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INTERIOR-EXTERIOR CONNECTION IN ARCHITECTURAL DESIGN BY ADOPTING COMPUTATIONAL DESIGN STRATEGIES: A COMPARATIVE ANALYSIS

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ABSTRACT

The seamless connection between indoor and outdoor environments has become a critical aspect of contemporary architecture, enhancing user experience and promoting sustainability. While traditional design methods have been effective in certain contexts, they may face limitations in seamlessly integrating interior and exterior spaces, which highlights the potential value of exploring innovative computational approaches. prompting the need for innovative approaches. Computational design offers a transformative solution by enabling architects to manipulate complex geometries. This research paper explores the integration of interior and exterior spaces in architectural design using computational design strategies. 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 interior-exterior connection refers to the seamless integration of indoor and outdoor spaces to enhance spatial fluidity, user interaction, and environmental sustainability. This research highlights the role of computational design strategies in achieving such integration, addressing limitations in traditional design approaches. The paper concludes with practical recommendations for architects and suggestions for future research to build upon the initial exploration of computational design's potential in achieving seamless interior-exterior connections.

KEYWORDS: Interior-exterior connection, Computational design strategies, Parametric architecture, Digital design techniques, Spatial integration

الاتصال الداخلي - الخارجي في التصميم المعماري من خلال اعتماد استراتيجيات التصميم الرقمي: تحليل مقارن.

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الملخص

أصبح الاتصال السلس بين البيئات الداخلية والخارجية عنصرًا محوريًا في العمارة المعاصرة، حيث يسهم في تعزيز تجربة المستخدم ودعم الاستدامة. وعلى الرغم من أن أساليب التصميم التقليدية أثبتت فعاليتها في بعض الحالات، إلا أنها قد تواجه تحديات في تحقيق التكامل السلس بين المساحات الداخلية والخارجية، مما يبرز أهمية استكشاف مناهج تصميم مبتكرة. في هذا السياق، يُعد التصميم الحسابي حلاً تحويليًا يتيح للمعماريين معالجة الأشكال الهندسية المعقدة وتحسين العلاقات المكانية ومحاكاة الأداء بدقة. يهدف هذا البحث إلى دراسة تكامل المساحات الداخلية والخارجية في التصميم المعماري باستخدام استراتيجيات التصميم الحسابي. ويستعرض البحث الأدبيات السابقة المرتبطة بموضوع الاتصال الداخلي-الخارجي، ويبحث في منهجيات التصميم الحسابي المختلفة، مع تحليل ثلاث دراسات حالة لمشاريع معمارية توظف هذه الاستراتيجيات بشكل فعّال. يشير مفهوم الاتصال الداخلي-الخارجي إلى تحقيق تكامل سلس بين المساحات الداخلية والخارجية بما يعزز انسيابية المساحات، وتفاعل المستخدمين، والاستدامة البيئية. يسلط البحث الضوء على دور استراتيجيات التصميم الحسابي في تحقيق هذا التكامل ومعالجة أوجه القصور في الأساليب التقليدية. ويختتم بتقديم توصيات عملية للمعماريين واقتراحات لأبحاث مستقبلية لتعميق فهم إمكانات التصميم الحسابي في تحقيق الاتصال السلس بين المساحات الداخلية والخارجية.

الكلمات المفتاحية : الاتصال بين التصميم الخارجي و التصميم الداخلي، استراتجيات التصميم الحاسوبي، التكامل والعلاقات المكانية ، تقنيات التصميم الرقمي.

1. INTRODUCTION

Achieving seamless integration between interior and exterior spaces presents significant architectural challenges due to various design complexities, including structural, functional, and environmental constraints. Despite these challenges, contemporary architectural research emphasizes innovative solutions aimed at bridging these boundaries to enhance spatial continuity and user experience. 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 research 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. 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].

2. Research problem

This research aims to address a core challenge in architectural design: enhancing the integration between interior and exterior spaces through computational strategies. By focusing on this integration, the study seeks to optimize natural light and ventilation, reduce energy consumption, and improve thermal comfort, all of which contribute to sustainable and user-centric architectural environments. This problem gains significance due to the increasing emphasis on creating seamless indoor-outdoor transitions in contemporary design practices.

3. 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 investigates the role of computational design strategies in achieving seamless integration between interior and exterior spaces in architectural design. It aims to explore how these strategies can address existing spatial challenges by optimizing visual, thermal, and functional connections between indoor and outdoor environments. The analysis draws on case studies and theoretical insights to provide a framework for enhancing spatial continuity using advanced computational methods [11].

