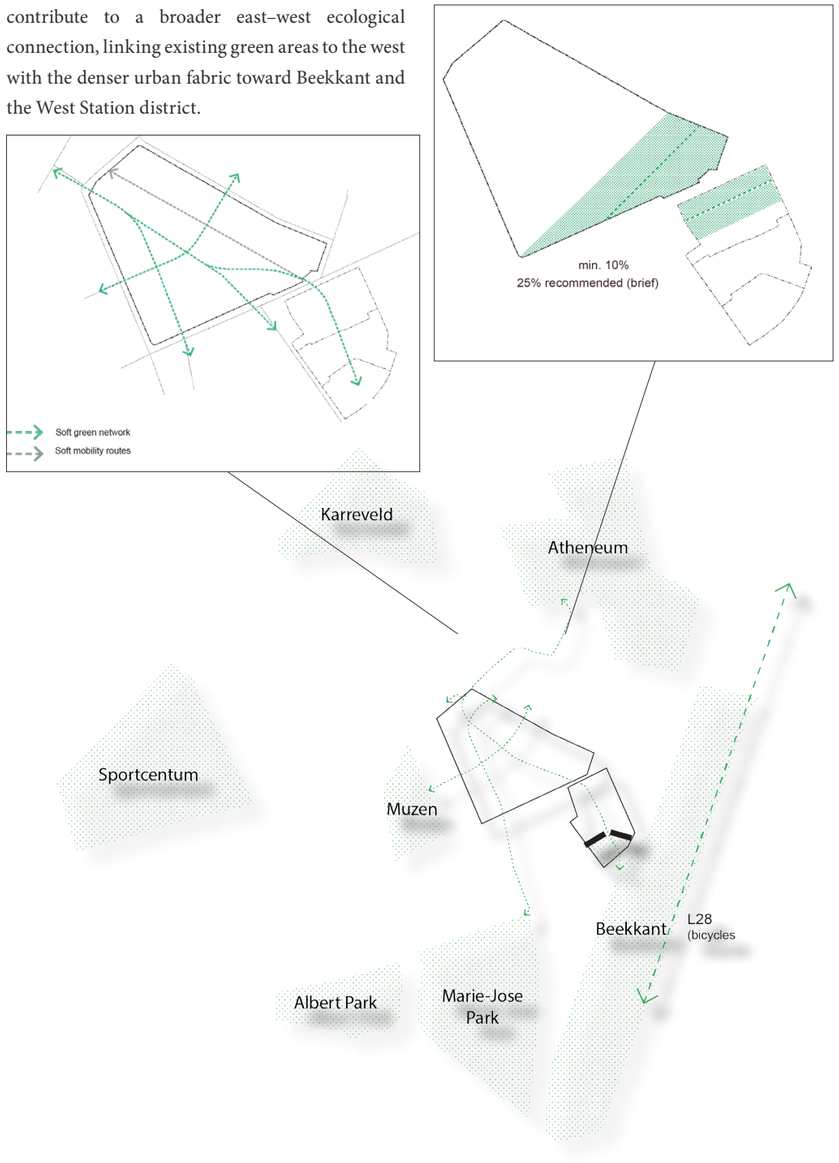


Fig 2.20 *Ecological continuity opportunity (a) 25% site recommended Green spaces (b) Proposed site green continuity network (c) regional green areas and the proposed east–west ecological link through the parcel.*

The ecological significance of the site can also be understood within the broader network of protected and publicly accessible green spaces in the Brussels-Capital Region. Regional mapping shows that major green and recreational areas are concentrated in the peripheral parts of Brussels, while the central canal zone and several inner-city neighbourhoods have more limited access to large green spaces. This uneven distribution reinforces the importance of introducing additional vegetation and ecological functions within redevelopment sites located in dense urban districts such as Molenbeek.

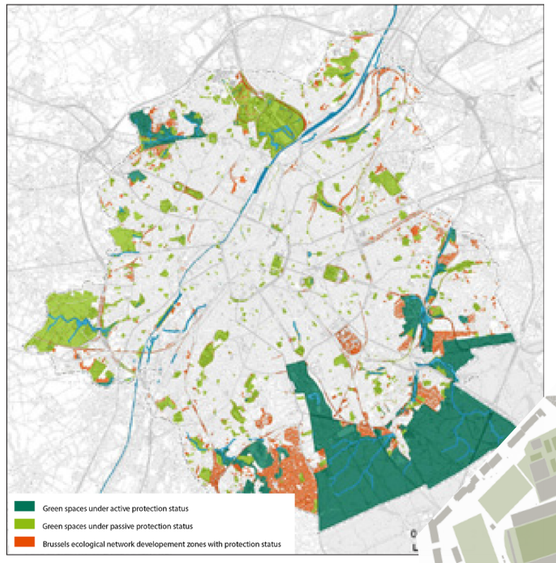


Fig 2.21 *Sites protected under various statuses in the Brussels-Capital Region.*

In addition to recreational green spaces, Brussels contains a network of sites protected under environmental and landscape designations that support biodiversity and ecological continuity at the regional scale. The value of neighbourhood-scale green interventions is illustrated by Parc de la Rosée, where a Neighbourhood Contract transformed former factory land into a public park. Through a participatory design process, the park combined diverse planting with recreational and educational facilities, allowing sporting activities to coexist with workshops focused on flowers and plants. As a result, it has become a valued “peaceful spot” within the district despite its active and varied use. Although the LionCity II site is not located within a protected area, its position between existing green spaces and urbanised districts offers an opportunity to strengthen ecological connections and contribute to the wider regional green network.

The redevelopment should therefore use remediation and landscape design to transform the site from a sealed industrial parcel into a connected ecological link, improving permeability, biodiversity, and environmental quality while reinforcing green continuity across the wider urban area.

Data basis: All datas shown in this section are



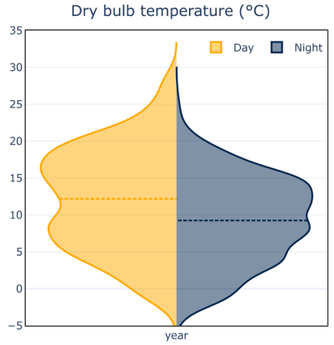
Fig 2.22 *Green and recreational spaces accessible to the public in the Study area: Based on BRAT 2009 – Unitary Green Objects (1997).*

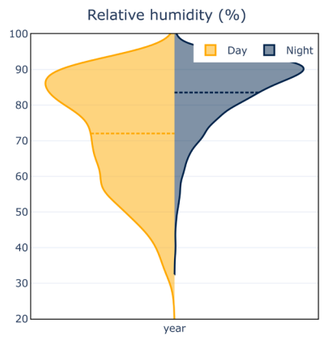
2.4 Climate and Environmental Context

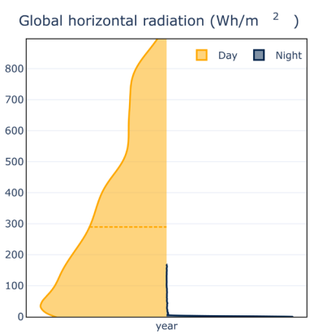
extracted from Brussels National Airport / Brussels–Uccle proxy EPW file, TMYx 2004–2018, 8,760 hourly records.

Key EPW Findings:

Indicator	Result
Mean annual dry-bulb temperature	10.7 °C
Annual temperature range in EPW	-4.7 to 30.6 °C
Mean annual relative humidity	78%
Annual precipitation in EPW	747 mm
Annual global horizontal radiation	1289 kWh/m²
Mean wind speed	3.8 m/s
Heating degree days, base 18 °C	2747 K-days
Cooling degree days, base 24 °C	0.5 K-days
Hours ≥ 25 °C	139 h/year
Hours < 0 °C	437 h/year







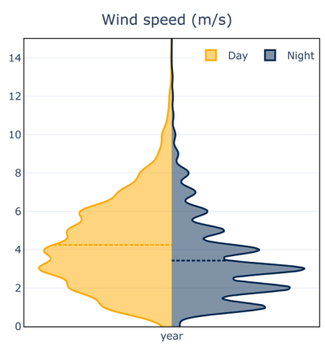


Fig 2.23 Climate Profiles (a) Dry buld Temperature (b)Relative humidity (c)Global Horizontal radiation (d)Wind speed

Climate Overview

The regional climate of the site is temperate and moisture-sensitive, with a mean annual temperature of 10.7 °C. Winter conditions produce the main heating demand, and there are only limited annual cooling degree days. Relative humidity remains high, and rainfall occurs throughout the year. The design response should therefore prioritise heat conservation, daylight access, moisture-safe construction, durable exterior materials, and controlled summer heat mitigation.

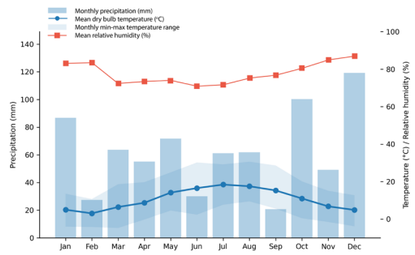


Fig 2.24 Climate overview for Brussels–Uccle: Yearly temperature range, precipitation and relative humidity.

Solar Access and Radiation

Solar availability is strongest in the southern sector and rises sharply from spring to summer with an annual global horizontal radiation of approximately 1,289 kWh/m², with the highest monthly values from May to July. This confirms that the project should preserve access to the southern sky where possible, while using shading, façade depth, vegetation and controlled glazing to limit warm-season gains.



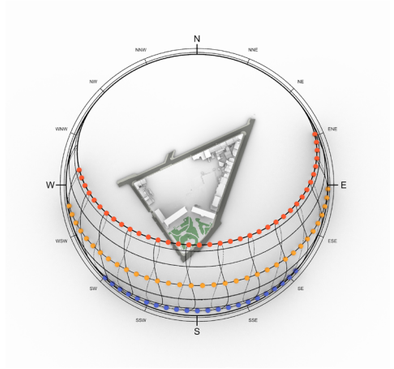


Fig 2.25 Monthly solar-radiation availability (a) global horizontal and diffuse horizontal radiation (b) a site-specific sun-path diagram with surrounding massing. (c) a seasonal shadow preview for spring, summer, autumn and winter

Spring



Summer

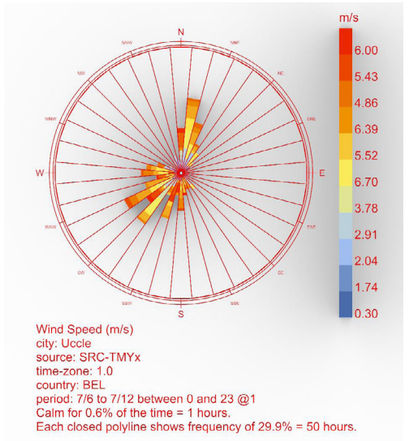


Fall



Winter





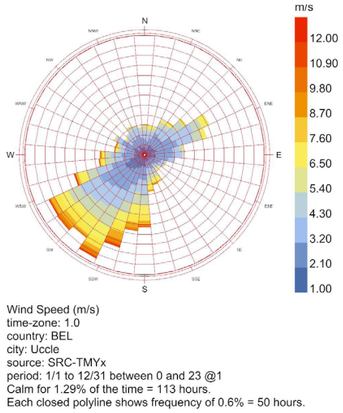


Fig 2.26 Wind rose for Brussels–Uccle: (a) annual wind direction and (b)wind-speed distribution.

Wind Analysis

The wind rose shows a clear dominance of south-west to west-south-west airflow, with secondary wind from the south and west. Mean wind speed is 3.8 m/s and calm conditions occur for only about 1.0% of the year. Wind should therefore be treated as a persistent site condition: useful for ventilation, but requiring protection in exposed public spaces, rail-side edges and areas near taller masses.

Required complementary image: a site wind-exposure diagram showing prevailing south-west airflow, rail-edge exposure, protected courtyards, and potential acceleration zones near taller masses.

Natural Ventilation Potential

Natural ventilation potential was assessed using outdoor temperatures between 10–24 °C, a range generally suitable for naturally ventilated spaces. These conditions occur during a significant part of the year, particularly in spring, summer evenings, and autumn as shown in fig 2.27.

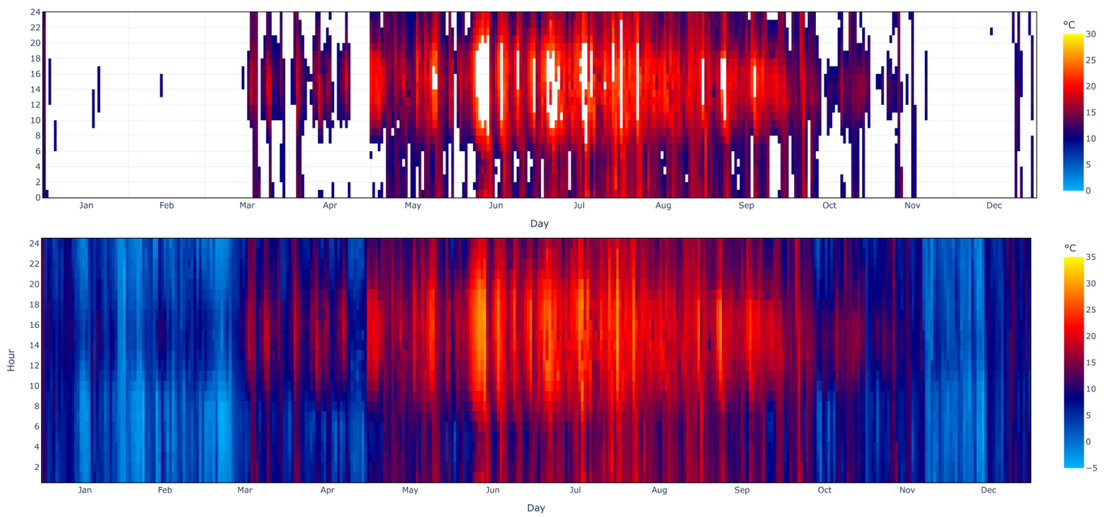
Combined with prevailing south-west winds and an average wind speed of about 3.8 m/s, these conditions create good opportunities for passive ventilation. For LionCity II, operable openings, sheltered courtyards, and vertical voids can support airflow, improving indoor comfort and air quality while reducing reliance on mechanical cooling and ventilation systems.

Temperature and Seasonal Thermal Behaviour

The temperature heat map shows a heating-led climate with a moderate but visible summer overheating risk. The data records 437 hours below 0 °C and 139 hours at or above 25 °C. Winter design should focus on continuous insulation, airtightness, thermal-bridge reduction and useful solar gain. Summer design should focus on external shading, night ventilation, thermal mass, reduced solar exposure and lower heat-absorbing surfaces.

Fig 2.27 Hours within the 10–24 °C dry-bulb temperature range and prevailing wind directions.

Fig 2.28 Annual dry-bulb temperature pattern: (a)annual dry-bulb temperature range compared with ASHRAE adaptive comfort bands.(b)hourly temperature distribution .



Humidity, Rainfall and Moisture Risk

Relative humidity is consistently high, with annual mean humidity of approximately 78%. Monthly humidity is highest in late autumn and winter, while rainfall is present across the year. The EPW total precipitation is approximately 747 mm, with the wettest months in this file occurring in December, October and January. This supports a permanent rain-management strategy rather than a seasonal one.

For envelope design, the results support ventilated rainscreen construction, durable exterior cladding, careful window and threshold detailing, controlled vapor flow, airtight construction, and drying-capable wall assemblies. Moisture performance should be treated as a primary envelope-selection criterion.

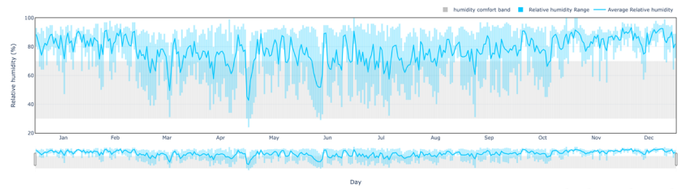


Fig 2.29 Annual relative humidity profile: hourly relative humidity range and average relative humidity compared with the humidity comfort band.

Fig 2.30 Psychrometric distribution for Brussels–Uccle: hourly dry-bulb temperature and humidity.

Bioclimatic Analysis

The psychrometric distribution confirms that most hours are cool to mild rather than extreme. Winter discomfort is primarily driven by low dry-bulb temperature, while summer conditions remain moderate enough for passive strategies to play a significant role. The suitable passive strategy is seasonal: retain heat and solar gain in winter, use natural ventilation in mid-season, and combine shading, thermal mass and airflow in summer.

Outdoor Thermal Comfort

Outdoor comfort was evaluated through UTCI and mean radiant temperature rather than air temperature alone with the results as shown below. For LionCity II, winter and shoulder-season comfort require wind protection and access to sunlight, while summer comfort requires shade, vegetation, permeable surfaces and reduced radiant heat from hardscape areas.

Climate-Based Design Implications

Climate finding	Design implication
Solar access	Preserve winter sun to key public spaces and south-facing façades; control summer gains with shading and façade depth.
Envelope thermal performance	Prioritise insulation, airtightness and thermal-bridge reduction while allowing summer heat dissipation.
Wind	Use south-west airflow for ventilation, but protect exposed public spaces with vegetation, setbacks and built edges.
Moisture	Use ventilated, durable and drying-capable envelope assemblies; design drainage as a permanent condition.
Outdoor comfort	Combine sun access, shade, trees, permeable surfaces and low-heat materials to stabilise comfort across seasons.
Armadillo relevance	Evaluate assemblies through thermal resistance, dynamic thermal behaviour, moisture safety, drying potential and rainscreen performance.

2.5 Site Synthesis

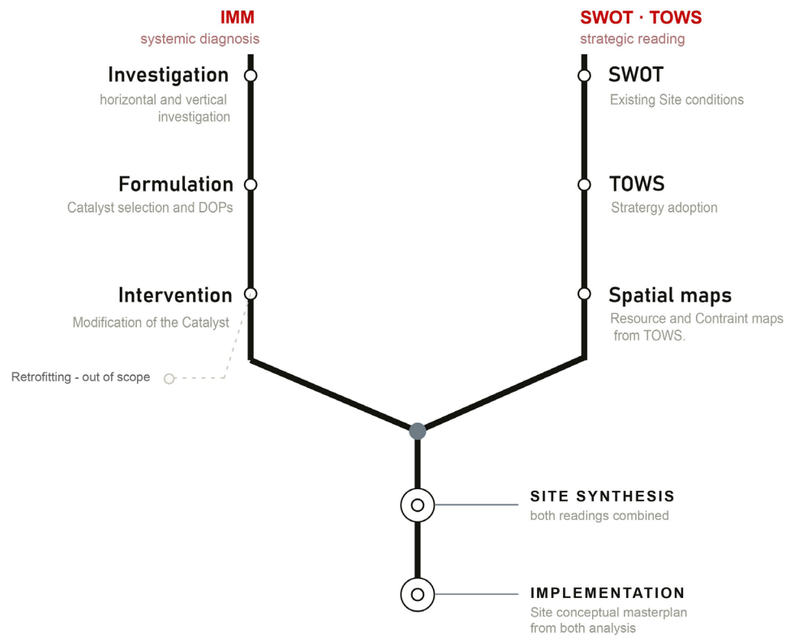


Fig 2.31 Methodological workflow for the site synthesis: IMM Phases 1–3 and SWOT–TOWS translated into Resources and Constraints maps, design drivers, and conceptual masterplan principles.

This section consolidates the findings of the site history, urban context, and climate analysis into a set of design drivers for LionCity II. The synthesis is structured through two complementary investigative tools the Integrated Modification Methodology (IMM), used to read the urban scape as a Complex Adaptive System and to identify the catalyst, Design Ordering Principles, and actions required for modification. SWOT–TOWS is then used to organise the broader site-scale strengths, weaknesses, opportunities, and threats into spatial strategies. Together, these two readings inform the Resources and Constraints maps and lead to the conceptual masterplan principles.

Intergrated Modification Methodology

Phase 1: Investigation

The IMM investigation reads LionCity II as a system composed of four interacting layers: volumes, voids, functions, and transportation. The analysis shows that the site's current underperformance does not result from a single isolated condition, but from the weak relationship between these layers.

The vertical investigation confirms that the weakest conditions are linked to interface, diversity, permeability, and local accessibility. Although Beekkant and Gare de l'Ouest provide strong regional accessibility, the parcel itself remains enclosed and poorly stitched into the surrounding street network. This creates a contradiction: the site is close to mobility infrastructure, but it does not yet function as a connected urban threshold.

CAS LAYER	KEY FINDING	DESIGN IMPLICATION
Volumes	The site lies between the low residential fabric of Rue Osseghem and the taller Machtens towers.	New massing must mediate the height transition rather than reproduce the rupture.
Voids	Existing open spaces are fragmented, sealed, and largely shaped by parking or service use.	Open space must become continuous, public, planted, and socially usable.
Functions	The former Delhaize site was historically mono-functional and inward-facing.	The redevelopment must introduce a balanced mix of housing, cultural, productive, commercial, and public uses.
Transportation	Regional accessibility is strong, but local east–west permeability is weak.	The Beekkant axis must become the primary pedestrian, cycling, and ecological connector.

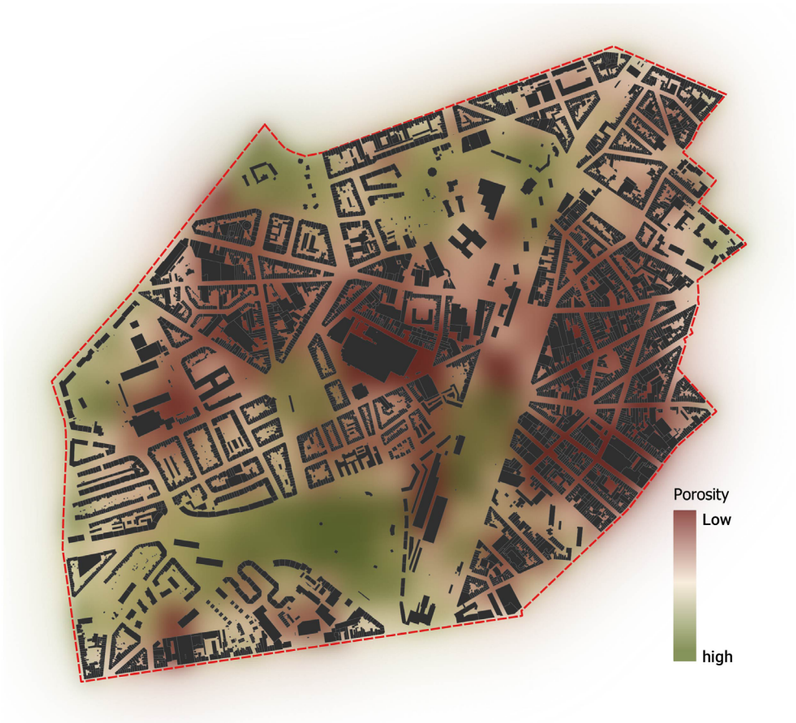


Fig 2.32 IMM vertical investigation: (a) porosity

The Porosity Map shows the balance between built mass and open space in the study area. Green areas indicate higher porosity, such as parks, courtyards, setbacks, or unbuilt parcels, which can support daylight, ventilation, pedestrian movement, and ecological connections. Brown areas show lower porosity, where the urban fabric is denser and open space is limited. Overall, the map helps identify where the area feels too compact and where new interventions such as pocket parks, shared courtyards, or pedestrian links could improve livability and environmental quality.

Fig 2.33 IMM vertical investigation: (b) proximity

The Proximity Analysis evaluates how easily residents can access key urban functions such as education, commerce, public services, and entertainment within a 300-meter walking distance. Using GIS buffers, the analysis identifies areas where multiple services overlap, showing strong walkability and functional diversity. Overall, the neighborhood benefits from good access to essential amenities, supporting connectivity, convenience, and quality of life.



Fig 2.34 IMM vertical investigation: (c) diversity

The Diversity Map was selected as the Catalyst because it reveals the distribution of Necessary Regular and Necessary Occasional functions across the study area. While the neighborhood has good access to daily services such as groceries, schools, pharmacies, and public transport, there is a clear lack of occasional services near Lion City, such as hospitals, administrative offices, and other less frequent but important destinations. This imbalance shows the need to introduce new complementary functions that can strengthen service diversity, improve urban vitality, and support Lion City as a more complete and resilient urban node.



Fig 2.35 IMM vertical investigation: (d) interface,

The **Interface Analysis** evaluates street connectivity around **Lion City, Brussels** using **DepthMapX** and space syntax integration values. The map shows how easily pedestrians and vehicles can move through the urban network, with **red lines** representing highly integrated and well-connected routes, **orange/yellow lines** showing moderate connectivity, and **blue lines** indicating more peripheral or less accessible streets. Overall, the analysis helps identify the main movement corridors and weaker connections, supporting urban design decisions that improve accessibility, circulation, and the relationship between Lion City and its surrounding urban fabric.

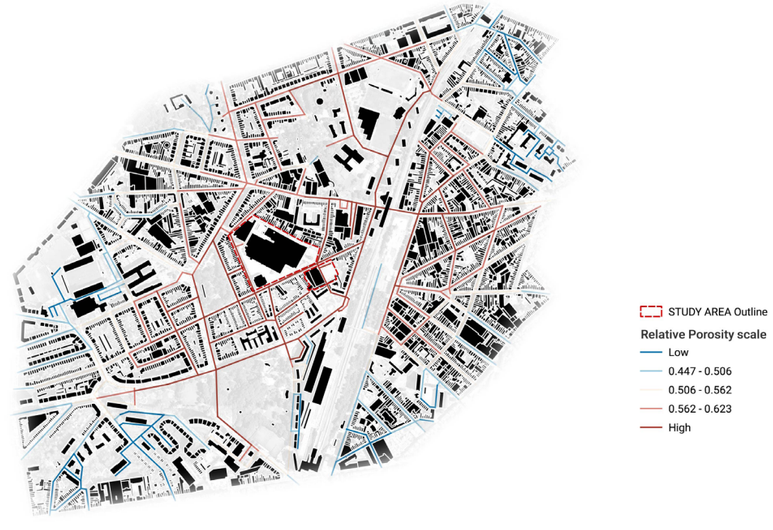


Fig 2.36 IMM vertical investigation: (e) effectiveness

The Effectiveness Map shows how efficiently different areas support and attract trips, especially through public transport. Red areas indicate higher effectiveness, with stronger transit use, better accessibility, or more active movement hubs, while green areas show lower effectiveness and weaker public transport performance. Overall, the map helps identify where mobility is already strong and where improvements such as better routes, increased service frequency, densification, or mixed-use development could enhance connectivity and support a more balanced urban environment.

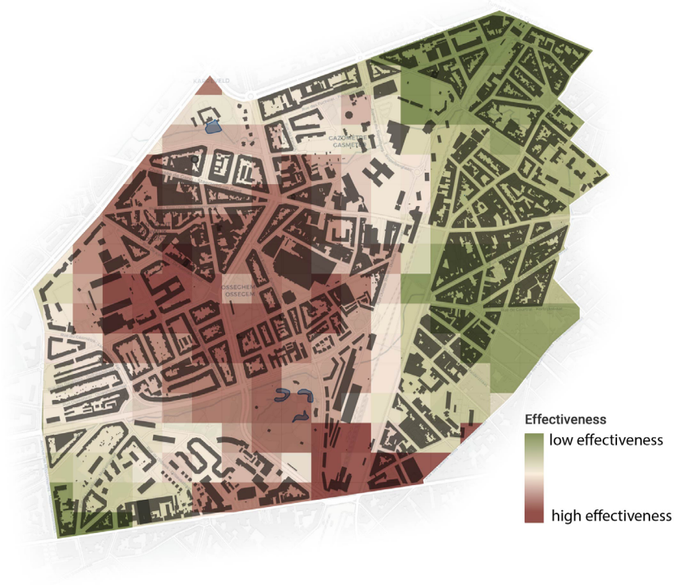


Fig 2.37 IMM vertical investigation: (f) accessibility by bus

The map focuses on bus stop accessibility, showing 2, 4, and 6-minute walking zones around each stop. Together, the maps reveal where public transport coverage is strongest, where service gaps may exist, and where tram, train/metro, and bus networks overlap to create potential intermodal connection points. The Transit



Fig 2.38 IMM vertical investigation: (f) accessibility by railway

Accessibility Maps evaluate how well the Lion City 2 area is served by different public transport modes. The first map shows walking catchments to tram stops and train/metro stations, using darker colors for shorter walking times and lighter colors for longer distances.



IMM Phase 2: Catalyst Selection

The selected primary catalyst for LionCity II is Interface. The main malfunction of the site is the weak relationship between the parcel and its surrounding urban systems: fenced edges, poor frontage activation, limited permeability, the rail barrier, and the absence of clear pedestrian and cycling continuity. Interface is therefore not simply one weak category among others; it is the condition that causes weakness in other categories, including proximity, accessibility, public-space continuity, and programme distribution.

A secondary catalyst is Diversity. The site's long industrial history produced a mono-functional, enclosed logistics landscape. The current redevelopment brief and PRAS strong-mixity designation create the possibility of transforming this condition into a mixed urban block combining affordable housing, cultural infrastructure, circular-economy uses, productive spaces, ecological systems, and public open space.

Fig 2.39 Catalyst selection diagram: Interface as the primary catalyst and Diversity as the secondary catalyst for the modification of the LionCity II local CAS.

Priority	DOP	Design Ordering Principle	Significance to site
1	DOP06	Reinforce walking, cycling, and public-transport integration	Opens the site through the Beekkant axis and reconnects it to the district.
2	DOP05	Create a connected open-space system	Converts fragmented residual space into a continuous green-public structure.
3	DOP02	Implement permeability to facilitate urban flow	Breaks the enclave condition and creates new pedestrian and ecological connections.
4	DOP03	Balance the distribution of uses and foster multifunctional spaces	Supports mixed use around the civic spine and active ground floors.
5	DOP04	Promote diversity in human and natural systems	Integrates biodiversity, social diversity, and programme diversity.
6	DOP01	Balance land coverage	Rebalances built form, open space, green areas, and public ground.

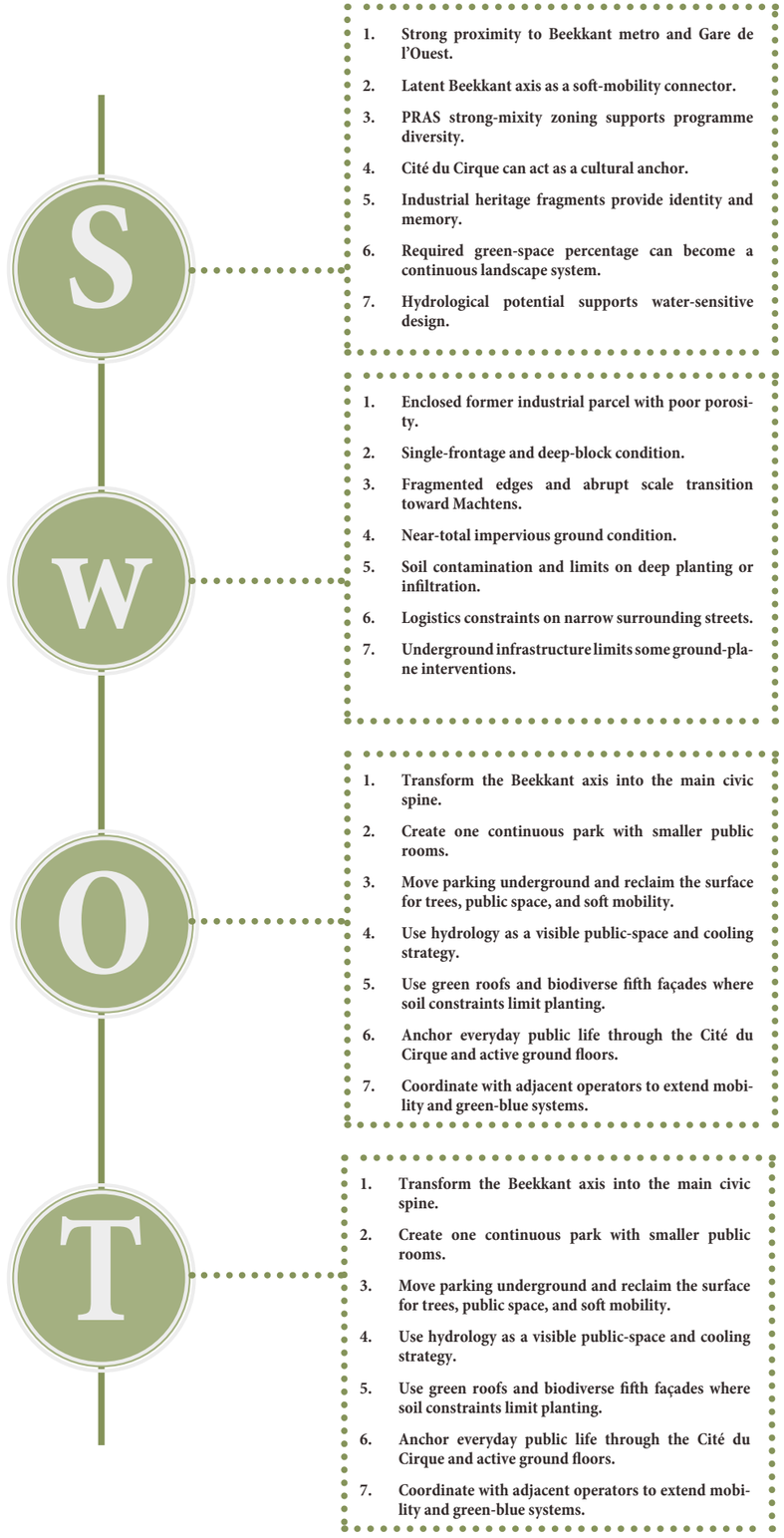
IMM Phase 3: Modification Actions

The selected DOPs are translated into site-specific actions. These actions do not represent a final design solution; they define the modification logic that the conceptual masterplan must carry forward.

DOP	Site-specific action
DOP06 — Walking, cycling, and public transport	Establish the Beekkant axis as a car-free pedestrian and cycling spine linking Rue Osseghem, Place Beekkant, Beekkant metro, Gare de l'Ouest, and the wider green network.
DOP05 — Connected open-space system	Deliver the 25% green-space requirement as one continuous public landscape supported by smaller adjoining rooms, rather than as fragmented residual pockets.
DOP02 — Permeability and urban flow	Open selected edges of the former industrial enclosure and create at least one strong east–west route and one supporting north–south permeability line.
DOP03 — Multifunctional spaces	Distribute housing, Cité du Cirque, circular-economy shops, productive uses, community services, and shared spaces around the civic spine.
DOP04 — Human and natural diversity	Integrate biodiversity, native planting, urban agriculture, inclusive public space, and social programmes into the landscape and ground-floor strategy.
DOP01 — Balanced land coverage	Reclaim the ground plane from surface parking and rebalance built footprint, green space, courtyards, public thresholds, and roof surfaces.
DOP12 — Water management	Use rain gardens, bioswales, permeable surfaces, planted retention zones, and roof-water strategies as visible elements of public-space design.

Phase 4 of the IMM process, which would normally evaluate the performance of the modified system against its initial condition, is outside the scope of this thesis. The thesis uses IMM up to the formulation and design-action stage, in order to establish a clear methodological basis for the conceptual masterplan.

SWOT Analysis



TOWS Strategy and Spatial Translation

The TOWS strategy translates the SWOT findings into spatial modification priorities. The strategies are not treated only as a table; they are spatialized through the Resources and Constraints maps.

SxO

Strengths × Opportunities

1. **Use strong transit access, PRAS flexibility, and the Cité du Cirque to activate the Beekkant axis as the civic spine of the project.**
2. **Convert the required green-space percentage into one connected landscape system rather than separate green fragments.**

WxO

Weaknesses × Opportunities

1. **Use new public routes, active ground floors, and the continuous park to break the enclave condition.**
2. **Use fifth-façade ecological surfaces, raised planting, and roof-based systems where soil pollution or underground infrastructure limit ground planting.**

SxT

Strengths × Threats

1. **Use the continuous green structure as a heat, stormwater, and public-comfort buffer against climate exposure.**
2. **Use mixed-use zoning to prevent the Cité du Cirque from becoming only an event-based destination.**

WxT

Weaknesses × Threats

1. **Consolidate logistics and servicing to prevent conflict with pedestrian and cycling movement.**
2. **Coordinate phasing with adjacent parcels to avoid dead ends, blank edges, and incomplete public-space links.**

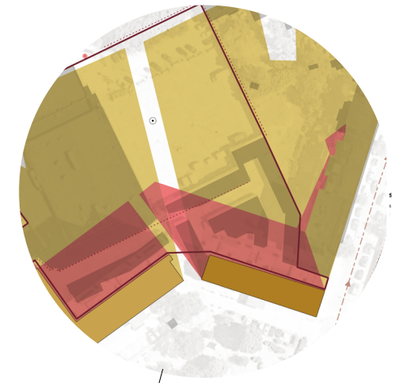
Resources and Constraints Maps

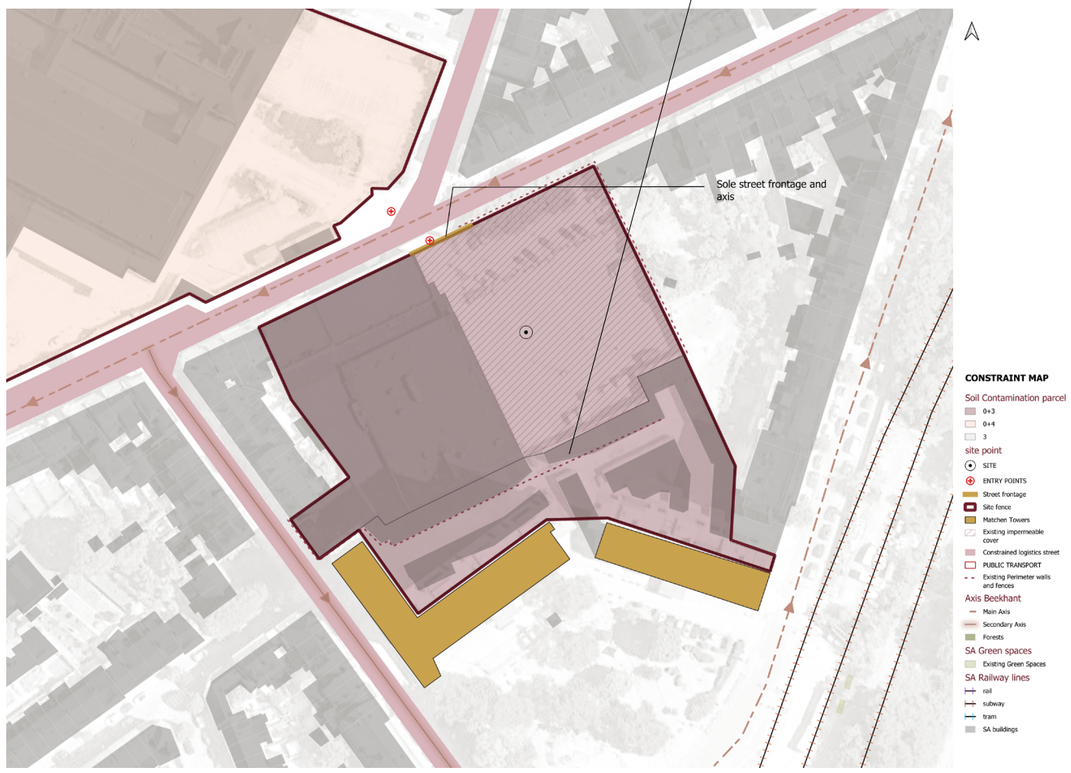
The Resources map identifies the conditions that can actively support the masterplan. These include the Beekkant axis, proximity to public transport, the Cité du Cirque programme, industrial heritage traces, existing green structures, hydrological potential, the 25% green-space requirement, and the possibility of active ground-floor uses.

The Constraints map identifies the conditions that must be managed by the design. These include the rail corridor, soil contamination, underground infrastructure, the Maelbeek collector, limited site frontage, logistics pressure on narrow streets, the height transition toward Machtens, southwest wind exposure, winter shadow zones, and the risk of fragmented open space.

Together, the two maps show that LionCity II should not be planned as a closed block, but as a connective threshold. The site must transform from an inward-facing industrial compound into a porous urban structure that links mobility, landscape, public programme, and envelope performance.

