Interior-exterior connection in architectural design by adopting computational design strategies: A Comparative Analysis

Yasmine Metwally Mohamed
Architecture Engineering
2000503@eng.asu.edu.eg

Abstract:
This research paper explores the integration of interior and exterior spaces in architectural design using computational design strategies. The integration of indoor and outdoor environments is crucial in contemporary architecture, enhancing user experience and promoting sustainability. Traditional design methods often fail to achieve this integration, leading to the need for innovative approaches. Computational design offers a transformative solution by allowing architects to manipulate complex geometries, optimize spatial relationships, and simulate performance outcomes with precision. The study reviews existing literature on interior-exterior connections, explores various computational design methodologies, and analyzes three exemplary projects that effectively employ computational strategies. The findings demonstrate that computational design not only facilitates innovative architectural solutions but also improves functionality, sustainability, and user satisfaction. The paper concludes with practical recommendations for architects and suggestions for future research to further explore the potential of computational design in achieving seamless interior-exterior connections.

Keywords: *Exterior design, Interior design, Computational design, Architectural, Digital design techniques.*

1. Introduction:

Architects aim to view interior and exterior spaces as one continuous surface, but complex issues make this impossible. Researchers are now focusing on integrating an environment and a building into a single continuum, emphasizing the importance of placing building occupants in a nature-based atmosphere. This enhances aesthetics and promotes a positive psychological link with the landscape.[1][2]

The paper focuses on two aspects: the connection between interior and exterior connection by Appling computational design strategies, and the architectural design process in implementing a building using computational design.[3]

Recent research on the relationship between interior and exterior spaces in buildings emphasizes the importance of these spaces for user experience, perception, and environmental connection. Architects can create dynamic spaces that blur indoor and outdoor boundaries, fostering continuity and harmony. However, the study does not address continuity relations related to interior space function type. Researchers focus on spatial layers, core, structure, and layout, and natural lighting for a healthy environment.[4]

In contemporary architectural practice, the integration of computational design strategies has revolutionized the way architects approach the design process. These strategies, which include parametric design, generative design, algorithmic design, digital fabrication, interactive design, machine learning, artificial intelligence, and Building Information Modeling (BIM), offer innovative solutions to complex design challenges. This chapter aims to compare these main computational design strategies and explain their effects on the critical domain of interior and exterior connection in architecture.[5]

1.1. Background and Rationale:

This research explores computational strategies for integrating interior and exterior spaces in architectural projects, aiming to bridge knowledge gaps and promote understanding among architects, students, and researchers. It emphasizes the importance of wholesomeness and beauty in achieving well-proportioned spaces.[6]

Recent discussions on open office lighting, circadian effects, employee satisfaction, noise management, and interior-exterior spaces have been limited. Research on shaping building connections is limited, and computational strategies are less researched. Optimizing spatial distribution to meet both indoor and outdoor activities has not been the focus of previous discussions. .[4]

It is worth stating that the design, manufacturing and functional process of any structure can be done parametrically, but using analogue methods. What the computer brings is processing power, able to iterate multiple options in a minute that would take a person days to complete. [7]

1.2. Scope and Objectives:

This research explores computational strategies for integrating interior and exterior spaces in architectural design, using a qualitative approach. It aims to identify common reasons and goals for this integration, classify important strategies, compile methods for evaluating and calibrating new linkages, and present a comparative analysis of computational integration strategies in the scientific literature. The goal is to create a unique framework for understanding seamless integration in architectural practice. [8][9]

1.3. Research problem:

This research problem is significant because it addresses a fundamental aspect of architectural design, the relationship between the interior and exterior of a building. A well-designed interior-exterior connection can provide several benefits, including improved natural light and ventilation, reduced energy consumption, enhanced thermal comfort, increased visual and spatial interest, and a stronger connection to nature.

1.4. Problem Question:

Main question: How can computational design strategies be used to enhance the interior-exterior connection in architectural design?

2.Theoretical Framework:

Interior and exterior spaces are integral to architecture, contributing to the aesthetic appeal of both old and new buildings. They are evolving concepts, and understanding and integrating them is crucial for architectural design. Different approaches discuss terminology, concepts, characteristics, relationships, qualities, techniques, and integration. For a critique of inside-outside, see Ching.[10]

This paper explores the importance of seamless integration between interior and exterior spaces in architectural design and emerging built environments. It uses both modified and traditional Finnish residential houses to explain this integration, excluding thermal comfort research that considers visual integration from inside to outside. [11]

2.1. Conceptualizing Interior and Exterior Spaces in Architecture:

Jacques Derrida, a French philosopher, emphasized the distinction between interior and exterior spaces in architecture. Interior design is private, while exterior design is public. Balancing these elements is challenging, as people often overlook boundaries, leading to incorrect designs.

Therefore, defining boundaries between interior and exterior spaces is crucial for successful architectural design. [12]

Architectural design should differentiate between interior and exterior spaces, with interior spaces focusing on daily behaviors and trust, and exterior spaces on sharing, communication, and public welfare. Cross-linked design helps maintain eye contact and visual tolerance, while logical transitions between spaces are essential. [13]

2.2. Importance of Seamless Integration:

Seamless integration is a crucial aspect of architecture, influencing luxury hotels, spas, medical centers, and private homes. It is widely adopted in parametric and computational design for residential homes and specialized rooms. This design strategy aims to create an open, spacious environment, connect users with outdoor experiences, and optimize insulation, lighting, furniture, and vegetation design. [14]

Designers can achieve seamless interior-exterior integration without traditional boundaries, allowing natural transitions between spaces. Schumacher suggests parametric models can lead to discontinuity and unspecified semantic meanings. Research on skylights for prefab housing units shows aesthetic and psychological benefits of extruding prefabricated volumes through the ground. This approach has positive design implications and is explored in computational design of building components. [15]

2. Methodology:

- Literature review: Explore existing theories, concepts, and case studies related to interior-exterior connection and computational design strategies.
- The case study analysis will focus on a building that utilizes computational design strategies to enhance the interior-exterior connection, providing a practical example of how such design can be effectively applied in architectural design.
- Computational analysis tools aid in evaluating design solutions' performance in daylighting, thermal comfort, and energy efficiency, thereby aiding in the identification of optimal interior-exterior connection design solutions.

4. Literature Review:

This study explores the concept of interior-exterior continuity and computational strategies to improve and measure the interaction between interior and exterior spaces at different scales. The research aims to provide an overview of the current state of the art, which often presents abstract representations of interaction scaled between different spaces. The study also explores cost predictive models that estimate urban screen computations based on chosen parameters in architectural environments. The research also focuses on seamless design strategies and visual correspondence between interior and exterior spaces at a building level, as well as human-computer interaction in architectural design using eye tracking techniques. The research aims to propose and measure these computational strategies and gauge their effectiveness.

4.1. Importance of Interior-Exterior Connection:

The relationship between interior and exterior spaces is crucial for movement, accessibility, and environmental connection. Location and form play a role in creating positive relationships. Interior spaces can be located between exterior and open areas, providing visual and environmental effects. There are six domains of relationships between outdoor and indoor spaces: visual, spatial, environmental, thermal, acoustic, and functional. However, the study does not address continuity relations related to interior space function type Figure 1. [16]

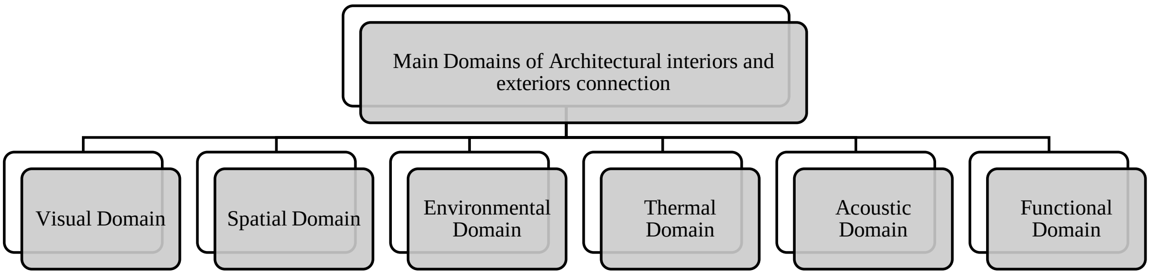


Figure 1. key of Main Domains of Architectural interiors and exteriors connection.