2.1. Conceptualizing Interior and Exterior Spaces in Architecture

Jacques Derrida, a French philosopher, emphasized the importance of defining boundaries between interior and exterior spaces in architecture, as balancing these elements can lead to incorrect designs and challenges in 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 interior-exterior integration without traditional boundaries, allowing natural transitions. Parametric models can lead to discontinuity and semantic meanings. Research on skylights for prefab housing units shows aesthetic and psychological benefits, exploring computational design of building componente [15].

3. METHODOLOGY

This research employs a mixed-method approach to explore the enhancement of interior-exterior connections through computational design strategies. The methodology includes the following components:

- Literature Review: A comprehensive analysis of existing theories and case studies to identify key computational strategies for spatial integration.
- Case Study Analysis: Examination of a selected architectural project that implements computational design strategies, aiming to assess its effectiveness in achieving seamless interior-exterior transitions.
- Computational Simulation and Analysis: Application of computational tools to evaluate design performance metrics, including natural lighting, thermal comfort, and energy efficiency. This step aids in identifying optimal design parameters for achieving enhanced connectivity between interior and exterior spaces.

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

1.1 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 **Fig. 1** [16].

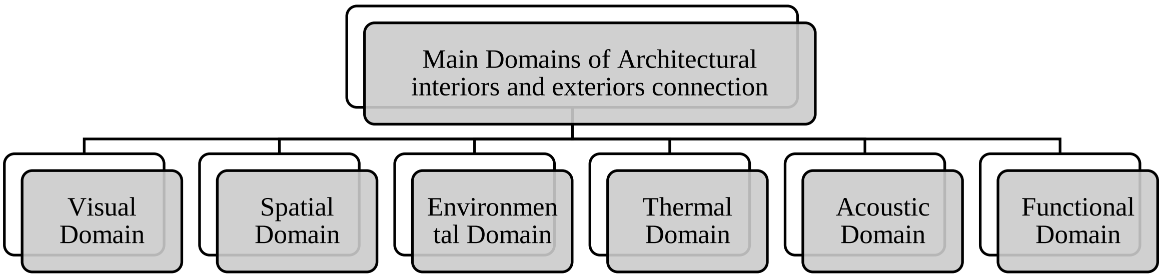


Fig. 1. key of Main Domains of Architectural interiors and exteriors connection.

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 [12].

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 [17].

1.2 The Significance of Computational Design in architecture

Computational design, a term encompassing various techniques, has significantly influenced architects by utilizing 21st-century tools to manage complexity in complex designs, bridging the gap between practical and professional aspects of architecture [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 transforming from reshaping to creating new designs, often using digital technology for complex forms. Technological advancements blur the boundaries between technology and creativity, enhancing the creative process [20].

1.3 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].

Computational tools in architecture, used by designers from various fields, are crucial for creative, cultural, and symbolic design expression. Key roles include generating, encoding, simulating, analyzing, and evaluating, causing ambiguities in their use and authorship [8].

Contemporary architectural design uses digital standards, including BIM, parametric design, and AI in Computational Design. However, practitioners often confuse these tools as techniques or strategies. Interest in computation began in the 19th century with geometric data programs, commercialized in the 1980s. Many computational-geared ideas have gained popularity or declined [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.

Fig. 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:

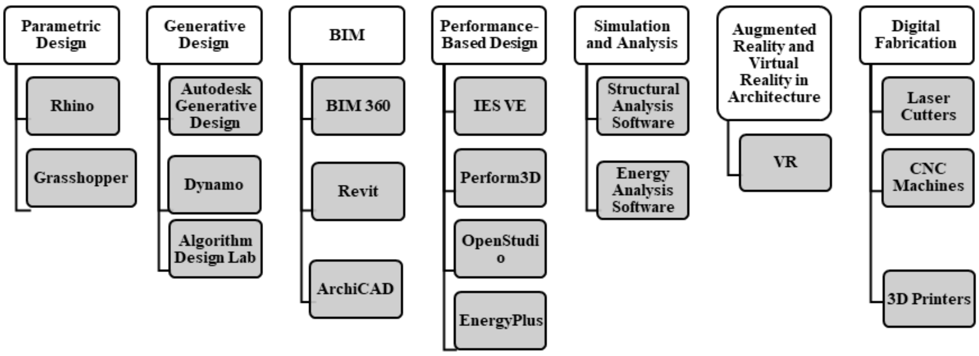


Fig. 2. Main tools are used for Main strategies for computational design

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

Table 1. 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, alignment with the research objectives. These criteria include:

1. Integration of Interior-Exterior Spaces: The cases must demonstrate significant integration between indoor and outdoor environments.

2. Use of Computational Design: Projects utilizing computational design strategies to enhance spatial connectivity were prioritized.

3. Diversity of Application: A range of architectural types (e.g., commercial, educational) was selected to provide diverse perspectives on the implementation of computational design in achieving seamless spatial transitions.