Fig 2.40 *Resources map: Beekkant axis, public-transport nodes, heritage traces, green-space potential, cultural anchor, and active-frontage zones.*
Fig 2.41 *Constraints map: rail barrier, soil constraints, underground infrastructure, hydrological limits, logistics pressure, shadow exposure, wind exposure, scale transition, and weak edges.*





Design Drivers

The synthesis produces seven design drivers for the conceptual masterplan.

1. De-enclave the parcel.
2. The site must be opened physically and visually through selected pedestrian, cycling, and ecological connections.
3. Establish the Beekkant axis as the civic spine.
4. The Beekkant axis should become the main public route, connecting transit, landscape, active ground floors, and the Cité du Cirque.
5. Create a continuous blue-green structure.
6. The required green space must be organised as one connected ecological and public-space system, supported by stormwater management and microclimate design.
7. Use programme diversity as an urban repair tool.
8. Housing, culture, productive uses, circular-economy shops, shared facilities, and community services should be distributed to support everyday public life.
9. Mediate the height transition.
10. Massing must step between the lower residential fabric and the taller Machtens towers, while preserving daylight, solar access, and comfortable public edges.
11. Treat the envelope as a climate instrument.
12. The climate analysis requires high thermal performance, moisture-safe construction, solar control, daylight access, durable materials, and ventilated façade strategies.
13. Reuse industrial memory selectively.
14. The Delhaize heritage traces, enclosure fragments, and structural memory of the site should be reinterpreted as identity anchors without preventing porosity.

Fig 2.42 Design drivers map: seven design drivers located across the LionCity II site and connected to the conceptual masterplan structure.

Endnotes

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03

ARCHITECTURAL DESIGN

Chapter 3 presents the architectural response to the site analysis and design drivers established in the previous chapter. The development focuses on the Cité du Cirque as the primary building intervention while situating it within the broader LionCity II masterplan. The chapter outlines the project's massing, programme, public realm strategy, passive design approach, and preliminary envelope logic, establishing the design framework for subsequent performance evaluation.

3.1 Structural and Technical Designz

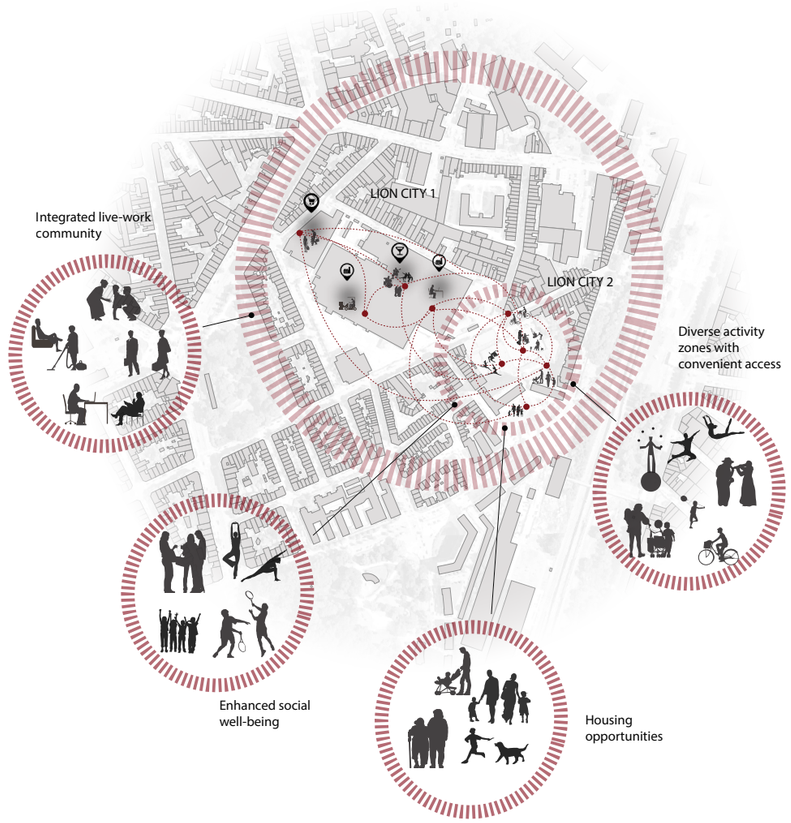


Fig 3.01 *From Site Diagnosis to Architectural Agenda*

Chapter 3 translates the site diagnosis of Chapter 2 into an architectural design response. The site history, urban context, climate analysis, SWOT–TOWS synthesis, and Integrated Modification Methodology are not repeated here; they are carried forward as design instructions. The chapter therefore shows how the findings of Chapter 2 become decisions at the scale of massing, programme, public realm, landscape, mobility, and envelope strategy.

The chapter also defines the architectural model and envelope conditions that will be evaluated in Chapter 4. To keep the evaluation focused, the architectural development concentrates on the principal cultural building, the Cité du Cirque, while the residential and supporting components are resolved at masterplan scale. This allows the envelope and performance investigation to operate on a coherent building model rather than a dispersed and heterogeneous mixed-use district.

Design Brief, Scope, and Project Vision

The architectural task proceeds from three conditions: the LionCity II programme brief issued by citydev.brussels, the performance ambition of the C40 Reinventing Cities framework, and the site synthesis established in Chapter 2. The brief is treated as an input to be organised through design, rather than as a checklist to be satisfied. The central ambition is to transform a mono-functional industrial enclosure into a mixed-use, low-carbon, climate-responsive urban block whose principal building, the Cité du Cirque, acts as a cultural anchor for the neighbourhood.fig 3.01

The architectural development focuses on the Cité du Cirque because it is the project's most spatially and environmentally demanding component. It contains large-span volumes, variable occupancy, public interfaces, controlled daylight requirements, and significant external wall area. These conditions make it an appropriate building through which to test the envelope-selection and performance workflow developed later in the thesis. The housing, circular-economy commerce, shared facilities, and landscape components are resolved at masterplan scale, with their massing, access, and relationship to the public realm defined, but their internal typological development left outside the scope of this chapter.

The design drivers established in Chapter 2 are carried forward as architectural strategies. The primary IMM catalyst, Interface, requires the project to open the parcel, repair weak edges, and create new relationships between the site and its surroundings. The secondary catalyst, Diversity, requires a programme and landscape structure capable of transforming a former industrial block into a mixed civic, ecological, and residential environment. The Beekkant restitch becomes a civic spine. The datum jump becomes a graded section between Rue Osseghem and the Machtens towers. The ecological and hydrological findings become a continuous blue-green structure. The climate analysis becomes an envelope and passive-design strategy. The historical reading becomes the selective reinterpretation of industrial memory.

3.2 Competition Requirements

The competition requires a mixed-use development of more than 6,500 m² of floor area, combined with public and private open spaces. The programme is not simply a list of functions; it establishes the social and spatial identity of the project. Housing provides continuity of everyday life, the Cite du Cirque introduces a cultural and public facility, and circular-economy or green-service activities activate the ground level while responding to broader environmental objectives.

The most important architectural consequence of this programme is the need to reconcile public intensity and domestic quality. The project must remain active, open and civic at ground level, while providing secure, comfortable and well-oriented housing above or alongside the public programme. This requires a clear hierarchy of entrances, controlled transitions between public and private domains, and a massing strategy that avoids functional conflicts between performance activities, training areas, commercial spaces and dwellings.

Programme component	Competition requirement	Architectural implication
Housing	Housing must be included; 30% to 50% should be accessible at affordable prices.	The residential component must be integrated without isolating it from the cultural and public functions. Massing, access cores, privacy, sunlight and acoustic separation become decisive design issues.
Cite du Cirque: stage infrastructure	A stage infrastructure of more than 1,100 m² is required to support UP Circus & Performing Arts.	The stage volume should act as a civic anchor and performance destination. Its scale, height, servicing and public entrance must be resolved as part of the overall composition.
Cite du Cirque: training area	A minimum of 2,500 m² is required for the circus training area, with spatial, functional and visual connections to the stage infrastructure.	Training and performance spaces should be linked to reinforce the identity of a coherent Circus City, while allowing shared uses and mutualisation where possible.
Shops / facilities	Shops or other facilities should stimulate the circular economy and green services.	Ground-floor functions should support public activity, local services and circular practices, rather than becoming generic commercial frontage.
Open spaces	Open spaces must encourage soft mobility and green areas, including the pedestrian walkway toward Beekkant metro station.	The public realm is a core design component. It should structure movement, biodiversity, social control and climate adaptation.

Tab 3.01 Competition Brief as Spatial Framework

Environmental and Climate Requirements

The architectural development must respond to the Brussels Air-Climate-Energy Plan, which sets the regional objective of reducing greenhouse gas emissions by 55% by 2030 and reaching carbon neutrality by 2050. The competition therefore expects the project to go beyond conventional building design and address energy use, material impact, water management, biodiversity, mobility and long-term adaptability as interconnected design parameters.

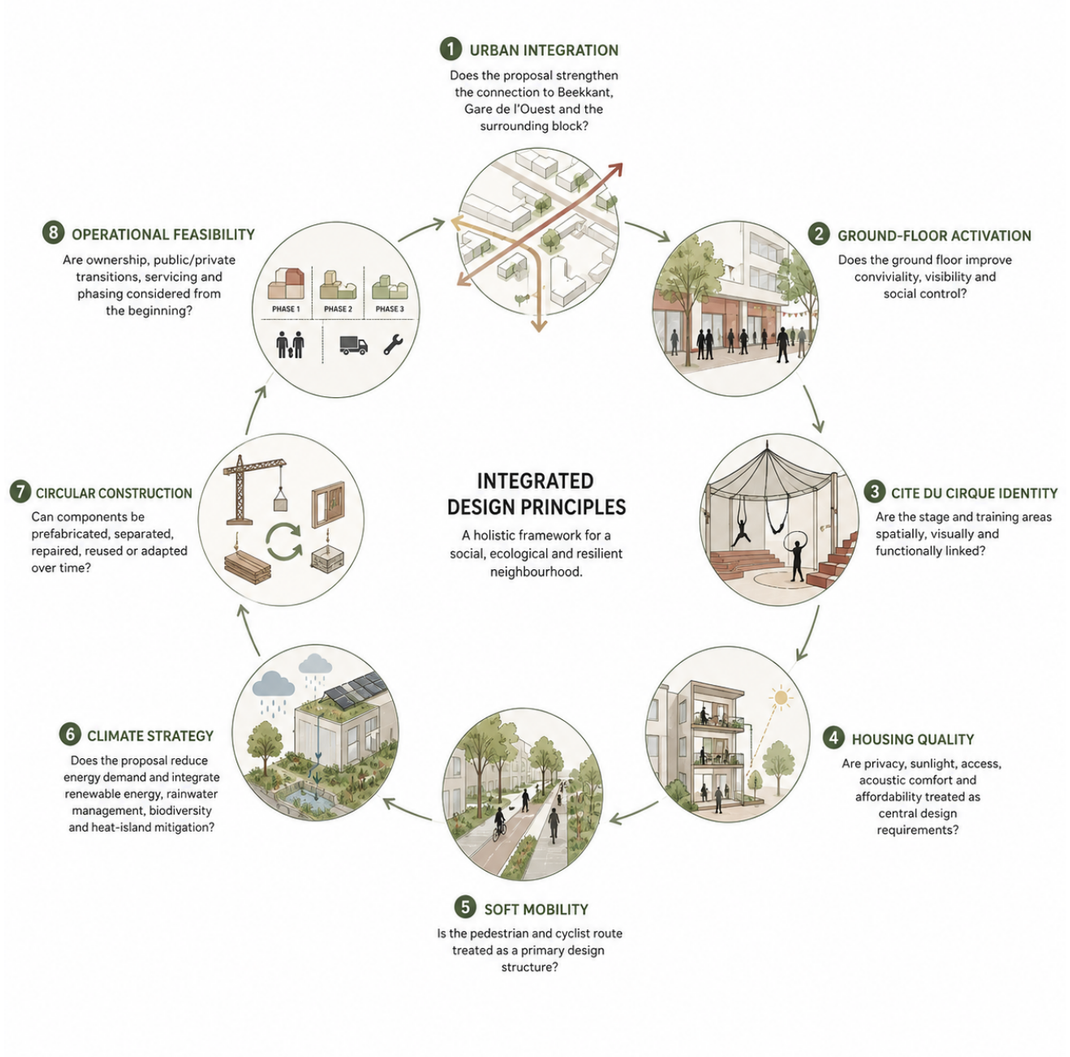
Tab 3.02 Integrated Design Principles for a Civic, Ecological and Resilient Block

Environmental theme	Requirement from the brief	Design response for Chapter 3
Energy efficiency	Design must reduce operational energy demand and use recognised environmental assessment tools such as TOTEM or equivalent methods.	Orient massing, envelope and shading to reduce heating/cooling demand; connect architectural decisions to energy simulation and material assessment.
Renewable energy	Solar energy should be used wherever possible, including photovoltaic panels. A feasibility study for a heating network is required.	Reserve roof and facade zones for PV integration; coordinate roof uses between energy production, green roofs and technical equipment.
Energy storage	Site-level energy storage proposals are expected.	Consider energy strategy as part of the site infrastructure, not as a later technical addition.
Circular construction	Use environmentally responsible materials, high recycled content, mechanical fixing, low ecological footprint and recoverable components.	Develop assemblies that can be prefabricated, dismantled and adapted. Avoid unnecessary complexity and prioritise standard modular components.
Flexibility and reversibility	Interior spaces and construction systems should allow future change with minor works.	Use structural spans, cores and service logic that permit programme change over time, especially in training, commercial and productive areas.
Water management	Rainwater should be returned to the natural environment as far upstream as possible; domestic rainwater use and greywater recycling should be considered.	Integrate rain gardens, permeable surfaces, water reuse, stormwater storage and separate drainage logic into the open-space design.
Green roofs and biodiversity	Flat inaccessible roofs should become intensive or extensive green roofs; PV roofs should include extensive substrate where compatible.	Treat roofs as ecological and energy surfaces; coordinate substrate depth, maintenance access and PV performance.
Soil pollution	The plot is potentially polluted and requires risk management before excavation or groundwater pumping.	Avoid unnecessary excavation where possible; coordinate foundation, landscape and water strategies with soil-risk constraints.
Citizen participation	The project should follow citydev.brussels participation procedures and aim to be exemplary on environmental issues.	Use the architectural narrative to communicate public benefits: access, shared spaces, climate adaptation and neighbourhood activation.

Design Evaluation Criteria for the Architectural Alternatives

The following criteria can be used to evaluate massing options, programme distribution and facade/environmental strategies during the architectural development process

Fig 3.02 Competition Brief as Spatial Framework

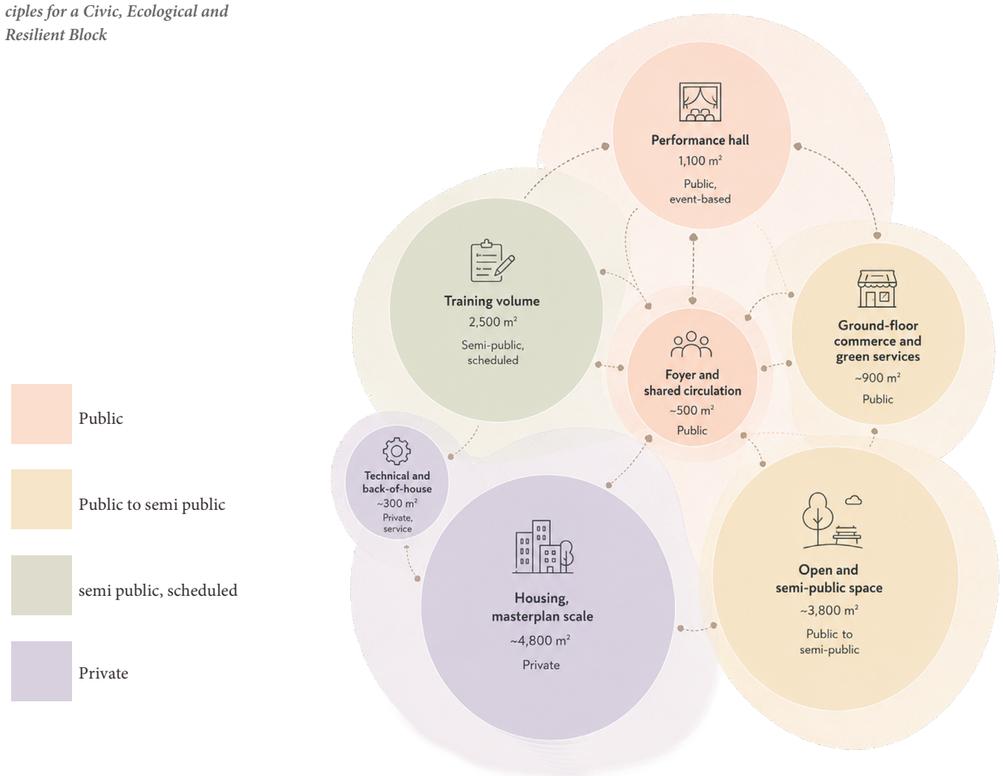


Programme and Spatial Strategy

The programme is organised as a design instrument. The project responds to the secondary catalyst of Diversity by distributing public, cultural, productive, residential, and ecological functions across the site. Public and productive uses occupy the ground plane, the Cité du Cirque anchors the central civic space, and residential massing is placed along quieter edges where privacy and environmental stability can be maintained.

The Cité du Cirque is treated as one functional cluster composed of the performance hall, the training volume, shared foyer, circulation, and technical premises. These spaces have different environmental requirements and will later inform the thermal zoning strategy in Chapter 4. The performance hall is tall and intermittently occupied; the training volume is more regularly occupied; the foyer and public ground floor are more open, glazed, and variable in use. For this reason, the building cannot be treated as one uniform thermal zone.

Fig 3.03 *Integrated Design Principles for a Civic, Ecological and Resilient Block*



Spatial Framework and Design Strategy

Before defining the architectural massing in detail, the project is structured through three interconnected spatial systems: movement, landscape, and programme. These systems translate the site synthesis of Chapter 2 into concrete design strategies. The Beekkant axis is reinforced as the primary civic and soft-mobility spine; fragmented open spaces are reorganised into a continuous green-public network; and the mixed-use programme is distributed through a clear hierarchy of public, semi-public and private thresholds. Together, these maps establish the spatial framework that guides the transformation of the former industrial enclosure into an accessible, active and climate-responsive urban block.



Fig 3.04 *Access Hierarchy and Beekkant Civic Spine*

The access strategy prioritises walking, cycling and public transport as the main structure of the masterplan. The Beekkant axis is reinforced as a car-free civic spine linking Rue Osseghem, Place Beekkant, Gare de l'Ouest and the internal public spaces of LionCity II. It connects the Cité du Cirque, mixed-use ground-floor activities and residential entrances. Vehicular access is limited to selected points, ensuring soft mobility remains the primary circulation system.



Fig 3.05 *Green-Public Network and Water-Sensitive Landscape*

The green-network map transforms fragmented open spaces into one continuous landscape system. Existing green areas are connected to new public green spaces, residential courtyards and planted pedestrian corridors. This supports the 25% green-space requirement as a connected ecological and public structure. The landscape also functions as environmental infrastructure for cooling, biodiversity and rainwater management.

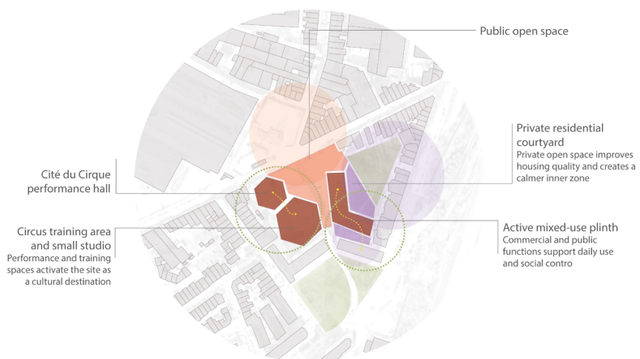
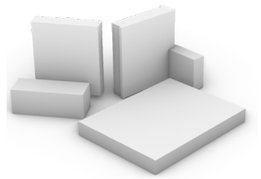


Fig 3.06 *Public–Private Thresholds and Mixed-Use Anchors*

The programme map defines the relationship between public, semi-public and private spaces. The Cité du Cirque acts as the main cultural anchor, while the mixed-use residential and commercial block activates the public realm. Public open space forms the central civic interface between the neighbourhood and the project. Private residential courtyards provide quieter spaces, balancing public activity with residential privacy.

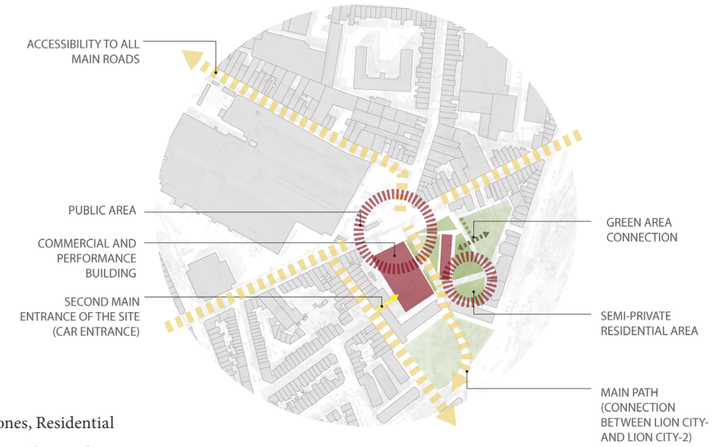
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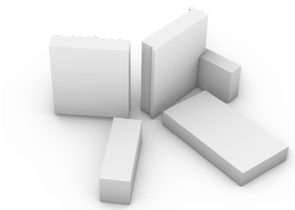


237	88	16	16%	283
Site EUI (KWh/m2)	Op. Carbon (S/m2)	Energy Cost	Saved Vs. Baseline	Baseline EUI (KWh/m2)

Includes two zones, Residential and Mixed-Use, with a total required area of 4150 m².
S/V factor: 0.08

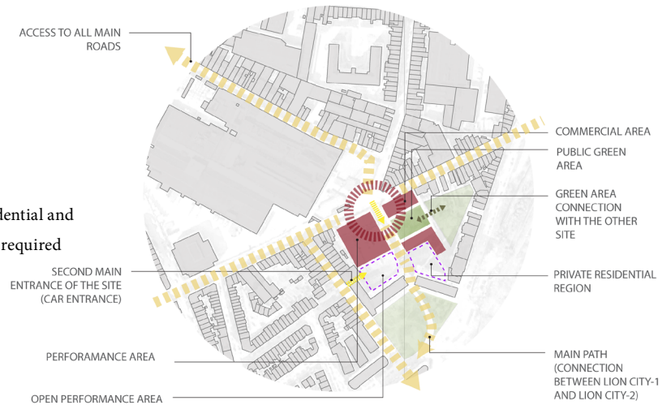
Massing Alternatives and Early Energy Feedback

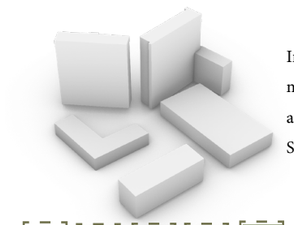




261	101	21	12%	292
Site EUI (KWh/m2)	Op. Carbon (S/m2)	Energy Cost	Saved Vs. Baseline	Baseline EUI (KWh/m2)

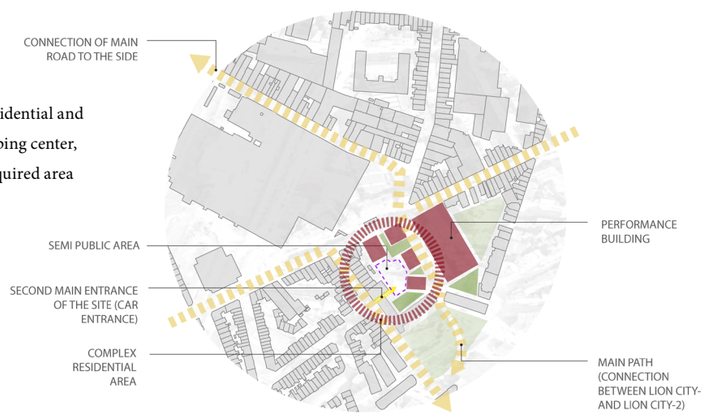
Includes two zones, Residential and Mixed-Use, with a total required area of 4150 m².
S/V factor: 0.08

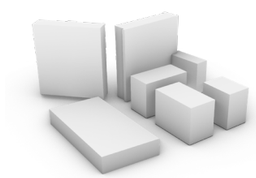




240	120	23	15%	292
Site EUI (KWh/m2)	Op. Carbon (S/m2)	Energy Cost	Saved Vs. Baseline	Baseline EUI (KWh/m2)

Includes five zones ,Residential and mixed used , with a total required area of 4150 m².
S/V factor: 0.09





262	125	21	15%	292
Site EUI (KWh/m2)	Op. Carbon (S/m2)	Energy Cost	Saved Vs. Baseline	Baseline EUI (KWh/m2)

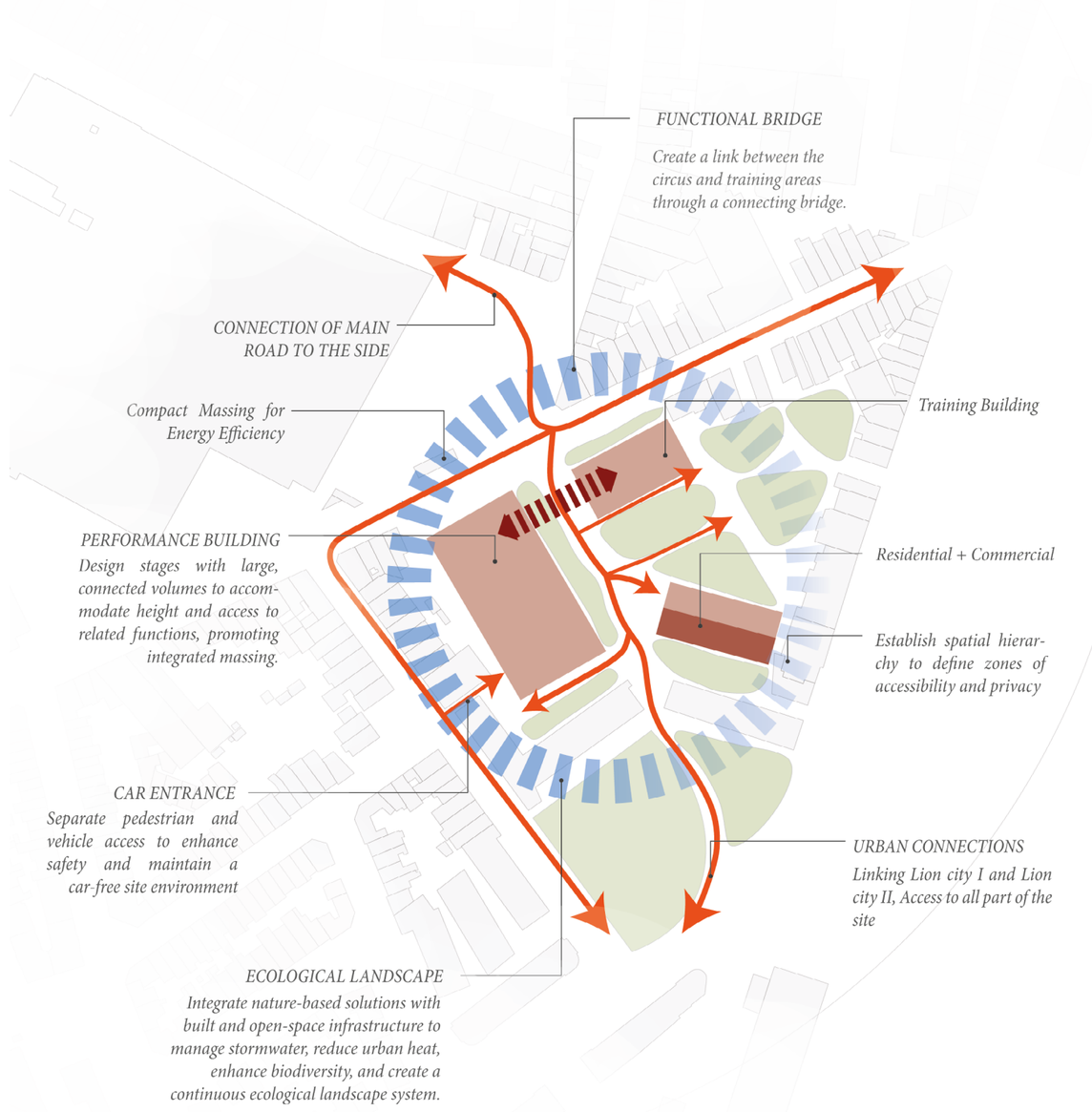
Includes five zones ,Residential and Performing Arts, Shopping center, Collage, with a total required area of 4150 m².
S/V factor: 0.09

Final Conceptual map

The final conceptual masterplan translates the massing optioneering process into a coherent architectural strategy. The proposal transforms the former industrial enclosure into a porous mixed-use block structured by the Beekkant civic spine, the Cité du Cirque cultural anchor, and a continuous ecological landscape. Circulation, programme, and landscape are integrated into one spatial system that organises access, public life, and environmental performance.

The Cité du Cirque acts as the main public anchor, with the performance hall defining the civic edge and the training building connected through a functional bridge. A clear hierarchy of pedestrian, cycling, and vehicular routes ensures efficient movement while prioritising soft mobility and preserving a pedestrian-oriented public realm. The landscape strategy strengthens biodiversity, stormwater management, and outdoor comfort through connected green spaces and courtyards. Together, these elements establish the project's core design logic: compact massing, strong public activation, clear mobility structure, and climate-responsive landscape integration.

Fig 3.07 Final Conceptual Master plan



Massing Evolution: From Industrial Block to Connected Urban Quarter

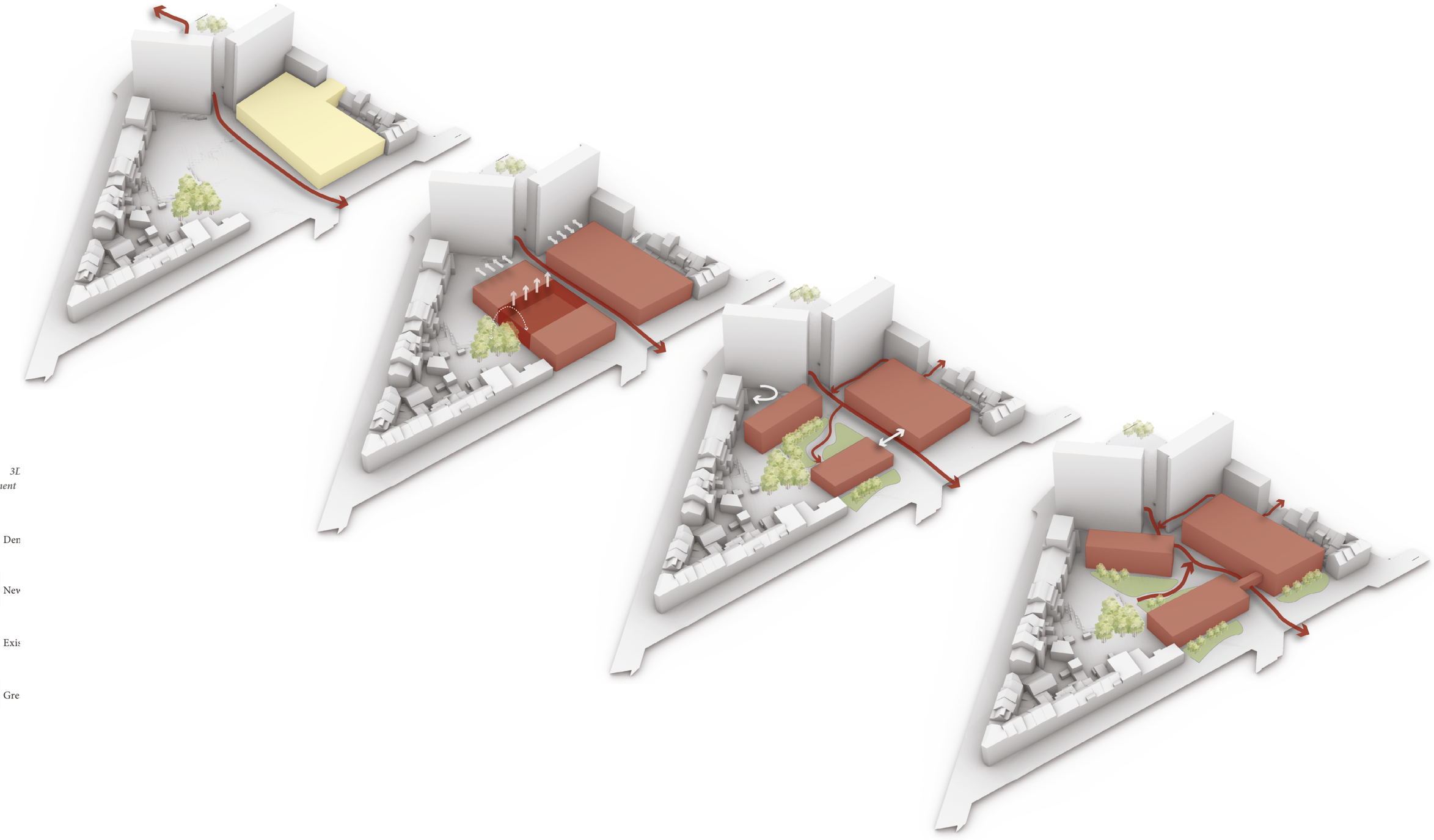


Fig 3.08 3D
development

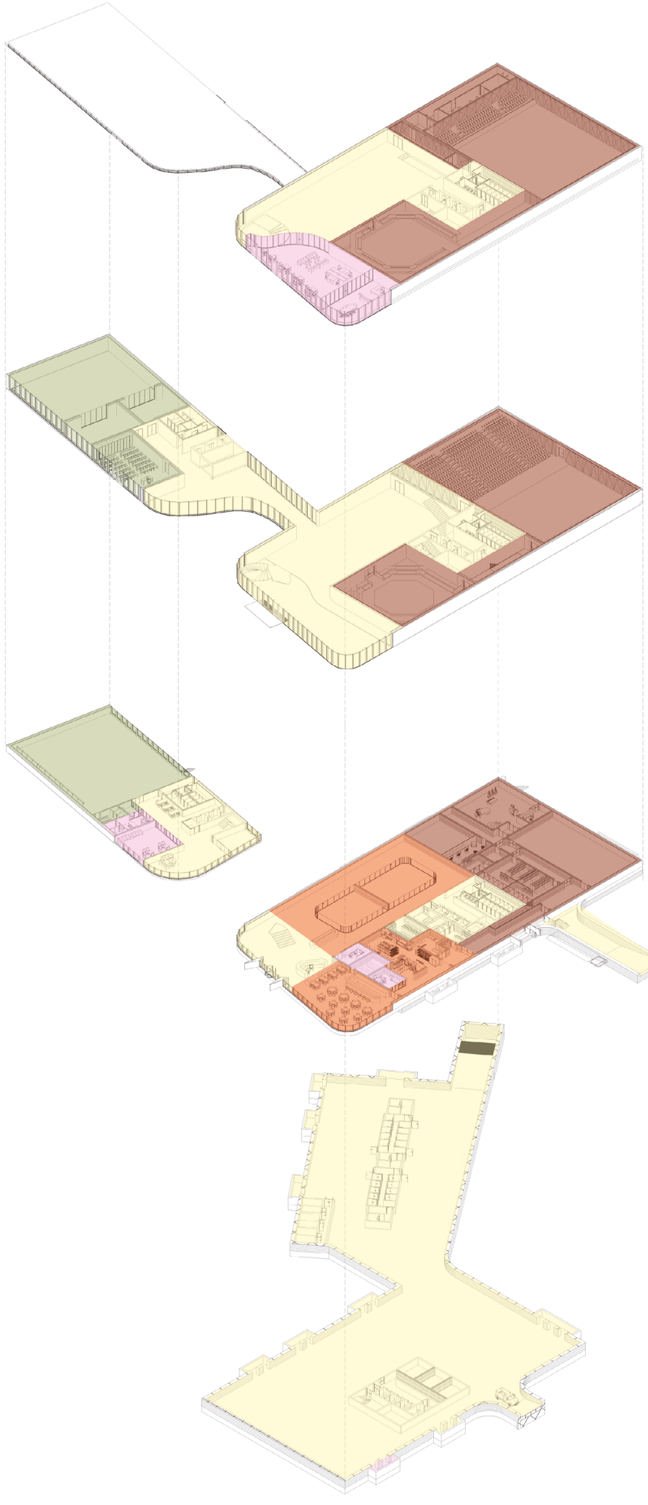
Den

New

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Gre

Functional organisation diagram



Public / Community Layer

- Main entrance
- Lobby / foyer
- Exhibition / waiting area
- Public toilets
- Public open interface
- Parking

Commercial / Social Layer

- Shops
- Café / restaurant
- Dining area
- Kitchen
- Community-support functions

Cultural Performance Layer

- Performance hall
- Main stage
- Audience zone
- Backstage support
- Dressing rooms
- Technical support

Training / Education Layer

- Training hall
- Small studio
- Dance studio
- Classrooms
- Workshop / learning rooms

Administration / Staff Layer

- Offices
- Meeting rooms
- Staff rooms
- Management / administration
- Staff toilets