The integration of interior and exterior spaces is crucial in architectural design, influencing both aesthetic and functional aspects. It enhances user experience, improves environmental performance, and creates a harmonious relationship between the built environment and its surroundings. By using computational design strategies, architects can create precise, adaptable, and sustainable designs.[38]

Architectural elements reveal a space's qualities and serve as identification. Basic elements like entrance, door, window, and dormer are predominantly exterior, while wall and floor expressions are inward-looking. Wall and roof are equally distributed, supporting both exterior and interior domains. An amalgamation of interior and exterior domains, such as staircases and loggia, can enhance the portrayal of host elements.[17]

4.2. The Significance of Computational Design in architecture:

Computational design has significantly impacted architects' work by utilizing 21st-century tools and techniques to manage complexity in complex designs. It is an umbrella term for various approaches, bridging the gap between practical and professional aspects of architecture, focusing on the application of technology and the Stone Age of the discipline.[18]

Differentiating between main strategies and key tools in computational design is crucial for understanding methodology and goal of each step in a work process. Conceptual abstractions like histograms, generative mechanisms, grammar, and algorithmic design organize workflows and our way of seeing. The concept of the project behavioral set is at the start of professional or practical interactions, connecting strategic strengths and key tools.[19]

Computational design in architecture is evolving from merely reshaping existing designs to creating new ones, often utilizing digital technology for complex forms and spaces. The process of architectural design is evolving with technological advancements, providing new functions and opportunities. This has led to increased research into computational tools and their integration into designers' practices. The boundaries between technology and creativity are blurred, as the creative process becomes an integrated aspect of the application of digital methodologies.[20]

4.3. Computational Tools and strategies:

Computational design in architecture is transforming from reshaping existing designs to creating new ones, often using digital technology for complex forms and spaces. Technological advancements have led to increased research into computational tools and their integration into designers' practices, blurring the boundaries between technology and creativity.[21]

Parametric or generative design can help achieve convergence between interior and exterior design in the conceptual design phase. It integrates top-down and bottom-up principles, including spatial volumes and detailed physicality. Both generative design and parametric algorithms use unconventional data representations and constantly alter their interconnection. As technology advances, new methodologies are developed for seamless transitions between design components.[22]
The use of computational tools in architecture often leads to ambiguities in their use and authorship. This ambiguity arises when designers from various domains, such as computer graphics, industrial design, and auto-efficient computer-aided design, immerse themselves in the concept. The question of who, how, and when computational design strategies must be implemented is fundamental for the creative, cultural, and symbolic expression of design. The problem-solving approach using computational tools can reveal these ways. Key roles most often performed by computational design tools in design activity include generating, encoding, simulating, analyzing, and evaluating.[8]
Contemporary architectural design incorporates digital standards, using tools like BIM, parametric design, and AI in Computational Design. However, practitioners often confuse these tools as techniques, methods, or strategies, leading to confusion about their role in the field.[23]
Architects' interest in computation began in the 19th century with computer programs providing geometric data. These computational models were commercialized in the 1980s with digital design tools. Since then, many computational-geared ideas have been selected for architectural designing, with some becoming popular, stagnating, or declining.[23]
The integration of architectural design (AD) and analysis sparked architects' interest in optimizing their buildings, particularly in relation to environmental impact. This led to the development of tools like Rhinoceros/Grasshopper/Galapagos, simplifying the exploration of optimization. This led to extensive research on design approaches focusing on energy, daylight, and thermal performance.[18]
Computational design is a dynamic field that merges creativity and technology to create innovative solutions, utilizing tools and strategies to transform ideas into practical models.
Figure 2. Computational design tools are programs and applications used to create 3D models, simulate environmental conditions, analyze data, and develop integrated designs. Some common examples of these tools include:

- 3D modeling software: such as Rhino 3D, Autodesk Maya, Blender
- Finite element analysis software: such as ANSYS, Abaqus, Autodesk Inventor Nastran
- Environmental simulation software: such as Autodesk Ecotect Analysis, IES VE
- Parametric design: such as Autodesk Dynamo, Grasshopper

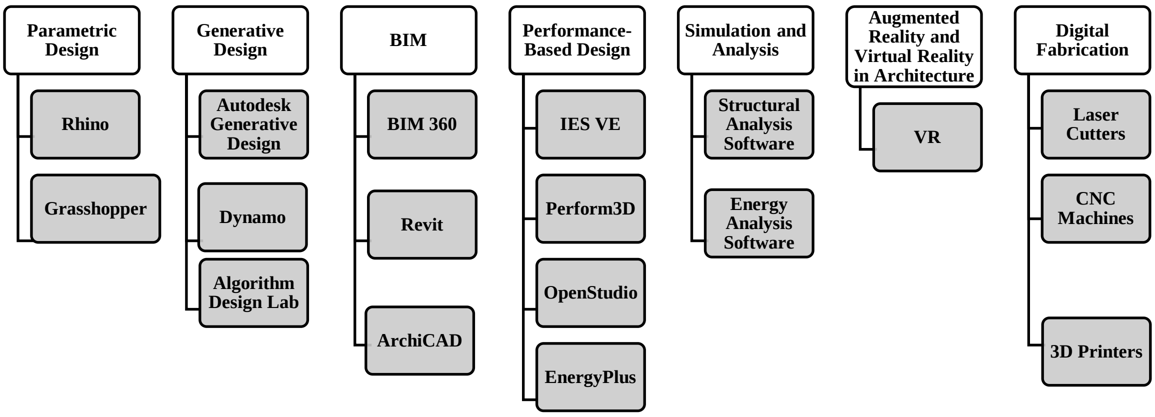


Figure 2. Main tools are used for Main strategies for computational design

Computational design is a crucial step in the development stage of architectural design, transforming the linear, sequential approach into a dynamic, iterative one, enhancing the designer's toolkit and transforming the design process from manual to digital.[20]

Table 1: Strategies of Computational Design in the Design Process

	Computational Design Application	Example Tools and strategies used	Benefits
Conceptual Design	Form Generation, Site Analysis, Massing Studies	Generative Design, Parametric Modeling, Simulation	Rapid exploration of design options, optimization of site response
Schematic Design	Spatial Planning, Circulation Analysis, Daylight Simulation	Parametric Modeling, BIM, Simulation	Efficient space planning, optimized daylighting, improved accessibility
Design Development	Structural Analysis, Energy Modeling, Cost Estimation	Structural Analysis Software, Building Performance Simulation, BIM	Optimized structural performance, energy efficiency, and cost control
Construction Documentation	Fabrication, Construction Simulation, Virtual Reality	BIM, CAM Software, VR/AR	Improved construction coordination, visualization, and quality control

Computational design strategies are still in their early stages of development, but they have the potential to revolutionize the way that architects design buildings for the interior-exterior connection. As these strategies continue to develop, we can expect to see even more innovative and creative ways to use them to design buildings that are both sustainable and human-centered. [19]

5. Case Studies:

In this section, we are going to present real-world examples which integrate interior and exterior spaces in one way or another. We aim to present the diverse application of the computational strategies regarding commercial architectures. Moreover, we will get insight into how effectively the strategies have been implemented. As our study persists on the architecture built to be used by humans, the presented cases also integrate natural dynamics as well as the usage aspect to analyze them from a broader perspective.

5.1. Case study 1: Tokyu Community Technical Training Center NOTIA, Tokyo:

The following Table 2 description of Project Information:

Table 2: Project Information

Project Information	Description
Project Name	Tokyu Community Technical Training Center 
Location	NOTIA, Tokyo
Architects	Hiroshi Imai, Architectural Design Tsuyoshi Kato, Architectural Design, Associate Professor, School of Science the university of Tokyo
Completion Date	2019

Project Scale	Commercial
Computational Design Strategies	- Performance-Based Design - Parametric design - BIM Design - Digital fabrication - Simulation and Analysis
Specific Tools and Software	- Custom Algorithms - Rhinoceros (Rhino) - Grasshopper - Annual average illuminance simulation - Energy Analysis Software - Structural Analysis Software
Optimization	Performance-Based Design, Parametric design Strategies and Simulation and Analysis used to achieve optimal interior-exterior integration

Design Challenge: The Tokyo Community Technical Training Center in Tokyo utilized digital design to create a NearlyZEB* building, integrating training facility and environmental concepts. That Approaching 3 themes through computational design [24].

