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THE PERFORMANCE-BASED INTERLINKED MODEL (PBIM) IN ARCHITECTURAL DESIGN: EXCHANGING ENVIRONMENTAL, STRUCTURAL AND SPATIAL PARAMETERS IN THE EARLY DESIGN STAGE

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INTRODUCTION

Building performance can be defined as the ability of buildings to satisfactorily execute certain tasks and functions (Li et al., 2020). Performance in architectural design is related to building behaviour, which can be computed by models based on physical phenomena. Performance issues can be evaluated from a range of perspectives associated with the different problems that arise (Mahdavi, 1999). Buildings must, therefore, accommodate certain performance criteria. These criteria cover technical matters (e.g., health, safety and security), functional concerns (e.g., efficiency and workflow), as well as behavioural, psychological, cultural, and aesthetic dimensions. Performance analysis usually requires engineering or other expert knowledge to apply performance algorithms and interpret the results.

The long-term impacts of buildings on people and the environment can be assessed through building performance analysis (Mallory-Hill, 2012, 3–28). Building performance evaluation allows design and construction professionals to properly consider performance aspects in the design and construction phases to minimize performance issues (Sharpe, 2019). Since the architectural design is complex and iterative—requiring ill-defined properties identified at the early design stage to be updated and improved over time—integrating assessment tools with well-defined properties at this stage is a challenging task. In this context, Performance-based Design (PBD) uses data supported by modelling and simulations (Tang et al., 2012). The most significant problem related to PBD is the integration of different tools and techniques to provide comprehensive building performance analyses (Arayici et al., 2018). Detailed simulation methods do not respond to the representations used in conventional Computer-aided Design (CAD) systems, and integration of simulation methods with the CAD has long been problematic (Mahdavi, 1999). Nevertheless, by using advanced tools and techniques, progress has been made in resolving

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interoperability problems, especially through the use of Computational Design (CD) models. It is possible to create intelligent models run by control parameters to create a flawless transition from concept design to construction (Fisher, 2012). Thus, critical parameters related to building performance can be determined, and complex functions can, in principle, be solved during the early stage of the design process.

Oxman (2009) introduced the term performance-based generative (performative) design, in which the design project is informed by feedback loops driven by performance. Analytical techniques are linked to the design model in performative models. Although simulation techniques are mostly considered to be analytical rather than generative, transformations and form modifications are enabled in performative design, referred to as "generative simulations" (Holzer, 2016). Thus, a geometric model can be modified or regenerated when performance goals are met in response to simulations, such as the morpho-ecologies approach—which emphasizes how the inherent performance capacity of materials are best at tuned to the local environment in which a building is situated (Hensel and Menges, 2008)—and data-driven computational design processes (Hensel and Sorensen, 2014; Sorensen, 2015). Topics—including energy, solar radiation, daylight and structural performance, thermal comfort, environmental impact, space allocation and cost—have been investigated in performative computational architecture (Ekici et al., 2019).

Computation should be evaluated as an integrated aspect of the design based on reasoning and making (Gurer et. al, 2015). A design problem in any level of complexity is defined by a set of variables and relationships among them in a computational model (Colakoglu and Yazar, 2007). Similarly, parametric models enable to resolve complex tasks in design by the use of generative and analytical methods. They obtain the advantage of incorporating performative issues into the model, in which parametric search space can be controlled by performance criteria. Performance analysis can be synthesized with design through the parametric control of form by generating design alternatives. Parametric models can be also coupled with external performance simulation tools (Gursel Dino, 2012). There were previous attempts to integrate CD logic in the pedagogy of architectural education by improving algorithmic thinking skills of students through scripting, visual programming languages and computational making (Kvan, et. al. 2004; Colakoglu and Yazar, 2007; Celani and Vaz, 2012; Yazici, 2020) and by using digital design models/ techniques, design theory and architectural discourse (Oxman, 2008).

The tension between design science and theory that serves towards design excellence has been a long term issue in architecture schools. Components in architectural curricula should be evaluated in terms of systems thinking by linking building performance to architectural design. Commonly, technical courses are taught independently from the studio environment without the generation of integrated design solutions. Usually, architecture students gain experience of an iterative design process between design and performance in their professional lives (Loftness et.al, 2005). Despite architectural design students take relevant courses during their undergraduate education related to building science and technology; they are usually unable to integrate the knowledge of performance acquired in these courses into their design projects. There have been previous attempts to investigate PBD in architectural design education by improving design generation and decision-making processes, such as generating a dialogue between performance-based data production and design issues (Natanian and Aleksandrowicz, 2018), identification of digital tool ecologies by informing morphological design with real-time building performance feedback (Holzer, 2016), incorporating energy performance with formal and spatial issues towards sustainable solutions in undergraduate design education (Zuo et al., 2010) and systems integration for total building performance into the studio (Loftness et.al, 2005). Nevertheless, the scope of current pedagogical approaches on PBD needs to be enhanced by CD. Interlinking different types of performances and assessing their relationships in the design process are important tasks that can be achieved by extracting critical design and performance parameters for use of architecture students.

The existing theory does not support the integration of Environmental, Structural and Spatial Performance into one model. Additionally, the incorporation of PBD into architectural design education needs to be improved. The research methodology of the present paper is geared toward addressing these issues. The paper aims to present a model that incorporates different types of performance issues into the early design stage to improve the decision-making process of students in the conceptual design and demonstrate its applicability in the context of architectural education. The Performance-based Interlinked Model (PBIM) in architectural design is advanced as an answer to this issue and to overcome the limitations of existing approaches and increase architecture students' knowledge of, and competencies with PBD.

METHODOLOGY

To recall, PBIM is a pedagogical approach for undergraduate architecture students that seeks to simplify PBD processes by extracting only critical parameters. The pedagogical approach is identified in the stages, including generating the design model (1), applying the performance computation method (2) and regenerating the design model by extracting critical parameters (3). The approach proceeds in three stages to best-fit students' learning and implementation process. In the first stage, the design model is generated, as in general architectural design studios. The second stage involves discerning the different types of performance computation methods and practising their use, wherein students recall and integrate their knowledge from courses other than a design studio, including building science and technology. In the third stage, feedback loops are generated between the analytical models of environmental, structural and spatial performance and the design model. These are the novel contributions of the PBIM to existing pedagogical approaches in undergraduate architecture. Data is collected via the process-analysis method driven by the selected case studies.

Generating the Design Model

Students are initially asked to describe the geographic location of their design projects to identify weather data along with the on-site positioning, as well as prevailing wind flows. Setting the context in this way by placing the existing buildings within the landscape is crucial for defining their relationship to the proposed building mass and façade, which also affects the quality of interior spaces. The building mass needs to be described from a geometric point of view in students' computational models. Using non-uniform rational b-spline (NURBS), surfaces and curves can describe form at any level of complexity. By defining architectural geometry, the building mass, outer walls and façade, including windows and openings, are described explicitly. Accordingly, floor plans can be generated. Based on the task undertaken for the performance computation, it may be necessary to specify additional geometric properties, such as the number of iso-curves on the NURBS surface. In addition to defining the architectural geometry, specifying materials is critical as well.

Applying the Performance Computation Method

Design is associated with discrete design variables for a building, which represent geometric information, such as volume and shape, as well as non-geometric (semantic) information, such as thermal mass and lighting (Mahdavi and Gurtekin, 2004). Geometric and analytical models should be combined in the design process for performance computation. Multiple platforms slow down the process, and interoperability problems can also arise in the models. Three methods for integrating design with performance analysis are commonly identified—the Combined Model, the Central Model and the Distributed Model. While the Combined Model allows modelling and simulations to be undertaken in the same environment, the Distributed Model offers a variety of performance analyses, such as middleware plug-ins like those developed for the Grasshopper (GH) algorithmic modelling tool. Building Information Modelling (BIM) is associated with the Central Model, in which building information data is centralized, and the same model can be used by a range of different analyses (Negendahl, 2015).