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 [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. Fig. 3. [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. Fig. 3. [24].

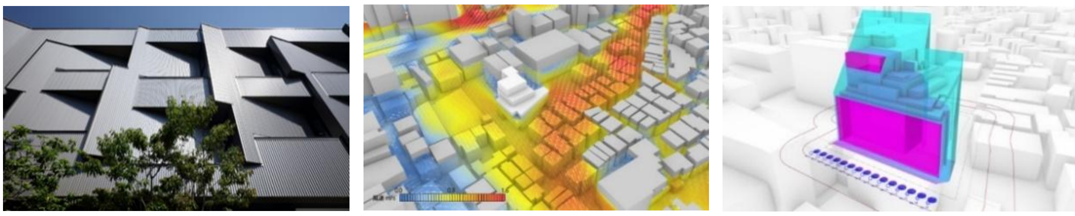


Fig. 3. Checking for Outdoor airflow simulation from main wind direction (north-northwest wind) [24].

Optimizing the light environment and line-of-sight control:

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. Fig. 4. [24].

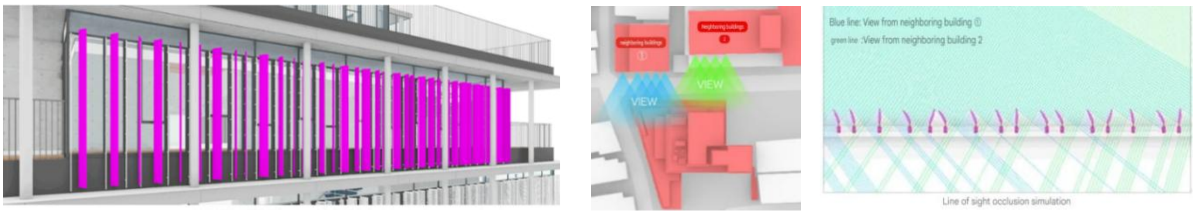


Fig. 4. Consider the position and angle of the fins while checking line of sight and solar radiation [24]

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. **Fig. 5** [24].

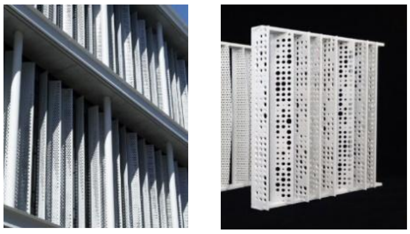


Fig. 5. Facade with gradation [24].

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

Fig. 6. 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.

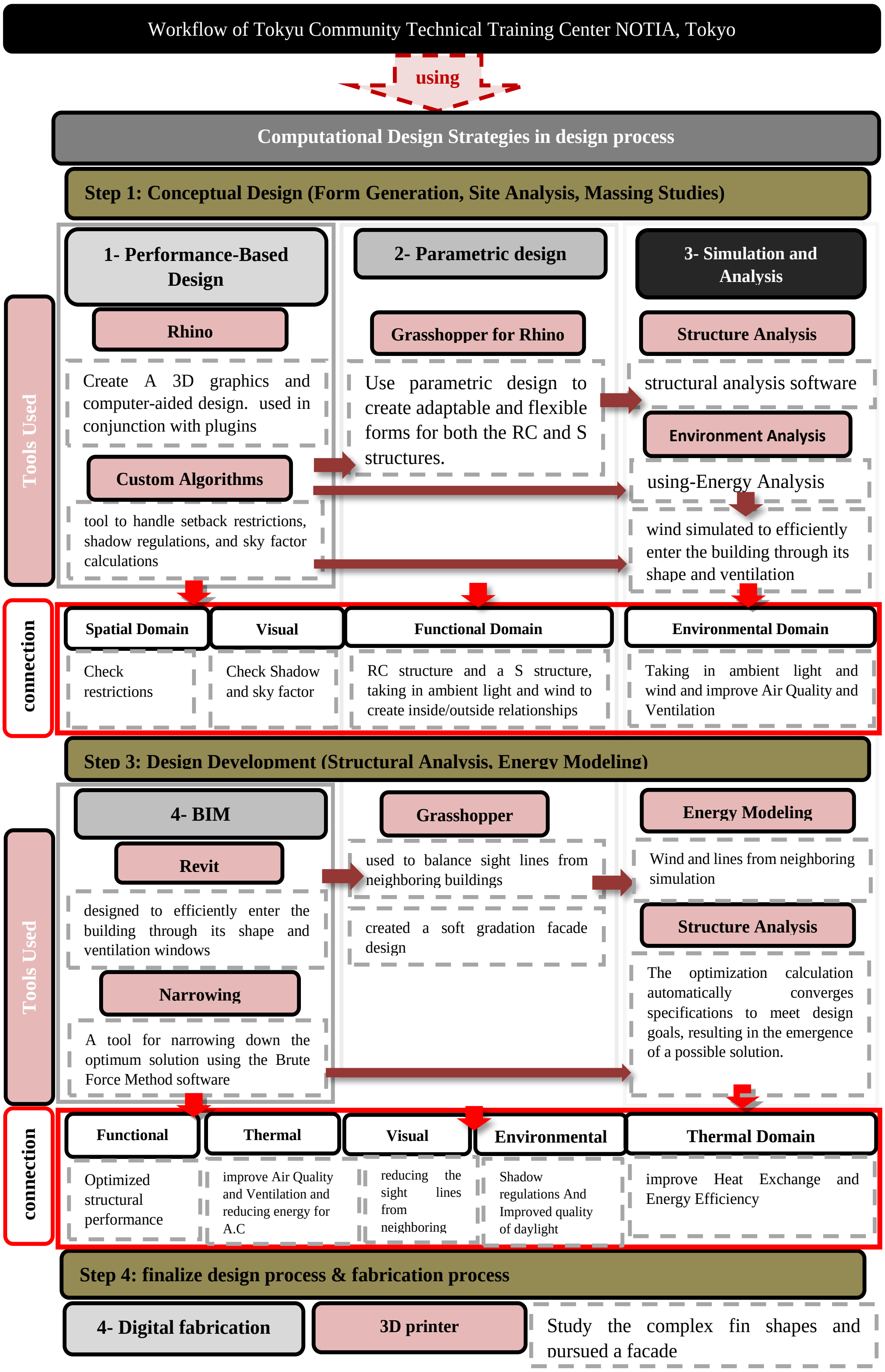
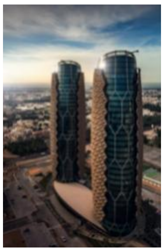