Design Concept: The Technical Training Center plans to create a complex effect by combining the Training HUB and Support Space, creating a mutually complementary relationship with the external environment.Figure 5. [24]

*NearlyZEB: A building that achieves 75% reduction in primary energy (first project for office use in the Tokyo metropolitan area to achieve this designation)[24]

5.1.1. Interactive volume study:

The site, divided into commercial and residential areas, required volume studies, legal checks, 3D visualizations, and interactive trials to design a training hub and support space. Figure 3, Figure 7. (Hiroshi Imai and Tsuyoshi Kato 2019

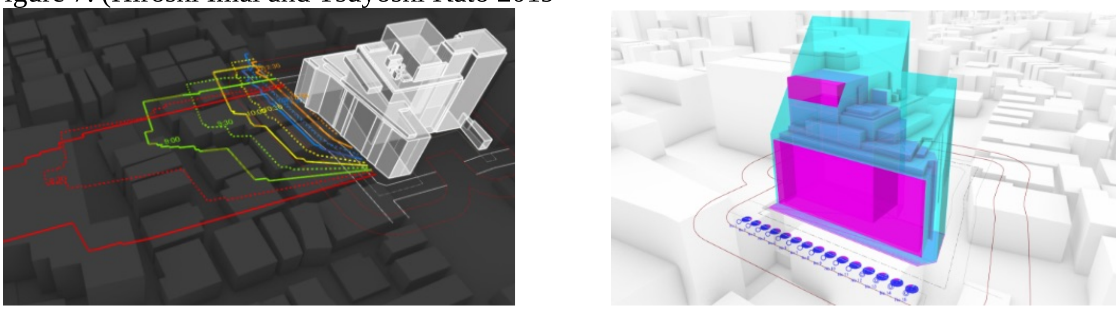


Figure 3. Checking for Shadow regulations and Sky factor calculations. [24]

5.1.2. Visualizations of natural energy led to Environmental architecture:

- **Facade design that takes in the wind:**

Wind was simulated and designed to enter a building through its shape and ventilation windows, causing wind-induced pressure on exterior walls. Ventilation openings and scaled walls were planned to enhance wind-catching effects, promote natural ventilation, and reduce visibility, improving living environments. Figure 8 [24]

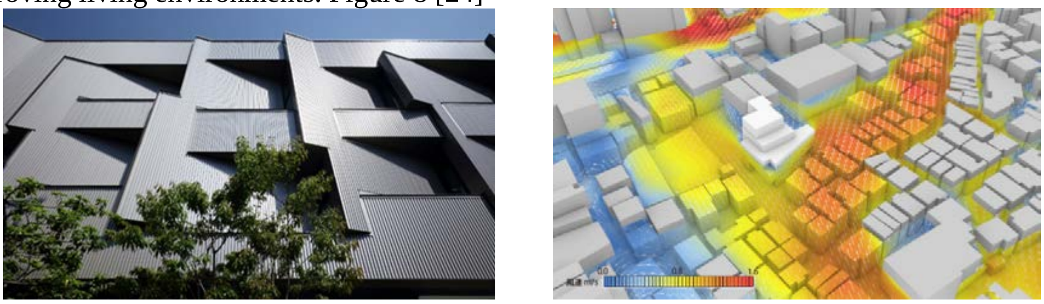


Figure 4. Checking for Outdoor airflow simulation from main wind direction (north-northwest wind).[24]

- **<u>Optimizing the light environment and line-of-sight control:</u>**

Grasshopper was used to balance sight lines from neighboring buildings, maintain bright communication areas, and block direct sunlight. A pattern was developed, ensuring comfortable brightness with indirect light while blocking direct sunlight. Figure 5.[24]

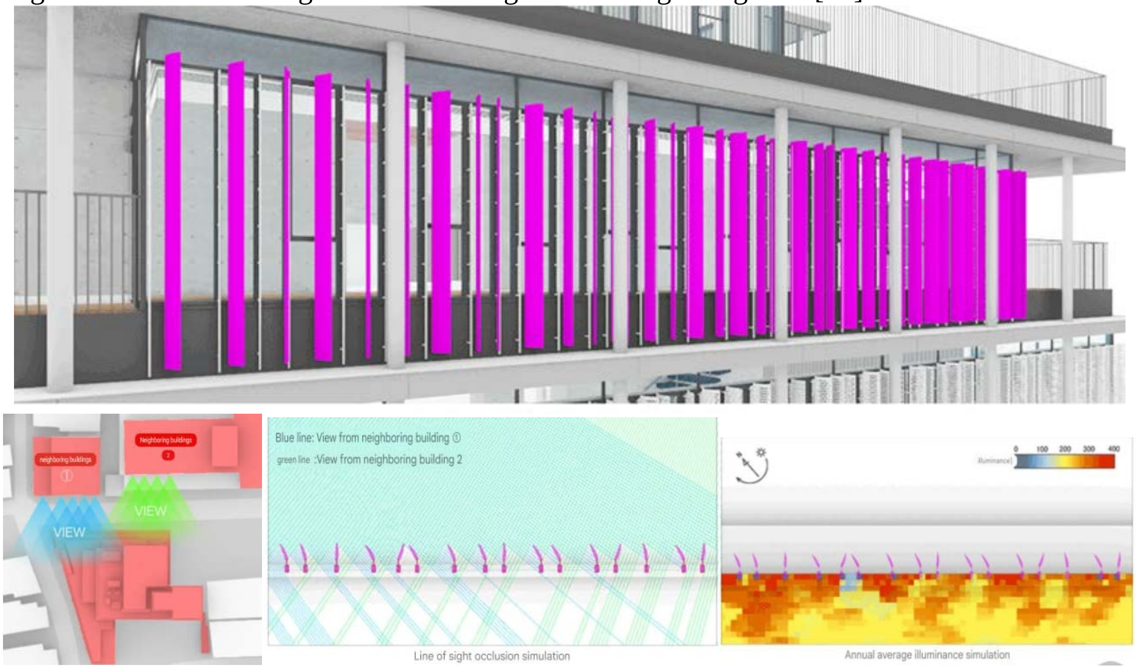


Figure 5. Consider the position and angle of the fins while checking line of sight and solar radiation [24]

5.1.3. The expression produced by a facade with soft gradation:

Utilizing 3D printer, created a soft gradation facade design for a bright communication space, incorporating natural light and privacy. Figure 6. [24]

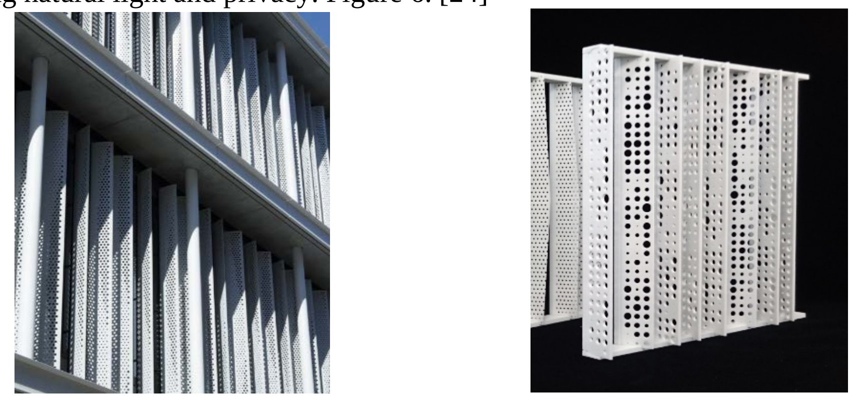


Figure 6. Facade with gradation. [24]

5.1.4. Workflow of the case study of Tokyu Community Technical Training Center NOTIA, Tokyo:

Figure 7 illustrates the importance of computational design principles in architectural theory and practice. These methodologies aid in identifying creative solutions, interpreting environmental demands, and optimizing solutions in constrained built environments. The interaction between interior and exterior domains is crucial in architectural design, with the meaning of both being open-defined. The selected computational design strategies and tools consider these two core architectural dimensions, enhancing the generation process knowledge in architectural design.