Performance computation topics should be understood and internalized sufficiently by students. Initially, lectures on the concepts of CD and PBD are provided by the instructor, supported by the evaluation of state-of-the-art research and practical work. Students are expected to frame research projects according to their design problems and decide which performance criteria have a critical impact on their designs, by selecting related performance computation methods and tools to undertake needed analysis at the early stages. Critiques are provided by the instructor, in terms of defining the design problem, selection of the relevant performance computation method and the tools of analysis. No technical tutorials on simulation tools are provided. Instead, information, which students gain in courses other than design, including building science and technology courses, such as physical environmental control, static and strength, should be integrated with their design.

Although a range of performance types are crucial to PBD, the present research focuses on a narrower set of five performance computation methods, including solar radiation analysis (1), daylight analysis (2), structural analysis (3), wind flow analysis (4) and spatial analysis (5) grouped into three clusters—namely, environmental, structural and spatial performance (**Figure 1**). These types are identified according to the generalized responses of the students throughout the implementation of the PBIM. Case studies on these five different methods are selected based on how readily performance parameters can be integrated into the design parameters, the aim being to improve conceptual design at the early stage. Some other performance types, including energy, thermal, acoustic and fire performance, are excluded from the present study. Although energy performance is directly related to studies on solar radiation and daylight analyses, no energy calculations are undertaken in the PBIM.

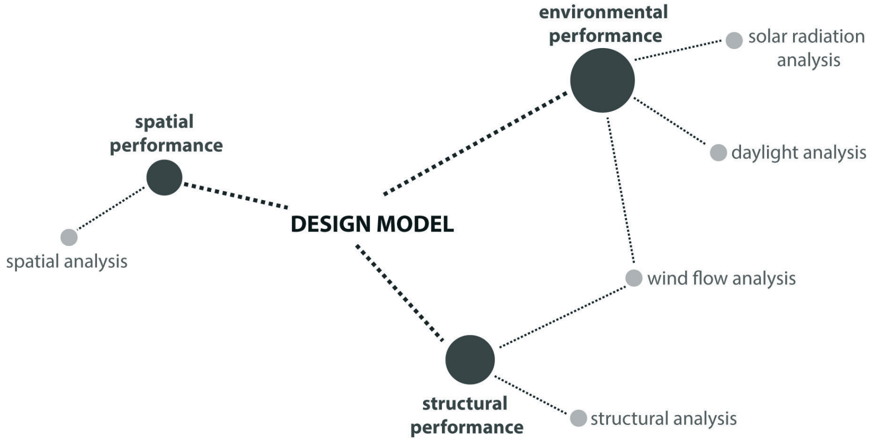


Figure 1. Performance computation methods included in the PBIM.

Solar Radiation Analysis (SRA)

Environmental conditions influencing design need to be identified in the design process. To evaluate the thermal comfort of occupants and the energy use of buildings, SRA provides an initial understanding of the model. Radiation data can be visualized in time ranges, as two-dimensional (2D) and three-dimensional (3D) graphs that indicate the amount of radiation (Roudsari and Pak, 2013). The radiation calculations use annual hourly data, inserted from weather data-driven by simulation engines, such as EnergyPlus, which is standard for building energy materials (Mackey and Rousari, 2018). The relationship between the sunlight angle and orientation of the surfaces is critical for the computations. Building mass and façade design can be re-interpreted according to the results of the SRA.

Daylight Analysis (DA)

DA plays a critical role in the quality of spaces. Currently, architects cannot use simulation environments to undertake efficient daylight analysis to inform design, because such simulations are designed with specific tasks in mind and the graphical user interfaces are generally difficult to use. They also require excessive computation time. Interpreting the results also typically demands expert knowledge (Reinhart and Wienold, 2011). Daylighting properties are greatly influenced by façade orientation and obstructions in the external environment, such as surrounding buildings or landscape elements. In addition to obstructions, glazing transmittances and the opening sizes of windows are factors affecting the amount of incoming daylight. The criteria of satisfaction are based on the quantity and uniformity of the daylight within a space due to space dimensions and surface reflectance (Reinhart and LoVerso, 2010).

The input parameters of an advanced daylight simulation environment are scene geometry, surrounding landscape, ground reflectance, optical material properties, the status of artificial lighting and shading devices, space usage, lighting requirements, schedule as occupancy and lighting, sky model as date, time, latitude, longitude, sky condition and weather data. Daylight simulation engines present luminance and illuminance values (Jakubiec and Reinhart, 2012). Luminance is the term used to describe the amount of light output or its reflection to assess glare in the interior space and visual comfort. The term illuminance concerns the amount of light received on a surface, expressed as a lux measure. Illuminance is considered to be an important performance indicator in assessing daylight in the space, along with the daylight factor, a parameter described as the ratio of indoor to outdoor illuminance (Reinhart and Herkel, 2000). According to the new European Standard for Daylighting (EN17037), released in 2018, the recommended target median value for daylight is at least 300 lux, while the recommended minimum value for daylight is 100 lux (Paule, et al., 2018). Useful daylight illuminance ranges from 100 lux to 2,000 or 3,000 lux. While values above 2,000 lux may cause glare with visual discomfort, values between 100 to 300 lux may require additional lighting (Hraska, 2018). In the present research, 100 lux is determined as the lowest limit for illuminance to accommodate the minimum standard of EN17037.

Structural Analysis (SA)

Buildings are affected by a series of load cases, including dead, live, wind and temperature loads, across the life cycle (Zhang et al., 2007). Static or dynamic analyses are needed to assess the structural performance of the system. For instance, earthquake ground motions generate dynamic behaviour in buildings. To predict a building's seismic response, both non-linear static and dynamic analyses are required (Bilgin and Frangu, 2017). Transient dynamic analysis is necessary along with static analysis for structures with long spans to examine structural vibrations that can cause fluctuation in the internal forces (Zhang et al., 2020). In the interests of simplifying the process and extracting critical parameters, only static structural analysis is currently included in the PBIM.

Finite Element Method (FEM) analysis is one of the most important computational techniques used to assess the structural performance of geometries at any level of complexity. Through the FEM, local stresses on the material can be identified based on disaggregation of the domain into a finite number of elements (Madenci and Guven, 2006). The size of these elements defines the resolution. The sensitivity of the simulation is increased by using the higher resolution as well as increased computation power and time. The computation requires describing the building mass, boundary, loads, supports and materials by specifying critical properties, including young modulus for the elasticity. Quantitative stress values and total deformations on the assigned material can be identified via the static SA using the FEM. Depending on the results, the building geometry, materials, loadings, vector or scalar forces and/or boundary conditions can be altered if the values are not within safety ranges (Yazici, 2013).

By using the FEM to assess structural performance, an optimization procedure can be applied. Design optimization is necessary at the construction phase allowing builders to solve architectural design problems by iterative information exchange between design and analysis (Aish et al., 2012). Structural optimization is investigated in four categories—namely, sizing (cross-section), shape (geometry), material and topology optimization (Dimcic, 2011; Kato, 2010). Drawing on these categories, topology optimization is used as a generative design tool adopted from natural systems, in which the topological arrangement of the material is optimized into the design domain by removing unnecessary material from the whole volume based on the FEM computation (Kazakis et al., 2017). It calculates the distribution of a necessary amount of material on geometry in response to the loads and supports by maximizing the stiffness. Through topology optimization, stresses on the geometry driven by the loads and boundary conditions can be computed and efficient structural arrangements can be organized accordingly, as investigated by

Evolutionary Structural Optimization (ESO) and Bi-directional ESO (BESO) methods (Xie et al., 2005; Xie, et al., 2011).

Wind Flow Analysis (WFA)

The behaviour of the fluids in motion and its influence on the process can be investigated using Computational Fluid Dynamics (CFD) as a part of the WFA. The physical characteristics of the fluid flow can be described by mathematical equations (Tu et al., 2013). Although physical wind tunnel modelling was widely used in the past, today, CFD is considered efficient in terms of time use and cost (Blocken and Carmeliet, 2004). CFD uses computational techniques to solve Navier-Strokes equations to provide a framework for conservation equations for mass, thermal energy and momentum. It has been used in various fields of building simulation, including natural ventilation design, smoke and fire, building material emissions and noise prediction in the environmental analysis (Malkawi, 2004). Additionally, it is considered to be a critical application tool to address problems related to wind engineering, thus affecting the building and its surroundings. Hence, CFD can be evaluated under both the environmental and structural performance categories.