Fig. 6. computational Strategic Design Workflows for Seamless Interior-Exterior Connections of Tokyo Community Technical Training Centre.

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

The following Table 3 description of Project Information

Table 3: Project Information

Project 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

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. Fig. 7 [25].

mid-season condition at 9.00

ext. Temp.	36	°C
int. Temp.	23	°C
vision area height (m)	3.10	
spandrel area height (m)	1.10	

gains due to conduction

Element of façade	U-value	external Temp.	internal Temp.	delta Temp.	internal gains	Total gains per (m) of façade
	(W/m²K)	(K)	(K)	(K)	(W/m²)	(W/m)
vision area	1.75	36	23	13	23	71
spandrel area	1.95	36	23	13	25	28
					solar gain on the inner façade surface (W/m)	98

solar gains due to Direct + Diffuse radiation

Element of façade	external solar radiation	g-value	internal solar gains	Total solar gains per (m) of façade	
	(W/m²)		(W/m²)	(W/m)	
vision area	220	0.28	61	191	
spandrel area	220	0.00	0	0	191

Max conductive + solar gains 289 W/m of façade

PTFE Mashrabiya performance	
solar absorption	0.40
solar transmittance	0.20
solar reflectance	0.40
Vision area performance	
Overall U-value (W/m² K)	1.75
g-value	0.28
Spandrel area performance	
Overall U-value (W/m² K)	2.10

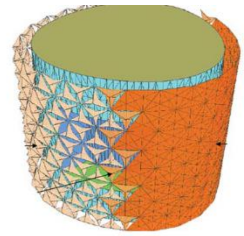


Fig. 7. Shading studies were used to explore the impact on energy performance of different Mashrabiya configurations. This figure illustrates the facade opening and resulting improvement in energy performance [25].

The study aims to design a solar-powered building envelope in the UAE, maximizing solar gain without external shading screens. The building's fluid aerodynamic geometry and dynamic mashrabiya system generate low pressures, with minimal floor-to-floor construction tolerance. Wind-tunnel tests anticipate local loads, and dynamic units are supported by cantilever arms for verticalmovements [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].

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].

5.2.4. Analysis of the case study of Al-Bahr Towers, Abu Dhabi

The following Fig. 8. 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.