Fig 3.09 Master plan map

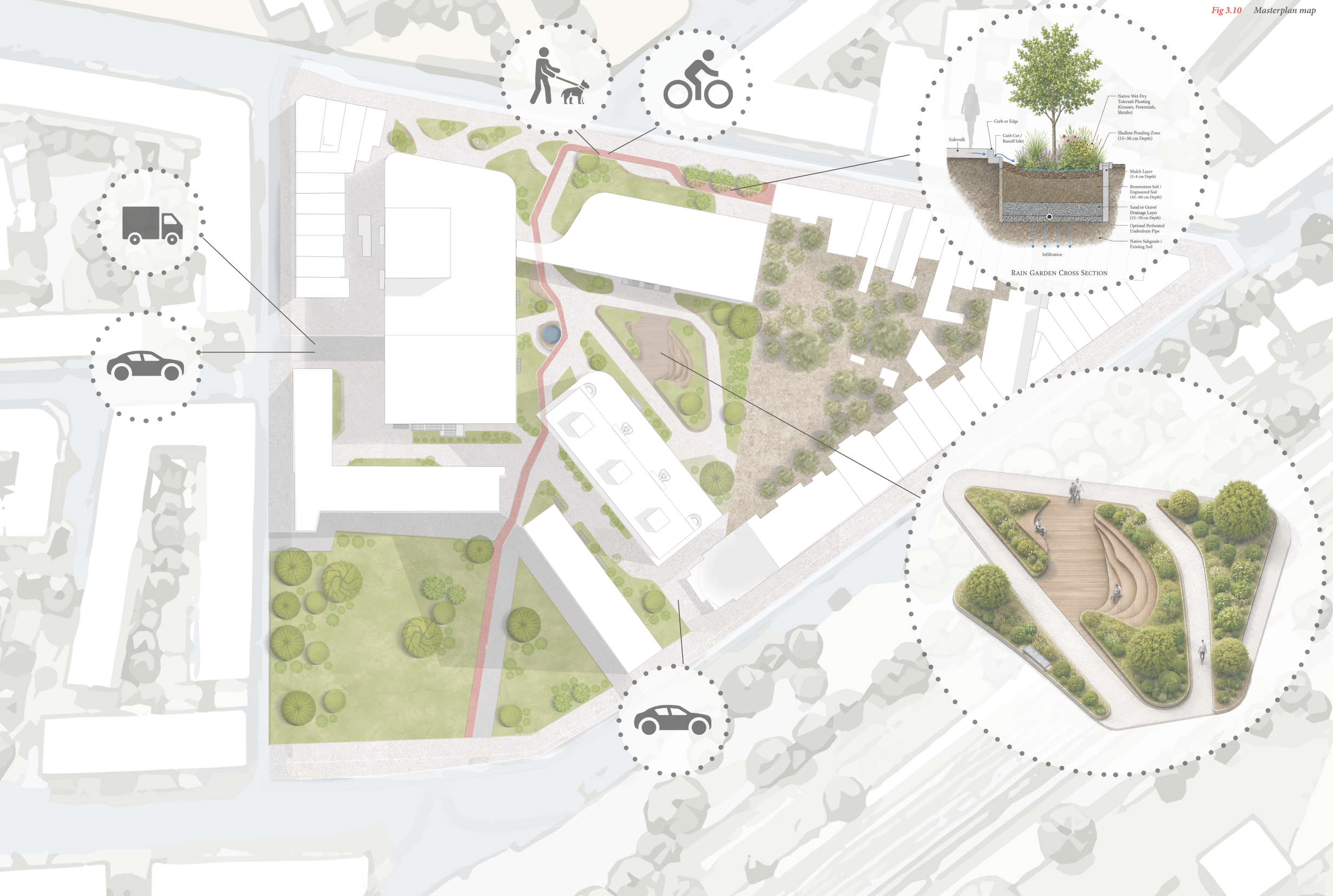


Fig 3.10 *Masterplan map*

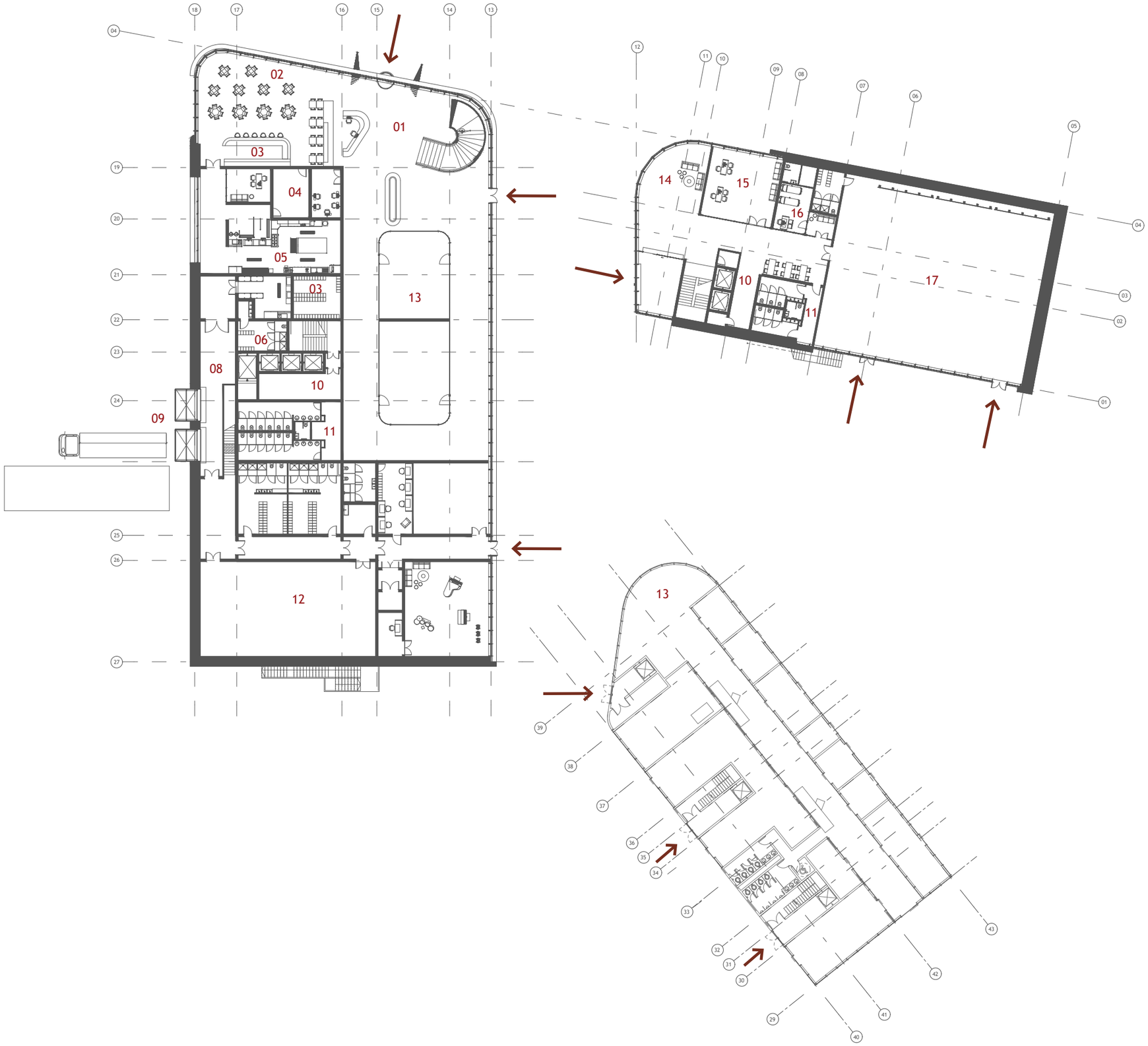


Fig 3.11 *Ground-floor plan*

1. Lobby
2. Dinning area
3. Bar
4. Offices
5. Kitchen
6. Staffs room
7. Lockers
8. Corridors
9. Loading dock
10. Vertical Circulation
11. Public Toilets
12. Backstage and facilities
13. Commercial area
14. School Lobby
15. Recption and offices
16. Infirmary
17. Dance Studio

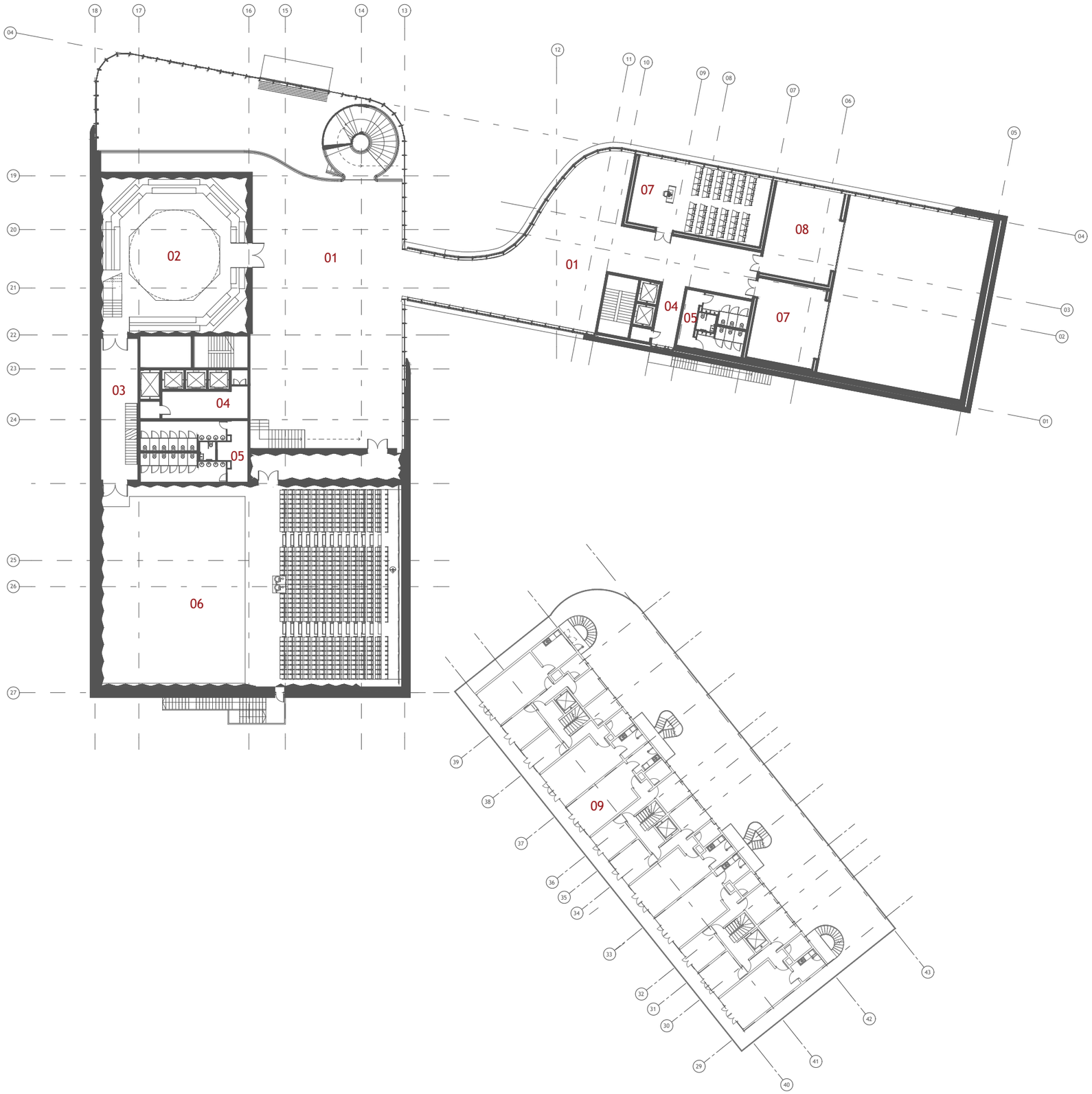


Fig 3.12 *First-floor plan*

1. Lobby
2. Small Hall
3. Corridor
4. Vertical Circulation
5. Public Toilets
6. Great hall
7. Classroom
8. Dance studio
9. Residential

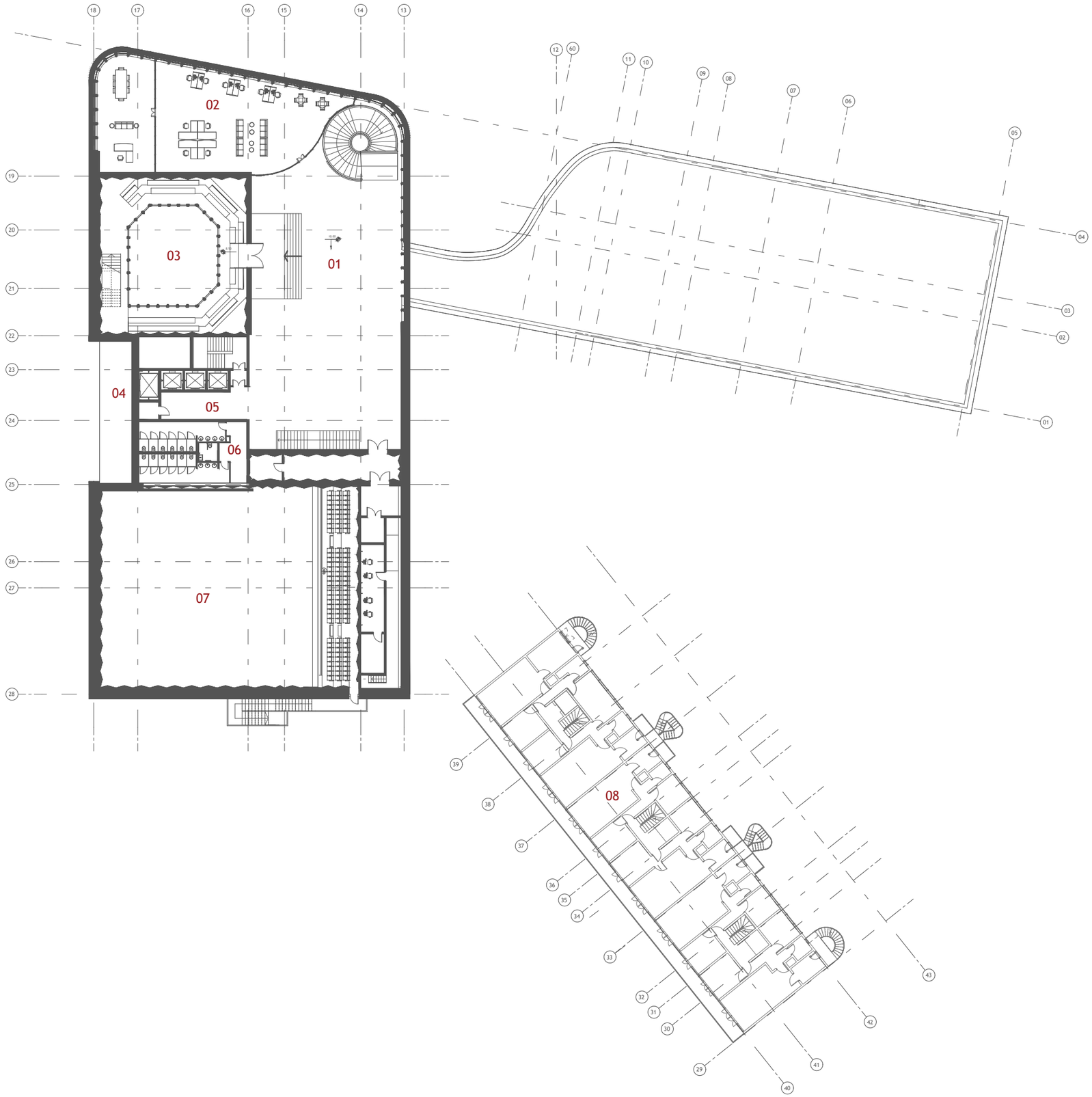


Fig 3.13 *Second-floor plan*

1. Lobby
2. Administration offices
3. Small Hall
4. Technical room
5. Vertical Circulation
6. Public Toilets
7. Great hall
8. Residential

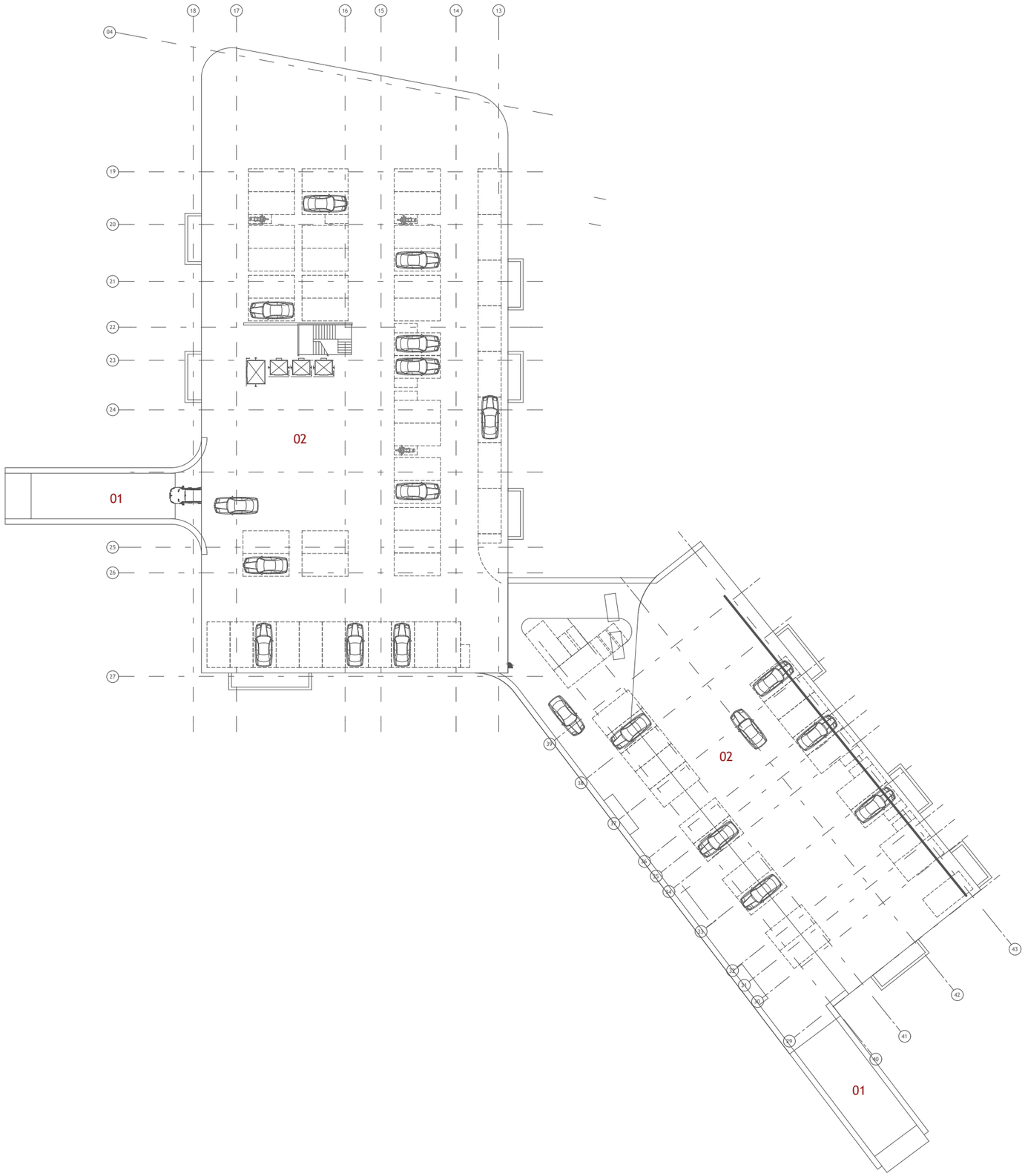
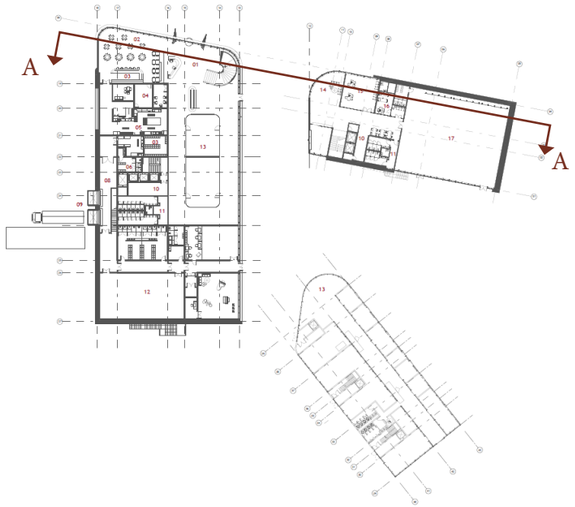


Fig 3.14 *Under-ground Parking*

1. Car Ramp
2. Parking area

Fig 3.15 *Section A-A*



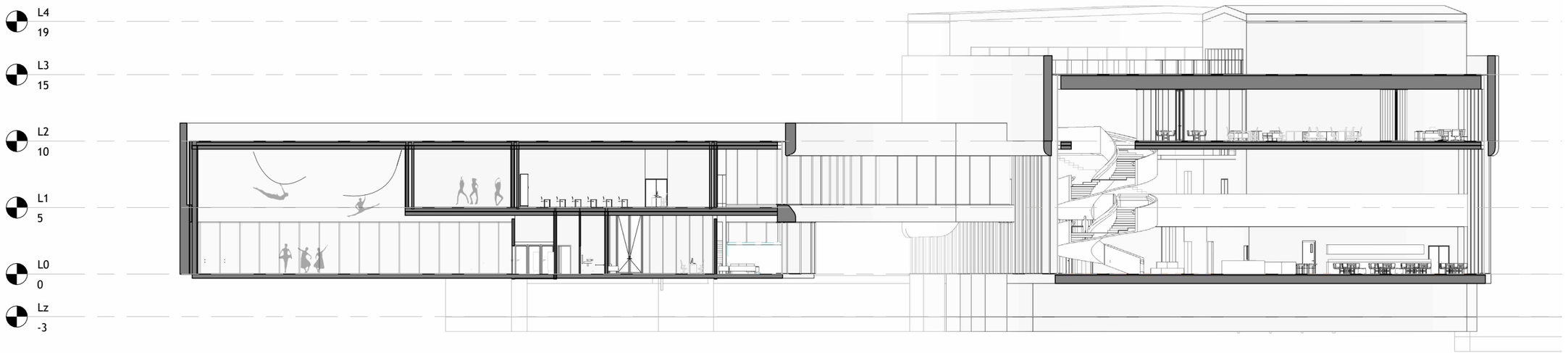
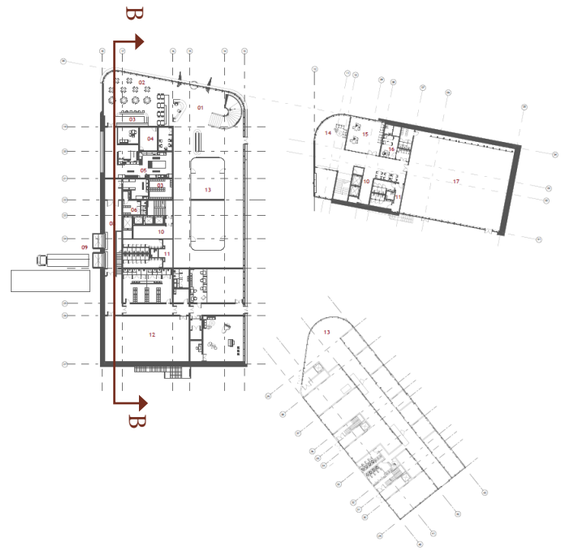


Fig 3.16 *Section B-B*



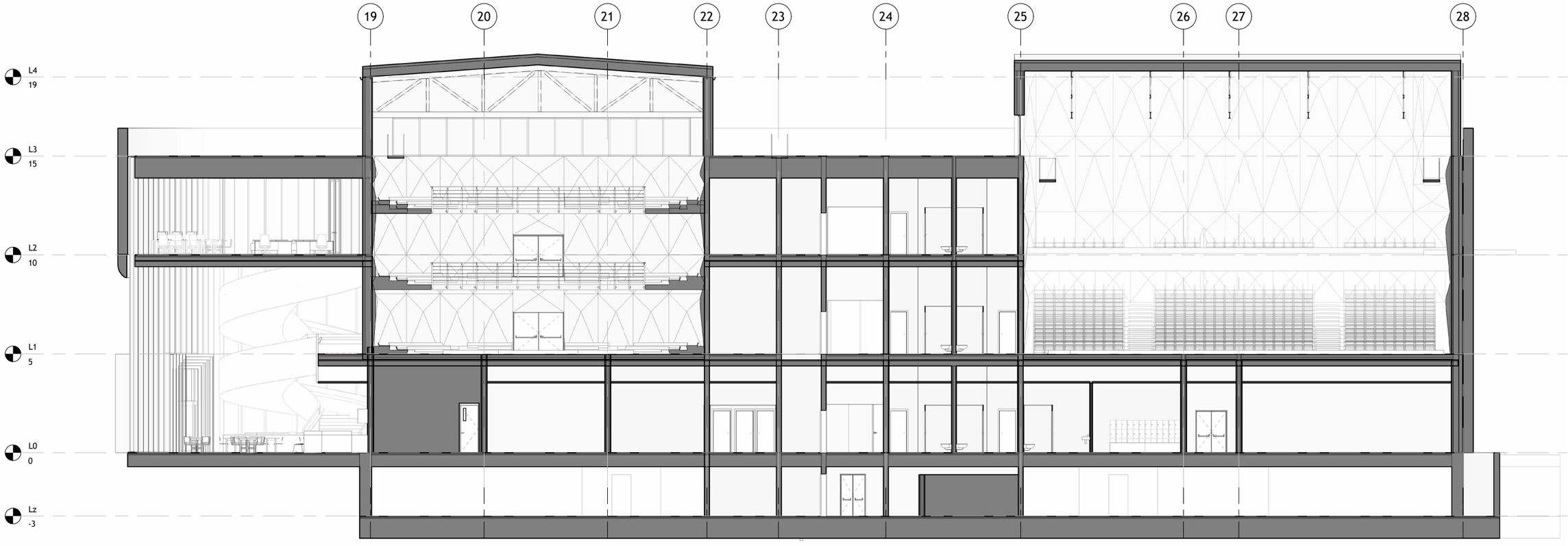
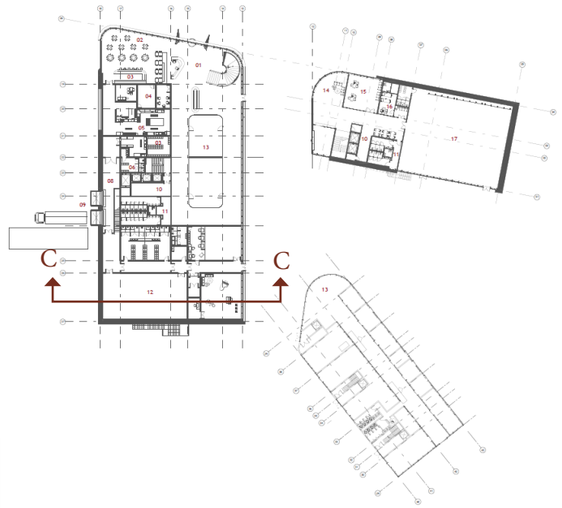


Fig 3.17 *Section C-C*



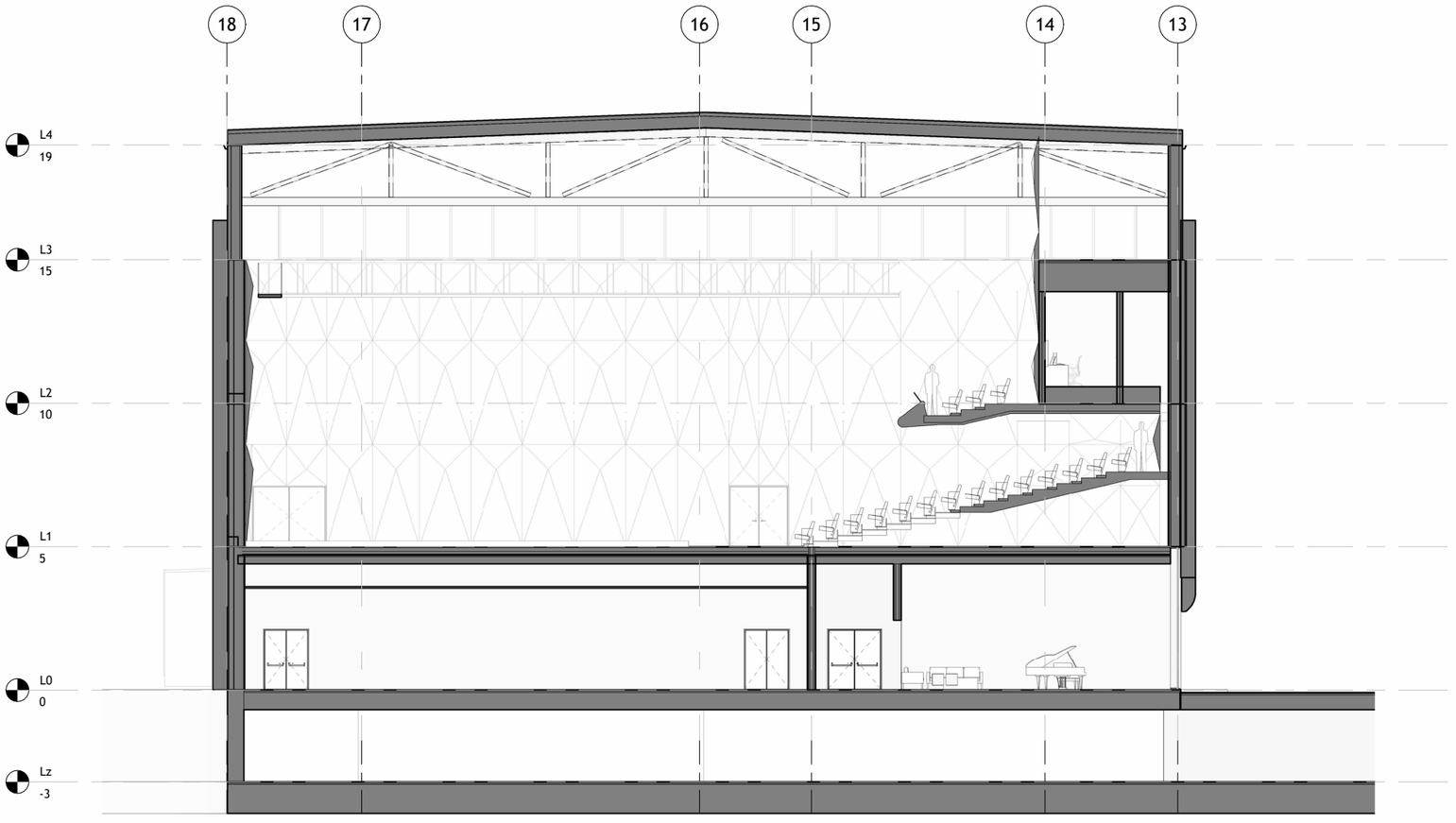
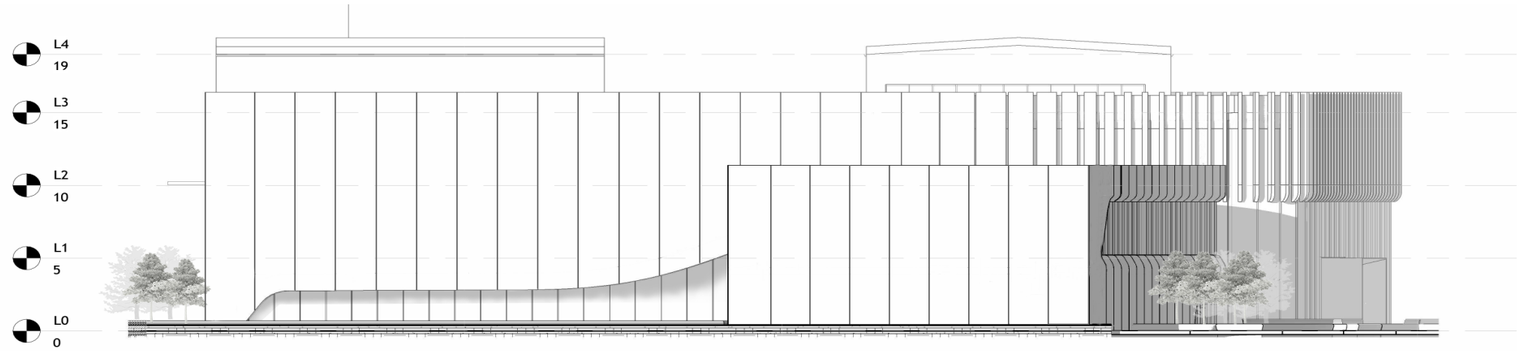
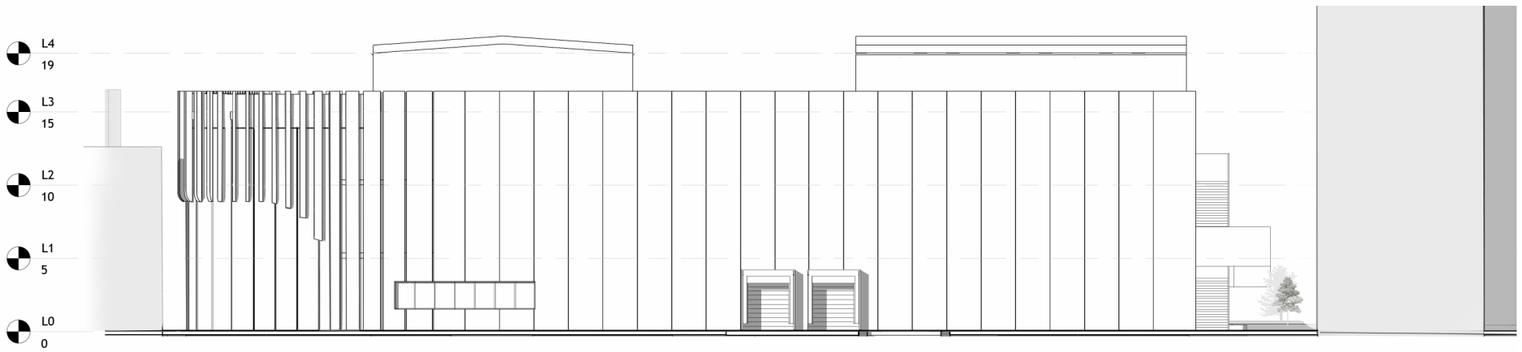


Fig 3.18 East Elevation
Fig 3.19 West Elevation
Fig 3.20 North Elevation
Fig 3.21 South Elevation

EAST ELEVATION



EAST ELEVATION



EAST ELEVATION



EAST ELEVATION



3.3 Structural and Technical Design

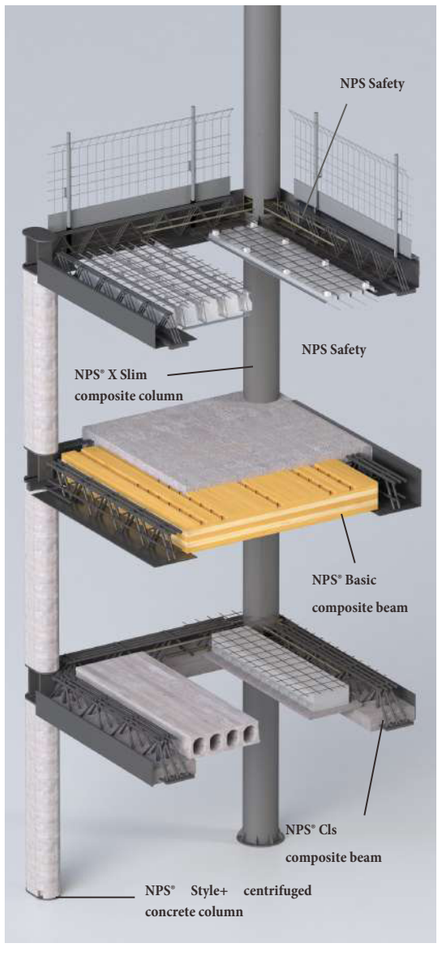


Fig 3.22 Composite Structural System: Integrated Slabs, Beams, and Columns

Scope of the Structural Design

The structural design is developed as a preliminary architectural strategy rather than as a final engineering verification. The aim of this section is to define a coherent structural logic for the architectural proposal, clarify the relationship between span, programme, construction system and envelope support, and establish assumptions that can guide later technical development. Final member sizing, reinforcement design, connection verification, fire performance, vibration control and foundation dimensions must be confirmed through detailed structural calculation and geotechnical investigation.

The New Performance Slim-System (NPS®) is a low CO_2-emitting, self-supporting composite system made from up to 93% recycled steel, allowing beams and columns to be combined with any type of slab. What makes the NPS® System distinctive is its advanced technology, which provides structural solutions that are lightweight and easy to transport. Its key advantages include cost certainty and a reduction in construction time by up to 40%. The structural elements are prefabricated in the factory and assembled on site, while the self-supporting nature of the system reduces the need for formwork by up to 90%.

Slab Strategy: Hollow-Core Slabs Supported by NPS® Composite Beams

The proposed slab strategy uses hollow-core slabs combined with NPS® composite beams. For larger spans in lobby and circulation areas, the system works as a beam-and-slab structure, where slabs span between beams and the beams carry loads to the columns.

This approach suits open public spaces where fewer columns are preferred while maintaining a realistic structural solution. Hollow-core slabs are prefabricated, lightweight, and support efficient construction.

The slab acts as the floor component, while overall span capacity depends on beam design and spacing, to be verified through structural calculation.



Fig 3.23 Preliminary structural system based on hollow-core slabs supported by NPS® composite beams, with NPS® Cls beams used for larger-span public areas and NPS® Basic beams used for regular programme zones.





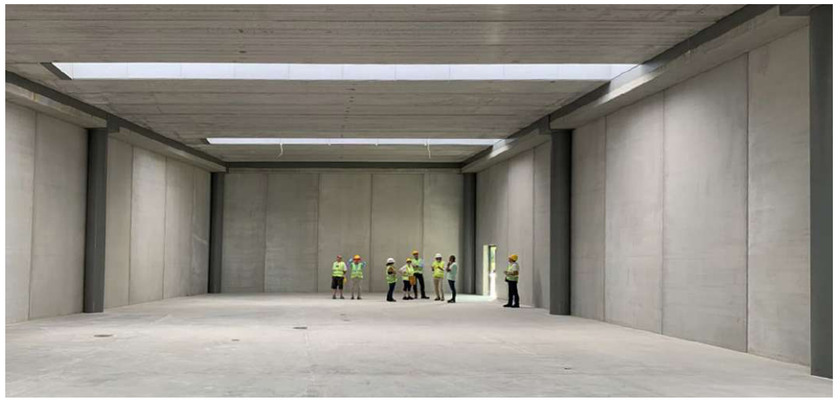


Fig 3.24 NPS® Cls beams supported on NPS® Slim columns allowed for the combination with hollow core slabs over 14 metres long.

Beam Strategy: NPS® Cls Composite Beams for Large-Span Areas

NPS® Cls composite beams are proposed for large-span, high-load areas such as the lobby, main foyer, and public circulation spaces, where spans of approximately 14–16 m are required while maintaining openness and limiting structural depth. These beams are suitable due to their capacity for large spans and integrated fire resistance, provided by the reinforced concrete base protecting the steel reinforcement. They also support prefabricated construction, enabling efficient off-site production and on-site assembly.

Fig 3.25 NPS® Cls beam for large span



Large Span Strategy: NPS® Basic Composite Beams for Regular and Educational Functions

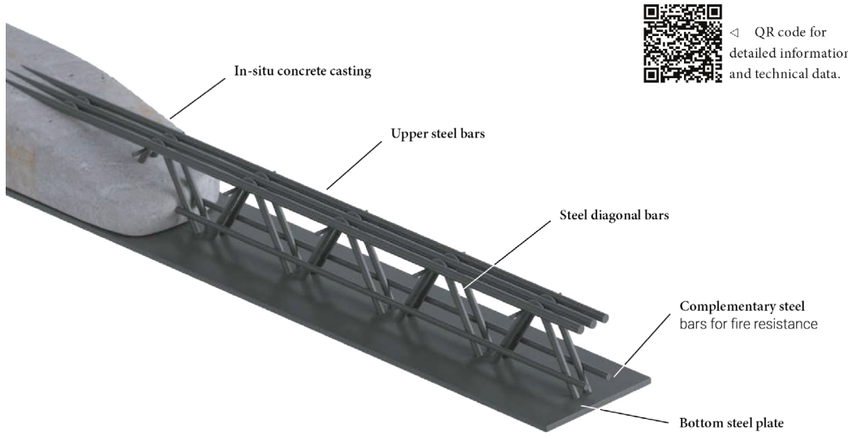
NPS® Basic composite beams are used in regular areas such as classrooms, offices, and studios, where long spans are not required. These spaces follow a rational and repetitive structural grid. The NPS® Basic beam is a slim-floor composite beam compatible with different slab types, helping reduce structural depth and coordinate floor heights and services.

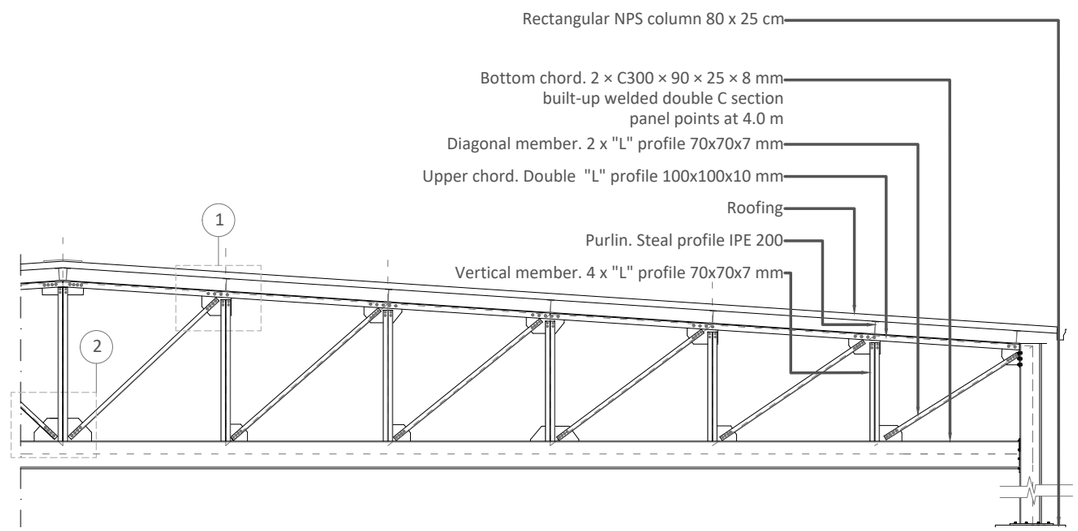
Together with NPS® Cls beams, this creates a clear structural hierarchy: large-span systems for public spaces and a more economical, repetitive system for standard areas.