Computing air flows around buildings is relatively more complex compared to the same analysis in an indoor environment (Aynsley, 1999). The behaviour of the wind flow is directly related to the form of the building, and CFD can be integrated to the wind-induced architecture by parametric design (Kormanikova et al., 2018). CFD simulations can be used to assess sand barriers affected by wind loadings as well (Horvat et al., 2020). Coupling methods between the CFD and FEM analyses are necessary to assess structural performance. Defining boundary conditions for them is critical. However, translation from one boundary condition to another causes difficulties (Malendowski and Glema, 2017).

By the use of CFD, velocity and pressure values can be estimated. While velocity describes how air moves around the model by depicting wind speed and direction, pressure represents pressure distribution throughout the flow, used to assess the wind resistance of an object. Additionally, flow lines can be shown with wind directions and speed. Parameters related to the building mass and positioning on the site can be altered based on simulation results.

In an advanced simulation setup, WFA can be coupled with the FEM for dynamic structural analysis. Additionally, material properties can be incorporated into the FEM. First, the building mass and context need to be generated in the model. Then, the mass should be converted into a mesh, by introducing the boundary conditions, wind tunnel boundary called as void more specifically. Voxel size represents the resolution of the simulation. By assigning the wind speed, driven by the geographic location and the positioning on the site, the CFD model and solver setups are generated. CFD analysis provides both quantitative and visual outputs, identified by the gradient of colours related to the velocity, pressure and flow lines.

Spatial Analysis (SpA)

The value of spatial performance is described by building layouts, in which rooms are connected by adjacency relationships and their effects on social interactions by time. The spatial attributes of each space can be described through Space Syntax Analysis, which represents the network configurations and proportions of the shape. Spatial performance parameters are driven by the building configurations, by using a convex representation of space, in which people interact, and all people see each other (Hillier and Hanson, 1984). High connections between spaces represent accessibility. SpA measures include depth (which calculates topological steps between single spaces), integration (which calculates the centrality by which space can be assigned as private or public and how easily other spaces can be reached), difference factor (which identifies whether space is differentiated), control value (which calculates how space is linked to other spaces), and choice value (which indicates how important a node is in a configuration by identifying how many times that node represents the shortest path between the remaining nodes) (Nourian et al., 2013). Space syntax analysis can be applied to 2D floor plans, informed by the building mass and urban plans to measure the characteristics of the layout and show how spaces are related to each other. Space is more integrated into the system if it can be reached easily or segregated if many other spaces should be passed. The spatial system is presented as a system of lines—namely, connection vectors representing movement between the units. The analysis can be based on isovists as well. They are called visibility polygons and represent all things that can be observed from a given point in the plan layout—namely, those that are not interrupted by a boundary. While eye-level isovists signify visibility, floor-level isovists denote accessibility. Intelligibility is a correlation between local and global measures, such as between connectivity and integration (Wineman and Peponis, 2010).

Regenerating the Design Model by Extracting Critical Parameters

Using computational techniques, critical parameters related to design and performance issues are identified in the process. By applying the method for performance computation, including SRA, DA, SA, WFA and SpA, each student needs to extract the inputs and outputs of their process. Feedback is provided from the performance simulation into the design model. Thus, the re-generation of the design model is enabled, if necessary. **Figure 2** represents the relationships between performance computation methods, site- and time-specific parameters along with the architectural geometry, material and structural conditions. The critical performance and design parameters include geographic location, positioning on the site, weather data, time, context, prevailing wind flows, wind speed, building mass, façade design, floor plan, material, boundary conditions, loads and supports, and geometrical properties.

CASE STUDIES

The PBIM was implemented between 2017 and 2019 in two different undergraduate architecture courses, including Architectural Design Studio IV (ADS IV) and an elective course, of which content was developed in the axis of CD, biomimicry and PBD. The task of the architectural design studio was to analyse the site, programme, and user requirements, along with critical performance criteria to be integrated into the conceptual design. As a part of the elective course, participants needed to research a phenomenon found in natural systems, understand the properties of the system and apply those to a design problem.

Architecture students can enrol to the ADS IV in their fifth term, which represents the first term of the 3rd year regular students. The majority of the

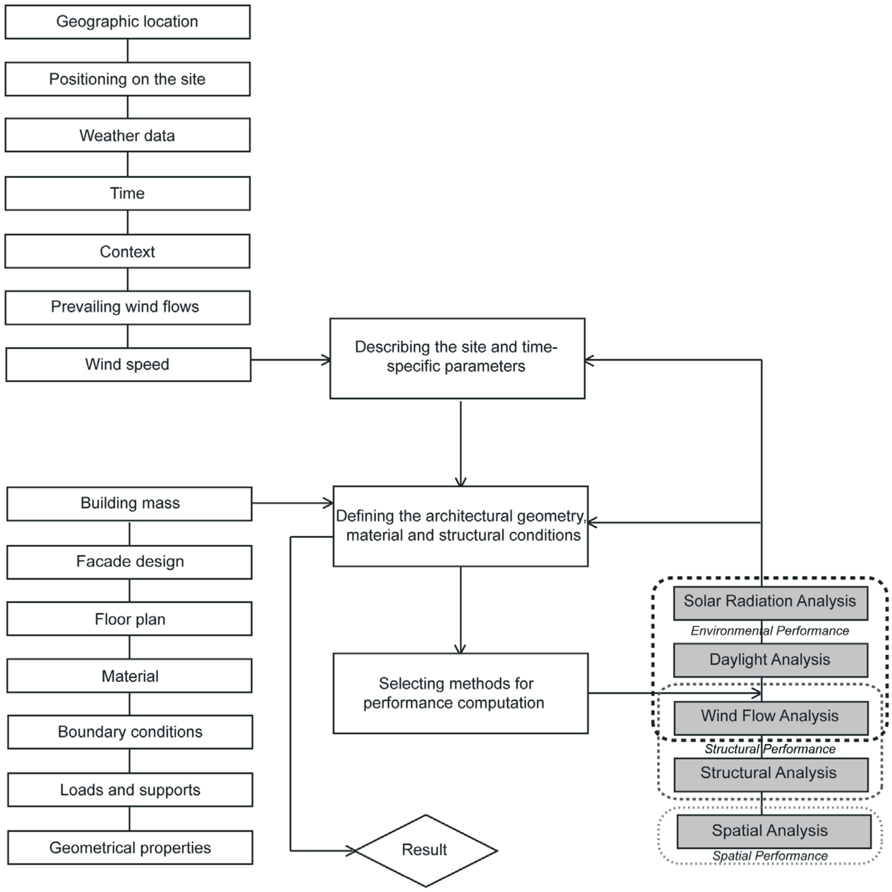


Figure 2. Critical parameters of the PBIM methodology.

building science and technology courses, including “Building Construction and Materials”, “Construction Technologies”, “Statics and Mechanics of Materials”, “Structural Analysis” and “Computer-aided Design I & II” were given in their third and fourth term according to their curriculum. While “Environmental Control” course was in the fifth term in parallel to the ADS IV, “Building Systems”, the last course of building science and technology section, was in their sixth term of study. Despite the majority of the students were not experts, they had already gained knowledge in terms of performance in architectural design. However, they were not familiar to integrate performance issues with the design projects during the conceptual development, undertake performance simulations and interpret the results. Since the profile of the students in the elective course was varied from the 2nd to the 4th year, their level of knowledge and skills were differentiated. Thus, both novice and expert participants were involved in the elective course.