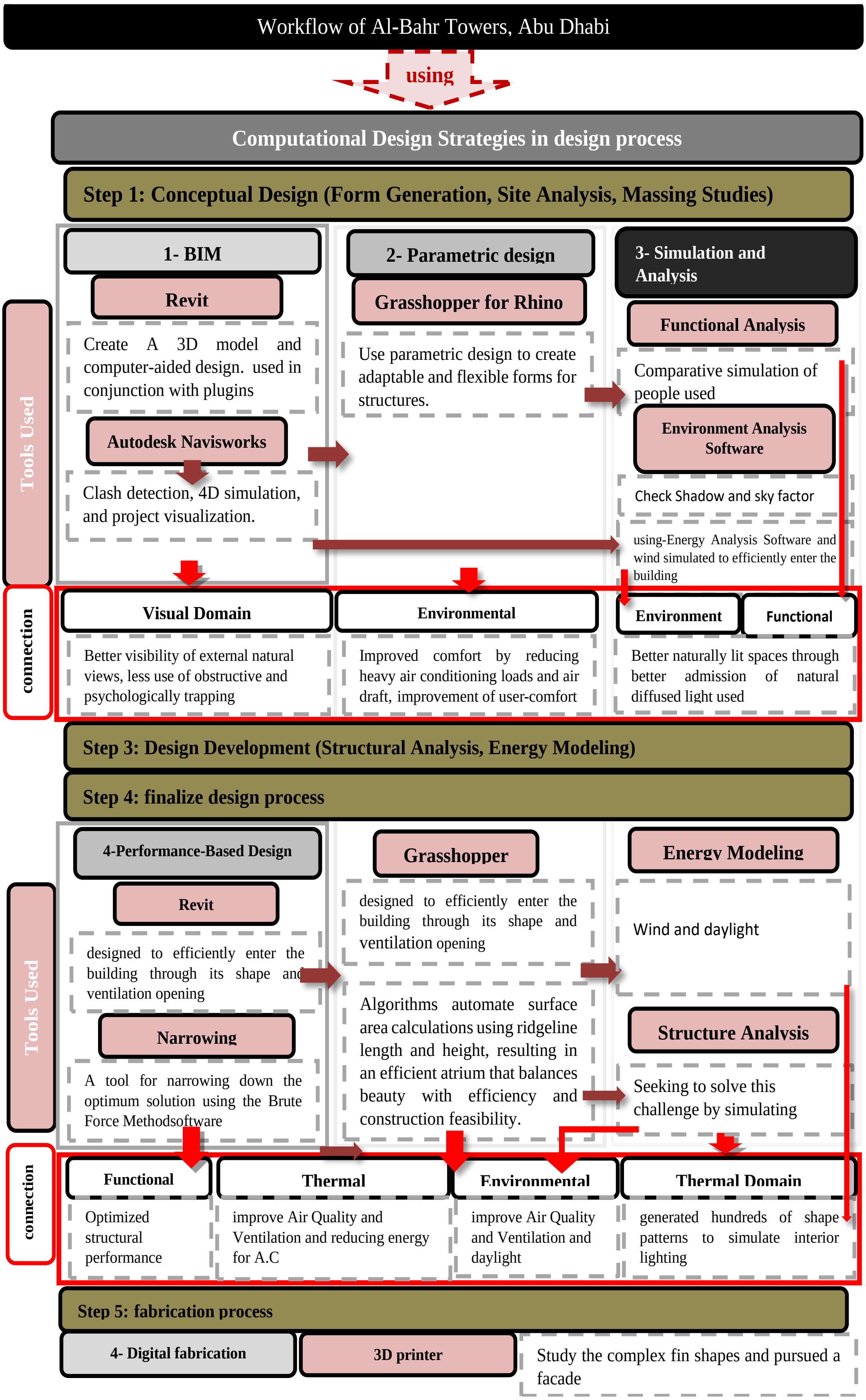


Fig. 8. Computational Strategic Design Workflows for Seamless Interior-Exterior Connections of Al-Bahr Towers, Abu Dhabi.

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. Fig. 9 [28].

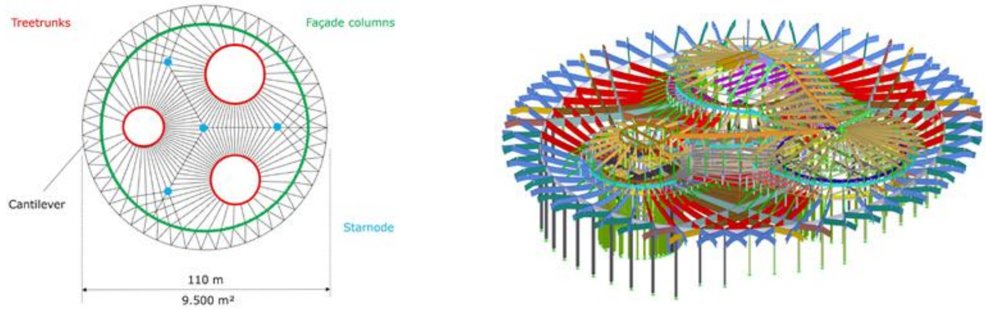


Fig.9. Plan view – Beam layout of main hall [28].

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 cloud-based BIM platform called "Trimble Connect" for coordination with other trades. The flat model addressed the requirement to warp CLT roof slabs. Fig.10. [28].