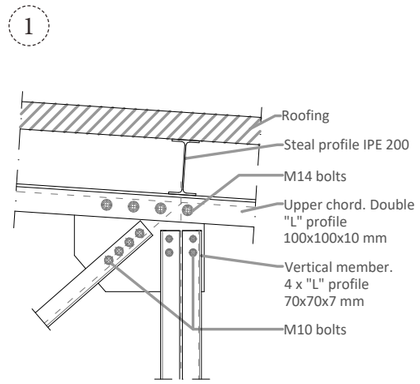


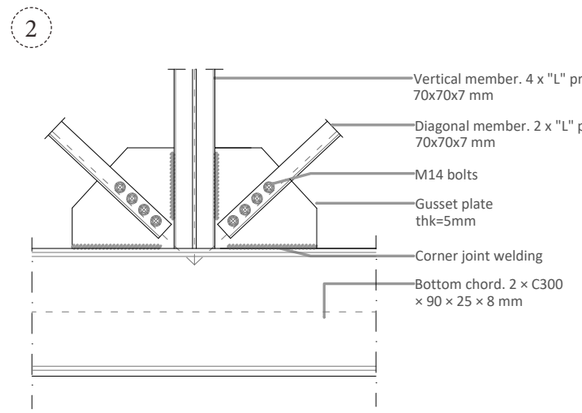
◁ QR code for detailed information and technical data.

Fig 3.27 NPS® Cls beam for small to medium span









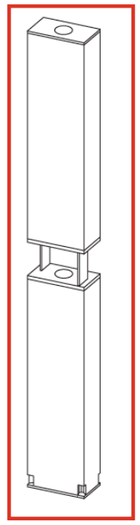
For the stage volumes, the large-span solution is based on a lightweight steel roof-truss system. This strategy is appropriate for performance and stage-related spaces because it allows the roof to span over a large column-free area while keeping the structural depth efficient and reducing unnecessary load on the vertical structure. The truss works through a clear hierarchy of upper chord, bottom chord, vertical members and diagonal members, transferring roof loads toward the main supports while maintaining openness below. The lightweight roof structure also supports the architectural and environmental objectives of the project. By reducing the weight of the roof over the stage volumes, the system limits structural demand on columns and foundations, while leaving the interior volume free for performance requirements, lighting equipment, acoustic treatment and service integration. At this stage, the truss is used as a preliminary structural concept; final member sizing, joint design and structural verification must be developed through detailed engineering calculation.

Fig 3.26 Large-span lightweight steel roof-truss strategy for the stage volumes, allowing column-free performance areas and efficient load transfer through upper chords, bottom chords, vertical members and diagonal bracing

Column Strategy: Rectangular NPS® Columns

The vertical structural strategy uses rectangular NPS® columns, chosen for their compatibility with the architectural grid, walls, façade modules and interior layout. They integrate more easily into partitions, service zones and façade lines than circular columns, making them suitable for mixed-use conditions.

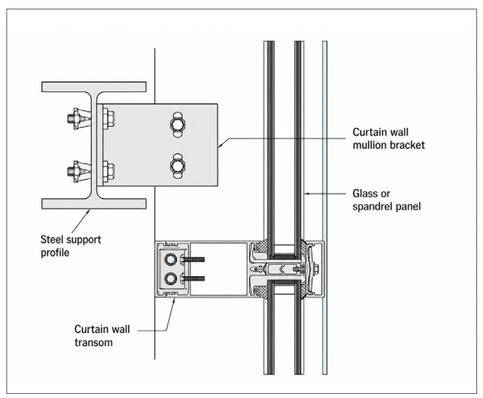
Fig 3.28 Rectangular NPS® Columns

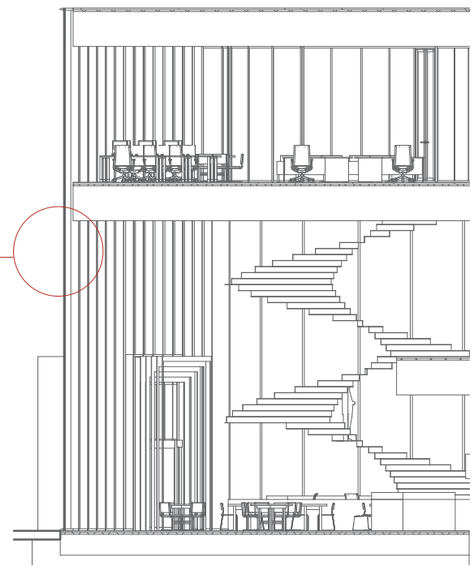


Prefabricated or composite NPS® columns support faster construction and reduce on-site work. In public areas, they align with the structural rhythm, while in regular zones they support a clear grid and flexible layouts. In selected areas, columns may remain visible as part of the architectural expression, reinforcing the integration of structure and design.

Fig 3.18 shows the proposed steel-supported curtain wall connection used in tall lobby areas where the façade reaches a significant height and cannot rely only on conventional aluminium mullions. A steel support profile is positioned behind the curtain wall and connected to the mullion/transom system through a steel bracket plate. The bracket transfers wind loads and façade self-weight from the glazed curtain wall back to the primary structural support, allowing the lobby space to remain open and visually transparent. The aluminium curtain wall components continue to perform the envelope functions, including glazing support, weather protection, drainage and airtightness. The steel profile provides the additional stiffness required for the tall glazed span and reduces the need for intermediate columns inside the lobby. This solution is therefore suitable for public entrance zones, double-height lobbies and other large glazed spaces where transparency, openness and structural reliability must be coordinated. Final sizing of the steel profile, bracket plates, bolts, anchors, movement tolerance and thermal separation must be verified through detailed façade and structural engineering.

Fig 3.29 Steel-Supported Curtain Wall Detail for Tall Lobby Façades

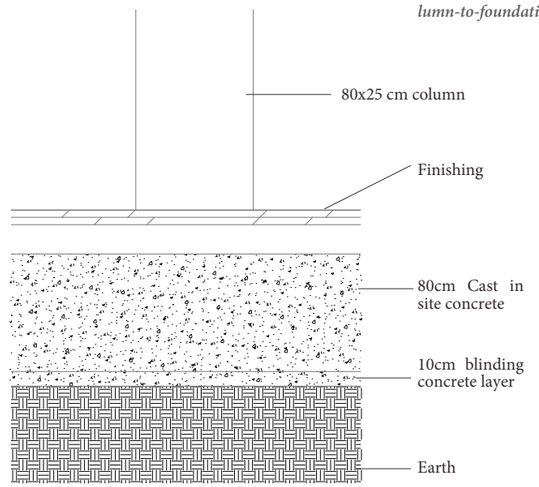




Foundation

The foundation strategy is presented as a preliminary structural detail to clarify the relationship between the vertical column system and the ground-bearing base. The detail shows a reinforced concrete foundation block supporting an 80 cm structural column, with a 30 cm upper finishing/build-up layer and a 10 cm lean concrete blinding layer below the foundation. This configuration provides a clear load-transfer logic from column to foundation while establishing a stable, clean and level base for construction. Final foundation dimensions, reinforcement, bearing capacity and soil interaction must be verified through detailed structural calculation and geotechnical investigation.

Fig 3.30 Preliminary column-to-foundation section detail



3.4 Technical Details

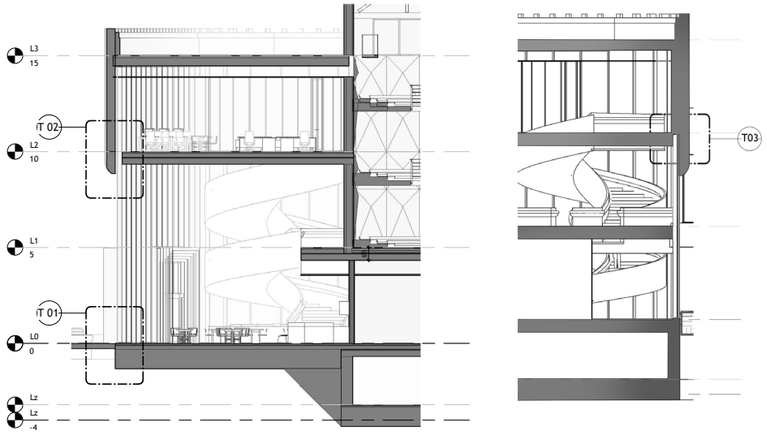
The Cité du Cirque uses modern construction methods, combining prefabricated structural systems with adaptable envelope technologies. The primary structure is based on an NPS prefabricated system with precast elements and slabs, enabling faster assembly, better control, and future disassembly or reuse. The building is conceived as adaptable rather than fixed.

The envelope follows this approach, using a stick curtain wall system with GFRC cladding. This allows the façade to respond to the building's curved geometry while maintaining a strong architectural expression. The drawings shown are representative sections illustrating constructability and the relationship between the envelope and prefabricated structure.

Transparents Details

The transparent envelope uses a stick curtain wall system, chosen for its flexibility with curved geometry and double-height spaces. It consists of mullions, transoms, glazing, and supports, allowing precise adaptation to the building form

The sections show connections to the structure, support of large glazing areas, and interfaces with slabs and opaque zones.



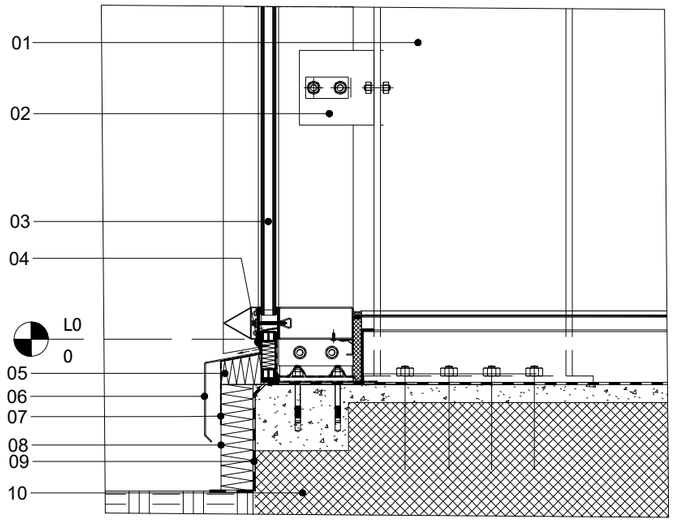


Fig 3.31 Curtain wall base connection at foundation level.

The detail illustrates the steel curtain wall base, including the H-column support, mullion bracket, drainage zone, perimeter insulation, damp-proof membrane, and cast-in-situ mat foundation.

1. Structural H column with cover with plasterboard exterior finishing.
2. Mullion Support bracket to H column
3. double grazed steel curtain wall system
4. Drainage at the front, outside via posts
5. Insulation wedge
6. Sheet metal edging
7. Windproof
8. Perimeter insulation
9. Damp proof Membrane
10. Mat Foundation (Cast In-Situ)

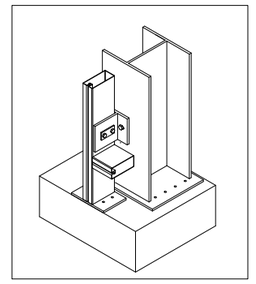
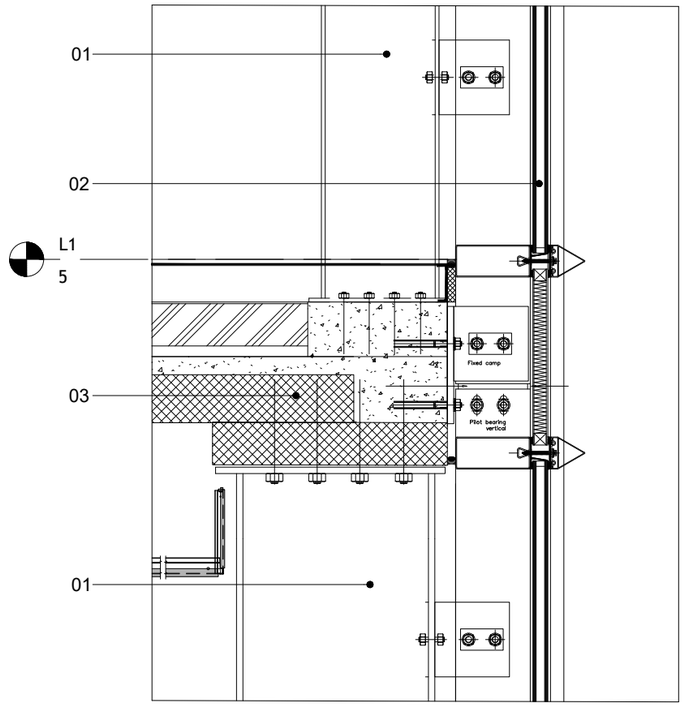


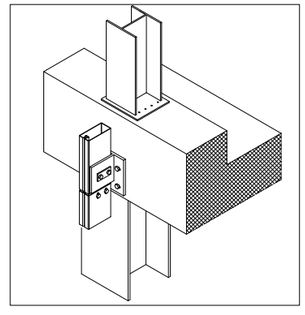
Fig 3.32 Axonometric close-up of the mullion support bracket.



1. Structural H column with cover with plasterboard exterior finishing.
2. Double grazed steel curtain wall system.
3. NPS prefabricated structural system

Fig 3.33 Curtain wall connection to prefabricated structural floor system.

Fig 3.34 Axonometric view of the primary façade support connection.



This detail shows how the double-glazed steel curtain wall is fixed back to the structural H-column and coordinated with the NPS prefabricated slab system.

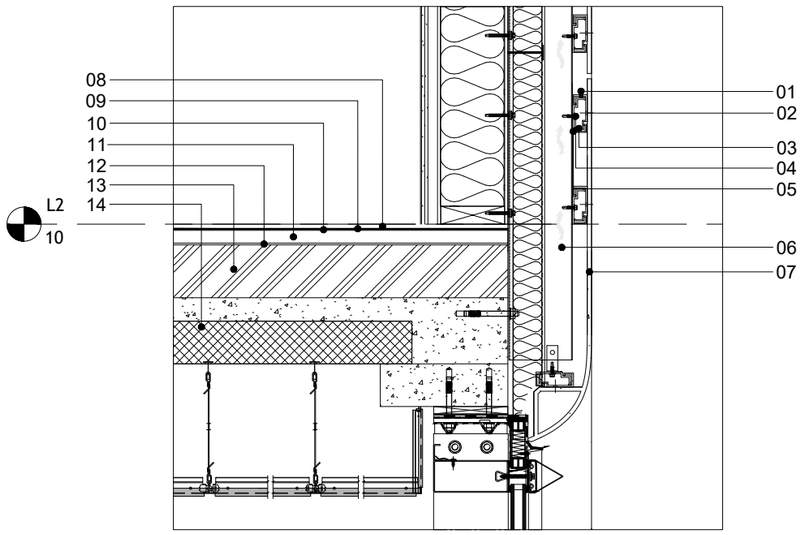
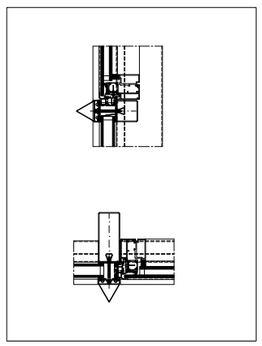


Fig 3.35 *Floor edge and façade support junction.*

This section highlights the continuity of the façade cladding system across the floor edge, including panel hangers, vertical girt system, insulation layer, and NPS structural slab connection.



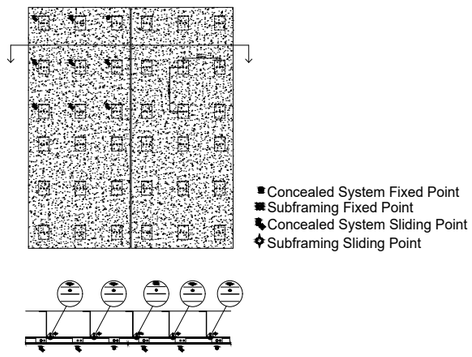
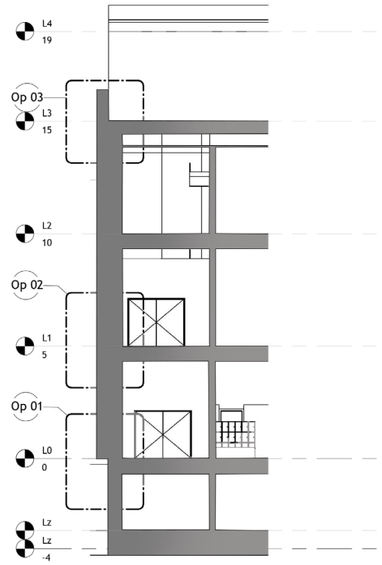
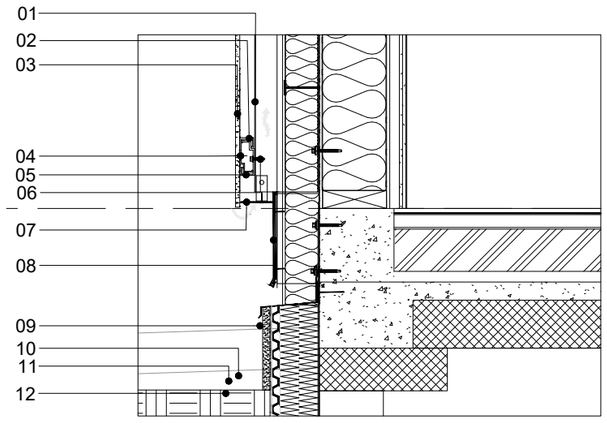


Fig 3.36 *Curtain wall mullion and support interface detail.*
Fig 3.37 *Façade panel fixing and movement-point diagram.*

Opaque Details

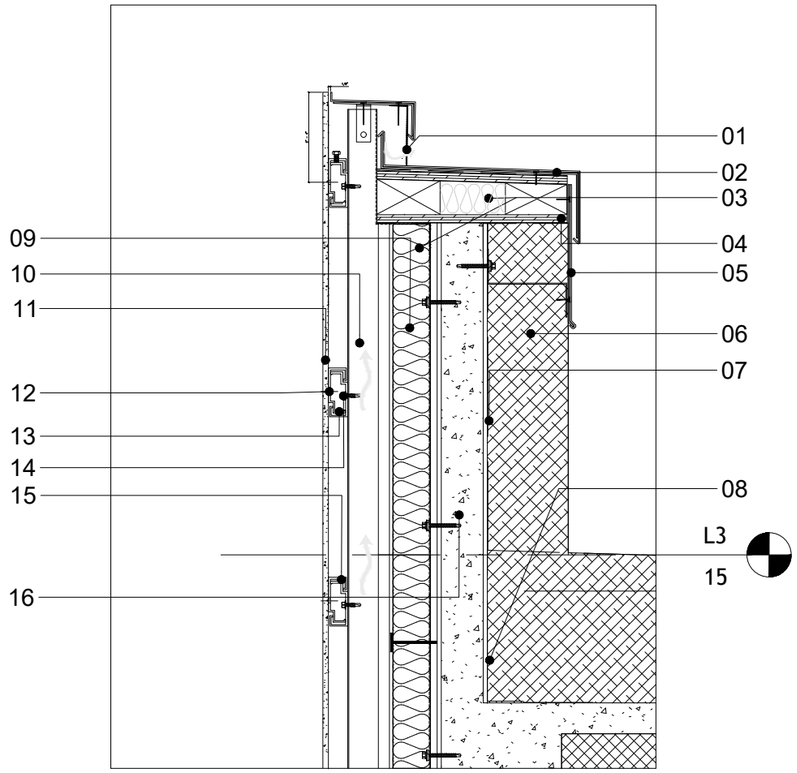
The opaque envelope uses a GFRC rainscreen supported by the prefabricated frame. GFRC provides a durable, lightweight, and expressive façade. Behind it are layers including substructure, cavity, insulation, moisture control, and internal lining, ensuring performance and maintainability. The sections illustrate key façade conditions, showing relationships between cladding, insulation, slab edges, and structure.





The detail shows the lower façade termination with kickplate, perforated vent closure, exterior insulation, waterproofing membrane, and concrete slab interface.

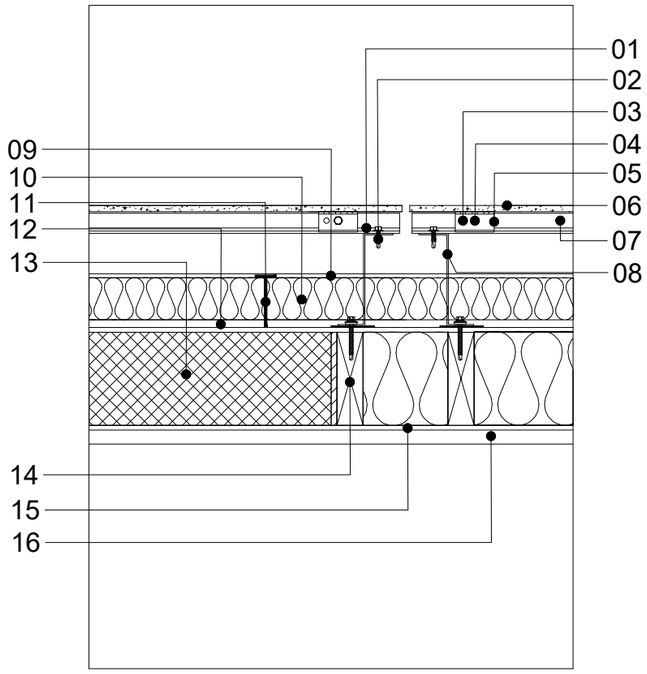
Fig 3.38 *Ground-level façade and plinth connection.*



1. Perforated Vent Closure / Insect Screen.
2. Metal Coping Assembly.
3. Wall internal Insulations
4. External Stone wool Insulation Board
5. Metal Kickplate Assembly
6. Insulation
7. Roofing membrane (single ply).
8. Waterproofing Membrane.
9. External Stone wool Insulation Board.
10. Vertical Girt System.
11. EQUITONE Fiber Cement Panel.
12. Concealed Anchor.
13. Aluminum Panel Hanger.
14. Self-Drilling Screw.
15. Aluminum Horizontal System Rail.
16. 15cm Cast in-Situ Concrete Parapet wall.

Fig 3.39 Parapet and roof edge detail.

This section shows the roof parapet build-up, including metal coping, waterproofing layers, insulation continuity, ventilated cavity, and EQUITONE fibre-cement rainscreen cladding

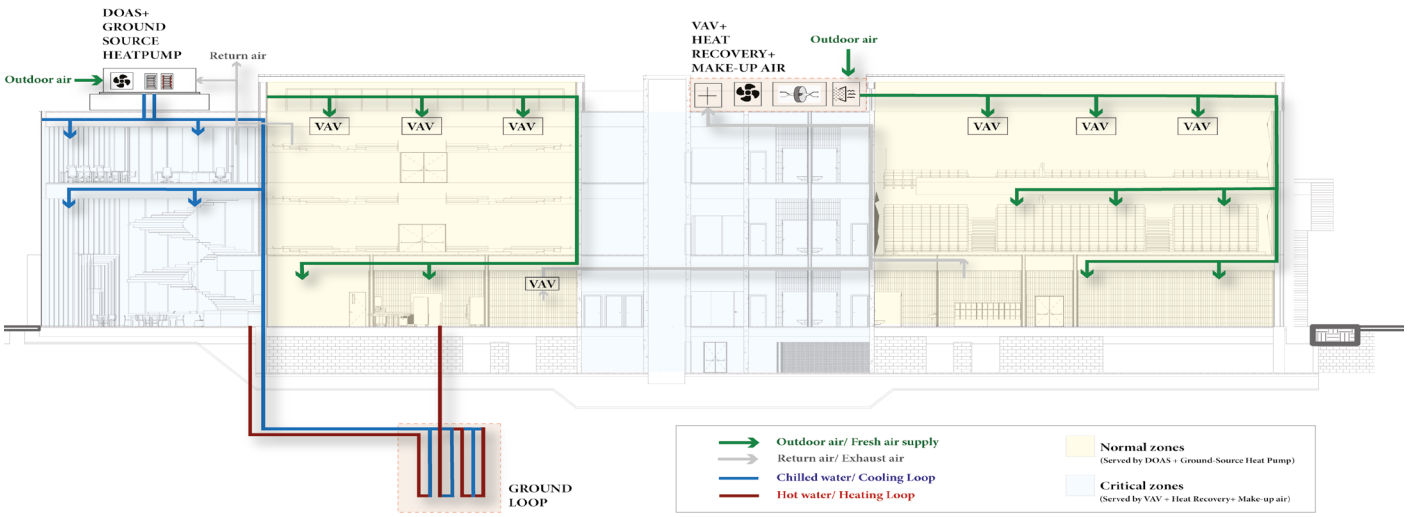


1. Aluminum Panel Hanger*
2. Self-Drilling Screw*
3. Horizontal Fixed Point (1 per Panel)
4. Height Adjustment Bolt (2 per Panel)
5. Aluminum Panel Hanger*
6. EQUITONE Fiber Cement Panel
7. Aluminum Horizontal System Rail*
8. Vertical Girt System
9. A1/A2 cementitious windtight sheathing board
10. External Stone wool Insulation Board
11. Insulation retainer
12. OSB, EN 300
13. NPS Prefabricated Column 30 x 80cm
14. Prefab Timber Cassette (Mineral-wool, A1, EN 13162 MW)
15. OSB, EN 300
16. Double fire-resistant gypsum plasterboard lining, Type DF, EN 520, 2 × 15 mm + Plaster

This section explains the full façade build-up, combining EQUITONE fibre-cement panels, aluminium subframing, external stone-wool insulation, OSB layers, prefabricated timber cassette, and internal fire-resistant gypsum lining.

Fig 3.40 Typical prefabricated wall assembly detail.

3.5 Final MEP Schematic Strategy



The final MEP schematic defines the building-services strategy according to the energy-analysis results developed in Chapter 4. The system separates normal zones from critical zones, allowing each area to receive a mechanical strategy that responds to its specific occupancy, internal gains, ventilation demand and thermal behaviour. Normal zones are served through a DOAS system connected to a ground-source heat pump, supporting efficient fresh-air supply and low-carbon heating and cooling. Critical zones, such as the stages and kitchen-related spaces, are served by a VAV system with heat recovery and make-up air to respond to higher loads and more variable operational conditions. These choices are therefore not treated as generic MEP assumptions, but as a direct outcome of the Chapter 4 energy analysis and the performance needs identified during the simulation process.

04

ENERGY ANALYSIS

Chapter 4 assesses the environmental performance of the proposed Cité du Cirque through simulation and envelope analysis. The chapter defines the building performance model, establishes the assessment criteria, and compares multiple external wall assemblies under consistent conditions. The results are used to evaluate envelope performance and demonstrate how Armadillo can support informed decision-making during the early stages of architectural design.

4.1 Simulation Methodology

The simulation methodology was developed as a performance-based workflow that responds to the central argument established in the literature review: early architectural decisions, particularly form, envelope configuration and operational assumptions, strongly influence the later energy and comfort performance of a building. Rather than treating simulation as a final verification step, the workflow used environmental analysis as a decision-support process throughout the design development. This allowed the relationship between spatial organization, envelope behaviour, internal loads, ventilation, thermal comfort, and renewable energy potential to be tested progressively. The simulations were carried out in Rhino–Grasshopper using Ladybug Tools, mainly Honeybee and Ladybug, to connect the architectural model with climate-based energy and comfort evaluation. The building was first divided into functional thermal zones according to its mixed-use program, and the Brussels weather file was used as the climatic reference. An initial whole-building analysis was then performed to identify the main energy and comfort issues, followed by focused optimization of critical zones through envelope, schedules, setpoints, natural ventilation, glazing, shading, and system-related adjustments. Finally, the optimized assumptions were reassembled into the complete model and assessed through annual energy consumption, EUI, operative temperature, heating and cooling sensation, and photovoltaic production. In this way, the simulation workflow translated the literature review's emphasis on integrated early-stage envelope and performance evaluation into a measurable design process.

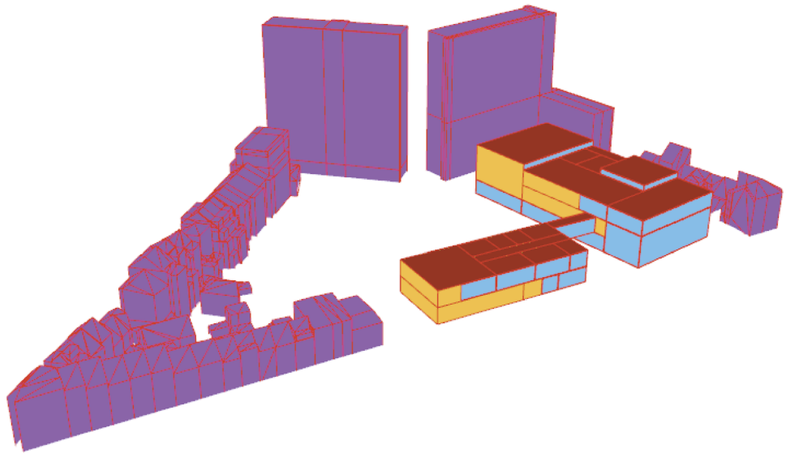
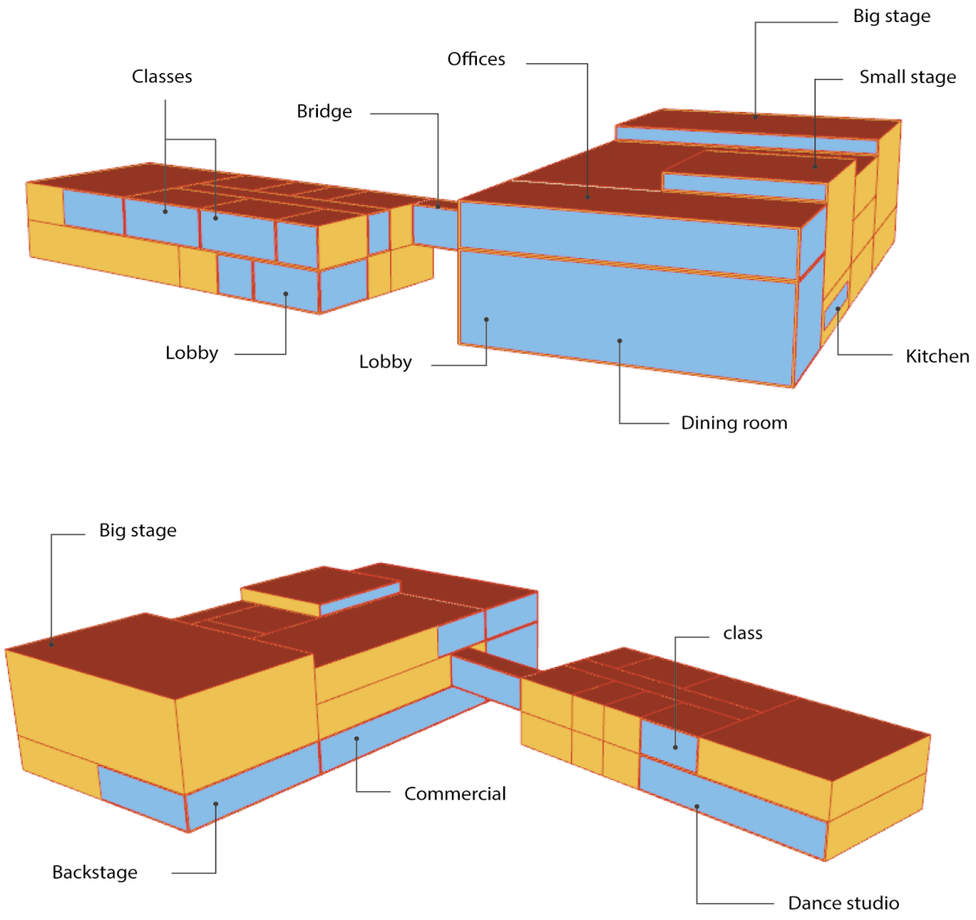


Fig 4.01 *Site context Energy model: the proposed full energy model with respective context*

Thermal Zoning and Spatial Segmentation

The building was divided into thermal zones according to functional use, spatial configuration, occupancy pattern, and expected internal load intensity. This zoning strategy was necessary because the project combines several programmatic conditions with different environmental requirements, including educational spaces, offices, dance studios, commercial areas, dining spaces, circulation zones, kitchen facilities, backstage areas, bridge connections, and performance stages. Rather than treating the building as a single uniform volume, each major functional area was segmented as an independent or semi-independent thermal zone, allowing schedules, internal gains, ventilation behaviour, setpoints, and comfort expectations to be assigned more accurately. This approach also made it possible to distinguish between regularly occupied spaces, intermittently occupied event-based spaces, high-load service areas, and transitional buffer zones. As a result, the simulation could capture the different thermal behaviours of the building more realistically and identify which zones had the strongest influence on annual energy demand and indoor comfort performance.

Fig 4.02 Thermal zoning , Rhino- Grasshopper



4.2 Daylight

Annual daylight was used to evaluate the overall spatial distribution of daylight across the building throughout the year. The results helped identify which zones benefit from consistent daylight access and which areas remain dependent on artificial lighting due to depth, orientation, façade exposure, or obstruction from adjacent volumes.

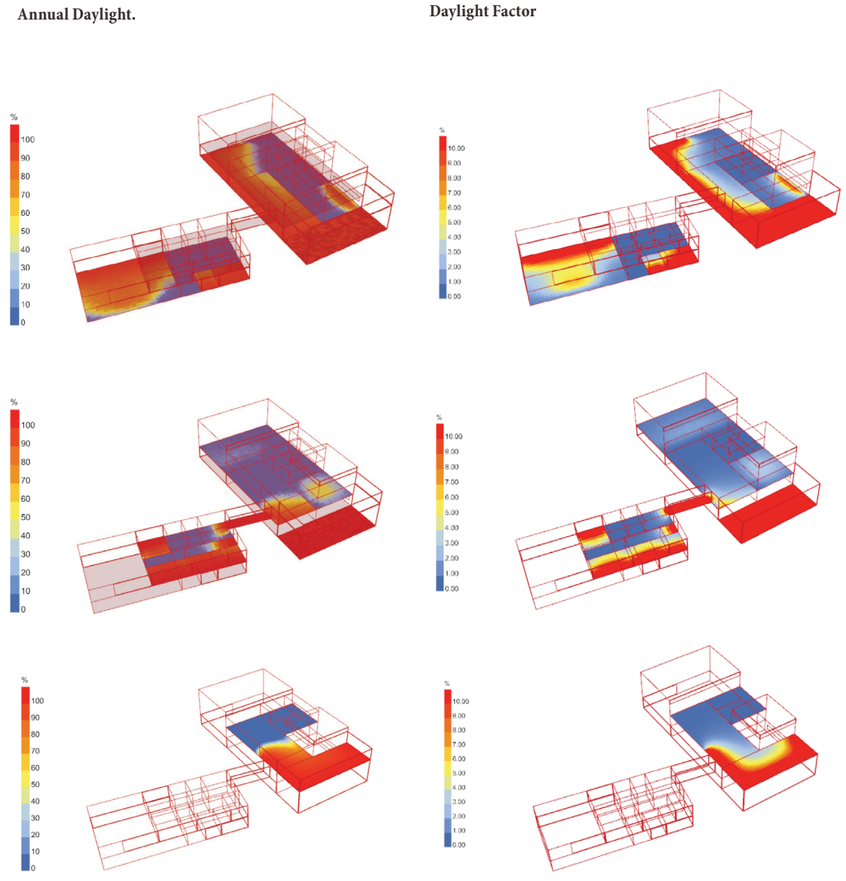


Fig 4.05 The second-floor Annual Daylightand Daylight-factor results.

Offices has good daylight potential near the glazed façade, but the deeper zone remains critical and requires artificial lighting support or improved daylight penetration

Fig 4.03 The ground floor Annual Daylight and Dayligh-Factor results

shows strong daylight access along the exposed perimeter, with annual daylight reaching around 80–100% and UDI 100–3000 around 60–90%. The problematic areas are Lobby of school , part of backstage and corridors at the back, where annual daylight drops to about 10–30% and the daylight factor result shows high values near the exposed façade areas, reaching approximately 7–10%, while deeper internal zones drop to around 1–3%.

Fig 4.04 The first-floor Annual Daylightand Dayligh-Factor results

shows very high daylight availability along the exposed perimeter zones, reaching approximately 80–100%, while the two stages areas drop to around 10–30% due to limited façade exposure. The daylight factor follows the same pattern: façade-adjacent areas reach about 6–10%, while internal zones fall closer to 0–2%, indicating weak daylight penetration in the deeper parts of the plan

UDI 100-3000 **UDI <100**

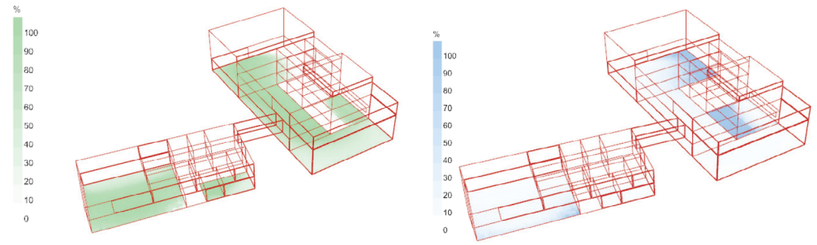


Fig 4.06 *The ground-floor UDI 100-3000 lux and less than 100 lux results*

The ground-floor UDI 100–3000 result shows that most perimeter and regularly occupied zones achieve useful daylight for approximately 50–80% of the occupied period. However, the UDI <100 map shows underlit conditions in deeper internal areas, particularly around the kitchen and corridors. This confirms that the ground floor has good useful daylight near façades, but the central enclosed zones remain dependent on artificial lighting.

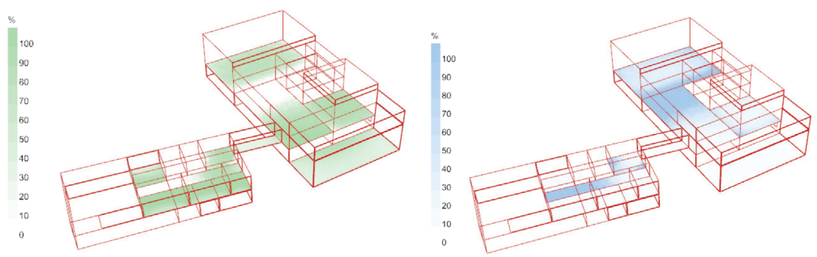


Fig 4.07 *The First-floor UDI 100-3000 lux and less than 100 lux results*

the first floor in both performance and school building has acceptable useful daylight near the perimeter where we have the lobbies and classrooms, but the internal and shaded zones still require artificial lighting support.

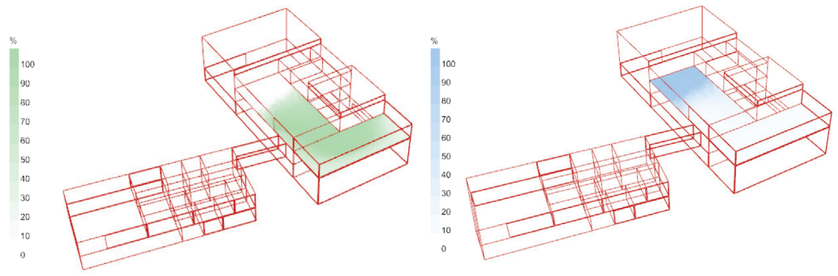


Fig 4.08 *The Second-floor UDI 100-3000 lux and less than 100 lux results*

The second-floor UDI 100–3000 lux result shows a moderate useful daylight range, with the main occupied surface reaching approximately 40–70%, especially toward the more exposed façade side where we have offices. The UDI <100 lux result shows that underlit conditions increase toward the deeper/back part of the space, reaching around 40–60%, while the perimeter side remains less problematic.

UDI 100–3000 was used to identify areas where daylight remains within a useful and visually acceptable range. High values indicate balanced daylight performance, while lower values suggest either insufficient daylight penetration or excessive brightness outside the useful range.

UDI <100 highlighted underlit areas requiring artificial lighting support. These conditions were mainly associated with deeper internal spaces, service areas, backstage zones, and parts of rooms with limited façade exposure.

UDI >3000 **Annual Sunlight Exposure (ASE)**

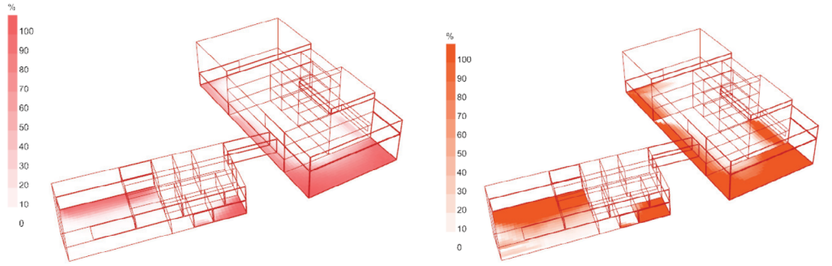


Fig 4.09 *The ground-floor UDI more than 3000 lux and Annual Sunlight Exposure results*

The ground-floor UDI >3000 lux result shows localized overexposure mainly along the perimeter façade zones, reaching approximately 30–60%, while most deeper internal areas remain lower and are not strongly affected by excessive daylight. The ASE map confirms that direct solar exposure is more critical in the exposed elongated block and the front/perimeter parts of the larger volume, where values rise to around 60–90%. This indicates that the main daylight problem on the ground floor is not general overlighting, but localized solar exposure near façades, requiring shading or solar-control glazing.