Five studies (Case Study I–V) have been selected and are explained further in terms of five different performance computation methods, due to their capability of integrating performance and design parameters in the early stage. Eleven different tools were used in the process for modelling and analysis purposes, including Rhinoceros for geometric modelling, the Rhinoceros GH plug-in for algorithmic modelling, the GH Ladybug add-on for sun path and SRA, EnergyPlus for weather data, Velux for DA, the GH Millipede add-on for SA by the FEM and topology optimization, the Rhinoceros T-Splines plug-in for geometric modelling, the GH Kangaroo add-on for physics-based form-finding, Autodesk Flow Design for WFA by

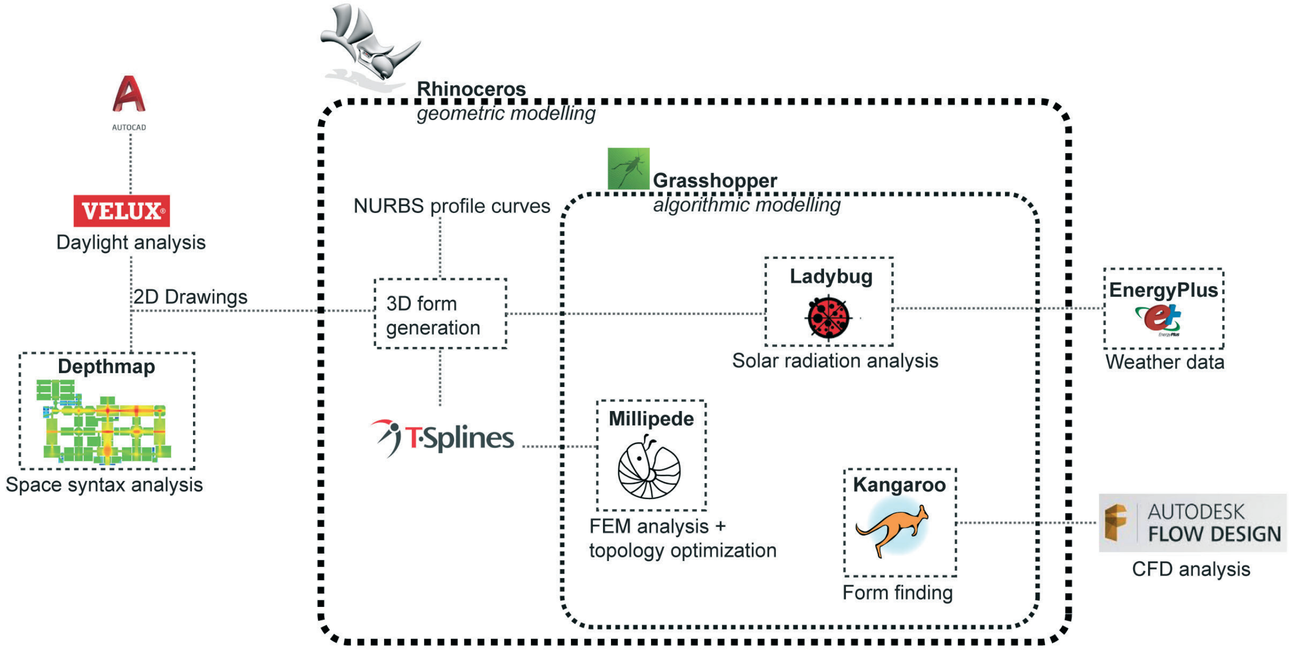


Figure 3. Tool ecologies representing geometric, algorithmic and analytical modelling used in the case studies and the relationships among them.

the CFD, AutoCAD for vector-based 2D drawings, and Depthmap for SpA (**Figure 3**). The tools used in the process have been selected according to their relatively simplified interfaces for undertaking complex performance simulations, such as Velux for DA or Autodesk Flow for WFA.

Case Study I

SRA as a performance computation method was undertaken in the first case study.

Generating the Design Model

The task of the architectural design studio was to develop an Architecture and Design Centre. Because the given site was surrounded by attached buildings in the vicinity, the effect of the sun concerning the architectural form played a critical role. The initial building mass and context were generated in the Rhinoceros geometric modelling environment, taking into account the site, user, and programme constraints. The building's positioning on the site reflects certain design decisions, such as the location of the entrances, public space allocation and the relationship of the mass with the context.

Applying the Performance Computation Method

The building mass was brought to the algorithmic modelling environment GH for the SRA using the Ladybug add-on. Ladybug is considered efficient for climate analyses, including assessment, visualization, massing and orientation, but not for complex environmental analyses. By assigning the geographic location, the weather file was inserted to the model in .epw format, driven by EnergyPlus. The time was set in the form of the month, day and hour. According to the analysis, solar radiation values on the geometry were indicated, along with colours on the building mass. In addition to SRA, sun path analysis was undertaken by the Ladybug add-on.

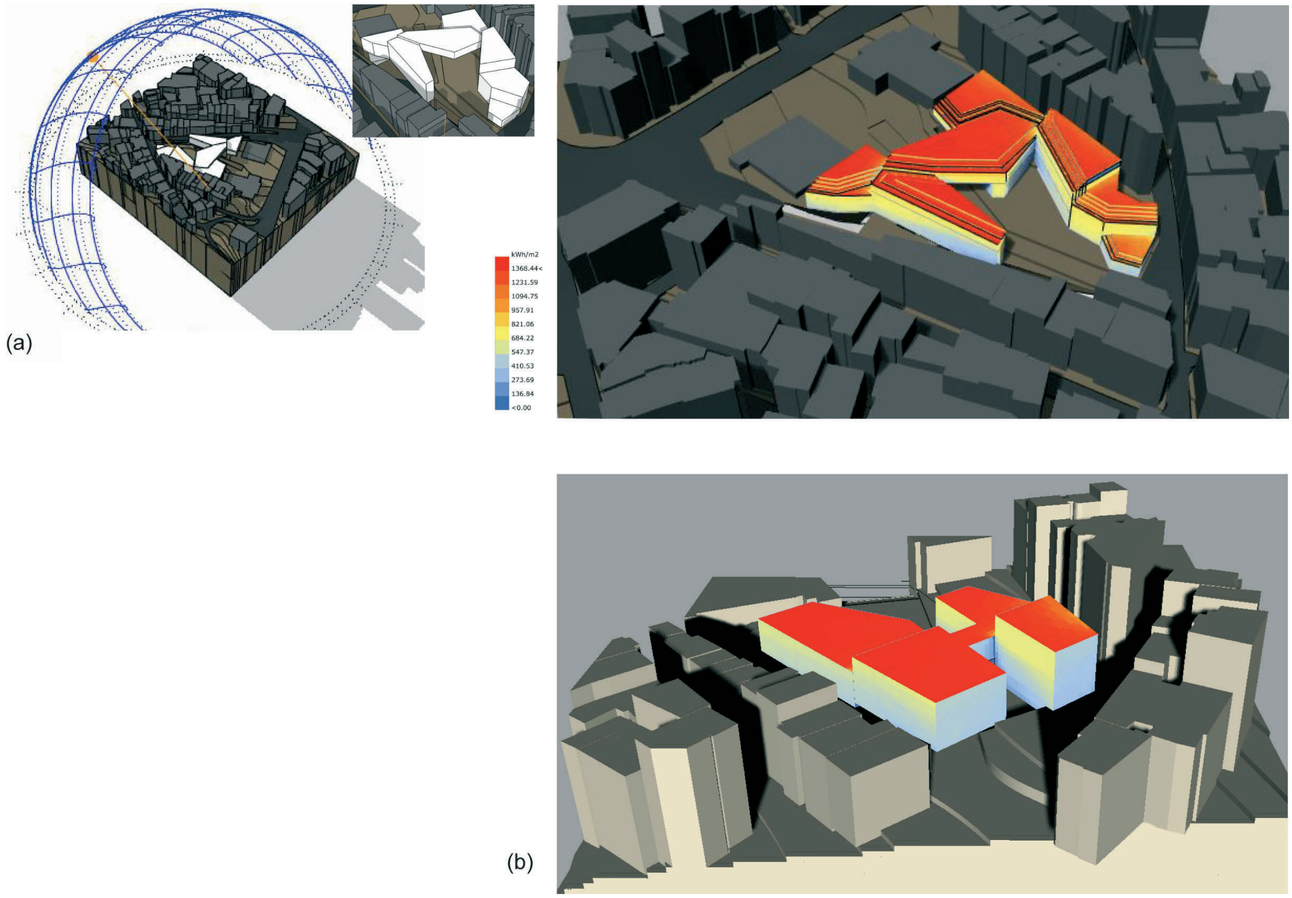


Figure 4. Case Study I. Solar Radiation Analysis, Participants names: Ayşe Özlem Dal and Osman Ensar Kandemir (a) Sun path analysis, (b) Solar radiation analyses for the given project location.