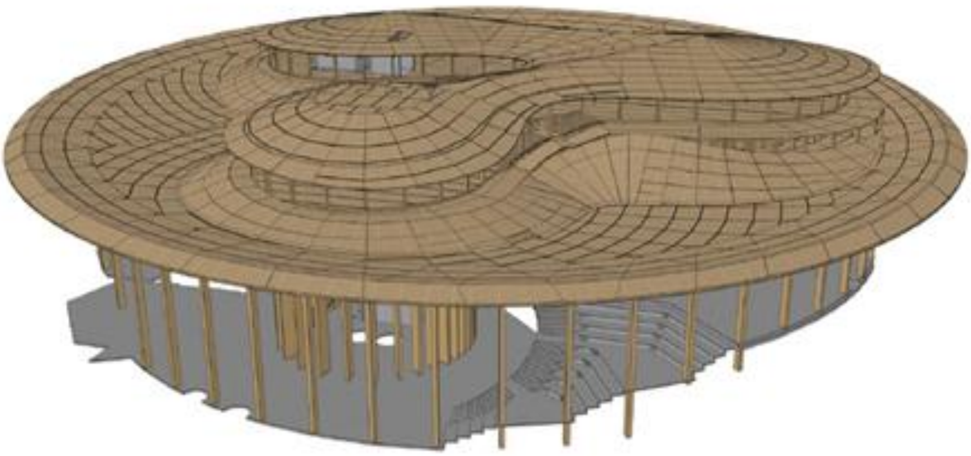


Fig. 10. 3D CAD model [28].

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].

5.3.2. 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 Fig. 11.