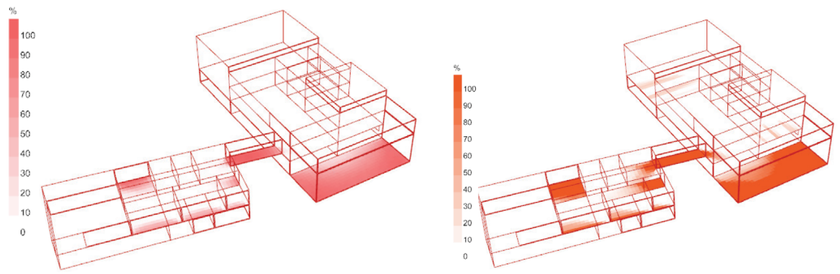


Fig 4.10 *The first-floor UDI more than 3000 lux and Annual Sunlight Exposure results*

The ASE result confirms that direct solar exposure is concentrated near the perimeter and bridge-side zones, with some areas reaching around 60–90%. Overall, the first floor does not show widespread overlighting, but localized solar exposure remains critical and should be controlled through shading and solar-control glazing.

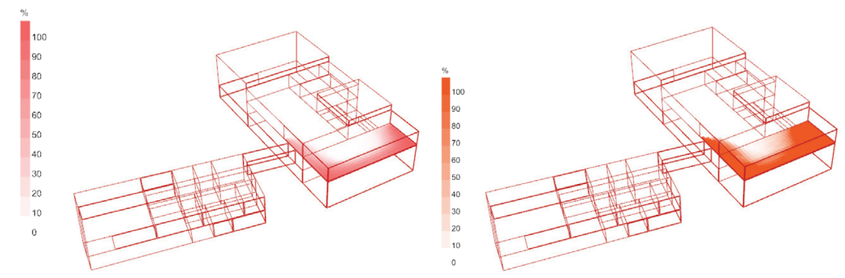


Fig 4.11 *The second-floor UDI more than 3000 lux and Annual Sunlight Exposure results*

The second-floor UDI >3000 lux result shows limited excessive daylight, mainly concentrated along the exposed perimeter zone, with values around 30–60% and lower values toward the interior. The ASE result indicates stronger direct solar exposure in the same perimeter area, reaching approximately 70–90%, which suggests potential glare and solar discomfort in this part of the floor. Overall, the second floor does not have widespread overlighting, but the exposed façade zone remains critical and requires shading or solar-control glazing.

UDI >3000 identified zones with excessive daylight exposure and potential glare risk. These results were important for detecting overexposed perimeter areas and informing the selection of solar-control glazing and external shading.

ASE was used to evaluate excessive direct solar exposure during occupied hours. High ASE areas were treated as critical for shading design, especially in learning, working, commercial, and dining spaces where glare and solar discomfort can affect usability.

4.3 Envelope Technology Selection

Purpose of the Selection

The preliminary Envelope selection was carried out before the initial all-zone indoor comfort and energy-demand analysis in order to define a consistent envelope baseline for the building model. At this stage of the workflow, the objective was not to determine the final optimized envelope solution, but to identify the most appropriate assembly to support the first comparative assessment of indoor comfort and initial energy demand across the whole building.

This step connects the contextual and climatic analysis of the project with the later performance optimization of selected zones. By comparing alternative wall technologies before detailed optimization, the envelope is treated as an early design variable rather than a fixed construction assumption. This establishes a clear decision process: define the envelope baseline, evaluate whole-building comfort and energy tendencies, identify critical zones, and then test more specific strategies such as glazing refinement, solar control, natural ventilation, schedules, internal gains, and system assumptions.

Position of the Envelope Selection within the Thesis Workflow

The case-study workflow is structured as a progressive performance-analysis process, where broad design variables are tested before more specific operational and system assumptions are introduced. Within this sequence, the wall technology comparison is positioned at the beginning of the building-performance analysis because the envelope directly influences the thermal boundary of the building and all consequent performance indicators that follow. It affects how each zone responds to external climate conditions, solar exposure, internal heat balance, and heat loss or heat gain through the envelope.

At this stage, the purpose of selecting a wall technology is not to define the final optimized envelope, but to establish a stable and comparable baseline for the initial all-zone assessment. If a particular envelope assembly remained undefined, the interpretation of operative temperature, heating and cooling sensation, and heating/cooling demand would depend on an unresolved construction variable. Selecting the envelope baseline first therefore makes the subsequent simulation results more reliable and allows the critical zones to be identified under consistent thermal conditions.

For this reason, more detailed variables such as natural ventilation, refined schedules, calibrated internal gains, glazing optimization, shading, and final HVAC assumptions are introduced only in later stages. The initial use of a simplified Ideal Air system also supports this logic, because it estimates heating and cooling demand without introducing the influence of a specific mechanical system. The results of this stage should therefore be understood as a controlled comparative baseline, not as the final operational performance of the building.

Simulation Conditions

The wall technology comparison was conducted under identical simulation conditions to isolate the impact of the opaque wall assembly on heating demand, cooling demand, and total EUI. Building geometry, zoning, climate data, setpoints, and baseline system assumptions remained unchanged across all cases.

The wall assembly was the only variable modified. Natural ventilation, detailed schedules, glazing optimization, shading strategies, and final HVAC assumptions were excluded at this stage. Heating and cooling demand were estimated using a simplified Ideal Air system for comparative purposes only. Each wall technology was modelled as a layered construction based on material thickness and thermal properties. Key indicators included U-value, total thickness, surface mass, decrement factor, periodic thermal transmittance, and time shift. These metrics were used to compare thermal performance and select the baseline wall system.

Discontinuous elements such as fixings, membranes, and rainscreen components were simplified where necessary. Results should therefore be interpreted as comparative baseline values rather than detailed construction assessments.

Scope of Envelope Design

All main envelope and construction components were defined in the simulation model, including external walls, roofs, floors, internal partitions, glazing systems, and ground-contact elements. However, to maintain a focused thesis scope, only the external wall technology is reported through a detailed comparative selection process.

The remaining components were assigned as fixed baseline inputs according to appropriate technical and performance assumptions for the building type. They are included in the whole-building simulation, but their individual selection processes are not discussed in detail. This allows the study to focus on the external wall as the primary reported envelope variable, while keeping the overall simulation model complete and consistent.

Envelope Technology Studies

The envelope technology study was carried out to define a reliable wall baseline for the initial whole-building comfort and energy-demand analysis. At this stage, the objective was not to select the final optimized façade, but to identify the most suitable envelope system for the first performance simulation of the building. Five external wall technologies were compared. Each case was developed as a complete façade build-up, from the exterior finish to the internal lining, and was assessed using the material tables presented in the following case-study sheets. The comparison considered Brussels design requirements, fire-safety logic, thermal resistance, U-value, decrement factor, time shift, and the initial simulation results for heating demand, cooling demand, and total EUI. The external wall technologies were modelled under the same simulation conditions in order to isolate the effect of the envelope system. Discontinuous elements such as rails, brackets, clips, fixings, open ventilated cavities, and thin membranes were not treated as continuous one-dimensional thermal layers. Instead, the main thermal construction was represented through the insulation layers, sheathing boards, internal linings, and airtight layers. Thermal bridges from brackets, studs, rails, openings, and junctions are therefore considered as detailed-design corrections rather than as part of the simplified layer-by-layer comparison.

Case	Envelope Technology	U-Value [W/m²K]	R-Value [m²K/W]	Decrement Factor [-]	Time Shift [hrs]
Case 01	Prefabricated Timber Cassette Rainscreen Façade	0.15	6.67	0.11	11.8
Case 02	Non-Combustible SFS-Based Ventilated Rainscreen Façade	0.15	6.67	0.13	10.9
Case 03	Mineral-Wool Core Insulated Metal Sandwich Panel Façade	0.16	6.25	0.18	8.4
Case 04	GFRC Ventilated Rainscreen Façade with Insulated Backup Wall	0.16	6.25	0.10	12.6
Case 05	Terracotta/Ceramic Ventilated Rainscreen Façade System	0.16	6.25	0.09	13.2

Tab 4.01 Envelope Technology alternativs used in Rhino-grasshopper

Case 01: Prefabricated Timber Cassette Rainscreen

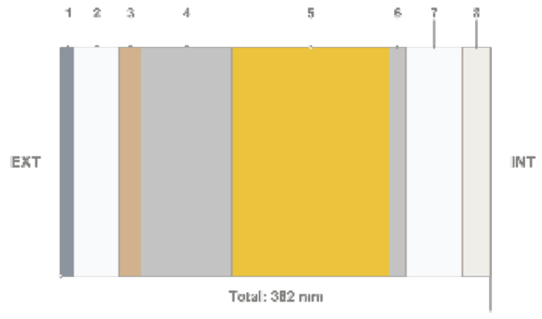


Fig 4.12 *Case 01: Prefabricated Timber Cassette Rainscreen*

Tab 4.02 *Layer Composition and Thermophysical Performance of the Prefabricated Timber-Based Rainscreen Façade Assembly.*

N	Layers names	Thickness [m]	λ [W/mK]	C [kJ/kgK]	ρ [kg/m3]	R [m2K/W]
1	A2-s1,d0 fibre-cement rainscreen facade panel, EN 12467	0.012	0.4	0.84	1700	0.03
2	Ventilated air cavity with fire barriers at floor lines	0.05	0.28	1	1.29	0.18
3	Aluminium substructure	0.04	160	0.88	2700	0.00
4	A1/A2 cementitious windtight sheathing board	0.0125	0.35	1	1150	0.04
5	External Stone wool Insulation Board EN 13162 MW	0.16	0.035	0.84	90	4.57
6	Prefab Timber Cassette (Mineral-wool, A1, EN 13162 MW)	0.2	0.037	0.84	45	5.41
7	OSB, EN 300	0.015	0.13	1.7	600	0.12
8	Insulated Service cavity	0.045	0.037	0.84	30	1.22
9	Double fire-resistant gypsum plasterboard lining, Type DF, EN 520, 2 × 15 mm	0.03	0.25	1	850	0.12
10	Plaster	0.005	0.49	1	1450	0.01
Rsi (Int.Heat transfer resistance)			0.13			
Rsi (Ext.Heat transfer resistance)			0.04			
RESULTS						
U - Value			0.086			
Total Thickness [m]			0.57			
ρ,total [kg/m2]			101.28			
df (Decrement factor)			0.20			
Periodic Thermal Transmittance [W/m2K]			0.02			
Timeshift periodical thermal transmittance (hours)			14.00			

Case02 Non-Combustible Ventilated Rainscreen Façade with SFS Backup Wall

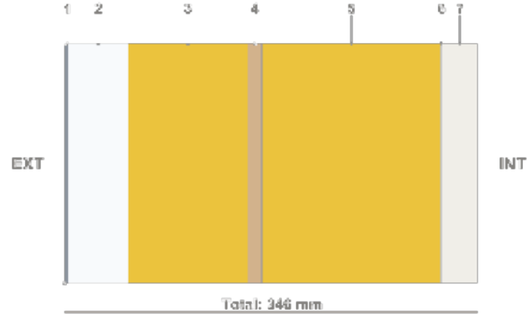


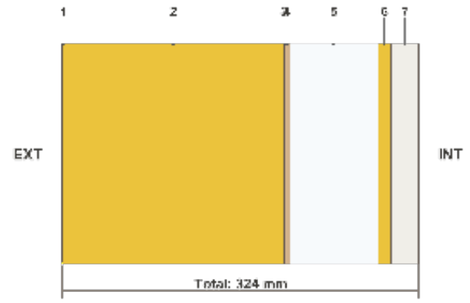
Fig 4.13 *Case02Mineral-Wool Core Insulated Metal Sandwich Panel Façade*

Tab 4.03 *Layer Composition and Thermophysical Performance of the Steel-Framed Terracotta Rainscreen Façade Assembly.*

N	Layers names	Thickness [m]	λ [W/mK]	C [kJ/kgK]	ρ [kg/m3]	R [m2K/W]
1	A1/A2 extruded terracotta panel	0.03	1	0.84	1900.00	0.03
2	Aluminium rainscreen fixing rails	0.04	160	0.88	2700.00	0.00
3	Ventilated and drained air cavity with cavity fire barriers	0.05	0.28	1	1.29	0.18
4	Continuous external stone-wool rainscreen insulation, A1, EN 13162 MW	0.16	0.035	0.84	90.00	4.57
5	glass-mat gypsum sheathing board, A1/A2	0.0125	0.35	1	1150.00	0.04
6	Weather-resistant breather membrane	0.001	0.87	0.8	1400.00	0.00
7	Galvanised SFS C-stud frame, 150 mm (Mineral-wool insulation between SFS studs, A1, EN 13162 MW)	0.15	0.037	0.84	45.00	4.05
8	Airtight smart vapour-control membrane with taped joints	0.001	0.87	0.8	1400.00	0.00
9	Double fire-resistant plasterboard lining, Type DF, EN 520, 2 × 15 mm	0.03	0.25	1	850.00	0.12
10	Plaster	0.005	0.49	1	1450	0.01
Rsi (Int.Heat transfer resistance)		0.13				
Rsi (Ext.Heat transfer resistance)		0.04				
RESULTS						
U - Value		0.11				
Total Thickness [m]		0.48				
ρ,total [kg/m2]		236.14				
df (Decrement factor)		0.13				
Periodic Thermal Transmittance [W/m2K]		0.01				
Timeshift periodical thermal transmittance (hours)		13.39				

Case03 Mineral-Wool Insulated Metal Sandwich Panel Façade System

Fig 4.14 *Case03 Mineral-Wool Insulated Metal Sandwich Panel Façade System*

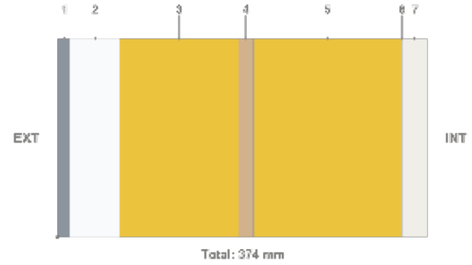


Tab 4.04 *Layer Composition and Thermophysical Performance of the Insulated Metal Sandwich Panel Façade Assembly*

N	Layers names	Thick-ness [m]	λ [W/mK]	C [kJ/kgK]	ρ [kg/m3]	R [m2K/W]
1	Pre-finished galvanized steel outer face, polyester	0.0007	50	0.46	7850.00	0.00
2	stone-wool sandwich-panel core, A1/A2, EN 13162 MW	0.2	0.04	0.84	110.00	5.00
3	Pre-finished galvanized steel inner face	0.0006	50	0.46	7850	0.00
4	Factory-formed sealed panel joints with EPDM gaskets	0.005	10	0.8	1000	0.00
5	aluminium support frame with thermally separated fixings	0.08	50	0.46	7850.00	0.00
6	flexible mineral-wool acoustic insulation	0.05	0.037	0.84	30.00	1.35
7	Double acoustic/fire plas-ter-board lining with painted interior finish, Type DF, 2 × 12.5 mm	0.025	0.25	1	850	0.10
Rsi (Int.Heat transfer resistance)			0.13			
Rsi (Ext.Heat transfer resistance)			0.04			
RESULTS						
U - Value			0.15			
Total Thickness [m]			0.36			
ρ,total [kg/m2]			687.96			
df (Decrement factor)			0.03			
Periodic Thermal Transmittance [W/m2K]			0.00			
Timeshift periodical thermal transmittance (hours)			10.65			

Case04 GFRC Ventilated Rainscreen Façade with Insulated Backup Wall

Fig 4.15 *Case04 GFRC Ventilated Rainscreen Façade with Insulated Backup Wall*

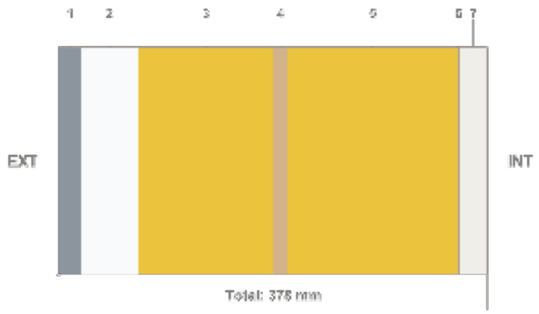


Tab 4.05 *Layer Composition and Thermophysical Performance of the GFRC Rainscreen Steel-Framed Façade Assembly*

N	Layers names	Thick-ness [m]	λ [W/mK]	C [kJ/ kgK]	ρ [kg/ m3]	R [m2K/W]
1	GFRC rainscreen panel, A1/A2 facade finish	0.013	0.8	0.84	2000.00	0.02
2	Aluminium SUB-STRUCTURE	0.005	15	0.5	7800.00	0.00
3	Cavity with cavity fire barriers	0.05	0.28	1	1.29	0.18
4	bracket substructure with thermal isolation pads	0.04	160	0.88	2700.00	0.00
5	stone-wool insulation board, A1, EN 13162 MW	0.18	0.035	0.84	90.00	5.14
6	A1/A2 glass-mat gypsum sheathing board	0.0125	0.25	1	850.00	0.05
7	Galvanised SFS C-stud backup wall (Mine-ral-wool insulation A1, EN 13162 MW)	0.15	0.037	0.84	45.00	4.05
8	Airtight vapour-control mem-brane	0.001	10	0.8	1000	0.00
9	Double acoustic/fire plaster-board lining, Type DF, EN 520, 2 × 15 mm	0.03	0.25	1	850.00	0.12
10	Double acoustic/fire plaster-board lining with painted interi-or finish, Type DF, 2 × 12.5 mm	0.025	0.25	1	850	0.10
Rsi (Int.Heat transfer resistance)		0.13				
Rsi (Ext.Heat transfer resistance)		0.04				
RESULTS						
U - Value		0.10				
Total Thickness [m]		0.51				
ρ,total [kg/m2]		254.39				
df (Decrement factor)		0.09				
Periodic Thermal Transmittance [W/m2K]		0.01				
Timeshift periodical thermal transmittance (hours)		15.82				

Case05 Terracotta/Ceramic Ventilated Rainscreen Façade System

Fig 4.16 *Case05 Terracotta/ Ceramic Ventilated Rainscreen Façade System*



Tab 4.06 *Layer Composition and Thermophysical Performance of the GFRC Rainscreen Façade Assembly with Steel C-Stud Backup Wall*

N	Layers names	Thick-ness [m]	λ [W/ mK]	C [kJ/ kgK]	ρ [kg/ m3]	R [m2K/W]
1	GFRC rainscreen panel, A1/A2 fa-cade finish	0.013	0.8	0.84	2000.00	0.02
2	Aluminium SUB-STRUCTURE	0.005	15	0.5	7800.00	0.00
3	Cavity with cavity fire barriers	0.05	0.28	1	1.29	0.18
4	bracket substructure with thermal isolation pads	0.04	160	0.88	2700.00	0.00
5	stone-wool insulation board, A1, EN 13162 MW	0.18	0.035	0.84	90.00	5.14
6	A1/A2 glass-mat gypsum sheathing board	0.0125	0.25	1	850.00	0.05
7	Galvanised SFS C-stud backup wall (Mineral-wool insulation A1, EN 13162 MW)	0.15	0.037	0.84	45.00	4.05
8	Airtight vapour-control membrane	0.001	10	0.8	1000	0.00
9	Double acoustic/fire plasterboard lining, Type DF, EN 520, 2 × 15 mm	0.03	0.25	1	850.00	0.12
10	Double acoustic/fire plasterboard lining with painted interior finish, Type DF, 2 × 12.5 mm	0.025	0.25	1	850	0.10
Rsi (Int.Heat transfer resistance)		0.13				
Rsi (Ext.Heat transfer resistance)		0.04				
RESULTS						
U - Value		0.10				
Total Thickness [m]		0.51				
ρ,total [kg/m2]		254.39				
df (Decrement factor)		0.09				
Periodic Thermal Transmittance [W/m2K]		0.01				
Timeshift periodical thermal transmittance (hours)		15.82				

Early stage of selection of Envelope Technology

The simulation results demonstrate that all five envelope technologies improved overall building performance compared with the base case. The reduction in heating demand was particularly significant across all options, confirming the importance of envelope performance within the Brussels climate context.

Case 01 achieved the lowest total EUI, reducing it from 562.00 to 535.31, while also producing the lowest heating demand at 378.00. This performance can be attributed to its combination of high thermal resistance, low U-value, and balanced dynamic thermal behaviour.

Case 02 performed almost identically to Case 01, achieving a total EUI of 535.73 and a heating demand of 380.20. Although it offers advantages from a fire-safety perspective due to its fully non-combustible backup wall system, its energy performance was marginally lower than Case 01.

Case 03 demonstrated the weakest overall performance among the proposed assemblies. While the sandwich-panel system offers construction efficiency and rapid installation, its lower thermal mass resulted in a higher decrement factor and shorter time shift, contributing to increased heating demand and total EUI.

Cases 04 and 05 achieved the lowest cooling demands due to their enhanced thermal mass and improved dynamic thermal response. However, these benefits did not translate into lower annual energy consumption. Both assemblies recorded higher heating demands and higher total EUI values than Cases 01 and 02.

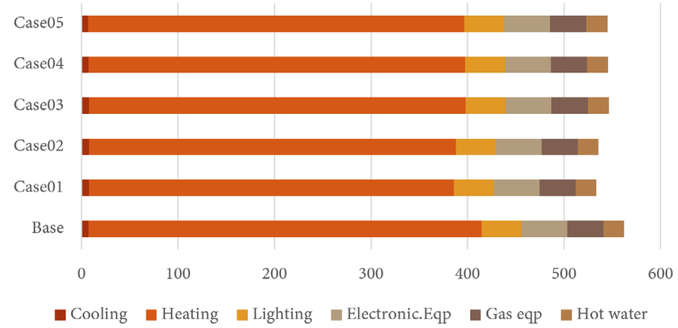


Fig 4.17 *Comparison of Annual Energy Demand by End Use for the Base Case and Wall Assembly Alternatives.*

Selection of the Initial Envelope Baseline

The results indicate that thermal comfort performance remained relatively consistent across all five envelope technologies, with no assembly demonstrating a decisive comfort advantage. Consequently, the selection was primarily driven by overall energy performance.

Case 01 was therefore selected as the envelope technology for the initial whole-building performance baseline. The decision was based on the following factors:

- Lowest total EUI among all tested assemblies.
- Lowest annual heating demand.
- Lowest U-value and highest thermal resistance.
- Strong overall balance between static and dynamic thermal performance.
- Compatibility with the intended facade design strategy.

Although Cases 04 and 05 exhibited superior time-shift performance and lower decrement factors, these advantages did not result in lower annual energy consumption. Similarly, Case 02 remained a strong alternative but was marginally outperformed by Case 01 in both heating demand and total EUI.

It is important to note that this selection represents the envelope baseline used for the subsequent all-zone comfort and energy-demand analysis. It should not be interpreted as the final optimized façade solution. Further design stages may refine the envelope strategy through glazing optimization, solar-control measures, natural ventilation strategies, HVAC integration, embodied-carbon assessment, moisture-risk analysis, durability considerations, and detailed fire-safety design.

This selection should be understood as the first operational-performance filter within a broader multi-criteria thesis framework. It does not claim that Case01 is automatically the final or universally most sustainable envelope solution. Rather, it identifies Case01 as the most appropriate baseline for the subsequent comfort and energy analysis. Later optimization stages can then refine the envelope strategy through glazing properties, shading, natural ventilation, internal gains, schedules, and HVAC assumptions, while broader whole-life criteria such as embodied carbon, material durability, moisture safety, and construction feasibility remain essential for the final evaluation.

Case 01 can be interpreted as a Modern Method of Construction due to its use of a prefabricated timber cassette envelope system. The assembly supports a fabric-first design strategy by integrating the structural backup wall, insulation layers, airtightness plane, service cavity, and internal lining into a repeatable off-site manufactured façade component. Compared with a fully site-built envelope, this approach improves dimensional accuracy, construction quality, airtightness control, and installation speed, while reducing on-site labour, material waste, and weather-related construction risks. The system is therefore technically suitable as an initial high-performance envelope baseline, particularly because it achieved the lowest heating demand and total EUI among the tested cases. However, its final application in a public building requires careful detailing of fire protection, cavity barriers, moisture safety, junctions, and thermal bridges to ensure that the prefabricated system performs reliably under Brussels design and regulatory conditions.

4.4 Critical-Zones Identification

Initial Analysis Setup

The first stage of the indoor comfort and energy demand assessment was developed as a preliminary baseline for the entire building model. The objective of this stage was not to optimize the building, but to establish a consistent reference condition for comparing the thermal behavior of all zones and identifying the zones that require deeper investigation.

All thermal zones were first defined according to their assigned program type. This allowed the model to distinguish the functional character of the spaces and provided an initial classification of the building according to use. The selected envelope configuration for this stage was Envelope Technology Case 01, which was applied consistently across the model in order to isolate the effect of geometry, orientation, exposure, and program distribution on the initial performance results.

The heating and cooling setpoints were kept uniform for the initial assessment:

Heating setpoint: 20°C

Cooling setpoint: 26°C

Natural ventilation was disabled in this stage. Detailed operational schedules and manually adjusted internal gains were also not activated. The HVAC system was represented using a simplified Ideal Air system, with all advanced control options disabled. This means that heat recovery, economizer control, demand-controlled ventilation, and other system-level improvements were not included in the initial simulation. The Ideal Air system was therefore used only as a neutral load-estimation method, not as a final HVAC strategy.

This setup intentionally represents a simplified base condition. It provides a controlled starting point before introducing additional variables such as occupancy intensity, lighting loads, equipment loads, schedules, natural ventilation, shading, glazing optimization, or actual HVAC system selection.

Critical-Zone Identification Method

The critical-zone identification followed a hierarchical evaluation method. The first selection layer was indoor comfort, based on operative temperature and heating/cooling sensation. The second layer was energy demand, based on heating demand, cooling demand, and total energy intensity. The third layer was design relevance, considering whether the zone's performance could be improved through architectural or envelope-related strategies.

Condition	Interpretation	Selection Priority
High discomfort + high energy de-mand	Strong critical condition	Very high
High discomfort + moderate energy demand	Comfort-critical condition	High
Low discomfort + high energy de-mand	Energy-intensive condition	Medium, separate investigation
Low discomfort + low energy de-mand	Stable condition	Low

Tab 4.07 The logic of critical zone selection

This method avoids selecting critical zones only because they have the highest EUI. Instead, it prioritizes zones where the indoor environment fails or is close to failing, and where energy demand confirms the need for further optimization.

Reason for Prioritizing Indoor Comfort Before EUI

Indoor comfort was prioritized before energy demand because the purpose of the critical-zone study is not only to reduce energy consumption but also to ensure that the architectural design can provide acceptable indoor environmental conditions.

If EUI is used as the first selection criterion, the analysis may be biased toward spaces with high process loads, high equipment intensity, or special operational functions. These zones may have high energy consumption, but their performance may not be primarily controlled by envelope design, orientation, glazing, shading, or passive strategies.

By contrast, zones with significant operative temperature variation or high heating/cooling sensation are more relevant for architectural optimization. These zones allow the study to test the effect of façade performance, glazing properties, shading, natural ventilation, infiltration, and passive thermal control.

Therefore, the adopted method gives priority to zones where comfort risk is clearly visible, and then uses energy demand to evaluate the severity and performance impact of that risk.

Use of Ideal Air in the Initial Stage

The Ideal Air system was used in the initial analysis as a simplified method for estimating heating and cooling demand. This approach is appropriate at this stage because the objective is to compare zone behavior under consistent assumptions rather than evaluate the performance of a specific HVAC system.

Using Ideal Air allows the analysis to focus on the effect of the building form, envelope case, zone exposure, and setpoint assumptions. If a detailed HVAC system were introduced too early, the results would be influenced by system efficiency, control logic, fan energy, heat recovery, and distribution assumptions. This would make it more difficult to isolate the architectural causes of comfort and load variation.

Therefore, the actual HVAC system is not selected at this stage. The simplified Ideal Air model remains a comparative tool for early-stage load and comfort assessment. The final HVAC strategy should be introduced later, after the passive and envelope-related optimization of the critical zones has been completed.

Critical-Zone Optimization: Indoor Comfort and Heating/Cooling Demand

After the initial all-zone indoor comfort and energy-demand analysis, the next stage of the study focused on the zones that showed the most critical thermal behaviour. The objective of this step was not only to reduce the total EUI, but to improve the balance between operative temperature, heating sensation, cooling sensation, and heating/cooling demand. Therefore, the optimization process was structured with indoor comfort as the primary criterion and energy demand as the secondary criterion.

The analysis followed a staged approach. First, the zones identified as thermally sensitive were reviewed according to their function, volume, exposure, and envelope characteristics. Then, selected critical zones were optimized through a sequence of operational, passive, and active strategies. This order allowed the effect of each intervention to be evaluated separately, avoiding premature conclusions based only on total EUI.

The optimization sequence was organized as follows:

1. Base case
2. Internal gains
3. Weekly schedules
4. Glazing optimization
5. Natural ventilation
6. Optimized Ideal Air / HVAC control
7. Thermal control setpoint sensitivity

This sequence reflects the logic of the thesis methodology: the model is first corrected through functional assumptions, then improved through passive envelope and ventilation strategies, and finally tested through system-control adjustments.

Preliminary Critical-Zone Review

The all-zone comfort and EUI analysis showed that several zones were outside the desired comfort range. The most severe thermal response appeared in the small stage of the performance building. This zone showed approximately 80% heat sensation, 10% cold sensation, and an operative-temperature discomfort indicator of approximately 25%.

Although this result indicates a critical thermal condition, the small stage was not selected as the first zone for detailed passive optimization. This decision was based on the specific characteristics of the space. The zone has a large volume, a low window-to-wall ratio of approximately 5%, and a function that is strongly dependent on occupancy peaks, artificial lighting, mechanical ventilation, and active conditioning. Its performance is therefore less controlled by façade optimization alone and more dependent on system-level strategies.

For this reason, the small stage was classified as a system-sensitive critical zone rather than the first target for envelope-led optimization. It will be addressed later in the all-zone energy optimization stage, where active strategies and HVAC system assumptions can be evaluated at building scale.

After this classification, the optimization focus moved to zones where the relationship between comfort, envelope, operation, and passive strategies could be assessed more directly. The kitchen and the south-facing classroom were therefore reviewed in more detail.

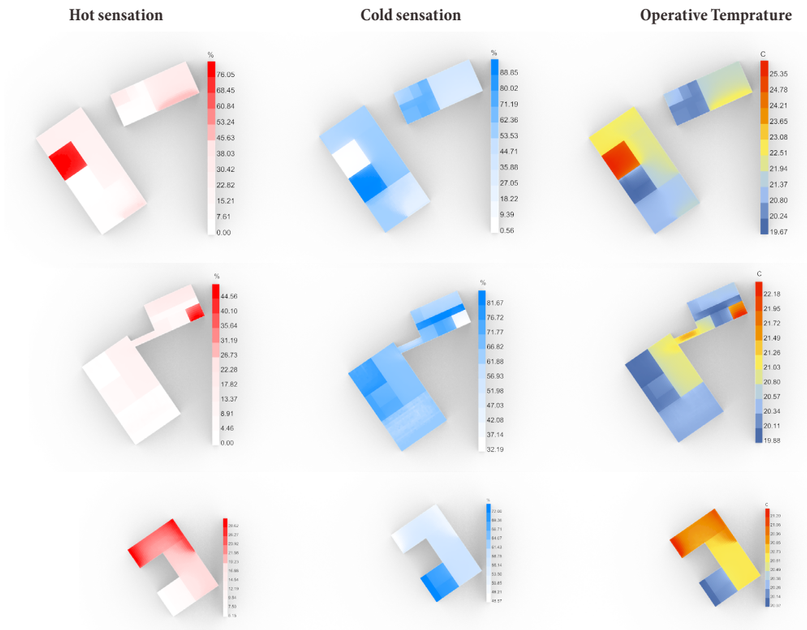
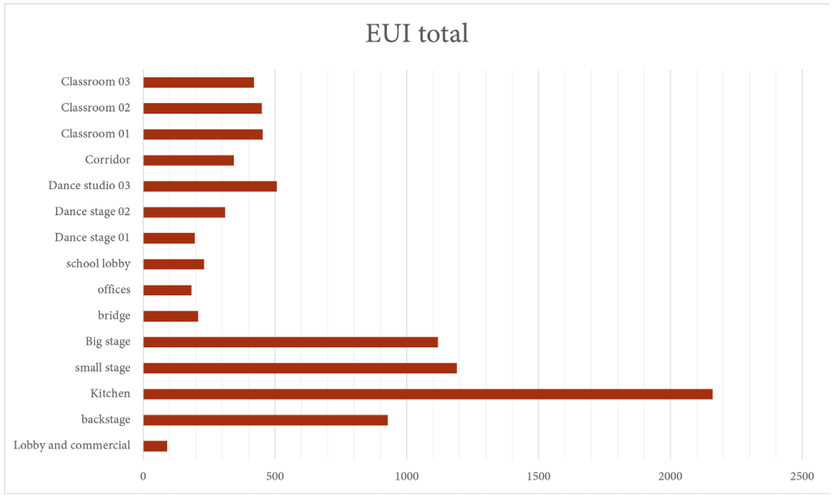


Fig 4.18 *Groundfloor, Initial Energy Analysis: Thermal Sensation and Operative Temperature Distribution*
Fig 4.19 *First-floor, Initial Energy Analysis: Thermal Sensation and Operative Temperature Distribution*
Fig 4.20 *Second-floor, Initial Energy Analysis: Thermal Sensation and Operative Temperature Distribution*

This figures presents the initial energy analysis of the building using three thermal performance maps: hot sensation, cold sensation, and operative temperature. The results show an uneven thermal distribution across the building, with the most critical zones identified in the kitchen, classrooms, small stage, and big stage areas. These spaces show higher thermal discomfort risks due to internal heat gains, occupancy density, equipment loads, and large-volume performance spaces, indicating the need for further optimization of envelope performance, ventilation strategy, and HVAC zoning



Zone / Functional Area	Initial EUI (kWh/m²·year)	Short Interpretation
Kitchen	2160	Extremely high process and equipment-driven load; primary critical zone.
Small Stage	1190	Very high event-based demand due to volume, lighting, and ventilation.
Big Stage	1118	Very high performance-space demand; requires schedule and system optimization.
Backstage	928	High support-zone demand linked to stage operation and ventilation.
Dance Studio 03	507	High active-use demand; requires schedule and comfort calibration.
Classroom 01	454	High educational-zone demand; critical for comfort and energy refinement.
Classroom 02	450	High demand; requires glazing, shading, and schedule optimization.
Classroom 03	420	High but slightly lower than other classrooms; still relevant for optimization.
Corridor	344.14	High for circulation; should be treated with wider comfort limits.
Dance Stage 02	311.42	Moderate-to-high demand linked to activity and ventilation.
School Lobby	231.3	Moderate demand; suitable for buffer-zone strategy.
Bridge	208.7	Moderate transitional-zone demand; avoid over-conditioning.
Dance Stage 01	195.58	Moderate active-zone demand.
Offices	182.95	Moderate demand; influenced by glazing, equipment, and schedules.
Lobby and Commercial	91	Lowest demand; comparatively balanced initial condition.

Kitchen Zone: Envelope Baseline and Operational Load Correction

The kitchen, located on the ground floor, was identified as one of the zones with high energy demand and comfort sensitivity. However, unlike the classroom and office zones, the kitchen performance is strongly influenced by its operational function. Its energy demand is affected not only by the envelope condition, but also by electric equipment, gas equipment, domestic hot water, ventilation, and exhaust requirements.

Before adjusting the operational assumptions, the selected wall technology, Case01, was applied to the kitchen as part of the global envelope baseline. This step already improved the thermal condition of the zone, indicating that the wall technology had a positive effect on the initial heating and cooling balance. The improvement shows that even in a functionally intensive space such as the kitchen, the envelope still contributes to stabilizing indoor conditions and reducing unnecessary thermal losses.

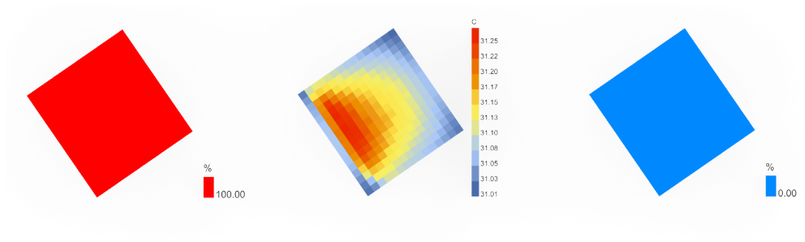


Fig 4.21 *Kitchen, Initial Energy Analysis: Thermal Sensation and Operative Temperature Distribution*

After this envelope baseline was applied, the second step focused on correcting the kitchen's internal gains and operational assumptions. More realistic values were assigned for equipment loads, occupancy, lighting, hot water, ventilation, and schedules. This produced a further improvement in both EUI and indoor comfort. The result confirms that the kitchen cannot be evaluated only through envelope performance, because a significant part of its demand comes from process-related loads and operating patterns.

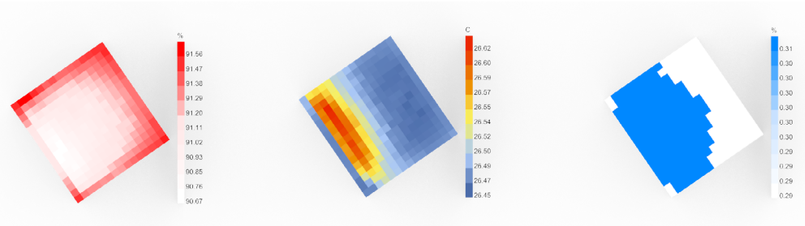


Fig 4.22 *Kitchen, After applying Internal gains: Thermal Sensation and Operative Temperature Distribution*

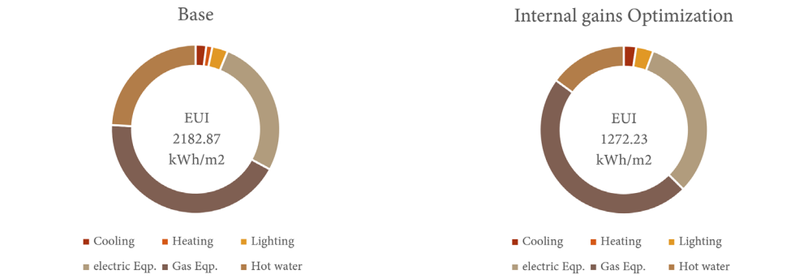
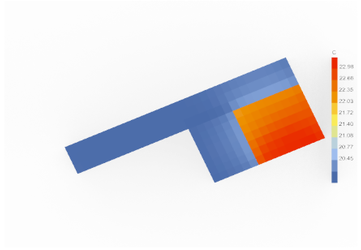


Fig 4.23 *Comparison of Energy Use Intensity and End-Use Distribution between Base Case and applying internal gains to Kitchen*



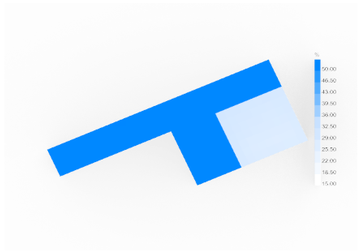




Fig 4.24 Classroom, Initial Energy Analysis: Thermal Sensation and Operative Temperature Distribution

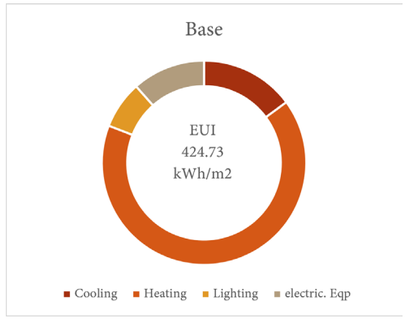


Fig 4.25 Classroom Base Case Energy Use Intensity and End-Use Distribution

Classroom Zone: Main Critical-Zone Optimization

The most important zone for detailed comfort optimization was the south-facing classroom on the first floor. This space was selected because its function requires stable indoor comfort for students and staff during occupied hours. Unlike the stage and kitchen, the classroom is more directly affected by the interaction between façade exposure, glazing, solar gains, internal gains, ventilation, and thermal control. For this reason, the classroom became the main test zone for the critical-zone optimization workflow. The goal was to improve comfort while reducing heating and cooling demand, without selecting the final HVAC system too early.