Regenerating the Design Model by Extracting Critical Parameters

Some modifications were necessary for areas where high radiation obtain, including adjusting the building mass vis-à-vis the positioning on the site. Additional protection layers, such as shading devices, needed to be designed and incorporated into the façade (**Figure 4**).

Case Study II

DA as a performance computation method was undertaken in the second case study.

Generating the Design Model

The task of the architectural design studio was to develop a Design Hub. The selected building mass was driven by a complex geometry, consisting of loops that form both the walls and floors. The geometric model was generated in Rhinoceros, taking into consideration the site—including geographic location, positioning on the site and weather data—and user and programme constraints. The window openings on the façade were tested as pattern studies and indicated in the model. Following the generation of the 3D geometric model, the floor plans were extracted by splitting the model according to the various levels.

Applying the Performance Computation Method

The objective was to ensure sufficient natural light in the interior spaces of the building. DA was integrated into the conceptual design of the Design Hub proposal. There was no artificial lighting, shading devices or schedules provided in the simulation to simplify the process. By generating the architectural geometry, 2D drawings as plan layouts were imported to the Velux Daylight Visualizer in.dwg format to assess the illuminance values for the interior spaces. Performance parameters included outer walls, façade windows, floor plans, orientation and location of the building, time, weather data, and context. Material properties were also critical, such as roughness, specularity, reflectance and colour values. Horizontal sections and plans were used in the process. Daylight levels were measured as lux values, presented as numbers and colours. The minimum requirement for an optimal condition was indicated as 100 lux according to the European Standard for Daylighting (EN17037) since lower values would generate relatively darker indoor spaces. The analyses were undertaken for the whole building, including spaces such as the library, co-working area, design studios, model laboratory, and cafes.

Regenerating the Design Model by Extracting Critical Parameters

By drawing out continuous feedback from the performance simulation model, the building mass, floor plans, façade design—including the outer walls and façade windows—selected materials and positioning on the site can be altered. In the case study, the problem areas were specified based on values lower than 100 lux. In this way, light-deficient spaces were indicated. Plan layouts were altered according to the results of the analysis. For instance, areas receiving less natural light in the library were assigned to house bookshelves and in the co-working space to lounge areas. A series of pattern studies were undertaken for the façade windows to achieve better performance in terms of daylight (**Figure 5**).

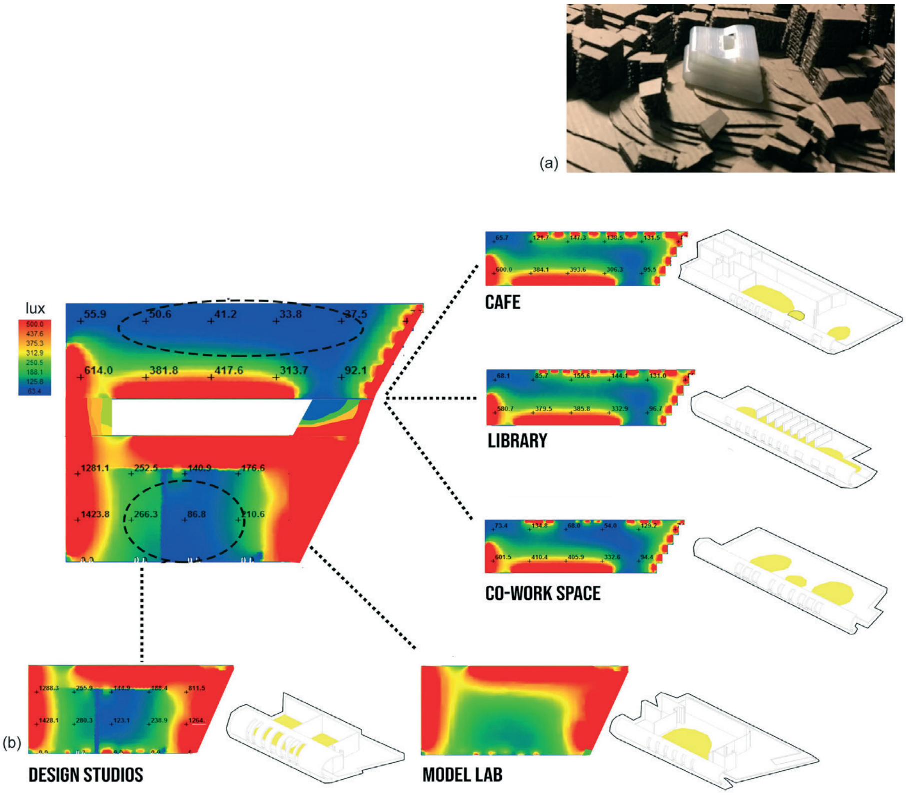


Figure 5. Case Study II. Daylight Analysis, Participant name: Can Müezzinoğlu (a) 3D printed model of the building geometry, driven by loop formations (b) DA undertaken for the Design Hub proposal according to the program distribution on the floors.

Case Study III

SA as a performance computation method was undertaken in the third case study.

Generating the Design Model

An Architecture and Design Centre was developed as a part of an architectural design studio. The geometric model was generated using Rhinoceros. Following the initial building mass study—which considered the site, user and programme constraints—further investigations were undertaken for the column designs in the interior space.

Applying the Performance Computation Method

Generative design solutions can be created by applying principles of SA and topology optimization. In the case study, column structures were shaped according to the forces by the use of the FEM. They were optimized through the evolution process. Columns were designed with the intent of generating structurally efficient geometries, by removing materials from the whole that are not needed from a structural point of view. Geometric and algorithmic modelling tools, including Rhinoceros and GH, were used in the process, as well as topology optimization add-on Millipede for GH, a SA and optimization component, used for linear elastic systems for frame and shell elements. The study defined the boundary (which indicates the place of the columns), self-weight as loads, supports, material, the number of iso-curves (which forms how columns fit the geometry), and optimization steps (which represent the number of iterations of the optimization).

Regenerating the Design Model by Extracting Critical Parameters

By applying the FEM and topology optimization, efficient structural design solutions can be generated through modifications in architectural geometry, materials, and structural conditions, including loads, supports and/or boundary conditions. During the process, a series of iterations for columns were developed. The geometries presented enough information about the topology, as well as stress values and deformations on the material, but the iterations did not produce sufficiently clean geometries. Therefore, after the columns were generated and selected through topology optimization, they were re-modelled and converted into NURBS surfaces to achieve smoother surfaces using the T-spline plug-in for GH (**Figure 6**).

Case Study IV

WFA as a performance computation method was undertaken in the fourth case study.