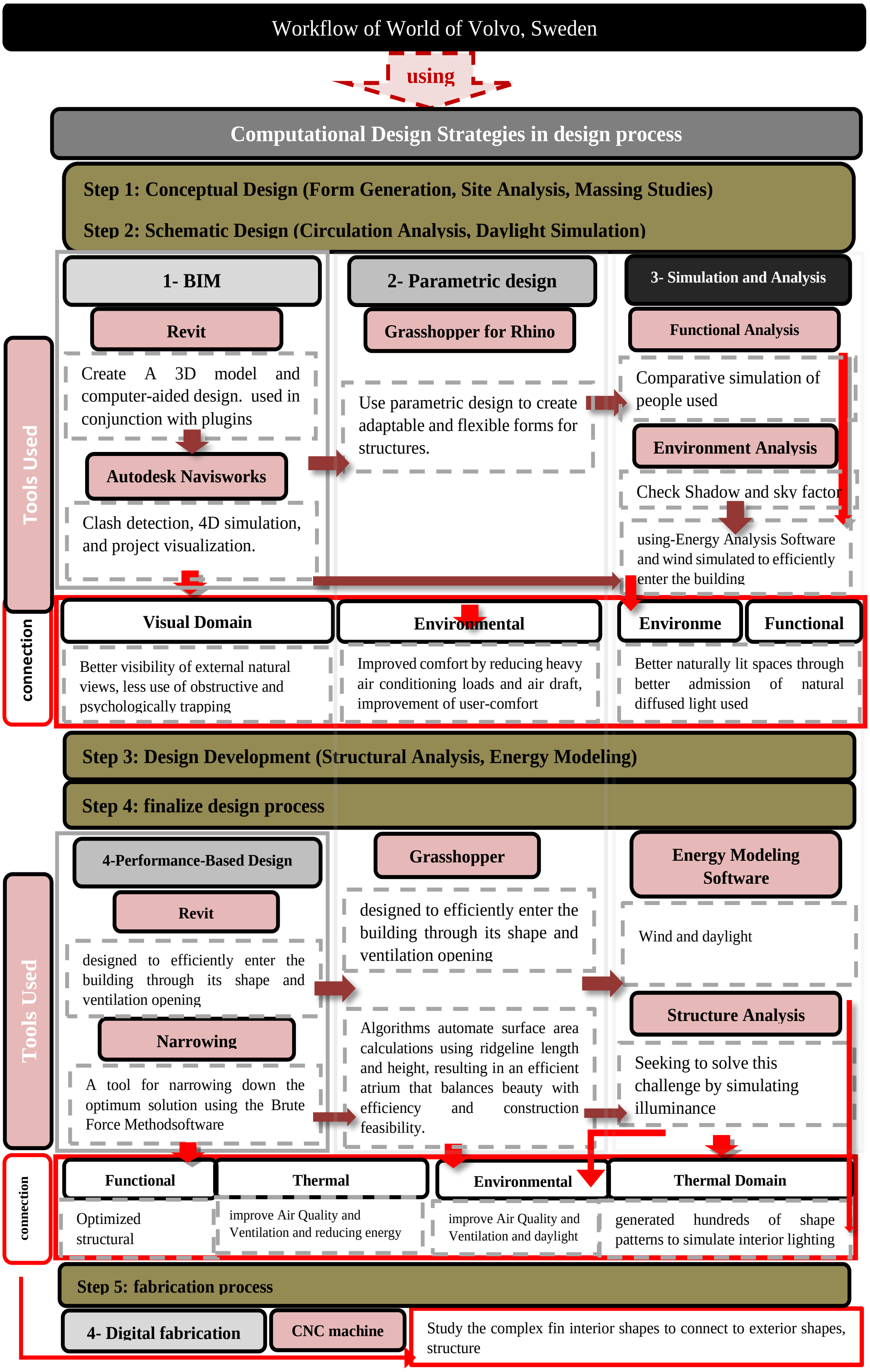


Fig.11. Computational Strategic Design Workflows for Seamless Interior-Exterior Connections of World of Volvo, Gothenburg native and one of Sweden's.

6. ANALYTICAL COMPARISON OF PREVIOUS CASE STUDIES

The study explores three computational frameworks for integrating interior and exterior spaces in architectural design, showing their diverse results and potential for building information modeling and data research. Combining these strategies with optimization tools can create more sustainable, innovative solutions, highlighting the need for further development. 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)	Interior-Exterior Connection Metrics
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.	**Training HUB enhances visual and physical connectivity with outdoor spaces, supporting a seamless user experience. Indoor&outdoor ratio70% Natural ventilation : 55%**
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.	**Façade shading :75% Double-skin façade provides shading, regulates indoor temperature, and enhances energy efficiency while maintaining visual connectivity. Dreduction in cooling load 40%**
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, blending modern elegance and Scandinavian minimalism, prioritize comfort, functionality, and sustainability, enhancing the overall driving experience and establishing the brand as a leader in the automotive industry.	**Blended indoor-outdoor spaces prioritize comfort, functionality, and sustainability, emphasizing fluid spatial transitions. Daylight autonomy : 70% Ventilation flow increase :50%**

7. Framework for applying Computational Strategies in Architectural Design

7.1. Key Similarities and Differences

The framework developed in this research provides a measurable approach to assess how computational design strategies enhance the interior-exterior connection in architectural projects. By integrating tools such as BIM, parametric design, simulation, and digital fabrication, this framework quantifies the extent of seamless integration. It focuses on key metrics, including spatial fluidity, thermal comfort, and visual connection, which are essential indicators of successful indoor-outdoor interaction.

7.2. Measurable Indicators for Interior-Exterior Connection

To address the reviewer's comment on quantifying the impact of computational strategies, the framework includes the following measurable indicators:

1. **Connected Space Ratio (CSR)**: Measures the ratio of connected interior and exterior space to total building space, reflecting spatial fluidity.

2. **Natural Ventilation Efficiency (NVE)**: Evaluates the proportion of natural airflow contributing to indoor ventilation, enhancing comfort.

3. **Daylight Penetration Index (DPI)**: Quantifies the amount of natural light that permeates the interior spaces.

4. **Energy Performance Savings (EPS)**: Measures energy savings due to computationally optimized interior-exterior integration, including thermal and light control strategies.

5. **Dynamic Architectural Elements Count**: Tracks the number of adaptive features (e.g., dynamic windows or shading devices) used to enhance the transition between interior and exterior spaces.

This section compares computational strategies used in designing seamless interior and exterior spaces, focusing on goals, design drivers, implementation approaches, results, and modeling. Key similarities include physics-based approaches, different tools, and computational strategies for environmental prediction and multi-objective optimization. Differences include different tools and strategies for maintaining distinct inside-outside transitions, providing insights for further analysis.