Classroom Optimization Sequence

The base comfort maps show that the initial classroom condition was not thermally balanced. In the heat-sensation map, the highest discomfort is concentrated near the south-facing façade, where the red gradient indicates a strong warm condition close to the glazed/exposed side of the room. This suggests that the base condition was affected by façade-related heat accumulation and solar exposure. The cold-sensation map shows a generally low cold-discomfort distribution across most of the classroom. The blue tone is relatively uniform and does not indicate a severe cold-stress condition. However, the presence of cold sensation in the deeper part of the room suggests that the initial model still had an uneven thermal response between the façade side and the interior side of the zone.

The base case represented the initial classroom condition before operational correction. In this case, the EUI was 424.73 kWh/m²·year, with heating demand as the dominant component.

Step 1 — Internal Gains

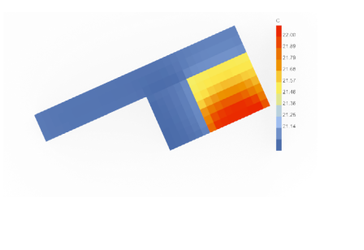
The first correction was the application of realistic internal gains for the classroom. This included occupancy, lighting, electric equipment, ventilation, and infiltration assumptions appropriate to the classroom function.

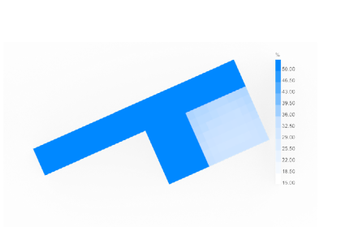
Compared with the base case, applying internal gains produced a clear improvement in the classroom comfort maps. The maximum heat-sensation value decreased from approximately 57.6% to 34.0%, corresponding to an approximate 41% reduction in warm discomfort intensity near the façade. This shows that the internal-gain correction reduced the excessive heat concentration previously visible on the south-facing side of the room.

The cold-sensation map remained relatively stable, with no major increase in cold discomfort. This indicates that the classroom did not shift from an overheating problem to a cold-dominant condition after applying internal gains.

The operative-temperature map also became more balanced. The maximum operative temperature decreased slightly, from about 22.36°C to 22.00°C, while the cooler areas increased from around 19.92°C to 20.93°C. This means the temperature range became narrower and more uniform across the classroom.

After adding internal gains, the total EUI decreased from 424.73 to 222.24 kWh/m²·year. Heating demand also dropped from 280.40 to 147.63 kWh/m²·year.





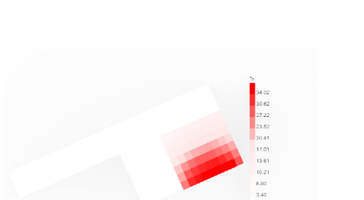


Fig 4.26 Classroom, After applying Internal gains: Thermal Sensation and Operative Temperature Distribution

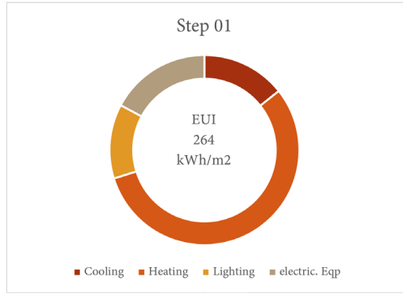
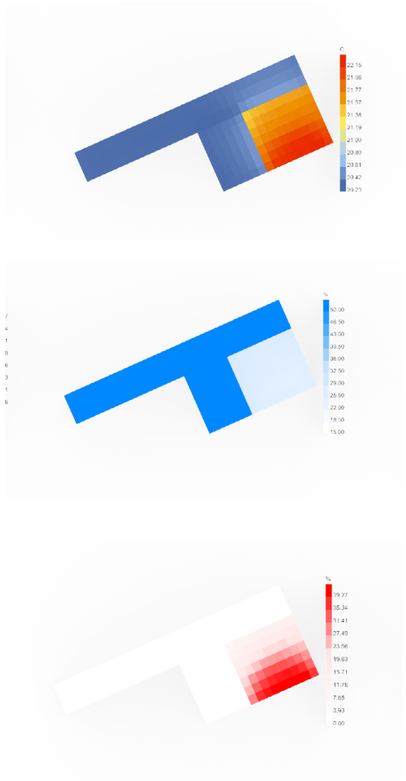


Fig 4.27 Classroom Step01 Energy Use Intensity

Fig 4.28 Classroom, After applying weekly schedule: Thermal Sensation and Operative Temperature Distribution



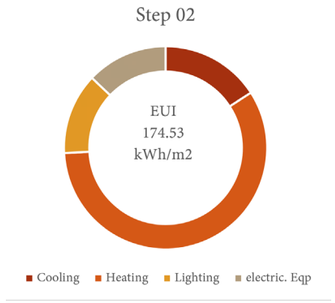
Step 2 — Weekly Schedule

The second step introduced a weekly operational schedule. This schedule defined when occupancy, lighting, equipment, and ventilation were active. After applying the schedule, the EUI decreased further to 174.53 kWh/m²·year. The reduction in lighting and equipment energy is directly related to the schedule definition. Cooling demand also decreased, because internal heat gains were no longer assumed to occur continuously. Heating demand decreased as well, showing that the schedule created a more realistic operating profile.

The maximum heat-sensation value increased from approximately 34.0% to 39.3%, which is about a 15% increase compared with the internal-gain case and The cold-sensation map remains broadly similar.

The operative-temperature map shows a slightly wider range again. Compared with the internal-gain case, where the temperature distribution was more balanced, the scheduled case shows warmer conditions concentrated near the façade, with the maximum operative temperature around 22.15°C. This indicates that scheduling introduced a more realistic occupied-use pattern, but the classroom still required further façade and passive-control strategies.

Fig 4.29 Classroom Step02 Energy Use Intensity



Step 3 — Glazing Optimization

After correcting internal gains and schedules, glazing optimization was introduced as the first passive envelope strategy. The selected glazing case used:

U-value = 1.1 W/m²K

SHGC = 0.50

Visible transmittance = 0.72

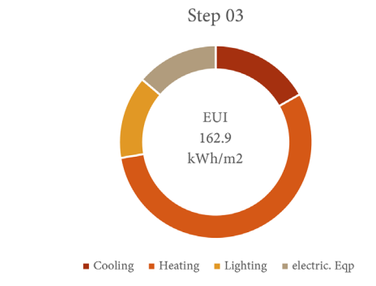
This glazing configuration was chosen to balance winter heat retention, solar gain, daylight admission, and overheating control. The classroom is south facing, so the glazing must allow useful daylight and winter solar contribution while avoiding excessive summer overheating.

The comfort maps showed a moderate improvement in the thermal distribution, but the classroom still required additional passive control to address warm-period discomfort.

Fig 4.30 Classroom, Glazing Optimization: Thermal Sensation and Operative Temperature Distribution



Fig 4.31 Classroom Step03 Energy Use Intensity



Natural Ventilation Setting

Natural ventilation was introduced as a passive cooling strategy after the glazing optimization. In the Honeybee model, it was defined through the window-opening method rather than as a fixed airflow input. The control settings allowed the windows to open only when the indoor temperature was between 23°C and 27°C, the outdoor temperature was between 18°C and 24°C, and the outdoor air was at least 2°C cooler than the indoor air. The operable window area was set to 30%, with an operable height fraction of 50% and a discharge coefficient of 0.60.

Based on the classroom volume and the calculated airflow rate, the effective natural ventilation rate was approximately 2 ACH. This means that, under suitable outdoor conditions, the air volume of the classroom could be replaced about two times per hour. This value was considered appropriate for the

Parameter	Value
Minimum indoor temperature	23°C
Maximum indoor temperature	27°C
Minimum outdoor temperature	18°C
Maximum outdoor temperature	24°C
Minimum temperature difference	2°C
Operable window area	30%
Operable height fraction	50%
Discharge coefficient	0.60
Calculated effective air-change rate	2 ACH

Fig 4.32 *Classroom, Applying Natural ventilation: Thermal Sensation and Operative Temperature Distribution*

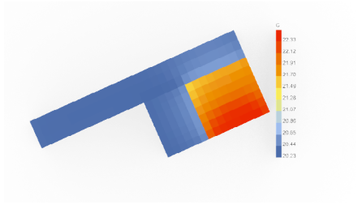


Fig 4.34 *Classroom, adding shadings: Thermal Sensation and Operative Temperature Distributio*



Fig 4.33 *Classroom Step04 and Step 05 Energy Use Intensity*

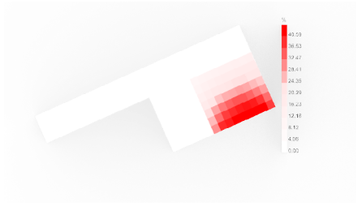
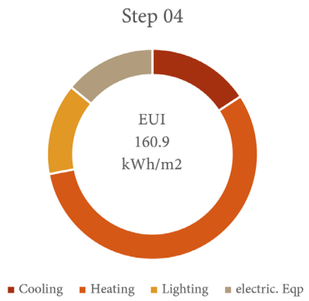
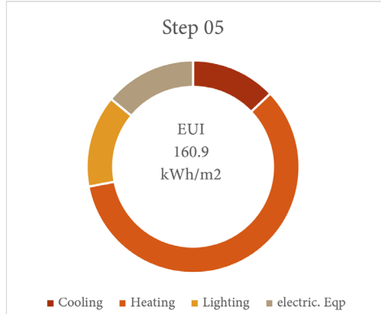


Fig 4.35 *Classroom ,final step: Thermal Sensation and Operative Temperature Distributio*





Step 5 — Horizontal Shading

Horizontal shading was then added as a calibrated passive solar-control strategy. The tested shading configuration used:

Horizontal shading depth: 0.90 m

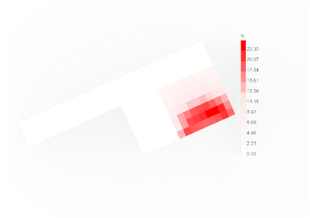
Distance between shading elements: 0.70 m

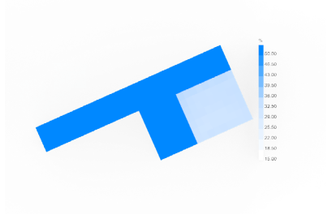
This intervention produced a clearer improvement in the classroom comfort maps. Compared with the natural ventilation case, the shading reduced the intensity of the warm zone near the façade and made the operative-temperature distribution more balanced. The warm area remained visible close to the glazed side, but it became more controlled and less dominant. At the same time, the cold-sensation map did not show the strong overcooling effect observed in the previous stronger shading test. This indicates that the revised shading geometry achieved a better balance between limiting excessive solar gain and preserving useful solar contribution.

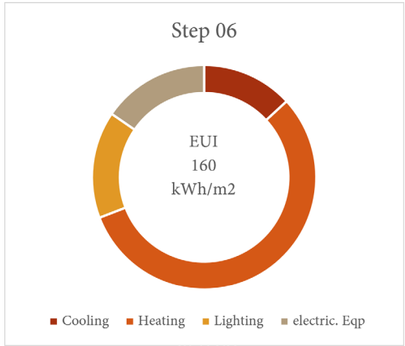
The EUI also improved slightly. Total EUI decreased from 170.90 to 169.00 kWh/m²·year, corresponding to a reduction of approximately 1.1%. Cooling demand decreased from 27.34 to 23.82 kWh/m²·year, equal to an approximate 12.9% reduction. Heating demand increased slightly from 98.48 to 100.08 kWh/m²·year, approximately 1.6% higher than the ventilation case.

This result shows the expected trade-off for a south-facing classroom in Brussels. The shading reduced cooling demand and improved localized summer comfort, but it also slightly increased heating demand by reducing useful solar gains. However, because the total EUI decreased and the comfort maps became more balanced, this shading configuration was considered successful.





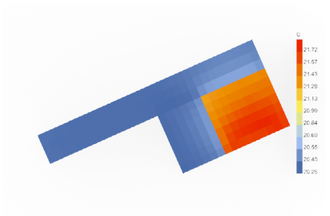




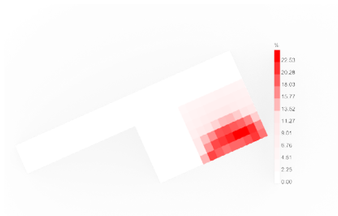
Step 6 — Optimized HVAC Control

After the passive measures were tested, an optimized HVAC control scenario was introduced as the final step for this critical zone. The aim of this step was not to replace the later whole-building HVAC selection, but to evaluate the effect of improved system-control assumptions after the passive load-reduction strategies had already been applied.

With the optimized HVAC control, the total EUI increased from 169.00 to 179.57 kWh/m²·year. Cooling demand decreased slightly from 23.82 to 22.21 kWh/m²·year, equal to an approximate 6.8% reduction, while heating demand decreased more substantially from 100.08 to 81.77 kWh/m²·year, equal to an approximate 18.3% reduction. However, despite these improvements in heating and cooling demand, the total EUI increased, which suggests that the optimized system-control case introduced additional system-related energy penalties or changed the balance of end-use demand







This result reinforces the role of the envelope as the main mediator between climate, solar exposure, and indoor comfort. The classroom did not improve only through mechanical assumptions; its comfort condition became more balanced when the façade response was adjusted through glazing and calibrated shading. The maps show that the shading reduced the warm concentration near the exposed side without creating the excessive cold discomfort observed in stronger shading tests. This is important for the Brussels context, where the design must reduce summer overheating while preserving useful solar contribution during cooler periods.

Daylight Reassessment After Shading Optimization

After the identification of critical zones through the initial energy and comfort analysis, daylight performance was re-evaluated to support the selection of façade shading strategies. The post-shading daylight results show that the areas with excessive daylight exposure were reduced, particularly in the zones previously affected by high UDI >3000 and elevated ASE values. This confirms that the shading strategy was not applied only as an energy-saving measure, but also as a visual comfort intervention to control direct solar penetration, reduce glare risk, and improve the balance between useful daylight and overexposure. The comparison also demonstrates that the shading system performs differently according to floor level, orientation, and room depth. While some perimeter areas still show localized high UDI and ASE values, these are more limited and concentrated than in the initial daylight condition. Therefore, the final shading configuration can be considered an appropriate compromise: it reduces excessive solar exposure in the most sensitive zones without excessively darkening the interior spaces or compromising the availability of useful daylight. This result supports the later energy optimization steps, especially the glazing selection, cooling-load reduction, and improvement of indoor comfort in the critical zones. Overview

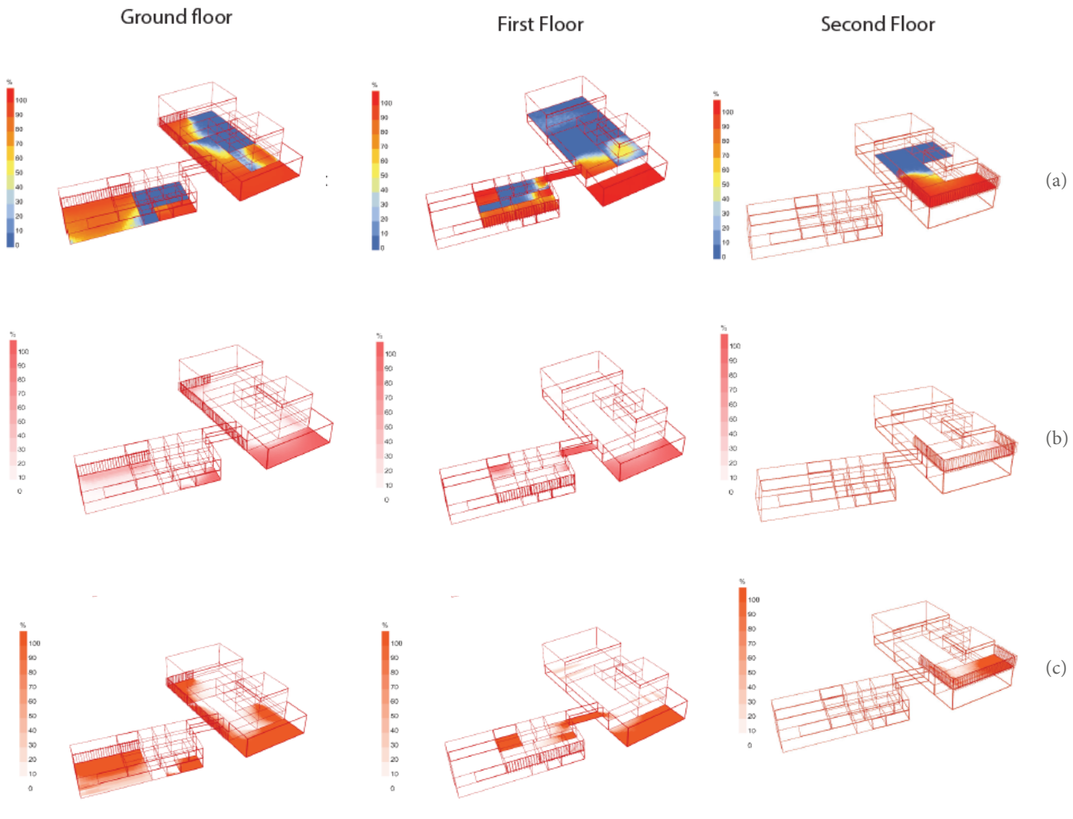


Fig 4.36 *Daylight Reassessment After Shading Optimization, Annual daylight map (a), UDI>3000 map (b) and ASE map (c)*

4.5 Final Energy Performance

The final whole-building energy analysis was carried out after completing the optimization of the main critical zones and integrating the final passive, active, and renewable energy strategies. The objective of this stage was to evaluate the annual energy performance of the complete mixed-use cultural and educational building under more realistic operational assumptions. The final model included zone-specific schedules, internal gains, occupied and unoccupied setpoints, natural ventilation controls, orientation-based glazing, façade shading strategies, and differentiated HVAC systems. The building combines several functions with very different energy behaviours, including classrooms, offices, dance studios, commercial spaces, dining areas, circulation zones, kitchen facilities, backstage areas, and two performance stages. Because of this mixed-use condition, the final energy result was not assessed as a simple school or office building, but as a high-performance cultural and educational facility with energy-intensive performance functions.

Across all final scenarios, the photovoltaic system was kept constant in order to isolate the effect of demand-side optimization. The PV panels were modelled with a 35° tilt angle and south-facing orientation. The annual photovoltaic production remained approximately:

149,482 kWh/year

This constant renewable production allowed the improvement of the building demand to be clearly compared between the different simulation steps.

Benchmarking Basis for High-Performance Classification

The energy performance of the building was

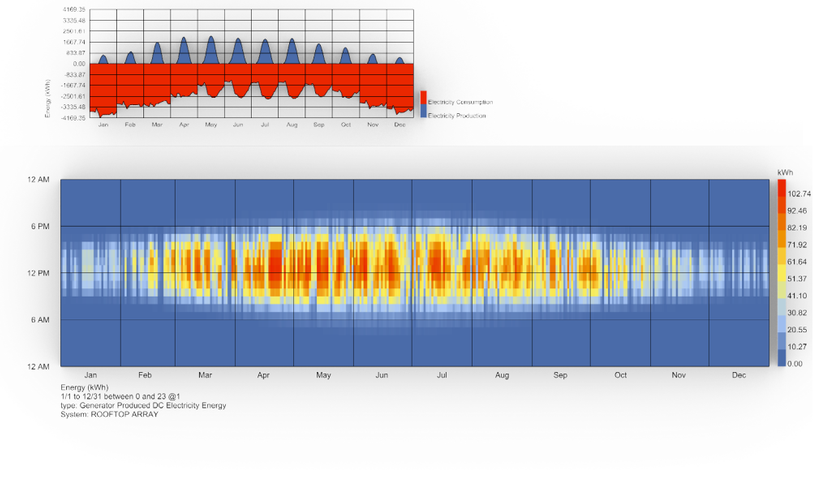


Fig 4.37 *Annual Rooftop PV Electricity Production and Monthly Energy Balance*

evaluated using Energy Use Intensity, expressed in kWh/m²·year. This metric allows annual building consumption to be normalized by floor area and compared with professional benchmark values.

For the purpose of this assessment, the building area was considered approximately 6,000 m². Based on this area, the simulated annual consumption values correspond to the following approximate EUIs:

Scenario	Annual Consumption	Approximate Floor Area	EUI
Initial final whole-building case	~600,000 kWh/year	~6,000 m²	~100 kWh/m²·year
After kitchen optimization	~400,000 kWh/year	~6,000 m²	~66.7 kWh/m²·year
Comparative case without stages	322,679 kWh/year	~6,000 m²	~53.8 kWh/m²·year

These values indicate a strong energy performance, especially when compared with professional benchmark categories for cultural and entertainment buildings. Entertainment halls, theatres, and performance spaces are typically energy-intensive due to large conditioned volumes, intermittent occupancy peaks, stage lighting, technical equipment, ventilation demand, and air distribution requirements. Therefore, achieving an EUI between approximately 54 and 100 kWh/m²·year for a mixed-use project containing performance halls, kitchen, classrooms, offices, and public spaces can be considered a high-performance outcome.

The post-kitchen optimization case, with an approximate EUI of 66.7 kWh/m²·year, is particularly significant because it remains within a strong performance range for a complex mixed-use building. The comparative case without stages, with an approximate EUI of 53.8 kWh/m²·year, demonstrates that the normal-use parts of the building — classrooms, offices, dance studios, commercial areas, dining spaces, circulation, and lobby zones — perform at a very high level when the high-intensity stage functions are isolated.

Scenario 1: Initial Final Whole-Building Analysis

The initial final whole-building analysis represented the first complete optimized model. This scenario included the selected high-performance envelope, separated roof and wall constructions, orientation-specific glazing, shading devices, natural ventilation controls, optimized schedules, differentiated setpoints, and the final HVAC system configuration.

The HVAC strategy was divided according to zone function. Normal-use zones such as classrooms, offices, dance studios, dining spaces, commercial areas, lobbies, circulation zones, and bridge areas were assigned to a DOAS water ground-source system. This system was selected because ground-source operation can reduce the annual heating and cooling energy required for spaces with relatively stable occupancy patterns.

The high-intensity zones, including the large stage, small stage, backstage, and kitchen-related areas, were assigned to a VAV system with heat recovery and make-up air. These spaces require higher and more variable air supply due to occupancy peaks, stage operation, kitchen exhaust, technical loads, and event-based operation.

In this first final whole-building scenario, the annual consumption was approximately:

600,000 kWh/year

For a building of approximately 6,000 m², this corresponds to an EUI of approximately:

100 kWh/m²·year

The PV system produced:

149,482 kWh/year

Therefore, the PV coverage ratio was approximately:

24.9%

This means that almost one quarter of the annual building demand was covered by photovoltaic production. The result already represents a strong improvement compared with a conventional cultural or entertainment building, especially considering the presence of high-energy functions such as performance stages and kitchen facilities. However, the result also showed that some specific programmatic zones were still dominating the total annual consumption.

Scenario 2: After Kitchen Optimization

The second stage focused on the kitchen, which had emerged as one of the most influential contributors to annual energy demand. This result is technically expected because kitchen spaces contain several high-load components, including electric equipment, process loads, hot water demand, exhaust ventilation, make-up air, and extended operating schedules.

The kitchen optimization included the refinement of:

equipment load assumptions;

kitchen operation schedules;

peak and off-peak equipment use;

ventilation and make-up air operation;

occupied and unoccupied thermal setpoints;

separation between process-related loads and general space conditioning.

After this optimization, the annual building consumption decreased from approximately:

600,000 kWh/year

to approximately:

400,000 kWh/year

This represents a reduction of approximately:

200,000 kWh/year

or about:

33%

compared with the initial final whole-building case.

For a building of approximately 6,000 m², the post-kitchen optimization energy demand corresponds to an approximate EUI of:

66.7 kWh/m²·year

This result is a strong high-performance outcome for a mixed-use cultural and educational building, especially because the model still includes the performance stages and other high-intensity functions.

Because the PV production remained constant at:

149,482 kWh/year

the PV coverage ratio increased to approximately:

37.4%

This shows that reducing demand significantly increases the relative effectiveness of the same PV system. The PV installation did not change, but its contribution became more important because the annual building consumption decreased. This confirms that demand reduction is essential before evaluating renewable energy contribution.

Scenario 3: Comparative Case Without Performance Stages

A third simulation was carried out by temporarily excluding the performance-stage zones from the model. This scenario was not intended to represent the final architectural proposal. Instead, it was used as a comparative sensitivity analysis to quantify the influence of the performance stages on total annual energy demand.

This method is useful because the performance stages have very different energy behaviour compared with the other zones. They include large volumes, intermittent but high occupancy, strong ventilation requirements, stage lighting, technical equipment, and event-based comfort requirements. By removing them temporarily from the simulation, the energy behaviour of the remaining normal-use building functions could be evaluated more clearly.

In this comparative case, annual energy consumption decreased to:

322,679 kWh/year

For an approximate floor area of 6,000 m², this corresponds to an EUI of approximately:

53.8 kWh/m²·year

This is a very strong high-performance result. It shows that the normal-use areas of the building including classrooms, offices, dance studios, dining, commercial spaces, lobbies, circulation, and support zones perform at a very efficient level when the stage-related energy demand is isolated.

The photovoltaic production remained:

Scenario	Annual Con-sumption	Approx. EUI	PV Production	PV Coverage	Interpretation
Initial final whole-buil-ding case	~600,000 kWh/ year	~100 kWh/ m²·year	149,482 kWh/ year	~24.9%	High-performance result for a mixed-use cultural building with stages and kitchen
After kitchen optimization	~400,000 kWh/ year	~66.7 kWh/ m²·year	149,482 kWh/ year	~37.4%	Strong high-performance condition after reducing process and service loads
Comparative case without stages	322,679 kWh/ year	~53.8 kWh/ m²·year	149,482 kWh/ year	~46.3%	Very high-performance result for the normal-use building functions

149,482 kWh/year

Therefore, the PV coverage ratio increased to approximately:

46.3%

This means that nearly half of the annual demand of the non-stage comparative case was offset by photovoltaic production. This is a substantial renewable contribution and confirms that the non-stage parts of the building operate within a highly efficient energy range.

Final Conclusion

The final energy analysis confirms that the project can be professionally described as a high-performance mixed-use cultural and educational building. The optimized whole-building case after kitchen refinement achieved an approximate annual consumption of 400,000 kWh/year, corresponding to an EUI of approximately 66.7 kWh/m²·year for a 6,000 m² building. This is a strong result for a project that includes performance stages, kitchen facilities, classrooms, dance studios, offices, commercial areas, dining spaces, and circulation zones.

The comparative case without stages achieved an even lower annual demand of 322,679 kWh/year, corresponding to approximately 53.8 kWh/m²·year. This confirms that the normal-use zones perform within a very high-performance range, while the kitchen and performance stages represent the main energy-intensive functions.

Overall, the results demonstrate that the building's energy demand is not evenly distributed across the program. Instead, a small number of high-intensity zones especially the kitchen and performance stages have a disproportionate effect on total annual consumption. The final design therefore establishes a strong high-performance baseline and clearly identifies where the remaining energy reductions should be focused.

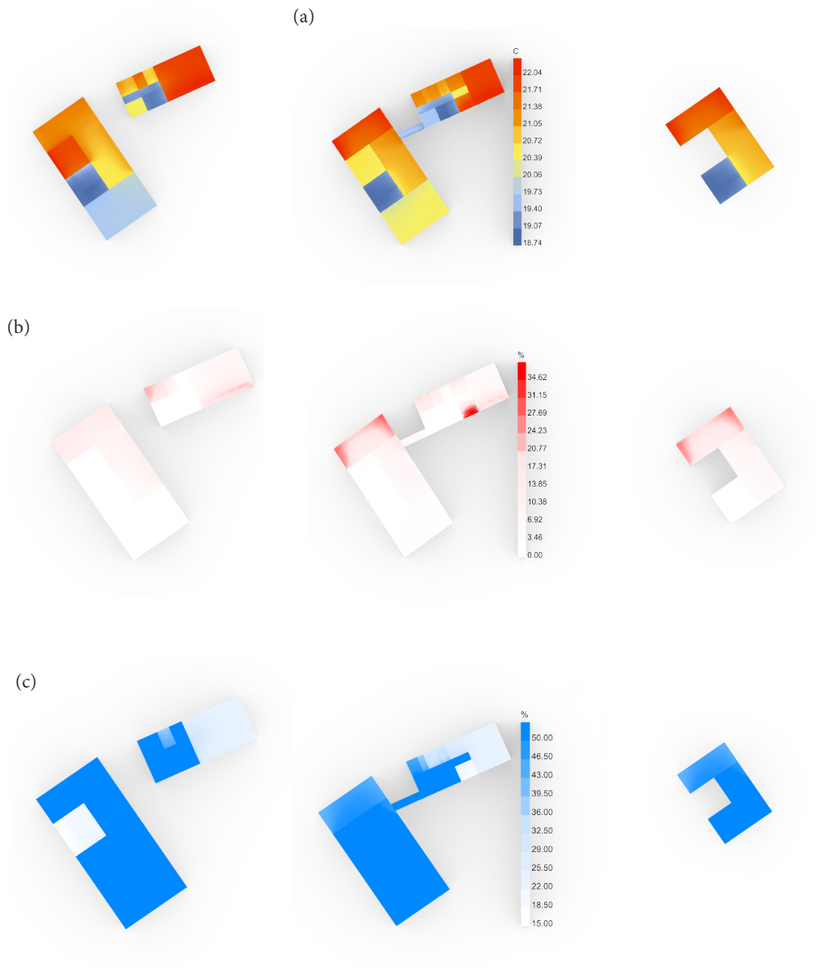


Fig 4.38 whole building final Thermal comfort analysis, Opra-tive Temperature map (a), Hot sensation map (b), Cold sensation (c)

Thermal comfort Evaluation

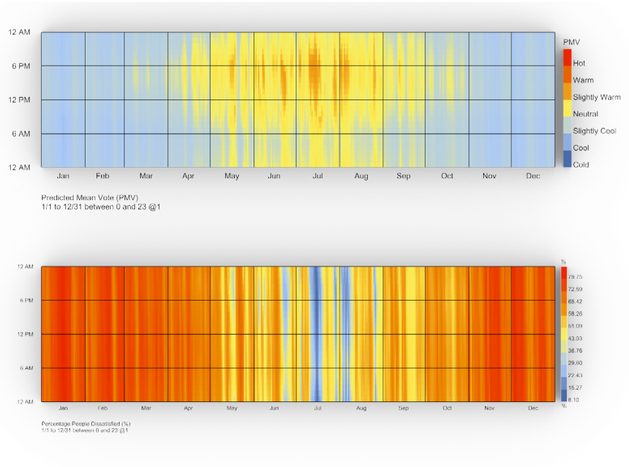
The final floor-by-floor comfort results show an overall controlled thermal condition across the building. Heating sensation remains limited and mostly concentrated in small perimeter areas, especially on exposed façade zones and upper-level volumes, indicating that overheating is not widespread after the final optimization. Cooling sensation is more visible, particularly in several larger zones, but it appears relatively stable and consistent rather than extreme; this suggests that the HVAC and setpoint strategy is effectively controlling internal temperature while avoiding major overheating risk. The operative temperature maps show a narrow annual temperature range, approximately between 18.5°C and 22.1°C, with most occupied areas remaining around 19.5–21.5°C. The ground floor and first floor show more variation because they include higher-load and more complex functions, while the second floor appears more thermally stable. Overall, the results confirm that the final strategy produces a balanced indoor environment, with remaining discomfort mainly localized in perimeter zones, bridge connections, and high-intensity functional areas rather than distributed across the whole building. The PMV and PPD results show two different comfort behaviours between the critical classroom and the dance studio. In the classroom, the PMV graph remains mostly within the cool to slightly cool range during much of the year, with only limited neutral or slightly warm periods appearing around summer months. The corresponding PPD graph shows higher dissatisfaction during winter and shoulder seasons, indicating that the main comfort issue in

this room is not overheating, but a tendency toward cool discomfort. This confirms why the classroom remained a critical zone: despite the reduction of overheating through glazing, shading, ventilation, and HVAC optimization, the room still requires careful control of winter comfort and occupied-hour heating conditions.

In contrast, the dance studio shows a more balanced annual PMV distribution. The PMV values move closer to neutral and slightly warm conditions during the occupied warm season, which is acceptable for an active-use space where occupants have a higher metabolic rate. The PPD graph also indicates lower dissatisfaction during the central summer period compared with the classroom, suggesting that the final settings are more suitable for the activity level and thermal expectations of the dance studio. Overall, the comparison confirms that the classroom has a more sensitive comfort profile and requires stricter thermal control, while the dance studio performs better because its higher activity level and wider comfort tolerance make slightly warmer conditions more acceptable.

Fig 4.39 *Annual PMV and PPD Thermal Comfort Profile for the Dance Studio and Classroom*

Dance studio



Classroom



Final Conclusion

The energy analysis chapter revealed not only the environmental behaviour of the building, but also the practical limitations of the current simulation workflow during envelope decision-making. Each envelope option required the manual definition of multiple material layers, construction assemblies, glazing properties, schedules, and performance assumptions before it could be tested in Honeybee. This process became time-consuming, especially when simulations took several hours or even overnight, and any mistake in material selection, layer order, thermal properties, or construction assignment required the model to be corrected and simulated again. In addition, the repeated insertion of detailed envelope layers made the Grasshopper file heavier, slower, and more difficult to manage during iterative design development.

This experience clarified the need for Armadillo as an early-stage envelope decision-support tool within the Grasshopper workflow. In early design phases, designers often need to compare many material and envelope alternatives while considering multiple criteria such as thermal performance, climate suitability, cost, function, moisture risk, construction logic, and compatibility with the overall building strategy. However, there is usually not enough time to build and simulate every option in full detail before making design decisions. Armadillo therefore becomes necessary as a parallel system that can organize material data, evaluate envelope assemblies, compare alternatives, and filter unsuitable options before they are transferred into Honeybee for detailed simulation. In this way, it reduces trial-and-error modelling, limits unnecessary heavy simulations, and helps designers make faster and better-informed envelope decisions during the early stages of the project.

Fig 4.40 *Rhino Grasshopper Full energy analysis*



05 ARMADILLO

Chapter 5 presents Armadillo, the Grasshopper-based decision-support tool developed as the main methodological contribution of the thesis. The chapter explains the tool's position within the design workflow, its standards-informed calculation basis, and its ability to evaluate opaque wall assemblies through thermal, dynamic, moisture, cost, carbon, and ranking indicators. The chapter concludes by applying Armadillo to the five LionCity II wall assemblies, demonstrating how the tool supports early-stage envelope comparison before detailed simulation and later technical verification.

5.1 Introduction to Armadillo

Armadillo is a parametric, standards-informed decision-support tool for evaluating the building envelope at an early stage, developed as the principal methodological instrument of this thesis. Armadillo is not presented as a standalone software product. It is the operational expression of the thesis argument established in Chapter 1: that envelope performance reasoning, grounded in recognised calculation standards, can and should be made accessible to architects at a point when design decisions are still open to change.

The three research questions formulated in Chapter 1 frame the tool directly.

- RQ1 asks how early-stage envelope selection can be supported by digital decision-support tools without disrupting the pace, openness, and creative agency of architectural design.
- RQ2 asks which envelope performance indicators can be meaningfully evaluated during conceptual and schematic design, and how they can be integrated into a parametric, standards-informed Grasshopper workflow.
- RQ3 asks how the proposed workflow can be applied to the LionCity II case study to demonstrate early-stage envelope comparison and support performance-informed decision-making.

Armadillo brings the three research questions together by demonstrating how early-stage envelope decision-making can be supported, which performance indicators can be evaluated at this stage, and how the proposed workflow can be applied and tested through the LionCity II case study. This chapter presents the tool developed in this research outlining its purpose, design, validation, application to the LionCity II case study, and key contributions and limitations. The chapter follows a development framework within the design science research paradigm (Hevner et al. 2004), in which the primary output is a tool whose validity is demonstrated through application rather than through controlled experiments.

Background

Early-stage design decisions have a strong influence on building performance as established in chapter 1, yet this is also the stage where detailed analytical feedback is often least available due to the fast pace and changing variables. This problem is particularly imperative for the building envelope, where decisions about envelope systems , insulation strategy, moisture-control, material selection, and façade systems are often made before their thermal, hygrothermal, carbon, and cost implications can be investigated. Existing tools provide valuable support, but they tend to operate either as early-stage climate-analysis tools, detailed simulation platforms, optimisation engines, BIM coordination environments, or specialist verification tools. What remains less developed is an intermediate decision-support layer that helps designers define, compare, and refine envelope systems while the design is still flexible. In many early-stage workflows, envelope decisions are still informed through a combination of design experience, rules of thumb, simplified checks, manual calculations, manufacturer data, and iterative testing. While these methods can support preliminary judgement, they often remain fragmented and are not always connected to a transparent comparative framework for evaluating thermal, hygrothermal, cost, and carbon implications before detailed simulation is undertaken.[75]

Armadillo was developed to address this gap. It is not positioned as a replacement for existing tools or workflows. Instead, it is positioned to work with the existing tools and methodologies supporting architectural judgment by making envelope performance more visible, comparable, and interpretable during conceptual and schematic design. The tool therefore favours transparent feedback, evaluating key envelope indicators, checking them against set targets, comparing alternatives, and support selection without removing the designer's responsibility to interpret the result. In this sense, Armadillo is intended to support and inform design decisions rather than prescribe solutions or automate the design process.

Tool Rationale and Design Ideology

The rationale behind Armadillo is based on support rather than automation. The tool does not attempt to prescribe a final envelope solution, but to make the implications of different envelope choices clearer at the point when design decisions are still open. This is necessary because envelope decision-making is not a single-variable problem. An assembly may perform well in thermal resistance while raising concerns in moisture safety, embodied carbon, cost, buildability, or dynamic thermal response. Armadillo therefore uses material and assembly data to organise these indicators into a comparative framework as seen in chapter 2, allowing designers to understand strengths, weaknesses, and trade-offs before moving into detailed simulation or technical verification.

The tool was shaped through the LionCity II case study rather than defined as an abstract software proposal at the beginning of the research. The project was first developed through a conventional workflow involving design exploration, manual envelope calculations, comparative tables, graph preparation, and later validation through Honeybee and EnergyPlus simulations. This process exposed where envelope-related decisions were being made, what information was available at those moments, and where the workflow became fragmented or inefficient. Armadillo was developed in response to these observations, with the aim of consolidating early-stage envelope evaluation within the design environment and testing whether this process could become more systematic, transparent, and useful for architectural decision-making.

5.2 Aim, Scope, and Methodology

Working definition:

Armadillo is a parametric, standards-informed envelope decision-support workflow for early-stage architectural design. It helps designers and communicate envelope options before detailed simulation, Rather than replacing detailed simulation tools or architectural judgement, Armadillo acts as an intermediate layer that makes the implications of envelope choices visible earlier in the design process, supporting the evaluation and refinement of alternatives while design decisions remain flexible.

MVP Scope

The tools minimum viable product (MVP) developed in within this thesis body is intentionally limited to opaque external wall assemblies, where the external wall was the primary envelope variable under investigation, and provides a clearly defined context in which the methodology can be tested and validated.

The minimum viable product (MVP), version 0.1, includes twelve performance domains: steady-state thermal performance (ISO 6946-2017), dynamic thermal behaviour (ISO 13786-2017), surface humidity and mould-risk screening (ISO 13788-2012), interstitial condensation screening by the Glaser method (ISO 13788-2012, and a decision support engine that is core to the thesis key issue.)

Full transient hygrothermal simulation, detailed thermal bridge modelling (ISO 10211), hourly building energy simulation, transparent envelope optimisation, daylight analysis, and local building-code automation are explicitly excluded from the MVP. These exclusions are not oversights; they define the boundary between what the tool claims and what it defers to validated specialist instruments.

Within the thesis framework, Armadillo occupies the third position in a layered digital ecosystem established in Ladybug assists by establish climatic context where armadillo evaluates envelope assemblies through low-input, standards-based performance logic, and Honeybee/Climate Studio provide deeper verification. The tool's success criterion, defined in the MVP specification, is a demonstrable thesis workflow: three to five assemblies built, evaluated, gated, ranked, explained, and exported.