Generating the Design Model

The case study was developed as a part of the elective course, in which no site or programme was given. Participants were required to explore natural systems, understand the system characteristics and implement what they had learned into a design problem. One participant proposed a shelter to be used under extreme weather conditions, located in a desert, where dunes were naturally generated by the wind flows. The intent was to adapt the form of building to its natural environment by reducing the most severe effects of the wind. After analysing the various dune types occurring on the earth, barchan dunes were selected for further investigation. The form-finding process was driven by the wind simulation undertaken by the

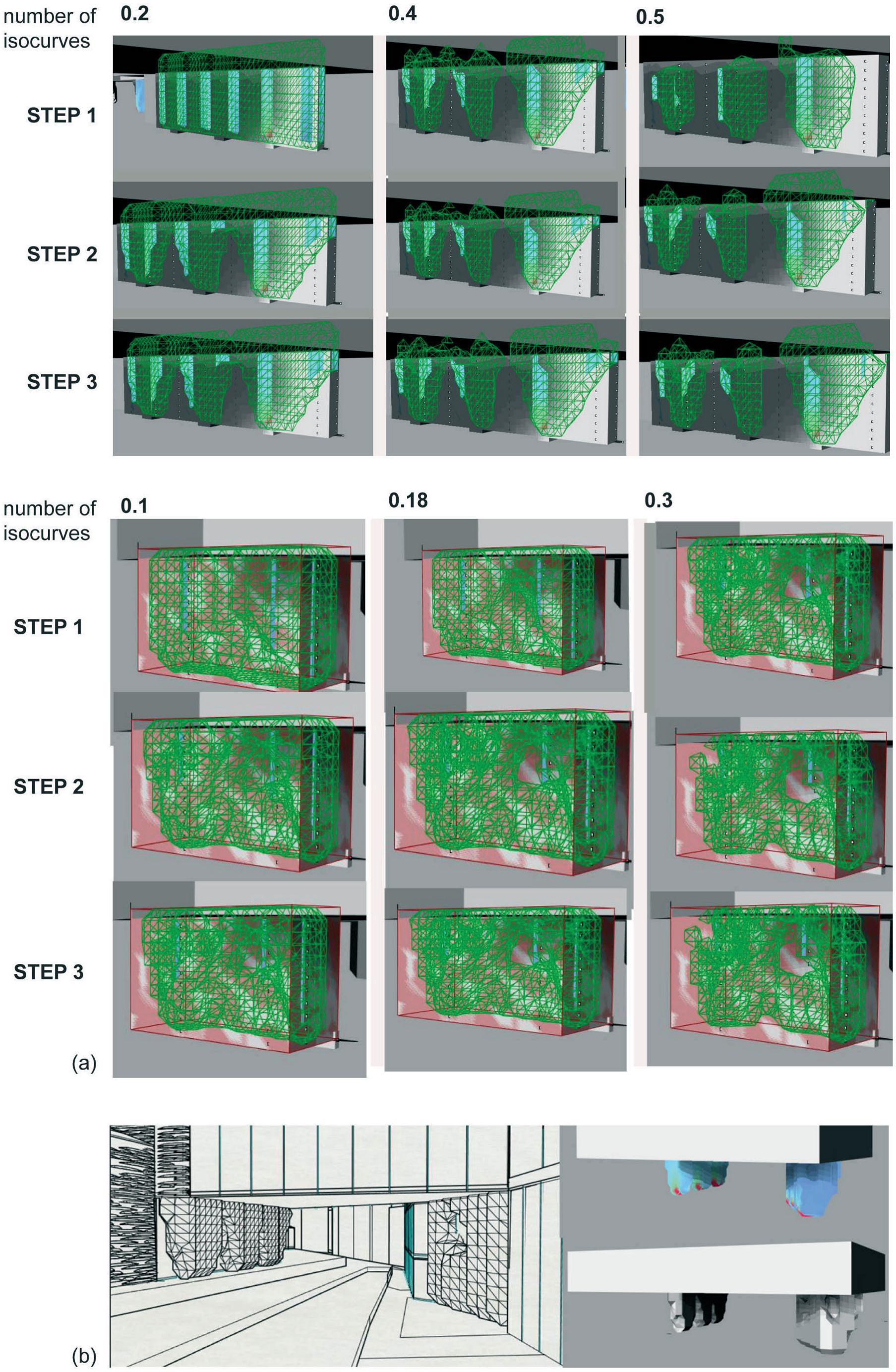


Figure 6. Case Study III. Structural Analysis, Participant name: Ayşe Özlem Dal (a) Iterations generated during the topology optimization undertaken by FEM (b) Optimized design of the columns inserted into the interior space.

Kangaroo add-on for GH, a physics-based simulation engine. The student in the selected case study was a 4th year student, who completed all the required building science/technology courses and was relatively an expert in the class. Novice participants experienced problems in interpreting the performance concept and using CD models.

Applying the Performance Computation Method

Considering the site conditions, wind flow effect needed to be integrated into the design process from the beginning. Following the form-finding step, geometry, in .mtl or .obj file formats, was introduced to the Autodesk Flow Design environment for the CFD analysis. The simulation needed to specify the following parameters: prevailing wind flow from east to west associated with the geographic location and positioning on the site, wind speed, the designated boundary of the wind tunnel simulation space, referred to as the void and defined by length, width and height, and voxel size, related to the grid resolution. A high-resolution grid requires smaller voxels.

An advanced simulation coupled with the FEM simulation can also adopt material properties. This possibility was, however, excluded from the present study. Flow lines, pressure (Pa) and velocity (m/s) values acting upon the system were computed. The results were evaluated both in 2D, including the top and side views, and in 3D views.

Regenerating the Design Model by Extracting Critical Parameters

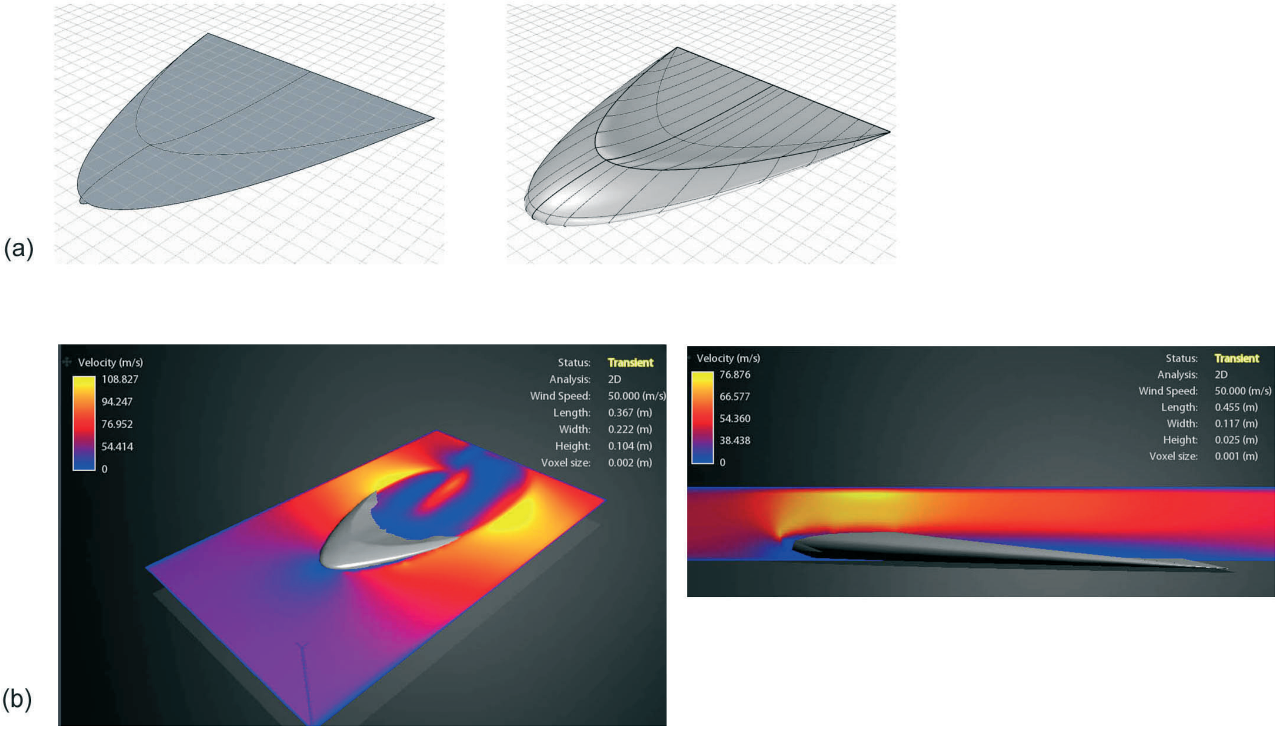
According to the results of the CFD analysis, the building mass and orientation of the building can be modified in the early design stage. In the case study, architectural geometry—including the height of the mass, along with its positioning on the site—needed to be altered to reduce the wind effects on the geometry and its surroundings based on the wind flow pattern (**Figure 7**).