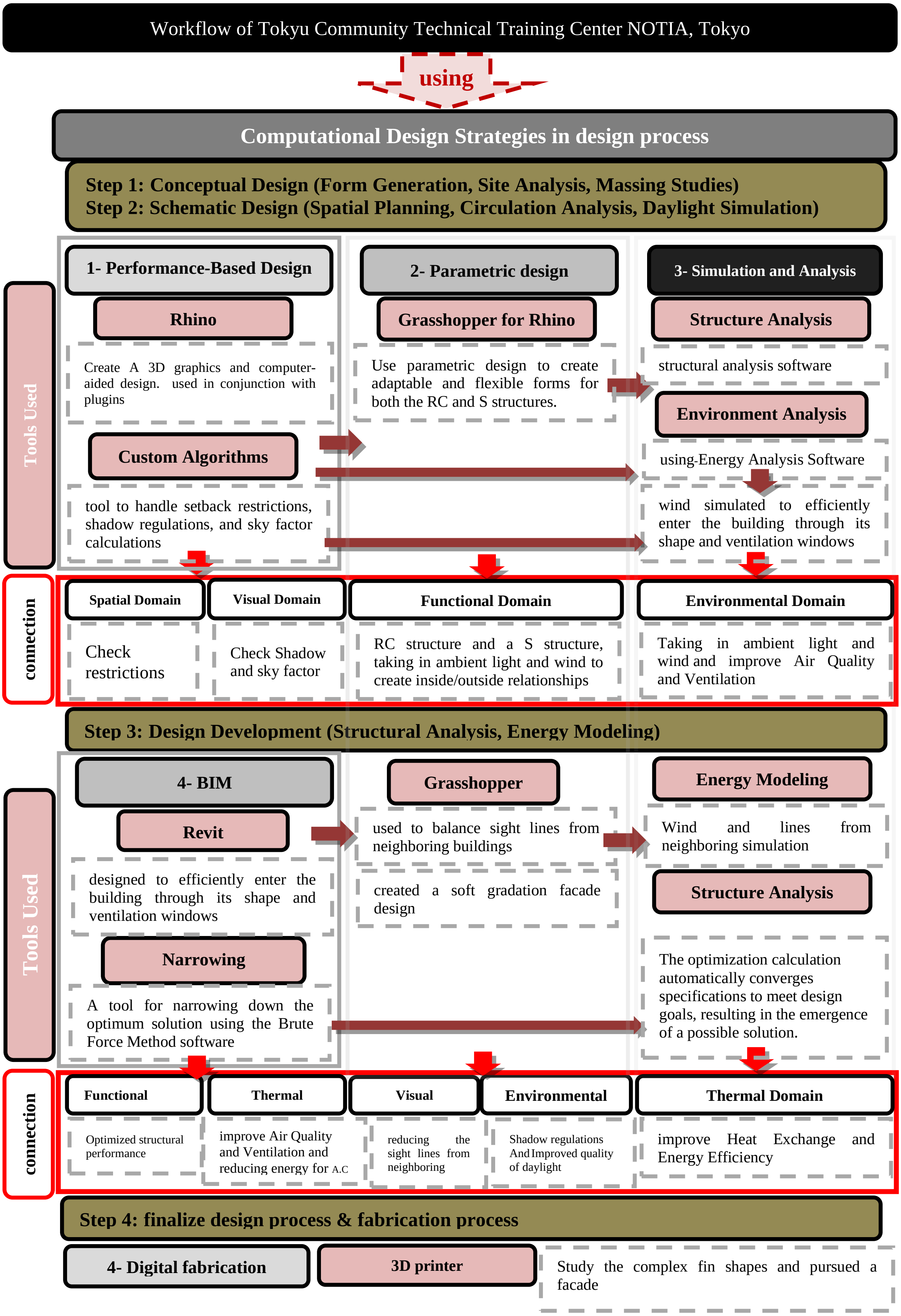
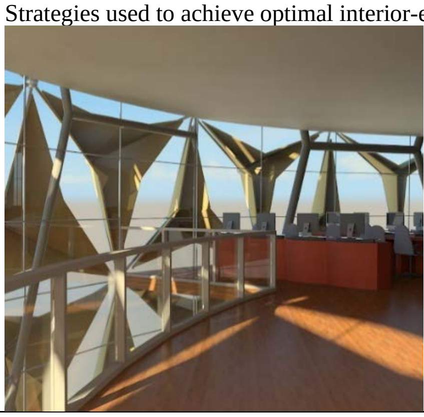


Figure 7. computational Strategic Design Workflows for Seamless Interior-Exterior Connections of Tokyo Community Technical Training Centre.

5.2. Case study 2: Al-Bahr Towers, Abu Dhabi:

The following Table 3 description of Project Information:

Table 3: Project Information

Project Information	Description
Project Name	Al-Bahr Towers   
Location	Abu Dhabi
Architects	Abdul Majid, AEDAS Architects
Completion Date	2012
Project Scale	Commercial
Computational Design Strategies	- Performance-Based Design - Parametric design - BIM - Simulation and Analysis
Specific Tools and Software	- Custom Algorithms - Revit - Algorithms Grasshopper - Annual average illuminance simulation - Energy Analysis Software - Structural Analysis Software - Dynamo - 3D printer
Optimization	Performance-Based Design, Parametric design, BIM and Simulation and Analysis Strategies used to achieve optimal interior-exterior integration 

Design Challenge: The Al-Bahr Towers, Abu Dhabi Investment Council's New Headquarters, were won in 2007 by Aedas-UK and Arup. The 150-meter-high twin towers feature a fluid form, honeycomb-inspired structure, and an automated solar screen.[25]

Design Concept: The Al-Bahr Towers design combines environment, tradition, and technology, with a dynamic facade. The architects aim to set new standards for environmental responsibility, focusing on areas requiring high levels of solar protection, inspired by Abdulmajid's sketches and an origami piece.[25][26]

5.2.1 Innovation of the Variable Structure with Parameter Logic:

An outer variable shading system is a practical solution for regulating solar radiation and indoor lighting, preventing glare and responding dynamically to environmental changes. Research institutions and laboratories have developed solutions like dynamic photovoltaic sunshade systems, bionic-logic-based projects, and variable element control of the outer layer to optimize indoor light environments, minimize energy consumption, and eliminate indoor glare.[25]

5.2.2. Tower façades: the Mashrabiya:

- **Envelope layers**

The building features a weather-tight glass curtain-wall and a dynamic solar screen, assembled using stainless-steel frames, aluminum frames, and fiberglass mesh infill. The mashrabiya, supported by cantilever struts, weighs around 625 kg. The dynamic solar screen, an automated feature, optimizes facade solar exposure using triangular units, transforming the screen into a lattice-like pattern. This reduces solar glare, improves visibility, and reduces artificial light use and energy costs. Figure 8. [25]

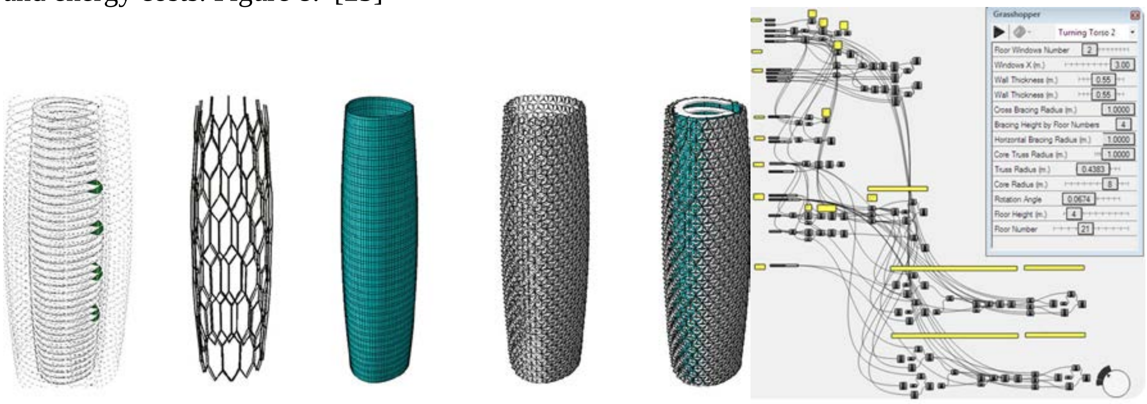


Figure 8. An assembled part of the building's facade demonstrates the realisation of the CODE principles. [25]

- **Performance criteria**

The dynamic mashrabiya solar screen blocks direct solar rays from entering occupied spaces during working hours, reducing solar gain and controlling solar glare. It responds dynamically to environmental changes, affecting natural daylight and air-conditioning cooling loads. Benefits include increased visibility, privacy, aesthetic appeal, and overall improvements. Figure 9.[25]