Workflow Gap and Comparative Positioning

Evidence from the Case Study

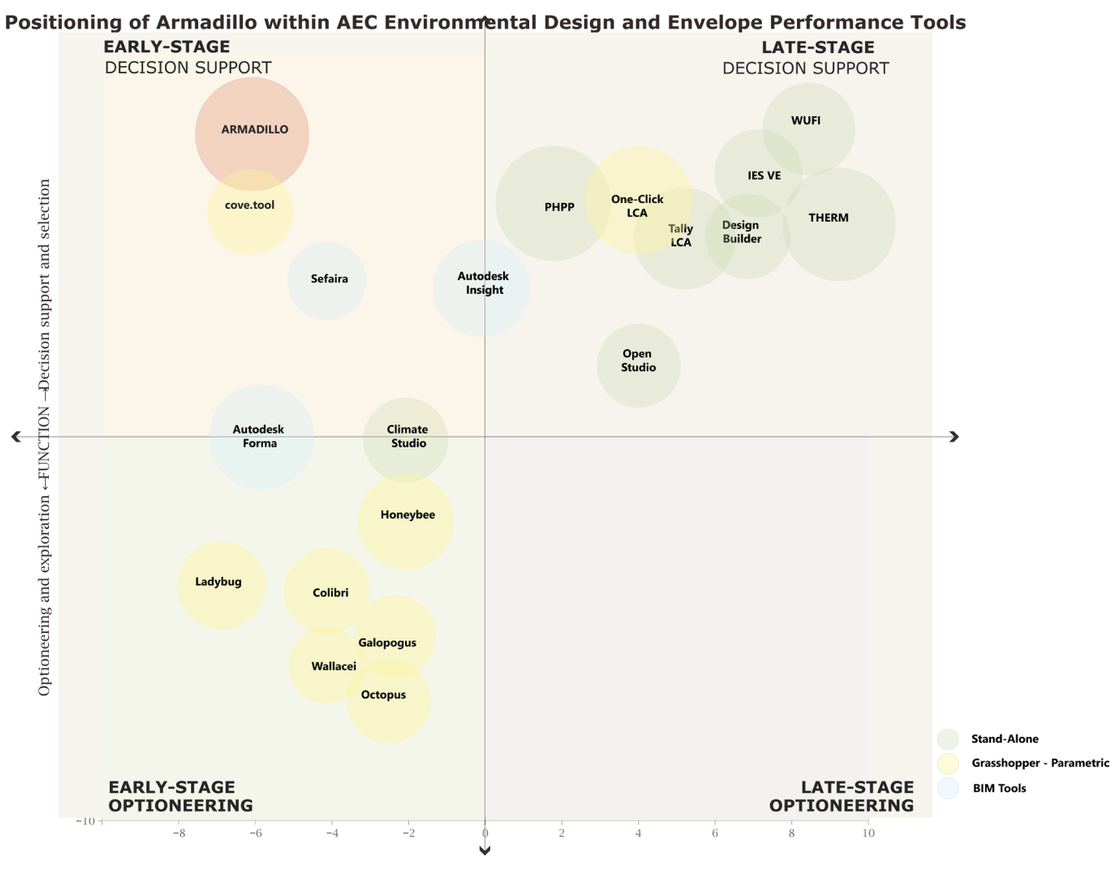
The design development of LionCity II, exposed multiple workflow gap in concrete terms. The architectural design process progressed through massing studies, passive environmental strategies, programme resolution, and structural coordination, leading to the selection of five candidate external wall assemblies. These assemblies were researched and identified as suitable for the project and were considered for early-stage comparison to determine the most efficient option for further validation. The assemblies were then evaluated Honeybee energy simulation, requiring a fully resolved geometric model, defined thermal zones, assigned schedules, internal loads, and HVAC assumptions. The time required to set up, run, and interpret these simulations was substantial, and the process could only begin after the building geometry and zoning strategy were resolved.

Between the architectural decision to compare five envelope options and the detailed simulation workflow to first compare them and then validate the final option, the case study revealed a stage where intermediate feedback would have been useful. At this stage, simplified simulations were used to evaluate the internal thermal conditions of a critical thermal zone using each envelope assembly option. The aim was to identify the best-performing assembly before proceeding with the development of a full building simulation model. Although the simulations were carried out under simplified assumptions, the process remained time-consuming, requiring multiple model iterations, result extraction, comparison of performance metrics, and manual organisation of findings. This workflow highlighted an opportunity to explore whether these early-stage envelope evaluations could be made more efficient, transparent, and better integrated within the parametric design environment through Armadillo.

does not compete with any of these tool categories.

It occupies the space between them: after climate analysis, before energy simulation, alongside parametric design, and downstream of detailed LCA, hygrothermal simulation, and BIM coordination as seen in the figure below.

Fig 5.01 The Comparative positioning Matrix: the comparative positioning of Armadillo against existing digital tool in their defined categories.



Methodology: Platform Selection and Interoperability

The choice of Grasshopper as the development environment was methodological rather than merely technical. Armadillo was conceived as an early-stage decision-support layer and therefore needed to operate inside the same visual and parametric environment in which architectural options are already being generated, tested, and revised. Grasshopper provides this environment because it allows for architectural and design exploration, Implementation Validation and well as documentation, all connected within a single iterative workflow.

This positioning was central to the development of Armadillo. The tool is located within the Grasshopper environment because this is where early-stage design, architectural and technical development as wale as late stage verifications can be done with a robust toolset and fluidity in design without leaving the design process. In this ecosystem, Ladybug and EPW data support climate interpretation, Honeybee and Energy Plus support later simulation, and specialist tools such as WUFI, LCA platforms, and BIM workflows support detailed verification, carbon assessment, and documentation. Armadillo is positioned between these workflows as an intermediate envelope-selection layer, allowing the thesis to investigate how early-stage assembly decisions can be better connected to both parametric design and later performance evaluation.

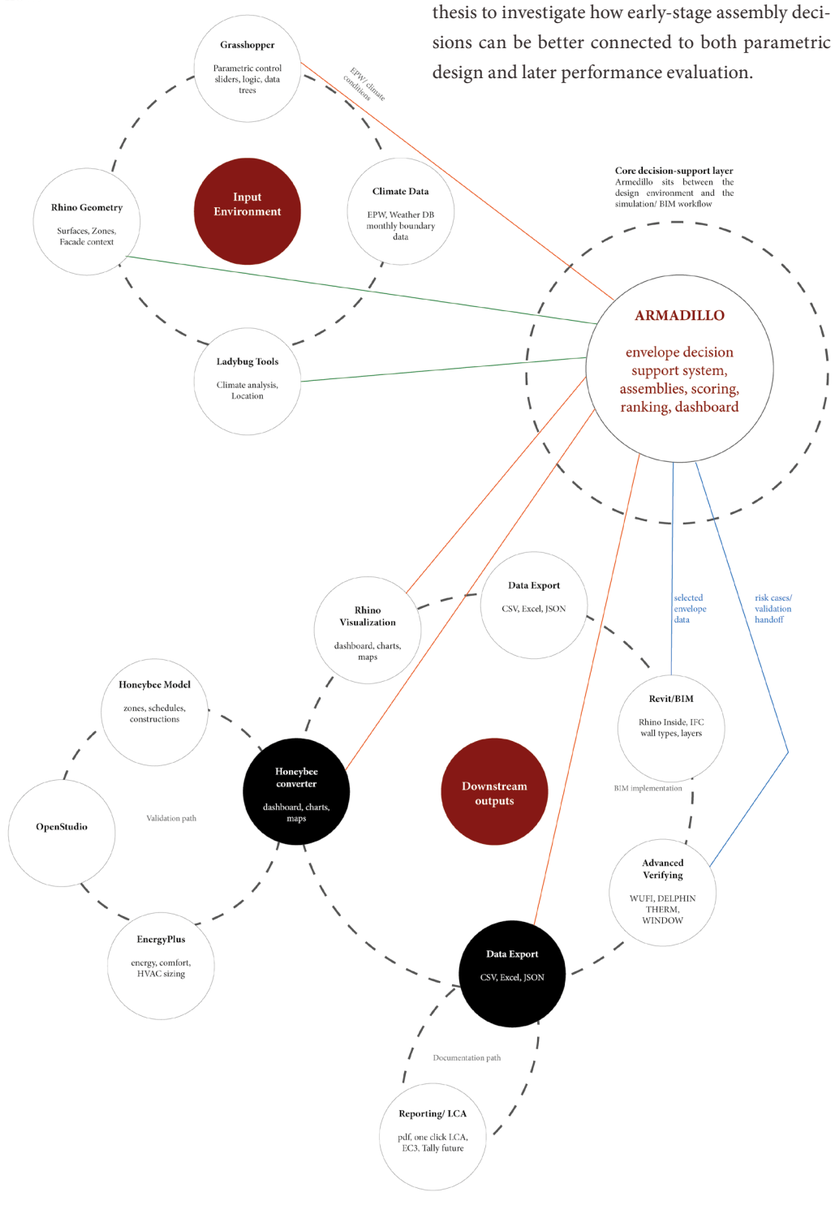


Fig 5.03 *Interoperability diagram of Armadillo within the Grasshopper ecosystem*

Methodology: Current Implementation and Workflow

The implementation of Armadillo is organised around workflow stages rather than a single isolated calculation component. The tool begins with project and climate inputs, then moves through material definition, layer construction, assembly creation, performance calculation, decision support, visualisation, and export. This structure reflects the sequence of early-stage envelope decision-making: the user first defines the design context, then constructs candidate assemblies, evaluates their performance, compares alternatives, and decides which options should be carried forward for further simulation or technical development.

At implementation level, the prototype is organised into functional component groups. These groups correspond to the main operations required for envelope assessment and comparison. Rather than listing every individual component in the main text, the chapter presents the architecture by workflow group, because this better explains how the tool operates as a design-support process.

The core data model is built on three principal objects that enforce a strict authoring sequence: materials first, then layers, then assemblies.

Tab 5.01 *Functional organisation of the Armadillo implementation.*

Workflow group	Purpose	Typical output
Climate and project inputs	Defines weather data, boundary conditions, project targets, and evaluation settings.	Climate profile, design conditions, performance targets
Material and layer definition	Creates material records and converts them into construction layers with physical and functional properties.	Material objects, layer objects, thermal and vapour properties
Assembly creation	Combines ordered layers into complete opaque wall assemblies.	Wall assembly object, total thickness, layer sequence
Performance calculation	Evaluates steady-state thermal, dynamic thermal, and moisture-related indicators.	U-value, R-value, decrement factor, time shift, condensation risk
Sustainability and cost screening	Adds preliminary environmental and economic indicators where data are available.	Cost estimate, embodied-carbon estimate
Decision support	Compares alternatives against targets and supports interpretation of trade-offs.	Scores, rankings, warnings, comparative summaries
Visualisation	Communicates assembly composition and performance results graphically.	Radar charts, bar charts, assembly stacks, moisture graphics
Interoperability and export	Transfers data toward reporting, simulation, and external workflows.	CSV/Excel outputs, report figures, Honeybee/HBJSON-oriented data

Fig 5.02 *Typical Armadillo Grasshopper canvas showing the connection between climate input, material and layer creation, wall assembly construction, performance calculation, and comparative decision-support outputs.*

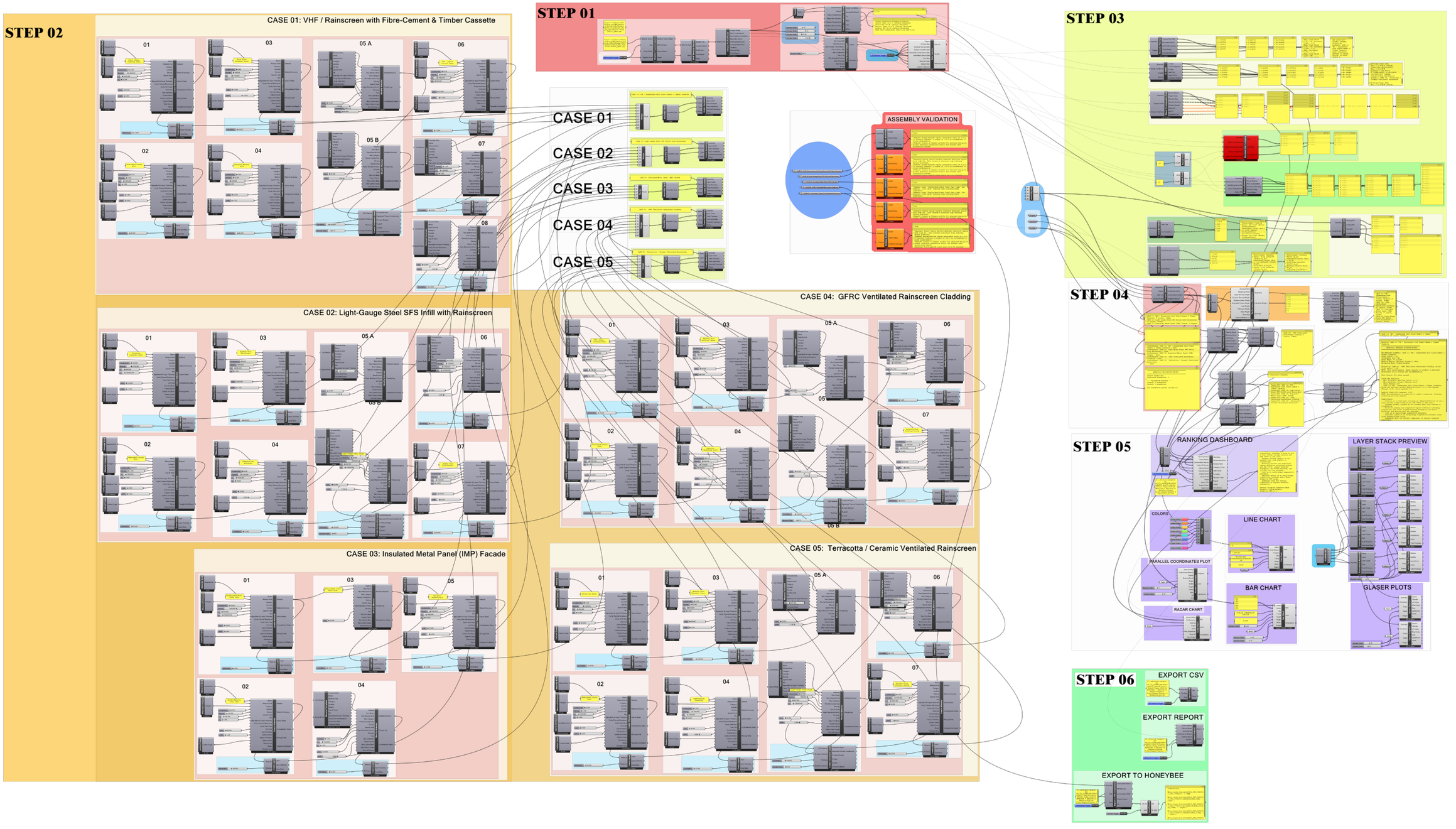
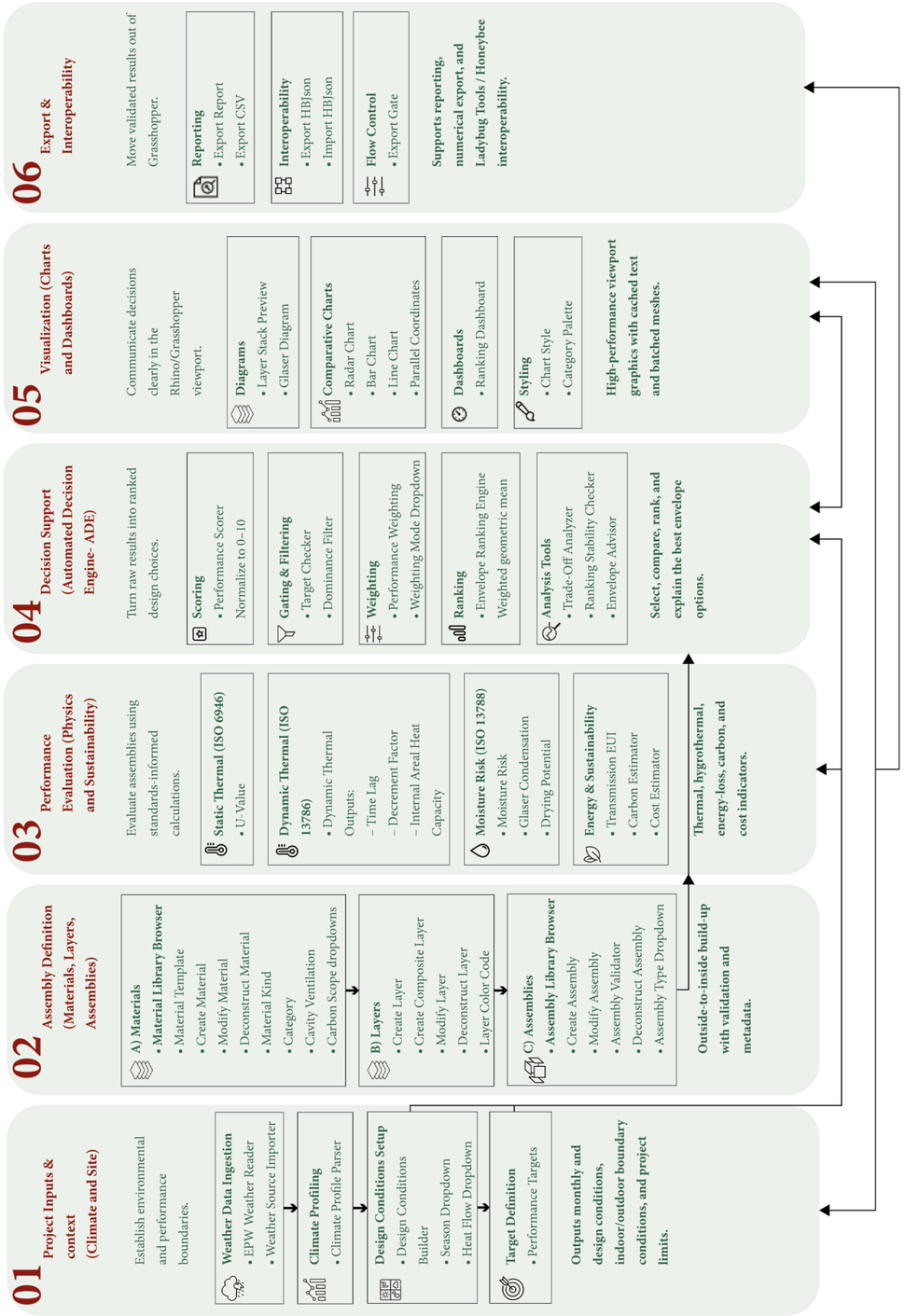


Fig 5.04 *Armadillo workflow structure in Grasshopper showing the progression from project inputs and assembly definition to performance evaluation, decision support, visualisation, and export.*



5.3 Data Model

ArmadilloMaterial stores design thermal conductivity λ [W/(m·K)], mass density ρ [kg/m³], specific heat capacity cp [J/(kg·K)], and water-vapour diffusion resistance factor μ as minimum required physical properties. Each material carries four status flags: data source (library, user-defined, manufacturer, or standard), completeness (all fields populated or partial), method basis (ISO 10456, manufacturer datasheet, or user defined), and limitation (any known constraint on the data). Air cavities are handled as a special material kind with a tabulated thermal resistance Rcav [m²·K/W] rather than a conductivity value.

ArmadilloLayer combines a material with a physical thickness d [m] and a construction function (insulation, structure, cladding, sheathing, membrane, cavity, or finish). Derived properties are computed automatically: thermal resistance R = d/λ [m²·K/W], areal mass ρs = ρ × d [kg/m²], areal heat capacity cs = ρ × cp × d [kJ/(m²·K)], and vapour-diffusion-equivalent air-layer thickness sd = μ × d [m]. A Layer Validator (Component 07) checks physical plausibility: thermal conductivity must be positive, density must be within material-class ranges, and thickness must be non-zero.

ArmadilloAssembly collects an ordered list of layers from outside to inside. This ordering convention is enforced because the ISO 13786 transfer-matrix cascade requires it: reversed layer order produces physically incorrect admittance and heat-capacity values, and the dynamic thermal calculator raises an explicit error if the assembly declares an inside-to-outside direction. The assembly computes aggregate properties: total thickness, total thermal resistance (excluding surface films), total areal mass, and an overall R-value breakdown per layer.

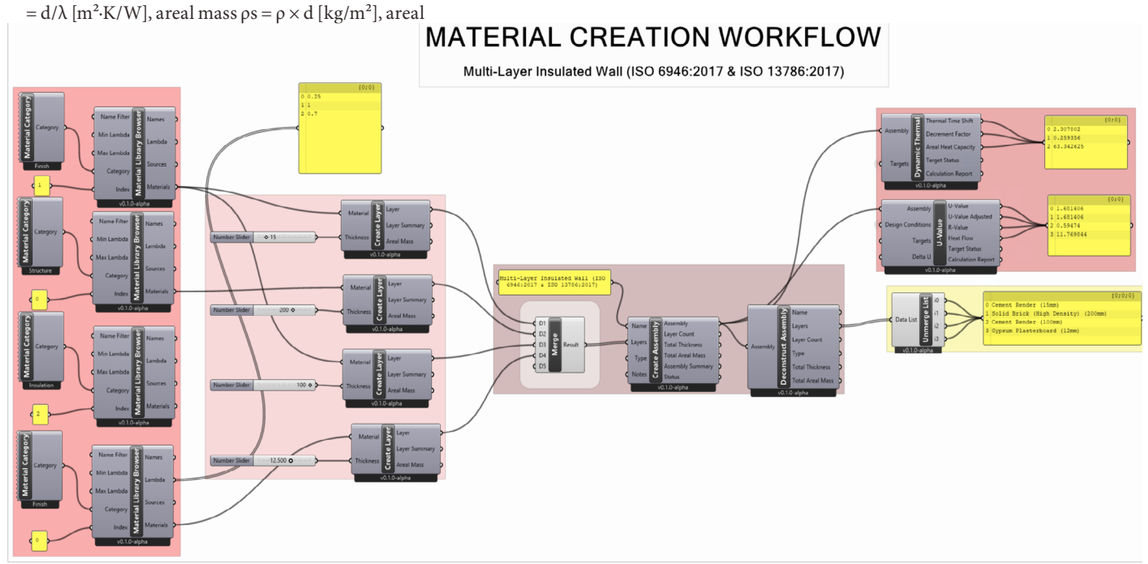


Fig 5.05 *Data model diagram showing the Material, Layer, Assembly hierarchy and derived properties.*

Calculation Engine: Mathematical Basis

Steady-State Thermal Performance (ISO 6946:2017)

The steady-state thermal module computes total thermal resistance R_T and overall thermal transmittance U following ISO 6946:2017. For a plane building component consisting of n thermally homogeneous layers, the total thermal resistance is:

$$R_T = R_{si} + R_1 + R_2 + ... + R_n + R_{se} \quad [m^2 \cdot K/W]$$

where R_{si} and R_{se} are the internal and external surface resistances respectively, and

$R_j = d_j / \lambda_j$ is the thermal resistance of each solid layer.

Surface resistances are resolved automatically from the assembly's declared envelope type per Table 1 of the standard: $R_{si} = 0.13\ m^2 \cdot K/W$ for walls (horizontal heat flow), 0.10 for roofs (upward flow), and 0.17 for floors (downward flow); $R_{se} = 0.04\ m^2 \cdot K/W$ for all external surfaces. Air cavities use tabulated resistance values rather than d/λ. The thermal transmittance is:

$U = 1 / R_T \quad [W/(m^2 \cdot K)]$

An optional thermal-bridge correction ΔU can be applied to produce an adjusted U-value, $U_{adj} = U + \Delta U$. The tool explicitly states in every output report that this is a simplified allowance, not a full ISO 10211 or ISO 14683 thermal bridge calculation. The distinction between clear-wall U-value and adjusted U-value is always maintained.

Dynamic Thermal Performance (ISO 13786:2017)

The dynamic thermal module implements the transfer-matrix (thermal-admittance) procedure of ISO 13786:2017, Sections 6 and 7. This method characterises how a multi-layer wall assembly responds to periodic (typically diurnal) temperature variations on the exterior face. The calculation proceeds as follows.

Each solid layer j is characterised by its periodic penetration depth:

$$\delta_j = \sqrt{(\lambda_j \cdot T / (\pi \cdot \rho_j \cdot c_{p,j}))} \quad [m]$$

where T is the period of thermal variation (default 86 400 s for a 24-hour cycle).

A complex parameter $\xi_j = (\lambda_j / \delta_j)(1 + i)$ is formed, and each layer is reduced to a 2×2 complex transfer matrix:

$$z_j = \begin{bmatrix} \cosh\gamma j & -(1/\xi_j).\sinh(\gamma_j) \\ -\xi_j.\sinh_{\gamma j} & \cosh_{\gamma j} \end{bmatrix}$$

where $\gamma_j = (d_j / \delta_j)(1 + i)$.

Surface films and air cavities enter as resistance-only matrices with zero heat capacity, which is essential because treating a cavity as massive would corrupt the result. The assembly transfer matrix Z is the ordered product of all layer matrices, including surface-film matrices at internal and external boundaries.

From the assembly matrix, four outputs are extracted following Section 7 of the standard:

Periodic thermal transmittance: $Y_{12} = -1 / Z_{12} \quad [W/(m^2 \cdot K)]$

Internal thermal admittance: $Y_{11} = -Z_{11} / Z_{12} \quad [W/(m^2 \cdot K)]$

Where the signs of Y_{11} and Y_{12} depend on how the heat-flow direction is defined

Decrement factor: $f = |Y_{12}| / U$

where lower values indicate stronger damping

Time shift (phase shift): $\Delta t = -(T / 2\pi) \cdot \arg(Y_{12}) \quad [h]$

Internal areal heat capacity: $\kappa = (T / 2\pi) \cdot |Y_{11} - Y_{12}|$ $[J/(m^2 \cdot K)]$, per Equation 8 of ISO 13786:2017

Where the warm-season diurnal amplitude ΔT_{ext} is connected from the EPW importer, the tool estimates the internal surface temperature swing as approximately $f \times \Delta T_{ext}$, delayed by Δt. More accurately $f \times \Delta T_{ext}$ is the equivalent attenuated external temperature amplitude or a proxy for transmitted thermal fluctuation and not the actual internal surface temperature swing.

This is the established early-stage method for estimating free-running internal conditions from component properties[76] (Marletta, Evola, and Giuga (2014).

Moisture Screening (ISO 13788:2012)

The moisture-screening module implements two calculations. The surface humidity screen computes the temperature factor at the internal surface,

$$f_{(R\,si)} = (\theta_{si} - \theta_e) / (\theta_i - \theta_e)$$

where

- θ_{si} is the internal surface temperature,
- θ_e the external temperature, and
- θ_i the internal temperature.

The critical threshold for mould growth is typically $f_{Rsi} \geq 0.72$ for surface relative humidity below 80% (EN ISO 13788, Section 5). Assemblies that fail this criterion are flagged for detailed investigation.

The Glaser condensation screen implements the monthly vapour-diffusion method of ISO 13788, Section 6. It computes temperature and vapour-pressure profiles through the assembly under monthly mean boundary conditions, identifies interfaces where the actual vapour pressure exceeds the saturation vapour pressure (indicating condensation), estimates the condensate mass, and recommends vapour-control layer placement. The saturation vapour pressure is computed using the exponential formula of ISO 13788 Annex B with the constant 610.5 Pa. The tool is explicitly labelled as a simplified screening method: it does not account for liquid moisture transport, capillary redistribution, or hygroscopic storage, and it recommends transient hygrothermal simulation (EN 15026) for any assembly flagged as at-risk.

5.4 Decision-Support Pipeline

The decision-support layer is the interpretive core of Armadillo. It transforms raw performance indicators into ranked, explainable design advice through a four-stage pipeline. Each stage is implemented as an independent Grasshopper component, allowing the user to inspect intermediate results and understand how the final recommendation was produced.

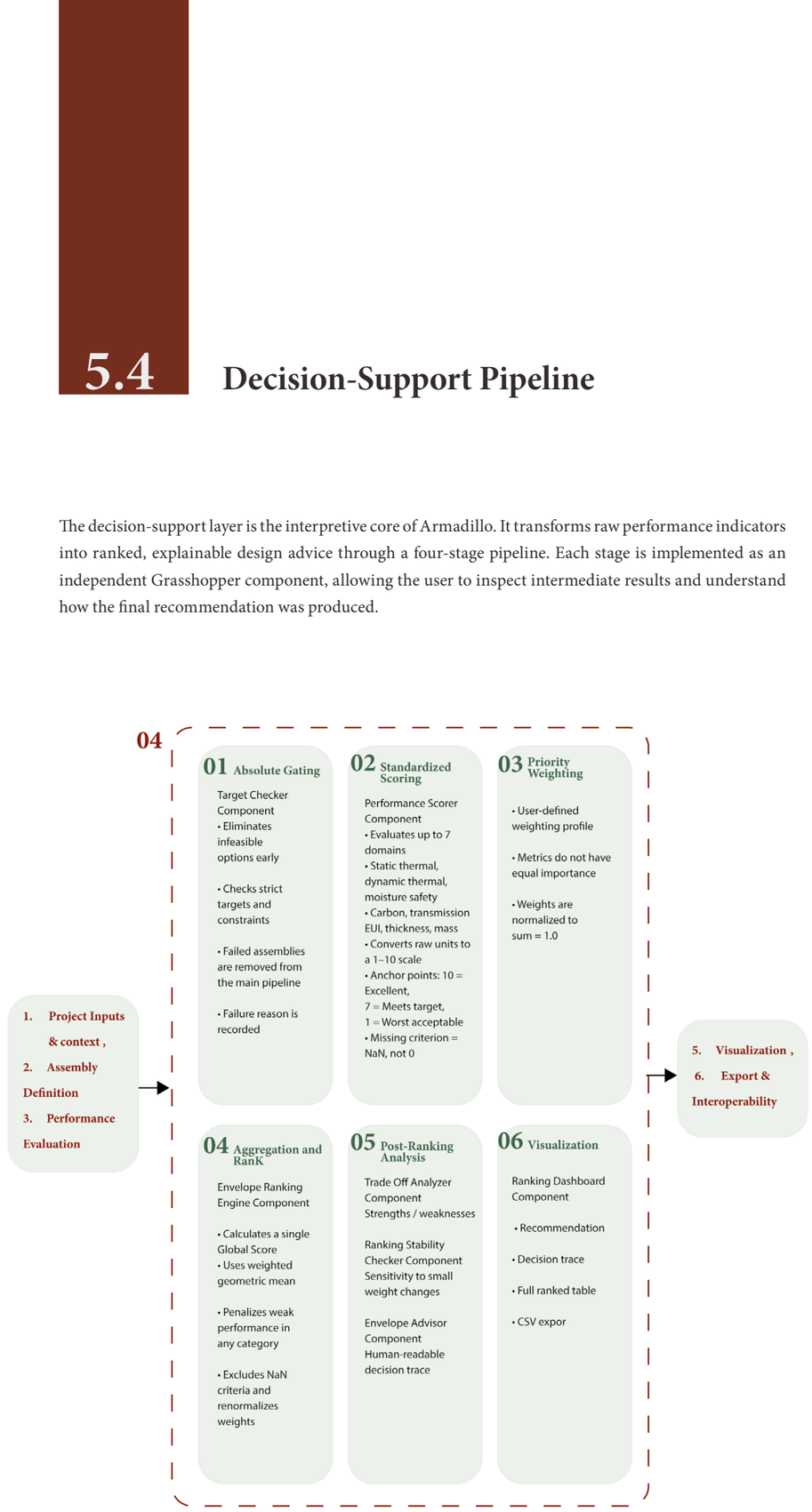


Fig 5.06 Decision-support pipeline

Stage 1: Target Checking and Gating

The Performance Target Checker evaluates each assembly against project-specific performance thresholds. Selected targets can be designated as gates: a failed gate excludes the assembly from the ranking regardless of its score in other categories. This prevents an assembly with, for example, excellent thermal performance but unacceptable condensation risk from appearing as a viable option. The gate mechanism reflects a fundamental engineering principle: certain performance failures cannot be compensated for by strengths elsewhere.

Stage 2: Dominance Filtering

The Dominance Filter removes any assembly from the conforming set that is equalled or beaten by another assembly on every single criterion. The result is a non-dominated shortlist. This step requires no weighting assumptions and is defensible regardless of any subsequent weighting argument. Its theoretical basis lies in multi-objective decision theory[77]: a dominated alternative is objectively inferior and should not be carried forward.

Stage 3: Scoring

The Performance Scorer (Component 29) maps each raw indicator onto a normalised 1-to-10 scale using a value function with two physically meaningful, documented anchor points. The anchor at 1 represents a minimally acceptable performance level; the anchor at 10 represents best practice. A score of 0 is reserved exclusively for gate failures, ensuring that a gated-out assembly cannot receive a positive score. This anchored normalisation avoids the instability of min-max rescaling (where the scale shifts whenever an assembly is added or removed) and makes scores comparable across different projects.

Six category scores are produced: static thermal performance (from U-value and R-value), dynamic thermal behaviour (from decrement factor, time shift, areal heat capacity, and periodic thermal transmittance), moisture safety (from surface humidity, Glaser condensation, and drying potential), cost performance, embodied carbon performance, and climate suitability (which cross-references the assembly's dynamic properties against the climate profile's design-day amplitude).

Stage 4: Ranking and Interpretation

The Envelope Ranking Engine (Component 30) computes a weighted aggregation of category scores and ranks the shortlist. The aggregation uses a weighted geometric mean:

$$s = \pi\left(s_k^{w_k}\right) \quad \text{where} \quad \sum w_k = 1$$

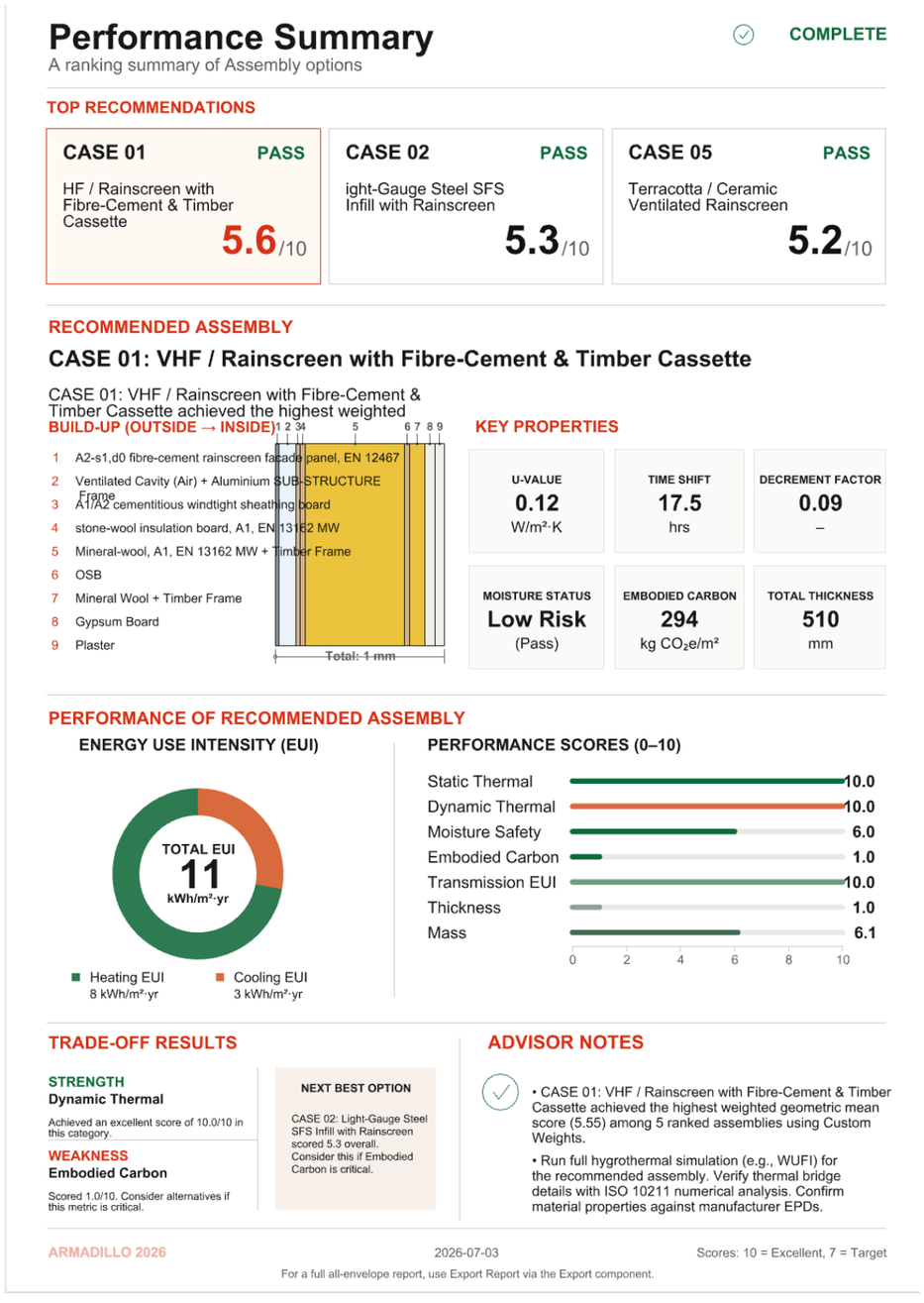
where:

- S_k is the category score and
- W_k is the normalised weight for category k.

The geometric mean was selected over the arithmetic mean because it penalises severe weakness in any single category more heavily. An assembly with scores of (9, 8, 9, 9, 1, 9) receives a substantially lower overall score under the geometric mean than under the arithmetic mean, reflecting the engineering reality that a wall with excellent thermal performance but uncontrolled condensation risk (score = 1) is not a viable envelope. Weighting is set to user-editable, with three preset modes (default set, climate based, and custom) and automatic normalisation to 100 percent.

The Trade-Off Analyser in the figure below identifies the strongest and weakest performance category for each assembly and flags cases where a high overall score conceals a significant weakness. The Envelope Advisor generates explainable design advice in plain language, connecting the ranking result, the trade-off analysis, and the target-check status into a structured recommendation. A Ranking Stability Checker tests whether the top-ranked assembly changes under plausible weight variations, providing a measure of decision robustness.

Fig 5.07 Ranking dashboard output with radar chart comparison, category scores, and the Envelope Adviser recommendation for the LionCity II case study.



End-to-End Workflow

Tab 5.02 Armadillo six-stage workflow.

Stage	Components	Produces	Consumed by
1	EPW Importer, Climate Profile, Climate Zone Defaults	Climate object, design days, diurnal amplitude	Design Conditions, Targets, Weighting, Dynamic
2	Design Conditions, Performance Targets, Weighting	Boundary conditions, targets with gates, weights	Physics, Decision Support
3	Create Material / Library, Create Layer, Create Assembly	One or more assemblies	Physics
4	U-Value, Dynamic Thermal, Surface Humidity, Glaser, Drying, Cost, Carbon	Seven indicator results	Performance Summary
5	Summary, Target Checker, Dominance Filter, Scorer, Ranking, Trade-Off, Adviser	Conformance, shortlist, scores, ranking, recommendation	Visualisation, Export
6	Radar, Bar, Timeline, Stack, Moisture, Carbon-Cost, Dashboard, HB Bridge, Report	Report-ready visuals and exports	The design team and Honeybee

The workflow is deliberately linear, and any subset of it is a valid Grasshopper graph. The minimal viable path requires only Stage 3 (create an assembly) and one physics component (for example, U-Value) to produce a useful result. The full six-stage path produces a complete, exportable decision report. Full list of components attached in Appendix 01.

5.5 Standards, Calculation , Verification

The verification framework distinguishes three claims following the terminology of Roache (1998) verification (does the tool solve the intended equations, tested against known answers), validation (does the model represent reality, tested against a higher-fidelity reference), and demonstration (applying the tool to a real case). Armadillo claims verification against the governing ISO standards and demonstration through the LionCity II case study. It does not claim empirical validation, and this boundary is stated in every output report.

Tier 1: Analytical Verification

Each physics component was tested against hand-calculated reference cases derived from the governing standard. The test suite comprises 47 NUnit tests organised into three groups (thermal, moisture, material) covering ISO 6946 U-value calculations, ISO 6946 inhomogeneous-layer calculations, ISO 13786 dynamic thermal properties, ISO 13788 surface humidity screening, ISO 13788 Glaser condensation screening, psychrometric functions, and material/layer property derivations.