Case Study V

SpA as a performance computation method was undertaken in the fifth case study.

Generating the Design Model

The case study was developed as part of the architectural design studio, the programme of which was a Cultural Hub, consisting of public and private spaces. The geometry was modelled in Rhinoceros, taking into account



Status: Transient
Analysis: 2D
Wind Speed: 50.000 (m/s)
Length: 0.367 (m)
Width: 0.222 (m)
Height: 0.104 (m)
Voxel size: 0.002 (m)

Status: Transient
Analysis: 2D
Wind Speed: 50.000 (m/s)
Length: 0.455 (m)
Width: 0.117 (m)
Height: 0.025 (m)
Voxel size: 0.001 (m)

Figure 7. Case Study IV. Wind Flow Analysis, Participant name: Tamer Kumaş (a) Form-finding process of barchan dune driven by physics-based simulation engine, (b) CFD analysis showing wind flow interacting with the building mass.

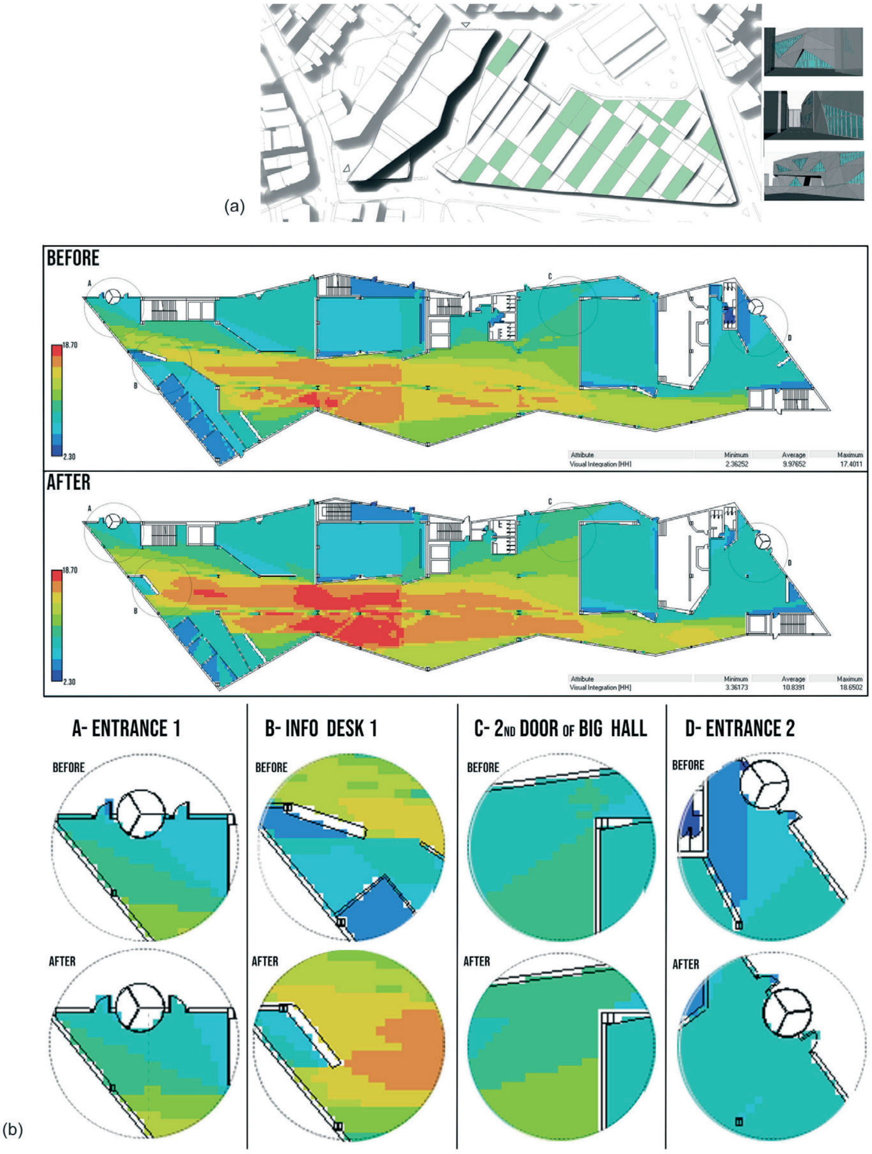
the site, user and programme constraints. The floor plans were generated through the 3D geometric model by splitting the model according to the assigned levels.

Applying the Performance Computation Method

The organizational principles of the floor plans played a significant role in space quality. The 2D plan layouts were introduced into the Depthmap, Space Syntax Analysis software in .dxf format to assess the connection vectors, isovists and visual integration. The results were depicted on the plans as quantitative values and colours.

Regenerating the Design Model by Extracting Critical Parameters

According to the space syntax analysis results, floor plans can be re-designed to meet better conditions for connections in the early design stage. In the case study, the initial plan layout was regenerated to increase connectivity. The main focus was to minimize visual obstacles and to enable enhanced human interactions. For instance, by re-designing the



Attribute	Minimum	Average	Maximum
Visual Integration [HH]	2.36252	9.97652	17.4011

Attribute	Minimum	Average	Maximum
Visual Integration [HH]	3.36173	10.8391	18.6502

Figure 8. Case Study V. Spatial Analysis, Participant name: Zeki Kaan Soyer (a) The building mass with the landscape (b) Space syntax analysis undertaken to improve interior space layout by assessing the visual integration.

plan, the visibility of the entrance was increased by making it more accessible. Additionally, rotating the info desk and minimizing the management area reduced obstacles around the entrance (**Figure 8**).

RESULTS AND DISCUSSION

As a result of implementing the PBIM in the selected case studies, three significant outcomes were identified—namely, evaluation of the model types and analysis tools (1), specification of the inputs and outputs (2), and identification of relationships between the input and output data (3). The PBIM was validated by using a different toolset, and a Sensitivity Rate (SR) for each study was calculated.

Evaluation of the Model Types and Analysis Tools

The case studies have been evaluated in terms of their performance types, the methods and tools used, the file formats used to transfer the model and model types for performance analysis. Rhinoceros, the T-Splines plug-in for Rhinoceros, GH, the Kangaroo add-on for GH and AutoCAD were used as geometric and algorithmic modelling tools. Analytical tools in the PBIM include the Ladybug and Millipede add-ons for GH as Distributed Models, and Velux Daylight Visualizer, Autodesk Flow Design and Depthmap as Combined Models - Central Models, associated with BIM applications, were not used in the PBIM because students preferred to use geometric modelling tools, in which they explored conceptual design alternatives flexibly in the early design stage (**Table 1**).

Specification of the Inputs and Outputs

The case studies were assessed by extracting both semantic and geometric information and specification of the inputs and outputs, driven by design and analysis processes. There were two input sets for the parameters related to the site and time, on the one hand, and architectural geometry, material and structural conditions, on the other. The former included geographic location, positioning on the site, weather data, time, context, prevailing wind flows and wind speed. The latter included building mass, façade design—such as outer walls and façade windows—floor plan, material, boundary conditions specified by boundary or void,

Performance type	Methods for performance computation	Geometric & algorithmic modelling tools	File format to transfer the model for analysis	Model type for performance analysis & analytical tools
Environmental Performance	Solar Radiation Analysis	Rhinoceros	.3dm	Distributed Model: Ladybug plugin for Grasshopper
Environmental Performance	Daylight Analysis	Rhinoceros	.dwg	Combined Model: Velux Daylight Visualizer
Structural Performance	Structural Analysis / FEM	Rhinoceros + T-splines plug-in for Rhinoceros	.3dm	Distributed Model: Millipede add-on for Grasshopper
Structural Performance	Wind Flow Analysis / CFD	Rhinoceros + Kangaroo add-on for Grasshopper	.obj and .mtl	Combined Model: Autodesk Flow Design
Spatial Performance	Spatial Analysis / Space Syntax	Rhinoceros or AutoCAD	.dxf	Combined Model: Depthmap

Table 1. Evaluation of the case studies, in terms of performance type, methods, tools, file formats, and model types for performance analysis.