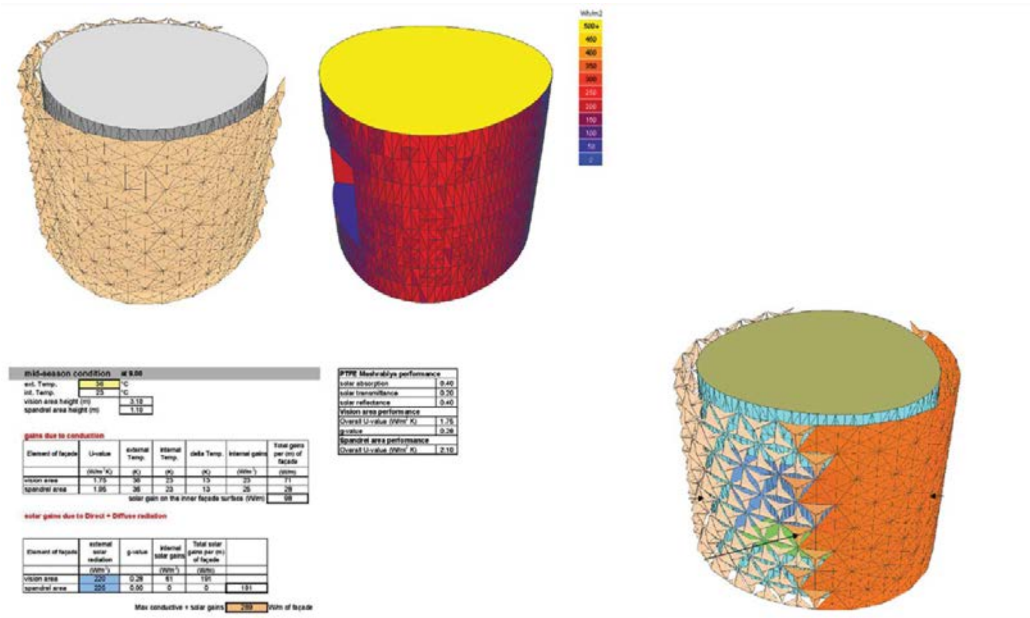


Figure 9. Shading studies were used to explore the impact on energy performance of different Mashrabiya configurations. This figure illustrates the facade opening and resulting improvement in energy performance. [25]

The study focuses on designing a solar-powered building envelope in the UAE to maximize solar gain without external shading screens, allowing natural diffused light to enter the building and maintaining a daylight threshold of 250 to 2000 Lux. Wind-tunnel tests were conducted to anticipate local loads. The fluid aerodynamic geometry of the building form and dynamic mashrabiya system generates low pressures, averaging 1.5 kPa up to 3.5 kPa. The main supporting structure is steel, allowing minimal floor-to-floor construction tolerance. Dynamic units are supported by cantilever arms, allowing vertical movements up to ±40mm and a total vertical tolerance of up to 50mm..[25]
The main supporting frame is designed to last for fifty years, with other components designed for a minimum of fifteen years before requiring replacement. The system is designed to resist high exposure to UV solar rays, humidity, corrosion, high wind-loads, impact and abrasion, and fire up to two hours.[26]
The materials chosen for the building envelope include 1.4462 Duplex Stainless Steel, PVDF coated Aluminium, glass, Teflon, and silicon. The solar gain and energy studies were intentionally left uninfluenced by the mashrabiya, and the geometric definition and opening configurations were optimized to improve lighting and visibility.[25]

5.2.3. parametric design methods in performance-based design in comparison to conventional methods:
Parametric design methods offer topological functionality, allowing efficient iterations and faster alternatives without extensive low-level modifications. Their infinite geometric forms highlight their potential for performance-based design, allowing exploration of a larger design space for optimal solutions. Parametric master models facilitate communication and coordination among architects, consultants, and contractors, enhancing understanding, speed, and synchronization of decisions across disciplines.[27]

3.2.4. Analysis of the case study of Al-Bahr Towers, Abu Dhabi:
The following figure 10. summarizes the workflow analysis of the example and explain that the Al-Bahr Towers used computational design to balance communication, security, design, and function in a project with various restrictions. The team's ability to share ideas from the initial design stage was key to the project's success. This collaboration between architectural and computational design, including people flows, light, airflow, and acoustics
The connection and interaction between interior and exterior main domains as part of the generation process knowledge in architectural design. The meaning of both exterior and interior is a field of open definitions. The consideration of these two core architectural dimensions in the selected computational design strategies and tools

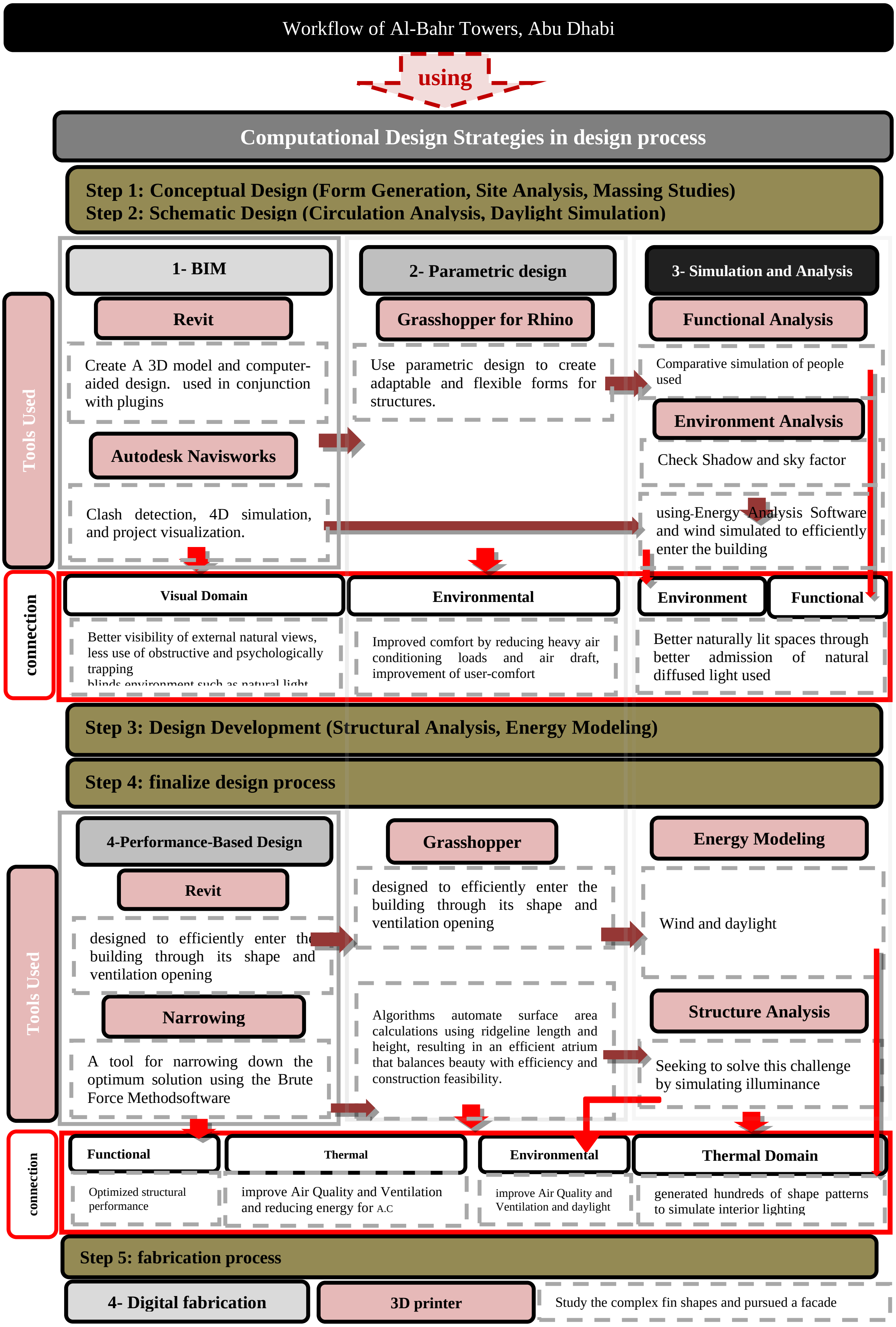
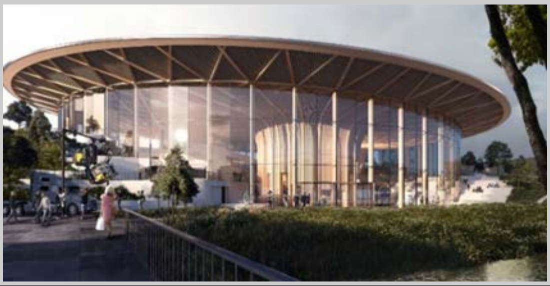


Figure 10. computational Strategic Design Workflows for Seamless Interior-Exterior Connections of Al-Bahr Towers, Abu Dhabi.