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 **Fig. 12.**

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 **Fig.12**

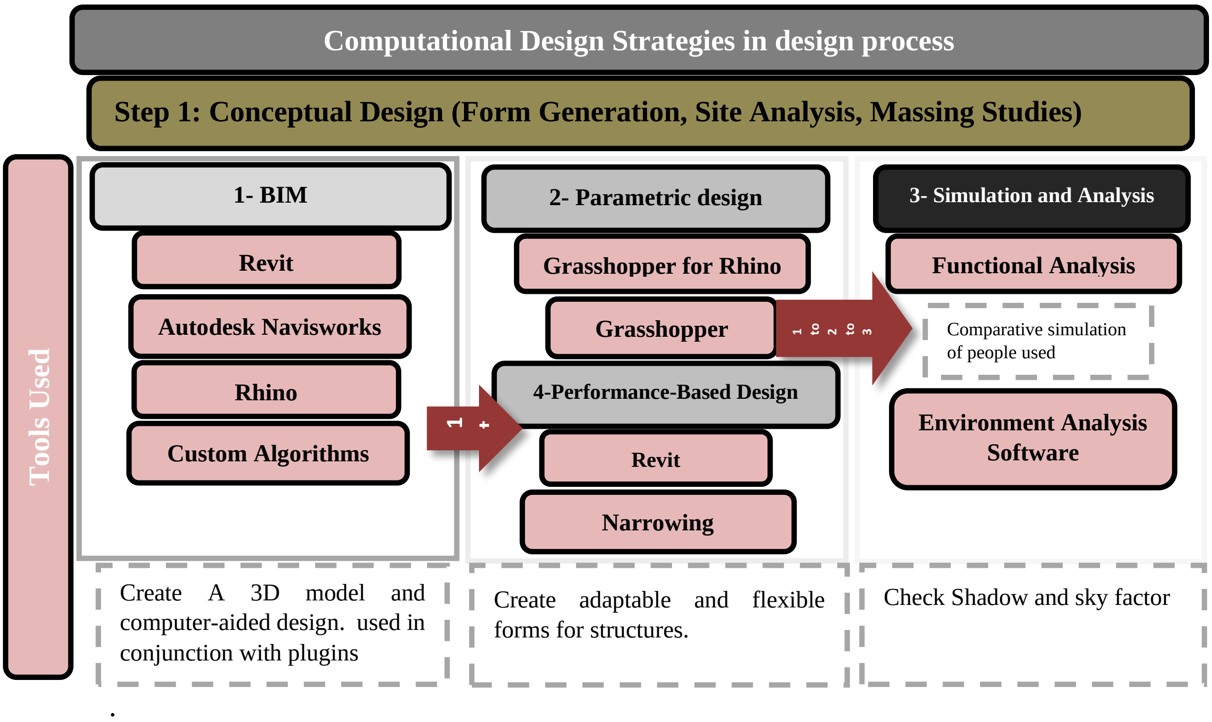


Fig. 12. Workflow Section 1

7.3.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 **Fig. 13**

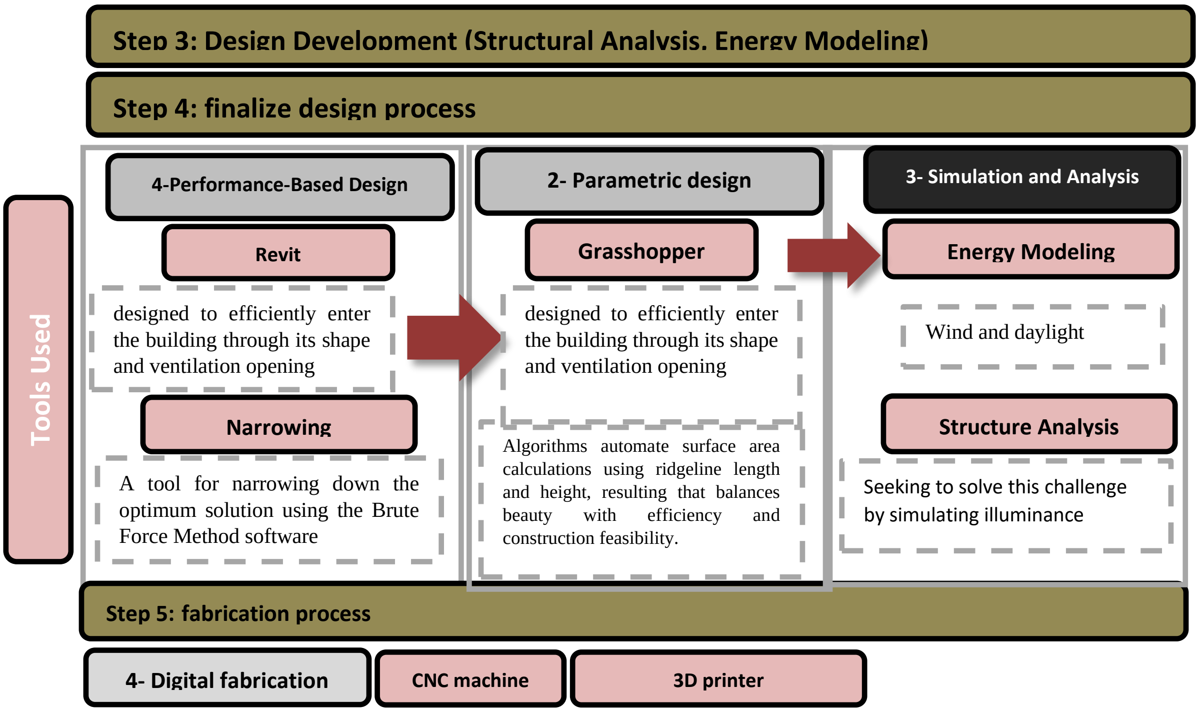


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Fig.13. Workflow Section 2

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.

CONCLUSIONS

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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