Tab 5.03 Tier 1 verification results: ISO 6946 steady-state thermal calculations.

Fixture	Assembly	Quantity	Hand-calc	Armadillo	Deviation	Status
01	200 mm solid brick (λ=0.77)	RT [m²K/W]	0.4297	0.4297	0.000	PASS
		U [W/m²K]	2.327	2.327	0.000	PASS
02	Multi-layer: render+brick+-MW+PB	RT [m²K/W]	2.9947	2.9947	0.000	PASS
		U [W/m²K]	0.3339	0.3339	0.000	PASS
03	Cavity wall: brick+air+-MW+PB	RT [m²K/W]	2.5299	2.5299	0.000	PASS
		U [W/m²K]	0.3953	0.3953	0.000	PASS
04	Adjusted U-value (ΔU=0.05)	U_adj [W/m²K]	U+0.05	U+0.05	0.000	PASS
05	Surface resistance auto-resolve	Rsi [m²K/W]	0.13/0.10/0.17	0.13/0.10/0.17	0.000	PASS

Tab 5.04 Tier 1 verification results: ISO 13786 dynamic thermal and ISO 6946 §6.7 inhomogeneous layer.

Fixture	Assembly	Test	Criterion	Result	Status
06	200 mm solid brick (λ=0.77)	Decrement factor bounds	f ∈[0, 1]	0.199	PASS
		Time lag bounds	Δt ∈[0, 24] h	9.05 h	PASS
		Areal heat capacity positive	κ > 0	65.5 kJ/m²K	PASS
		Heavy masonry time lag physical	Δt > 6 h	9.05 h	PASS
		Insulated wall decrement physical	f < 0.5	0.199	PASS
		Layer direction guard	Error if reversed	Exception	PASS
07	Multi-layer: render+brick+-MW+PB	Inhomoge-neous layer identity	R_upper = R_lower	±0.001	PASS
		Equivalent lambda in range	λ_min < λ_eq < λ_max	In range	PASS
		ISO 6946 accuracy ratio	≤ 1.5	Met	PASS

The ISO 6946 U-value calculations produce exact agreement with hand-calculated reference values across all test fixtures, confirming that the implementation correctly solves the intended steady-state equations. The ISO 13786 dynamic thermal verification uses physically motivated bounds and plausibility criteria. The bounds-based approach is appropriate because ISO 13786 does not publish a single canonical worked example with all four output quantities (κ, Y12, f, Δt) at the precision needed for automated regression testing. The tests confirm that the transfer-matrix algebra is assembled correctly, that massless layers are handled as resistance-only matrices, and that physically unreasonable inputs are rejected.

5.6 Case-Study and Results

Armadillo was applied to the five candidate external wall assemblies developed in Chapter 3 for the Cité du Cirque and evaluated through the Honeybee energy simulation reported in Chapter 4. This section presents the Armadillo results, verifies them against an independent calculation, and discusses the implications for envelope selection.

Assemblies Evaluated

Five external wall technologies were compared, each developed as a complete facade build-up from exterior finish to internal lining. Case 01 is a prefabricated timber cassette system with a ventilated fibre-cement rainscreen, representing a modern method of construction (MMC) baseline. Case 02 is a non-combustible steel-framed system (SFS) with a ventilated terracotta rainscreen, offering fire-safety advantages. Case 03 is a mineral-wool-core insulated metal sandwich panel, representing a rapid-installation industrialised system. Cases 04 and 05 are GFRC and terracotta ventilated rainscreen facades with SFS backup walls, offering enhanced thermal mass. The assemblies span a range of construction approaches, thermal mass levels, fire-safety strategies, and material philosophies relevant to the project's zero-carbon performance brief.

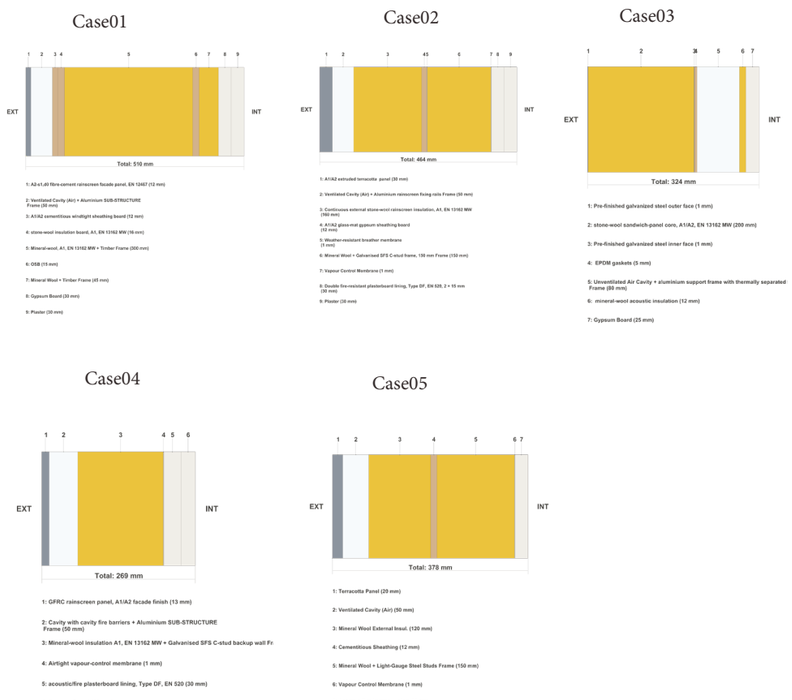


Fig 5.08 *Comparative assembly sections for the five candidate wall technologies, showing layer order, thicknesses. (from Armadillo*

Armadillo Results

Assembly	U [W/m²K]	RT [m²K/W]	f	Δt [h]	Y_{12}	ρ_s [kg/m²]	EUI [kWh/m².year]
Case 01: Timber Cassette	0.16	11.69	0.20	14.0	0.02	101	11.07
Case 02: SFS Rainscreen	0.184	9.17	0.13	13.4	0.01	236	12.698
Case 03: Sandwich Panel	0.229	6.62	0.03	10.7	0.00	688	15.846
Case 04: GFRC Rainscreen	0.139	9.80	0.09	15.8	0.01	254	9.666
Case 05: Terracotta	0.175	9.80	0.09	15.8	0.01	254	12.106

Tab 5.05 *Armadillo performance indicators for the five LionCity II candidate wall assemblies. EUI values from Honeybee simulation (Chapter 4).*

Independent Verification

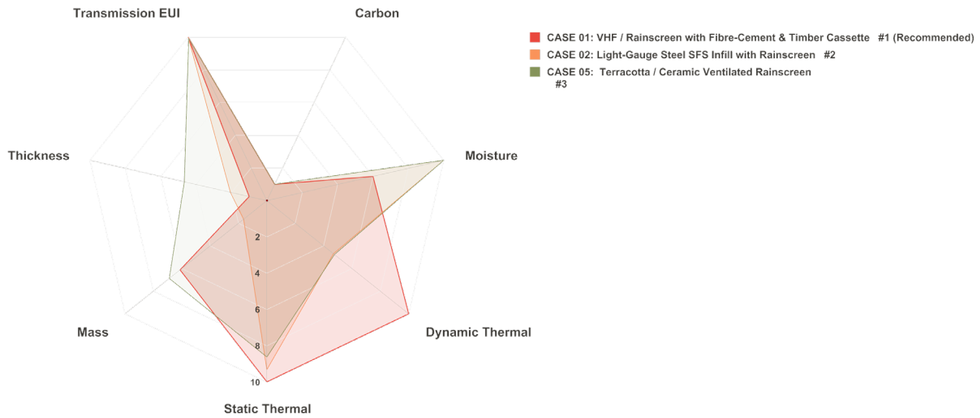
The Armadillo outputs were independently verified by replicating the ISO 6946 and ISO 13786 calculation procedures in a separate Python implementation. The independent code reproduced the exact algorithms from the Armadillo C# source (UValueCalculator.cs and DynamicThermalCalculator.cs), using the same material properties and layer ordering. Code is attached in Appendix 02

U-values agree within 0.1 to 1.7 percent across all five assemblies, well within the ±2 percent acceptance tolerance. Dynamic thermal properties for Cases 02 through 05 match within the resolution of the reported results. The larger deviation in Case 01's decrement factor (0.20 vs 0.24) is attributable to differences in how the ventilated-cavity and fixing-system layers are treated in the transfer matrix: an open ventilated rainscreen cavity can be either included as a resistance layer or excluded per the ISO 6946 ventilated-facade guidance, and the two treatments produce different dynamic results while converging on the same steady-state U-value. This sensitivity to cavity treatment is itself a finding relevant to future tool development.

Assembly	U_{arm}	U_{exe}	ΔU%	f_{arm}	f_{exe}	Δf	Δt agreement
Case 01: Timber Cassette	0.16	0.157	0.1%	0.20	0.24	0.09%	Within 2h
Case 02: SFS Rainscreen	0.184	0.19	0.9%	0.13	0.13	0.00%	Exact
Case 03: Sandwich Panel	0.229	0.229	0.7%	0.03	0.03	0.00%	Exact
Case 04: GFRC Rainscreen	0.139	0.1374	1.7%	0.09	0.09	0.00%	±0.01h
Case 05: Terracotta	0.175	0.173	1.7%	0.09	0.09	0.00%	±0.01h

Tab 5.06 *Independent verification of Armadillo outputs against Python calculation.*

Fig 5.09 *Radar chart comparison of five assemblies across static thermal, dynamic thermal, and EUI performance.*



Discussion

Case 01 achieved both the lowest U-value (0.086 W/m²K) and the lowest simulated annual energy use intensity (EUI = 535.31 kWh/m²). This performance is mainly driven by its deep insulation strategy, with 360 mm of mineral wool distributed across three layers, and by its compatibility with a fabric-first prefabricated construction approach. Case 02 performed almost identically in energy terms (535.73 kWh/m²), while offering fully non-combustible construction. This makes it a strong alternative where fire-safety obligations under the Brussels regulatory framework are prioritised.

Cases 04 and 05 achieved the strongest dynamic thermal performance, with a time shift of 15.8 hours and a decrement factor of 0.09. These values indicate improved attenuation and delay of diurnal temperature swings. However, this dynamic advantage did not translate into lower annual energy consumption under the Brussels temperate oceanic climate. This supports the observation developed in Chapter 1.2 that high thermal mass can offer diminishing returns in heating-dominated climates when steady-state insulation remains the dominant factor.

Case 03 demonstrated the weakest overall energy performance despite having the highest surface mass (688 kg/m²). Its higher U-value (0.151 W/m²K) and shallower insulation depth resulted in the highest EUI among the five cases. This shows that surface mass alone is not a reliable proxy for envelope quality when thermal resistance is insufficient. The result reinforces the need for a multi-criteria assessment approach: if the assemblies were assessed only through dynamic indicators, Case 03 could appear favourable because of its very low decrement factor (0.03). Under the integrated assessment, however, it is clearly the weakest option.

These findings highlight the importance of a multi-criteria approach to envelope assessment. U-value, dynamic response, surface mass, and EUI each describe different aspects of performance, and no single metric provides a complete evaluation. Armadillo's role is to bring these indicators together early in the design process, enabling informed comparison before decisions are fixed. The alignment between its outputs and the Honeybee simulation supports its use as a reliable intermediate tool, guiding schematic-stage decisions without replacing detailed modelling.

Based on the verified calculation results, Case 01 was selected as the envelope technology baseline for the initial whole-building performance simulation reported in Chapter 4. The alignment between Armadillo's early-stage assessment and the subsequent Honeybee simulation supports the central thesis argument: structured, standards-based calculation at the schematic design stage can provide reliable guidance for envelope selection before a full simulation workflow is fully developed.

Limitations of the Current Prototype

The limitations of the current prototype are categorized primarily by interoperability challenges, workflow constraints, and physical scope limitations.

Interoperability and Data Exchange Limitations. The current workflow demonstrates a clear path from early-stage Armadillo assessment to detailed whole-building simulation (e.g., Honeybee/EnergyPlus), but the data exchange remains imperfect. Transferring assembly intelligence relies on translating Armadillo structures into Honeybee-compatible JSON formats (HBJson). This translation process can occasionally result in metadata loss, particularly when mapping bespoke material properties or complex dynamic thermal behaviors between Armadillo's ISO-based calculation logic and EnergyPlus's underlying ASHRAE-based algorithms. Ensuring absolute parity between the two environments currently requires careful user oversight.

Workflow Integration Constraints. While Armadillo successfully bridges the early-design gap within the Grasshopper environment, it currently operates largely as a unidirectional pipeline. There is no automated bidirectional feedback loop to pull full building simulation results back into the Armadillo dashboard for direct comparative analysis. Furthermore, integration with broader Building Information Modelling (BIM) workflows via Industry Foundation Classes (IFC) or gbXML is not yet fully realized. Consequently, if an assembly is heavily modified downstream in Revit or other BIM authoring tools, the Armadillo analysis must be manually updated, presenting a risk of data divergence.

Physics and Scope Limitations. The current calculation engine evaluates only opaque envelope assemblies. Transparent elements, glazing performance, and detailed 2D/3D thermal bridges at assembly junctions are excluded from the Minimum Viable Product (MVP), requiring manual intervention in later simulation stages. Additionally, while the dynamic and steady-state thermal calculations have been strictly verified via independent hand calculations, the Glaser condensation screen remains a steady-state, vapor-diffusion-only method. It does not account for liquid moisture transport, capillary redistribution, or hygroscopic storage, meaning it may produce non-conservative results for certain vapor-open assemblies, it should also be established that the scope of the tool overall is focused on early stage design, capping the calculation engines to this particular stage.

Verification and Validation Limitations. Following Roache's (1998) terminology, the testing framework distinguishes between verification (solving the intended equations correctly), validation (representing physical reality accurately against higher-fidelity references), and demonstration (applying the tool to a real-world case). While the tool has achieved robust verification (via independent Excel hand calculations) and successful demonstration (through the LionCity II case study), full validation remains incomplete. Specifically, the steady-state Glaser condensation screen has not yet been comparatively validated against a higher-fidelity transient hygrothermal reference model, such as WUFI (EN 15026). As a result, while the tool accurately computes the Glaser algorithm, the algorithm's ability to represent complex transient moisture realities in highly insulated or vapor-open assemblies remains unvalidated within this prototype.

5.7 Future Development

The development of Armadillo within this thesis establishes a foundation for research and development across six connected trajectories, expanding from core validation to advanced computational assistance.

Seamless Interoperability and BIM Integration

Addressing the workflow integration constraints identified in Section 5.8, a primary development trajectory involves tightening the interoperability of parametric design workflows. Future iterations will target lossless, bidirectional data exchange between Armadillo and detailed simulation engines (e.g., Honeybee), allowing late-stage energy simulation results to feed back directly into the Grasshopper environment for side-by-side verification. Furthermore, extending export capabilities to support open BIM standards (IFC and gbXML) will ensure that the envelope intelligence generated during schematic design persists seamlessly into construction documentation, lifecycle analysis, and downstream authoring tools.

Strengthening the Validation Framework

Following Roache's (1998) framework, while the calculation engine has achieved verification, full validation against transient realities remains a priority. The immediate next step is to complete the comparative validation of the steady-state Glaser condensation screen against a transient hygrothermal model compliant with EN 15026 (such as WUFI). This requires running a representative LionCity II wall or the ISO standard cases through both Armadillo and the transient model under identical boundary conditions to produce a divergence map, illustrating exactly where the simplified Glaser method diverges from complex transient realities. Further validation will be extended to the entirety of the calculation Engine as well.

Extending the Physics and Assessment Scope

Technical extensions planned for future versions include: evaluating transparent envelope components (glazing thermal and optical properties, solar heat gain coefficients, and daylight transmittance); incorporating simplified linear thermal transmittance (ψ-values) for thermal bridge assessments per ISO 14683; and implementing a clearer biogenic versus fossil carbon split within the embodied-carbon module following the methodological framework of Hoxha et al. (2020)[78], which will facilitate tighter integration with regulatory lifecycle tools such as TOTEM.

Advanced Decision-Support Methods

While the current ranking engine mitigates subjectivity natively via climate-suggested weightings, future development must address the uncertainty introduced by custom user overrides. Implementing the Analytic Hierarchy Process (AHP) as a structured pairwise-comparison weighting method (Saaty 1980)[79] could better guide user modifications. More critically, integrating Stochastic Multi-objective Acceptability Analysis (SMAA), as proposed by Lahdelma, Hokkanen, and Salminen (1998)[80], would enable automated robustness testing of the ranking under weight uncertainty. This would produce acceptability indices indicating how stable a ranking result is across all plausible weighting scenarios, transforming the system from a reactive evaluator to a robustness-testing engine.

Artificial Intelligence and Agent-Based Extensions

Although Armadillo currently relies on deterministic calculations and rule-based logic, its structure allows for future integration of AI and agent-based systems. From the outset, the goal has been not only to compute envelope performance but to support designers in interpreting results based on project priorities. AI could enhance this by filtering options according to specific goals such as energy efficiency, cost, durability, or design intent.

An AI-assisted Envelope Advisor could act as an intent-aware agent, identifying the most relevant assemblies based on project priorities and explaining key trade-offs. Instead of simply ranking options, it would guide designers toward informed decisions and highlight which solutions merit further analysis.

The existing rule-based advisor could evolve into an intelligent agent powered by a Large Language Model (LLM), capable of recognising complex interactions between materials, climate, and performance. For example, it could detect condensation risks and suggest targeted design adjustments rather than issuing generic warnings.

Similarly, an AI-powered Climate Profiler could translate EPW climate data into clear design implications, helping users understand whether to prioritise insulation, solar control, moisture management, or thermal mass.

Finally, machine-learning surrogate models could enable rapid exploration of large sets of envelope variations, supporting faster iteration in early design stages or set up the material for faster setting up of materials before calculations are done (the most time consuming section).

Despite these possibilities, AI in its implementation in Armadillo should remain a support tool. Recommendations must stay transparent and grounded in verified calculations, ensuring that designers retain control while benefiting from clearer insights and structured guidance.

Broader Research and Academic Applications

Beyond its immediate role in this thesis, Armadillo opens research questions regarding how performance reasoning is embedded into practice. Potential applications include:

- parametric envelope optimization studies coupling Armadillo with multi-objective engines (such as Wallacei or Octopus);
- comparative early-stage envelope assessments across diverse climate zones and building typologies;
- field studies comparing Armadillo-guided decisions with conventional practice and academic deployment in architectural design studios,
- introducing students to standards-based envelope reasoning within a familiar parametric environment.

5.8 Conclusion

This chapter has reported on the development, verification, and application of Armadillo as the principal methodological instrument of the thesis. The tool was conceived as a direct response to the four workflow gaps identified in Chapter 1.2: the timing gap between consequential decisions and available feedback, the integration gap across fragmented assessment domains, the decision-support gap between output generation and informed selection, and the envelope-assembly gap in existing parametric workflows.

The calculation engine implements ISO 6946 for steady-state thermal performance, ISO 13786 for dynamic thermal behavior via the transfer-matrix method, and ISO 13788 for surface humidity and Glaser condensation screening. Verification against independent Microsoft Excel hand calculations confirmed strong numerical agreement for both steady-state U-values and dynamic thermal properties, ensuring the computational fidelity of the physics modules. The decision-support pipeline then transforms these raw indicators into ranked, explainable design advice through a documented sequence of gating, dominance filtering, normalized scoring, trade-off analysis, and a weighted geometric mean ranking that is natively anchored by data-driven, climate-suggested weightings.

Applied to the five candidate wall assemblies for the LionCity II Cité du Cirque, the tool identified Case 01 (prefabricated timber cassette) as the highest-performing baseline. This selection was subsequently confirmed by the Honeybee energy simulation in Chapter 4, demonstrating strong convergence between the early-stage Armadillo assessment and the later detailed simulation. This convergence forms the core evidence for the thesis argument: structured, standards-informed early-stage calculation can reliably guide envelope decisions well before the full simulation infrastructure is deployed, directly reducing the repetitive back-and-forth revision cycles identified as a persistent inefficiency in current design practice.

The limitations of the current prototype define the immediate scope of future work, centering primarily on workflow interoperability constraints, the restriction to opaque assemblies, and the absence of a completed comparative validation of the steady-state moisture screen against a transient hygrothermal model (e.g., WUFI). Consequently, future development trajectories heavily emphasize establishing lossless, bidirectional data exchange with detailed simulation engines and open BIM standards (IFC/gbXML). Alongside these necessary technical extensions, future research will target advanced robustness testing (SMAA) and AI-driven extensions including an LLM-powered intelligent envelope advisor and narrative climate profiler. These developments aim to ultimately transform Armadillo from a reactive evaluation instrument into a proactive, highly interoperable design assistant, all while strictly preserving the transparency and computational traceability that define its intellectual identity.

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06

Synthesis

Chapter 6 synthesises the architectural, environmental, and computational outcomes of the thesis. It discusses how the LionCity II case study exposed the limitations of traditional envelope-selection workflows and how Armadillo responds to this gap by providing earlier, clearer, and more structured decision support. The chapter concludes by reflecting on the thesis contributions, practical implications, research limitations, and future development of Armadillo as a tool positioned between design intuition and detailed simulation.

6.1 Results & Discussion

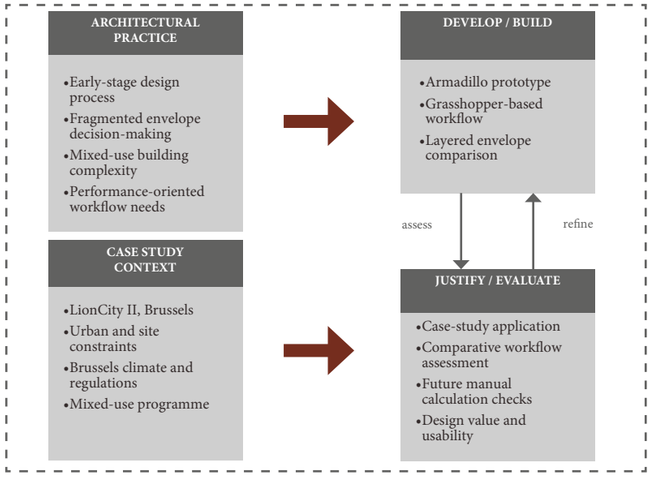


Fig 6.01 *traditional envelope testing, Armadillo evaluation*

Chapter 6 synthesizes the architectural, environmental, and computational aspects of the thesis. It addresses a key issue: envelope decisions are made early, while reliable performance feedback typically comes later, creating a gap in the design process.

The LionCity II case study explores this gap through a real project in Molenbeek-Saint-Jean, Brussels. The transformation of an industrial site into a mixed-use, climate-responsive block highlighted the importance of the envelope as a system linking climate, materials, comfort, and performance.The traditional workflow revealed that envelope selection is fragmented and time-consuming, requiring multiple tools and iterations to understand performance impacts. Armadillo was developed to address this issue. It supports early-stage envelope decisions by providing structured, comparative feedback before detailed simulation. It does not replace simulation but helps guide it.

This chapter evaluates both the LionCity II outcomes and the alignment **between conventional methods and Armadillo**, assessing the tool's relevance as an early-stage decision-support system.

Key Design Outcomes

The architectural outcome of LionCity II transforms an inward-facing industrial parcel into a porous, mixed-use, and environmentally responsive urban block. Guided by Interface and Diversity, the project repositions the former Delhaize enclosure as a connective threshold within the broader Molenbeek-Saint-Jean context. The masterplan reinforces the Beekkant axis as the main civic and soft-mobility spine, prioritizing walking, cycling, and public transport while limiting vehicular access. The public realm becomes a primary organising system rather than a secondary addition.



Fig 6.02 *Key Design Outcomes: Lion city II*

workflow. This convergence suggests that the tool can provide a reliable early-stage direction, even if it is not intended for final compliance verification.

Armadillo's value lies in its decision-support logic. It filters options through performance thresholds, removes weaker alternatives, and ranks the remaining assemblies based on multiple criteria. This avoids reliance on single indicators and highlights trade-offs more clearly. By translating technical data into comparative scores and design guidance, the tool improves interpretability and supports communication among stakeholders.

The comparison also clarifies the role of simulation. Detailed tools remain essential for validation, but they are more effective when applied to a reduced set of well-informed options. Armadillo helps

The second outcome is a continuous green-public network. Instead of residual planting, green space is structured as a connected ecological and social landscape supporting biodiversity, water management, urban cooling, and public use.

The third outcome is the integration of the Cité du Cirque as a civic anchor. Its spaces are organized through clear public-to-private gradients, positioning the complex as an open interface between the neighborhood and its internal functions.

The fourth outcome is a compact and coordinated architectural form. The massing mediates between surrounding heights while improving performance through reduced exposed surface and clearer envelope relationships.

The fifth outcome is the integration of structure, envelopes, and systems. Prefabricated and composite structural elements support efficiency, long spans, and constructability, while façade strategies balance transparency and performance.

Finally, environmental analysis translated the design into measurable results. Case 01 was selected as the baseline envelope, with critical zones identified for optimization. Adjustments to internal gains, schedules, glazing, ventilation, and HVAC systems led to a balanced strategy separating normal and high-load zones.

The final energy scenarios highlight the relationship between demand reduction and renewable production. With a constant PV output of approximately 149,482 kWh/year, optimization reduced demand to around 400,000 kWh/year (66.7 kWh/m²·year). The results confirm the project as a high-performance mixed-use cultural and educational building.

Integration of Tool and Case Study Discussion

The central finding is that LionCity II and Armadillo are closely linked: the case study exposed the complexity of envelope selection, and the tool was developed to address it. Envelope design is a multi-criteria decision involving thermal performance, moisture risk, carbon, cost, and constructability—factors that are difficult to evaluate early using conventional simulation alone.

In LionCity II, five wall assemblies were assessed through standard methods, leading to the selection of Case 01. Armadillo independently reached the same conclusion through its structured pipeline, demonstrating consistency with the traditional

establish this shortlist, allowing simulation to confirm rather than discover solutions. Overall, the tool supports earlier and more structured decision-making. It does not replace professional judgement but strengthens it by making envelope performance more transparent and comparable during the design process.

Limitations of the Research

The limitations of the research define the boundary of the contribution and prevent the findings from being overstated. **The first limitation** is that Armadillo remains a research prototype. Its results are intended as comparative decision-support indicators, not certified compliance results. The tool can guide early-stage envelope selection, but it cannot replace regulatory energy calculation, certified hygrothermal assessment, detailed thermal-bridge modelling, LCA documentation, or professional façade engineering.

The second limitation is the scope of the minimum viable prototype. Armadillo currently focuses on opaque external wall assemblies. This is appropriate for the thesis because the external wall was the primary envelope variable investigated in the LionCity II workflow, but it means the tool does not yet provide a complete envelope assessment. Transparent elements, curtain walls, glazing ratios, solar heat gain coefficients, daylight transmittance, shading geometry, roofs, ground floors, junctions, and thermal bridges require further development. Since many critical performance issues in LionCity II were linked to glazing, shading, and zone exposure, the future inclusion of transparent envelope logic is especially important.

The third limitation concerns moisture assessment. The tool includes surface humidity and Glaser condensation screening, which is useful as an early warning method, but simplified steady-state moisture checks cannot fully represent liquid transport, capillary redistribution, hygroscopic storage, driving rain, or transient boundary conditions. Assemblies flagged as risky require further verification through transient hygrothermal simulation. This limitation is not a failure of the tool; it is a necessary boundary between screening and detailed physics.

The fourth limitation is related to validation. The thesis verifies selected calculations against standards-based reference methods and demonstrates the tool through the LionCity II case study. However, it does not validate Armadillo against measured building performance, post-occupancy data, or a large database of completed projects. The convergence between Armadillo and Honeybee in the selection of Case 01 is promising, but it remains a case-study demonstration rather than universal proof. Future validation should test the tool across different climates, building typologies, wall systems, and design priorities.

The fifth limitation lies in the energy model itself. The LionCity II simulations depend on assumptions about zoning, schedules, internal gains, ventilation, setpoints, ideal air systems, HVAC systems, and PV configuration. These assumptions were refined through the thesis, but they remain design-stage approximations. The project is not an occupied building, and the energy results should therefore be interpreted as comparative design evidence rather than measured performance. This is particularly important for the stages and kitchen, where event-based use, process loads, exhaust requirements, and occupancy variation can strongly affect annual demand.

The sixth limitation is that the research focuses on early-stage decision support, not full project delivery. Structural design, MEP sizing, fire strategy, acoustic performance, façade detailing, cost planning, procurement, construction sequencing, and maintenance are addressed only where they support the thesis argument. A complete professional project would require deeper coordination with specialists. The thesis therefore contributes a decision-making method, not a fully resolved technical package. These limitations do not weaken the thesis. They clarify the scale at which the contribution is valid. The research addresses the stage before detailed verification, where design decisions are still open and where a structured, transparent, and fast comparison method can have the greatest value.

This seventh limitation is the restricted treatment of life cycle assessment within the scope of the thesis. Although LCA tools such as TOTEM are discussed in relation to Brussels regulatory expectations, and the developed tool includes a rudimentary early-stage embodied-carbon check, the thesis does not provide a full LCA methodology or detailed life cycle evaluation. Instead, the implementation prioritises static thermal performance, dynamic thermal behaviour, and simplified transient performance indicators. As a result, the environmental assessment remains preliminary and should be understood as a future extension rather than a fully validated LCA component of the research.

6.2 Conclusion

Synthesis of Research Findings

This thesis set out to investigate how early-stage building-envelope selection can be supported through a digital decision-support workflow without interrupting the pace and openness of architectural design. The research began from the observation that envelope decisions have long-term consequences for energy demand, comfort, durability, moisture safety, cost, and embodied impact, yet they are often made before detailed simulation can be properly used. This mismatch creates a practical design problem: designers must commit to material and assembly choices while the full consequences of those choices remain difficult to compare.

The literature review established that this problem is not caused by the absence of digital tools. Contemporary practice already includes BIM, building performance simulation, parametric environmental analysis, LCA tools, and optimization workflows. The problem is that these tools do not fully converge around the specific task of rapid, interpretable, multi-criteria envelope assembly selection during conceptual and schematic design. The gap is therefore one of timing, integration, interpretation, and decision support.

The LionCity II case study confirmed this gap through design practice. The architectural process required decisions across urban structure, landscape, programme, massing, structure, envelope, daylight, thermal comfort, HVAC systems, and renewable energy. The envelope selection process was essential, but it also became one of the most iterative and fragmented parts of the workflow. Comparing assemblies manually and then verifying them through simulation required significant time, model preparation, and interpretation. This confirmed the need for an intermediate decision-support layer.

Armadillo was developed as that layer. The tool translates standards-informed envelope calculations into a Grasshopper-based workflow that allows designers to create, modify, compare, gate, score, rank, and interpret opaque wall assemblies. Its calculation basis gives the workflow technical grounding, while its visual and parametric structure keeps it accessible to early-stage design practice. The tool therefore responds directly to the research questions. It supports early-stage envelope selection without replacing design judgement; it identifies indicators that can be meaningfully assessed before detailed simulation; and it demonstrates its relevance through the LionCity II case study.

The most important result is the convergence between the conventional LionCity II workflow and Armadillo's recommendation. Both processes identified Case 01, the prefabricated timber cassette rainscreen façade, as the most appropriate baseline among the five candidate wall assemblies. This does not prove that Armadillo can replace simulation, but it shows that the tool can provide a reliable early-stage direction before the complete simulation infrastructure is in place. The thesis therefore supports the argument that performance-informed envelope reasoning can be introduced earlier, with lower computational effort and clearer decision logic.

Contributions to Knowledge

The first contribution of this thesis is methodological. It reframes early-stage envelope selection as a decision-support problem rather than only a simulation problem. This distinction is important. Simulation produces performance data, but designers also need a way to compare, interpret, and prioritise alternatives while the design is still flexible. Armadillo contributes to this methodological gap by structuring envelope comparison through gating, dominance filtering, scoring, ranking, and explanation.

The second contribution is technical. The research develops a standards-informed Grasshopper prototype that links material layers, assembly definition, thermal performance, dynamic thermal behaviour, moisture screening, cost, embodied carbon, and ranking logic within one workflow. The value of this contribution is not only the calculation itself, but the integration of multiple criteria into a design-accessible environment.

The third contribution is applied. The LionCity II case study demonstrates how the tool can be positioned within a real architectural workflow. The project shows that envelope selection cannot be separated from climate, programme, urban form, daylight, internal gains, HVAC strategy, and renewable energy production. By applying Armadillo to the same wall alternatives studied through conventional methods, the thesis shows how early-stage decision support can guide and simplify later simulation.

The fourth contribution is pedagogical and communicative. Armadillo makes envelope performance easier to discuss. By converting technical indicators into visual comparisons, scores, rankings, and design advice, the tool can support communication between architects, engineers, students, clients, and consultants. This is important because many envelope decisions fail not because information is absent, but because the information is difficult to interpret at the right moment.

The fifth contribution is the clarification of a future research path. The thesis identifies how Armadillo can be extended toward transparent envelope assessment, thermal-bridge logic, stronger moisture validation, advanced weighting methods, BIM interoperability, TOTEM or LCA integration, and AI-assisted envelope advising. These extensions do not change the core identity of the tool. They build on the same principle: computation should support judgement rather than replace it.

Practical Implications for Practice

For architects and engineers, the practical value of Armadillo lies in its ability to support early decisions before the design becomes too fixed. In daily practice, envelope selection often begins with precedent, supplier information, rough U-value targets, and fragmented material tables. Armadillo offers a more systematic alternative. A design team can enter candidate materials, adjust layer thicknesses, define assemblies, set project-specific targets, and **compare the consequences immediately.** This allows the envelope to be discussed as a performance system rather than as a catalogue choice.

Engineers can use Armadillo during concept and schematic design to **test whether an assembly is worth carrying forward**. Instead of waiting for a full energy model, they can quickly identify whether a wall build-up has sufficient thermal resistance, whether its dynamic response is appropriate for the climate, whether moisture risk requires attention, whether cost or carbon values are problematic, and whether the assembly passes basic project gates. This does not remove the need for detailed calculation, but it improves the quality of the options that reach detailed calculation.

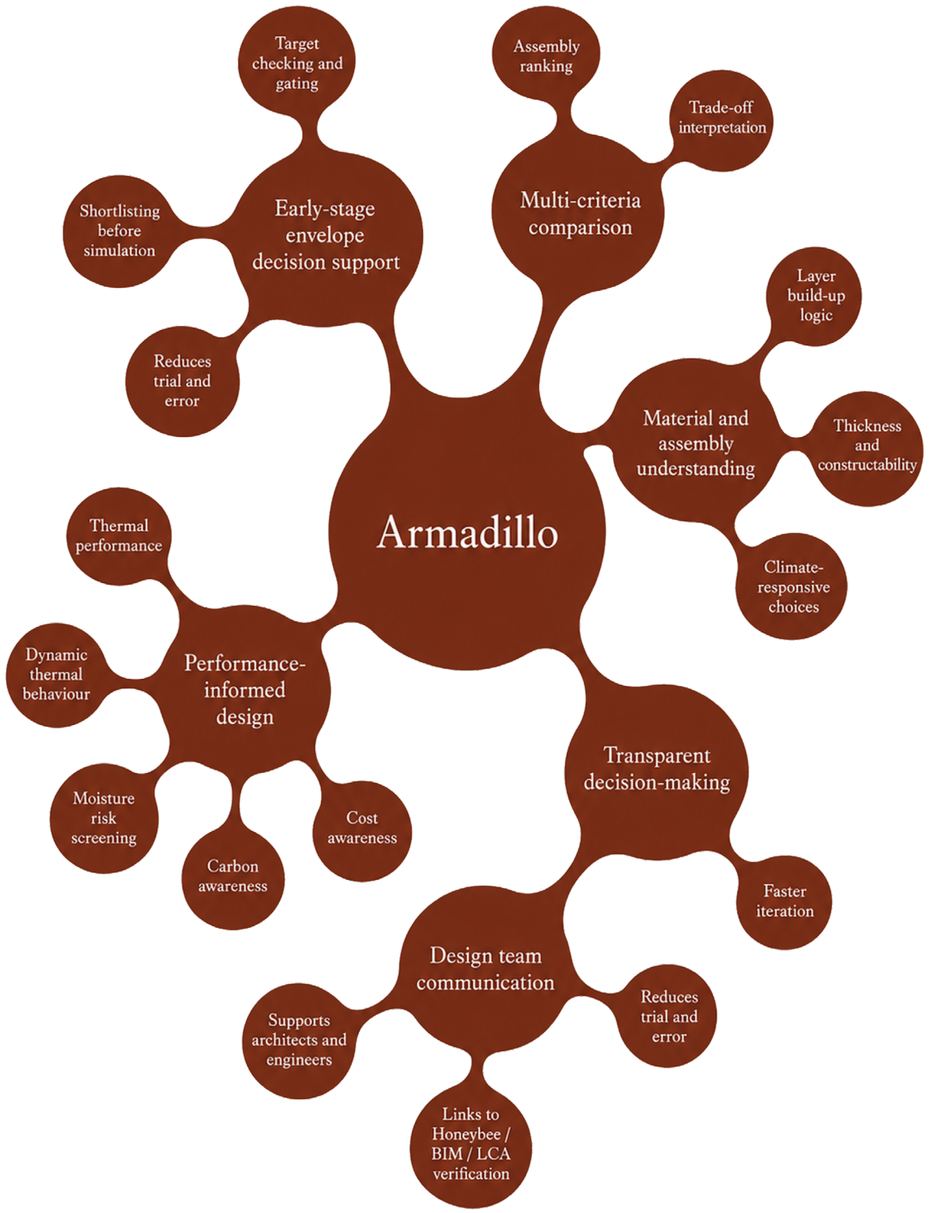
Architects can use the tool to **understand materials more clearly**. The performance of an envelope is often hidden inside technical layers, and early design drawings may show only a façade expression rather than a performance logic. Armadillo helps reveal how each layer contributes to resistance, mass, heat capacity, time shift, moisture behaviour, cost, and carbon. This supports better design conversations, especially when architectural identity, environmental performance, and construction method must be coordinated.

The tool is also useful for **interdisciplinary communication**. In a typical design meeting, different stakeholders may prioritise different criteria: architects may focus on appearance and spatial quality; engineers may focus on performance and risk; contractors may focus on buildability and speed; clients may focus on cost and long-term value. Armadillo provides a shared comparison framework where these criteria can be made visible. Weighting does not remove disagreement, but

it makes the basis of disagreement explicit.

In early-stage high-performance design, this is especially valuable. The aim is not only to find the wall with the lowest U-value, but to identify an envelope strategy that is thermally effective, moisture-conscious, constructible, economically reasonable, and compatible with the wider design. By giving designers multiple perspectives on the same envelope options, **Armadillo supports better judgement before the project enters the slower and more expensive stages of technical development.**

Fig 6.03 Practical Use of Armadillo in Daily Practice



Closing Reflection

The title of this thesis, **Between Design Intuition and Simulations**, defines the intellectual position of the work. Architectural design cannot be reduced to calculation, but it can no longer rely only on intuition when decisions affect energy demand, comfort, carbon, moisture safety, and long-term performance. The challenge is not to replace the designer with computation. The challenge is to give the designer better feedback at the moment when feedback can still change the project.

LionCity II made this challenge visible. The project required the design team to move across urban regeneration, mixed-use programming, landscape strategy, structural logic, envelope selection, daylight analysis, thermal comfort, HVAC assumptions, and renewable energy production. Through this process, the envelope emerged as one of the most important points of connection between architectural intention and environmental performance. It also emerged as one of the areas where early-stage decision support is most needed.

Armadillo is the response proposed by this thesis. It is intentionally limited, but its limitation is part of its value. By focusing on early-stage opaque wall assembly selection, it addresses a precise and recurring decision in architectural practice. It provides enough technical structure to support meaningful comparison, but remains light enough to be used before the design is fully resolved. Its role is not to give a final answer, but to improve the quality of the questions, options, and discussions that lead to a final answer.

The thesis therefore concludes with a clear position: high-performance envelope design depends not only on better materials or more advanced simulations, but on better decision timing. If designers can understand the consequences of envelope choices earlier, they can reduce unnecessary revisions, select more appropriate assemblies, and use detailed simulation as verification rather than correction. Armadillo demonstrates one possible path toward that shift. It turns envelope selection into a more transparent, comparative, and performance-informed process, helping design teams move more confidently between intuition and simulation.

BETWEEN DESIGN INTUITION AND SIMULATIONS



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