5.3. Case study 3: World of Volvo, Gothenburg native and one of Sweden's:

The following Table 4 description of Project Information:

Table 4: Project Information

Project Information	Description
Project Name	World of Volvo 
Location	**Gothenburg** native and one of Sweden's
Architects	Henning Larsen
Completion Date	2024
Project Scale	Commercial
Computational Design Strategies	- Performance-Based Design - Parametric design - BIM - Simulation and Analysis
Specific Tools and Software	- Custom Algorithms - Revit - Algorithms Grasshopper - Annual average illuminance simulation - Energy Analysis Software - Structural Analysis Software
Optimization	Performance-Based Design, BIM and Simulation and Analysis Strategies used to achieve optimal interior-exterior integration  

Design Challenge: The World of Volvo is a unique experience center in Gothenburg designed by Henning Larsen, focusing on Scandinavian landscape, environment, and traditions. Developed after winning an interview competition in 2018, it embodies the brand's values and aspirations. The center aims to provide a premium experience combining entertainment, exhibitions, talks, conferences, music, food, drinks, and shopping, reflecting its human-centric approach.[28]

Design Concept: "This project is incredibly special to us," says Søren Øllgaard, Design Director at Henning Larsen. "With its deep connection to Scandinavia, from its landscapes to its architectural radition, World of Volvo has given us to the opportunity to explore the profound relationship between architecture and the natural environment."[28]

The World of Volvo in Gothenburg, Sweden, is an architectural marvel that incorporates Swedish nature. The structure is based on the concept of The Mountain, the landscape and building's base, and The Tree, the building itself. The large landscape features delicate flowers, native plants, rocky outcroppings, and meandering paths, encouraging visitors to inhabit it while adhering to the principle of allemansrätten. The three vast "Trees" offer exhibit spaces, vertical circulation, brand exhibition, and service functions.[28]
World of Volvo is a Swedish design that promotes the concept of "Allemansrätten," or the fundamental right to roam freely on land, showing consideration for nature and others. The circular form encourages visitors to create their own experiences, regardless of whether they attend exhibitions inside. The project's timber construction is forward-facing and traditional, using glulam timber for beams and columns, computer-controlled fabrication for precision, and locally sourced CLT for floor and roof slabs.[28]

5.3.1. Design, and Install of the Timber Structure:

- **Total Stability**

WIEHAG faced the challenge of ensuring the stability of a timber structure due to extreme vertical loads transferred from roof beams to faced and tree trunk columns. They chose rigid star nodes and moment rigid connections for beam junctions, meeting the architectural requirement for "no bracing" in the façade line. Total lateral stability was achieved through portal frames with moment rigid corners and the diaphragm action of the CLT roof deck. figure 11. [28]

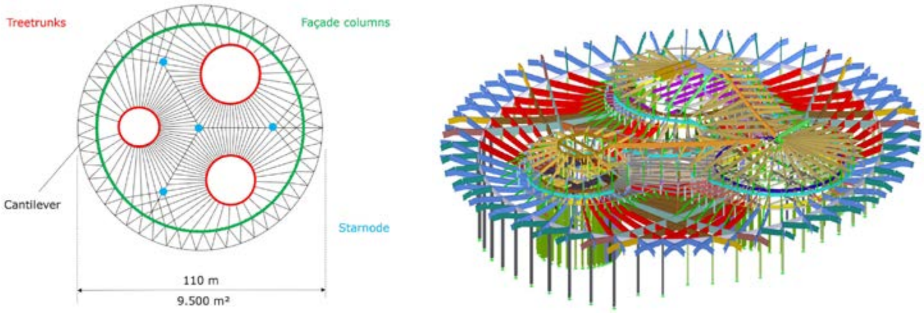


Figure 11. Plan view – Beam layout of main hall [28]

- **Details:**

The corner connection between columns and beams is crucial for structural stability, with forces of up to 2,300 KNm. A machined curvature was chosen instead of a bended solution, resulting in thinner laminations. Steel plates with inclined screws transfer tension and moment from the beam to the column. The Star node was designed with FEM to ensure proper plate thickness. Most screws are precision installed at the factory, but some bolts are site-fixed. Over 4,000 timber infill panels made of three-layer boards were used to cover access areas. However, exposure to UV light could cause lighter marks on the beam's surface, so exposure should be minimized. [28]

World of Volvo uses traditional Scandinavian timber in their building materials, blending modern methods with traditional Scandinavian materials. A flexible computational workflow allowed for experimentation with building height, roof geometry, inner circle radius, and column number, while evaluating structural implications with the manufacturer. This advanced digital collaboration informed material-based decisions, ensuring optimal material use without compromising on the concept.[28]

- **Model:**

WIEHAG engineers created a 3D model, shop and installation drawings for a complex organic structure over a year. The model was combined with parametric design and a cloudbased BIM platform called "Trimble Connect" for coordination with other trades. The flat model addressed the requirement to warp CLT roof slabs. figure 12. [28]

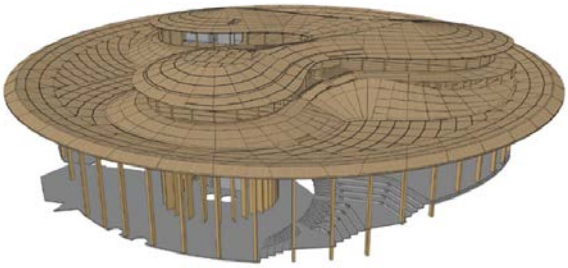


Figure 12. 3D CAD model [28]

5.3.2. Fabrication & Shipping:
WIEHAG, a Swedish company, has successfully produced a glulam made of PEFC certified European Spruce. The glulam was block glued and shipped 1,400 km from Altheim, Austria, to Gothenburg. The shipment involved Stora Enso's Swedish facility in Grums, while the CLT traveled 220 km. WIEHAG organized permits, escort cars, and night deliveries for the long-span elements. figure 13. [28]

Figure 13. Curved corner connection during installation [28]

5.3.3. installation :
WIEHAG successfully installed 2,200 Glulam and 2,750 CLT single items within 28 weeks using three tower cranes and multiple MEWPs. The project required only 65 printed installation drawings for the crew on site, highlighting the importance of offsite prefabrication. Tablets and mobile phones were used to supplement the large printed drawings, and Stora Enso's software "CLT360" was used for coordination. Minor challenges were quickly resolved through screensharing between WIEHAG's engineers in Austria and the team on site. Proper water management and temporary protection were crucial for maintaining the quality of the timber structure during the installation phase. A factory applied a two-pack clear hydrophobic UV coating to protect the glulam during rainy days in Gothenburg. The joints of the CLT were taped together, and good coordination with WIEHAG and the roofer was crucial for applying the watertight membrane. [28]

5.3.4. Analysis of the case study World of Volvo, Gothenburg native and one of Sweden's:
The World of Volvo, a Swedish attraction, uses computational design to balance communication, security, design, and function. The building, made of glulam and cross-laminated timber, features tree-trunk-like columns and a welcoming canopy, encouraging visitors to create their own journeys indoors and outdoors. The design considers the connection between interior and exterior domains, incorporating the regional landscape in form, materiality, and culture. “Our goal was to give form to something very essential to the Swedish spirit. World of Volvo's circular form, the timber materiality, its integration with the landscape, and, fundamentally, its openness – these things are all parts of a core collective identity." Martin Stenberg Ringer Figure 14

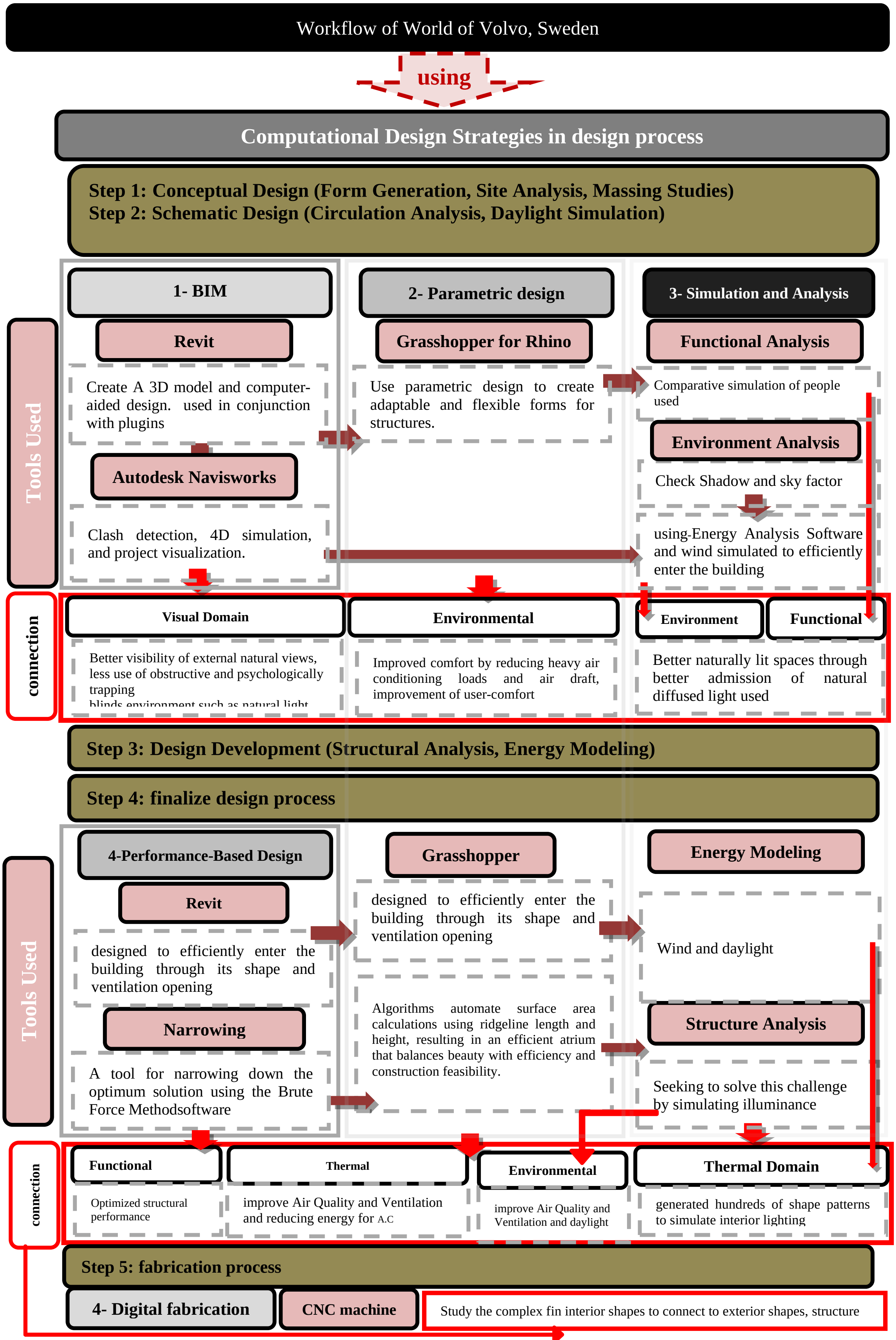


Figure 14. computational Strategic Design Workflows for Seamless Interior-Exterior Connections of World of Volvo, Gothenburg native and one of Sweden's.

6. Analytical comparison of previous Case studies:

The study explores three computational frameworks for integrating interior and exterior spaces in architectural design. It reveals that each strategy yields diverse results, reflecting the impact of interior and exterior shapes on overall shape configuration. These strategies allow for a priori specification of an area of interest in the configuration space, circumventing exploration in solution space. The study suggests these strategies may be useful in building information modeling and data research. Combining these strategies with optimization tools can lead to original configurations in less time than existing methods. The study concludes that computational strategies can revolutionize the way architects approach interior and exterior spaces, creating more harmonious, sustainable, and innovative architectural solutions. Future research should focus on further development and addressing challenges.

The goal of this comparison is to demonstrate the application of computational design in enhancing the interaction between interior and exterior spaces in buildings. Previous case studies applied focusing on the design process steps, the computational design tools used, the strategies at each stage, how this affects the interaction between interior and exterior, the design objectives, and the results achieved. Table 5

Table 5: comparison of previous Case studies

Project Name	Project Scale	Computational Design Strategies Used	Tools and Software Used	Optimization (interior & exterior connection)
Tokyu Community Technical Training Center, Tokyo	Commercial	-Performance-Based Design -Parametric design -BIM -Digital fabrication -Simulation and Analysis	-Custom Algorithms -Revit -Algorithms Grasshopper -Annual average illuminance simulation -Energy Analysis Software -Structural Analysis Software -Narrow -3D printer	The training space, known as the "Training HUB," is designed to create a complex effect by creating a mutually complementary relationship with the external environment. The "Support Space" surrounds the training HUB, incorporating ambient light and wind to create various inside/outside relationships, resulting in a unique and effective training environment.
Al-Bahr Towers, Abu Dhabi	Commercial	-BIM -Performance-Based Design -Parametric design -simulation and Analysis -Digital fabrication	-Custom Algorithms -Revit -Algorithms Grasshopper -Annual average illuminance simulation -Energy Analysis Software -Structural Analysis Software -Dynamo -3D printer	The Bahariya Towers in Abu Dhabi, featuring large windows, glass panels, and a double-skin façade, are designed to enhance aesthetic appeal and energy efficiency. The design incorporates traditional Emirati motifs, creating a sense of place and identity. The sleek exterior features curved forms and a double-skin system for heat gain, showcasing the importance of interior-exterior connection in contemporary architecture.
World of Volvo, Sweden	Volvo Cars AB and Volvo Group	-BIM -Generative design -Performance-Based Design -Parametric design -Simulation and Analysis -Digital fabrication	-Custom Algorithms -Revit -Algorithms Grasshopper -Annual average illuminance simulation -Energy Analysis Software -Structural Analysis Software -Dynamo -CNC	Volvo Cars' interior and exterior design have been optimized to enhance the overall user experience and brand identity. The exterior design embodies modern elegance and Scandinavian minimalism, while the interior prioritizes comfort, functionality, and sustainability. The relationship between the two elements is crucial for a cohesive and harmonious driving experience. Volvo's focus on aesthetics, functionality, and sustainability has established the brand as a leader in the automotive industry.

7. Framework for applying Computational Strategies in Architectural Design:

7.1. Key Similarities and Differences:

This section examines the similarities and differences in computational strategies used in designing seamless interior and exterior spaces. It aims to compare the goals, design drivers, implementation approaches, results, and use of computational modeling in each case study. Key similarities include the use of physics-based approaches, different tools, and computational strategies to predict environmental conditions, support multi-objective optimization, and investigate the inside-outside transition based on changes in atmosphere and light. The comparison helps frame the literature review and provides insights for further analysis. The main differences include the use of different tools and strategies to investigate and maintain distinct inside-outside transitions.

In the initial stages of the design process, various strategies were employed to facilitate the integration of interior and exterior spaces. One such strategy involved the use of Building Information Modeling (BIM) to construct a comprehensive and integrated model of relationships. This model served as a foundation for simulating the proposed design, considering aspects such as usage, orientation, and spatial relationships within the overall site context. Figure 29.

Subsequently, strategies were implemented to enhance the impact of both the general and interior environments. This included the application of performance improvement strategies aimed at achieving the highest possible level of integration between interior and exterior spaces. Figure 15.

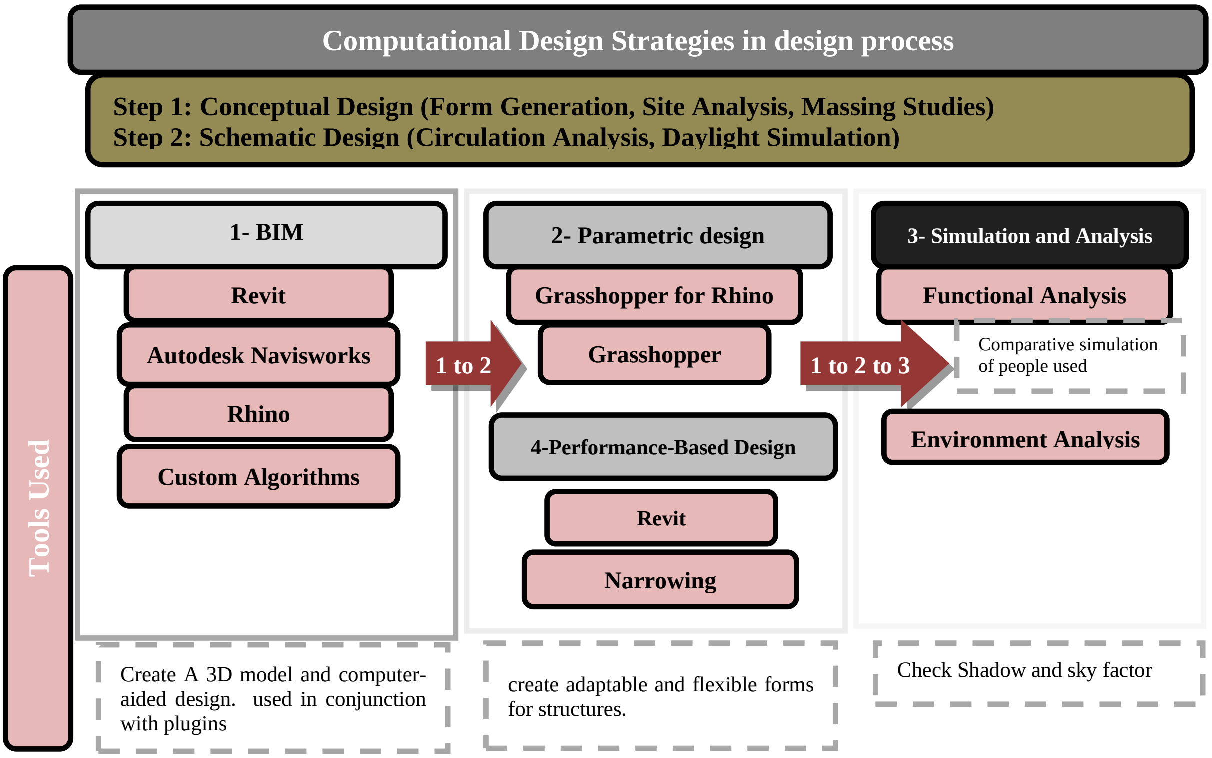


Figure 15. Workflow Section 1

7.2. Effectiveness of Integration Strategies:

This study explores the effectiveness of four computational strategies for integrating a cuboid with a freeform shape. The strategies aim to improve the smooth transition between interior and exterior spaces, generate creative and flexible transitional spaces, and generate suitable outcomes for architectural design. Feedback on individual shapes and datasets is obtained, with a focus on providing insights within the scope of Karamba3D for structural analyses and thousands of simulation scenarios. The study also explores the relation between architectural designing and

concerns with silence or energy simulations. The new proposed shape has the potential to provide smooth transitions between interior and exterior spaces naturally and generate more intricate and flexible interior inner shells of transitional spaces. The study highlights that architect may design the same scenario without inner curve optimization and a valid inner curve compatible with a specific initial cuboid in one shot, taking advantage of computation without intentionally considering surface generation, joining surfaces of simple entities, or curve network optimization.
In the third and fourth stages, the focus shifted to the completion of the building structure. This involved detailed design development and the refinement of the integrated model to ensure coherence and functionality. Advanced computational design tools were utilized to optimize the spatial configuration and to address any emerging challenges in the integration process.
Finally, in the fifth stage, the design process culminated in the manufacturing phase. This phase encompassed the fabrication of building components and the implementation of construction techniques that align with the integrated design strategy. The use of digital fabrication methods and prefabrication techniques played a crucial role in realizing the design vision, ensuring precision and efficiency in the construction process. Figure 30.

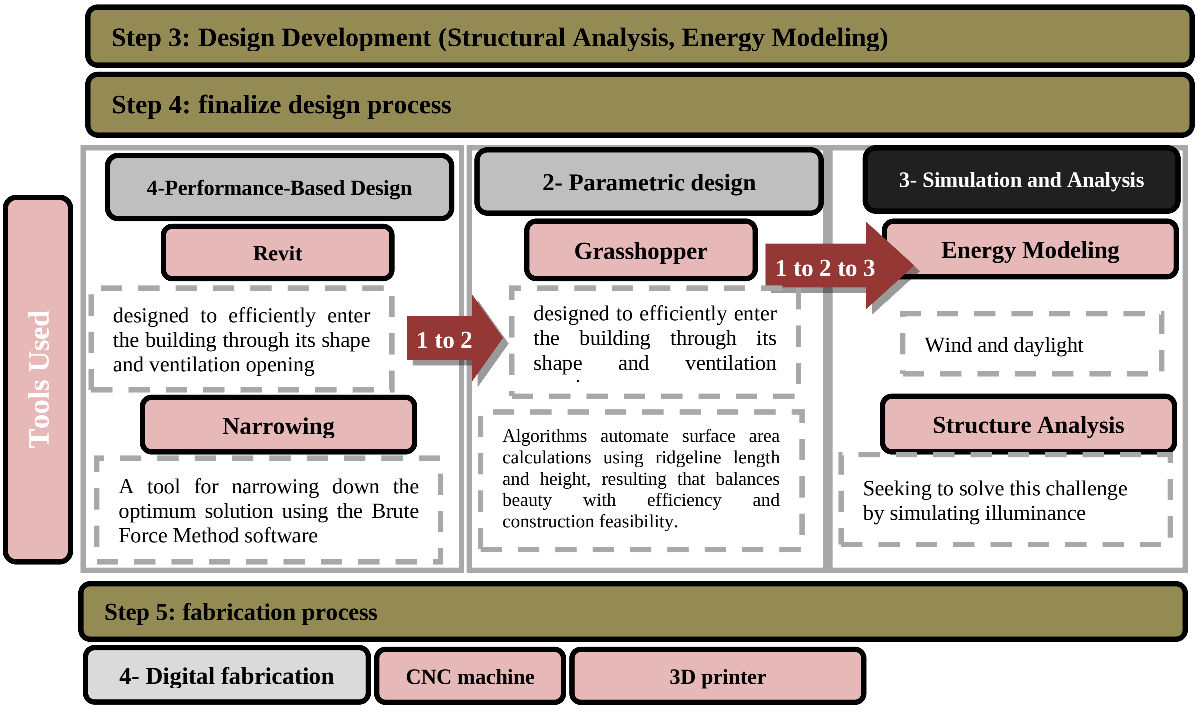


Figure 16. Workflow Section 2

8. Discussion:

The study compares computational strategies for integrating interior and exterior spaces, revealing differences between elementary cell layouts, qualitative layouts, and quantitative layouts. Despite these differences, the strategies still show potential for integrating spaces. The results are particularly interesting for architects and computational design researchers as they provide insights into designing specialized computational methodologies that can intelligently guide behavioral diversity towards final spatial layouts without compromising spatial relations. However, the conclusions are still indecisive, suggesting that preference-based evaluations are necessary to assess the spatial design promoting properties of computational methodologies. The proposed evaluation methodology could be used for further studies defining multiobjective design problems, incorporating the preferences of evaluators as a multiobjective optimization. Future work could also include a spatial analysis of other key-interacting parameters, such as spatial flexibility/monotony or spatial connectivity.

The study reveals breakthroughs in the field of architectural design by analyzing computational strategies for integrating interior and exterior spaces. It suggests research directions for advanced design and architectural computing, focusing on multiscale strategies for cohesive plastic forms. The research proposes automatic population computations in a 3D cellular environment for smart cities and algorithms for optimizing dissimilar parameters. Future research should prioritize integrating design decisions at different scales, especially at the interior and exterior, to ensure design convergence and user experience.

9. Conclusion:

This study examines three computational frameworks that aim to integrate interior and exterior spaces in architectural design. The researchers apply these strategies to a tree-shaped building, exploring their architectural potential. They find that each strategy yields highly diverse results, confirming the capacity of the approaches to reflect on how the integration of interior and exterior shapes affects the overall shape configuration. Additionally, each strategy allows for the a priori specification of an area of interest in the configuration space, circumventing exploration in solution space.

The study suggests that by representing boundary-free topological interconnections, these computational strategies may find interesting applications in current research on building information modeling and data. Combining the investigated strategies with optimization tools may lead to highly original configurations in less time compared to existing state-of-the-art implementation from literature.

The study highlights the potential development of novel strategies for exterior-interior couplings, providing integrated results in acceptable computational time. Practical implications have been identified and discussed. The findings of this academic research will be valuable for practitioners, researchers, students, and those who need to learn more about developing computational strategies to blur and seamlessly connect exits and entry, roof and ground, and interior and exterior in architecture.

The research results contribute to architectural production, theory, and practice by producing computational strategies for creating seamlessly integrated architecture in exterior space. These strategies blur exits and entry points, gently and magnetically draw individuals outside without feeling they are leaving the building. The connection between ground and roof is not evident yet, contributing to an atmosphere of simultaneous 'in'ness and 'out'ness.

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