Case Studies	Inputs: Site and time	Inputs: Architectural geometry, material and structural conditions	Outputs
Solar Radiation Analysis (SRA)	1 Geographic location 2 Positioning on the site 3 Weather data 4 Time 5 Context	6 Building mass	20 Solar radiation
Daylight Analysis (DA)	1 Geographic location 2 Positioning on the site 3 Weather data 4 Time 5 Context	6 Building mass 7 Outer walls 8 Façade windows 9 Floor plan 10 Material	21 Illuminance
Structural Analysis (SA)	None	6 Building mass 10 Material 11 Boundary 12 Loads 13 Supports 14 Number of iso-curves 15 Steps for optimization	22 Optimized design 23 Stress 24 Deformations
Wind Flow Analysis (WFA)	1 Geographic location 2 Positioning on the site 5 Context 16 Prevailing wind flow 17 Wind speed	6 Building mass 18 Voxel size 19 Void	25 Flow lines 26 Velocity 27 Pressure
Spatial Analysis (SpA)	None	6 Building mass 9 Floor plan	28 Connection vectors 29 Isovists 30 Visual Integration

Table 2. Inputs and outputs generated by the case studies.

loads and supports, and geometric properties identified by the number of iso-curves, steps for optimization or voxel size. As a result of the performance simulations, the extracted outputs were solar radiation, illuminance, optimized design, stress, deformations, flow lines, velocity, pressure, connection vectors, isovists and visual integration. The results are presented in the form of numerical and graphical outputs (**Table 2**).

Identification of Relationships between the Input and Output Data

Design can be considered as an optimization, in which the designer makes decisions according to the importance of parameters. Even though performance computation is a complex task for architecture students, case studies were developed towards particular design tasks, in which the relationships between design and performance parameters were investigated and internalized by students. Students started to evaluate parameters towards finding optimal solutions since case studies assisted their decision-making process. A building mass and space can be formed in any level of complexity in the PBD, unlike the simplified examples used in building science and technology courses. The contribution of this study is based on not only extracting critical design and performance parameters driven by different performance computation algorithms that can shape conceptual design decisions in the early design stage, but also it underlines that creative design solutions can be supported by the use of PBD.

According to the evaluation of the case studies, the relationships between the 19 input and 11 output data are identified (**Figure 9**). The results

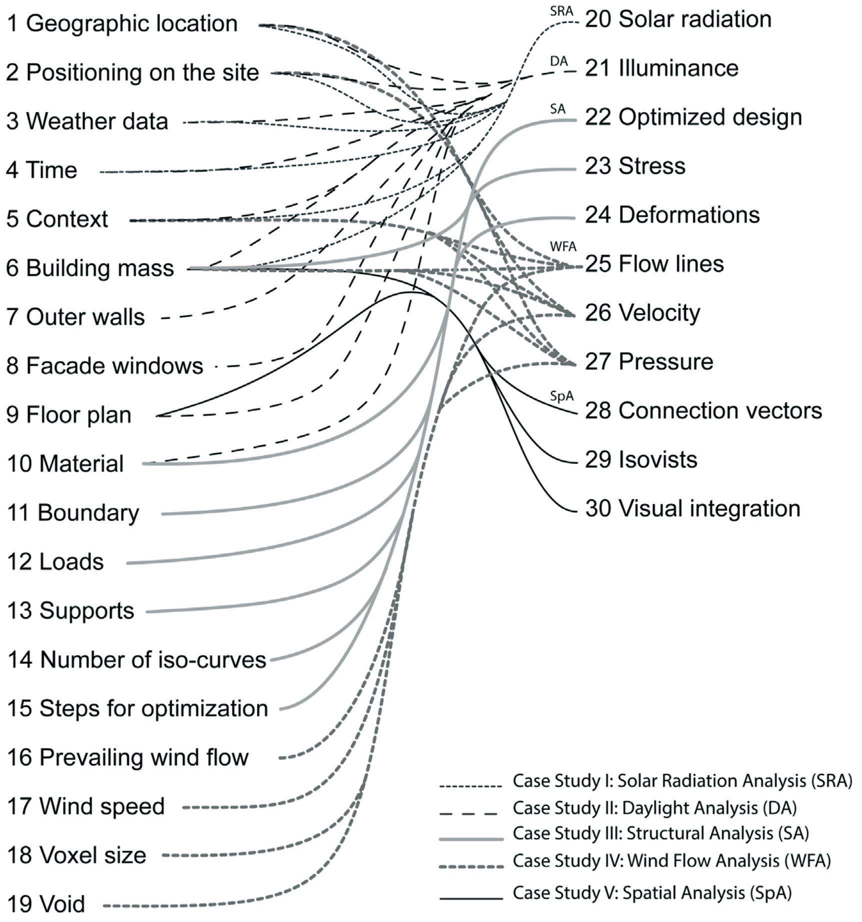


Figure 9. Diagram representing the relationships between the inputs and outputs.

indicate that some data are more salient in the process than others, due to greater interlinkages, which is visualized through ConnectTheDots, open-source software that uses network graphs. The dataset is generated by Microsoft Excel in CSV format.

Data analysis allows us to gain insight by representing the data as nodes and connections. The nodes should be linked by an edge, referring the connections made. Specific terms are used to describe network graphs, such as centrality, which measures the relative degree to which a given node is a connector. The higher the centrality score for a node, the greater the number of other nodes that can go through it. Another property is the degree, which represents the number of connections obtaining for a given node. Therefore, the overall characteristics of nodes can be interpreted based on their degree and centrality values, which are normalized to be independent of the number of cases and to fit a certain range. The equation below is applied to the values in Table 3 to calculate the normalized values (NNVE, 2020):

$$X\_normalized = (b - a) * [(x - y) / (z - y)] + a$$

In this equation "b" is the max value and "a" is the min value to normalize to which are "1" and "0" respectively in the study. The assigned degree or centrality value is shown by "x". While "y" represents the minimum, "z" symbolizes the maximum of the input range.

Node	Degree	Centrality	Normalized Degree	Normalized Centrality
Building mass	11	0.497	1,000	1,000
Illuminance	10	0.292	0,900	0,588
Flow lines	8	0.097	0,700	0,195
Pressure	8	0.097	0,700	0,195
Velocity	8	0.097	0,700	0,195
Deformations	7	0.103	0,600	0,207
Optimized design	7	0.103	0,600	0,207
Stress	7	0.103	0,600	0,207
Solar radiation	6	0.063	0,500	0,127
Context	5	0.033	0,400	0,066
Geographic location	5	0.033	0,400	0,066
Positioning on the site	5	0.033	0,400	0,066
Floor plan	4	0.025	0,300	0,050
Material	4	0.058	0,300	0,117
Boundary	3	0.001	0,200	0,002
Loads	3	0.001	0,200	0,002
Number of iso-curves	3	0.001	0,200	0,002
Prevailing wind flow	3	0.001	0,200	0,002
Steps for optimization	3	0.001	0,200	0,002
Supports	3	0.001	0,200	0,002
Void	3	0.001	0,200	0,002
Voxel size	3	0.001	0,200	0,002
Wind speed	3	0.001	0,200	0,002
Connection vectors	2	0.007	0,100	0,014
Isovists	2	0.007	0,100	0,014
Time	2	0.002	0,100	0,004
Visual connectivity	2	0.007	0,100	0,014
Weather data	2	0.002	0,100	0,004
Facade windows	1	0	0,000	0,000
Outer walls	1	0	0,000	0,000

Table 3. Analysis of the data according to their degree and centrality values driven by network graph.

The graph has two types of nodes—namely, the source and target nodes—which can be translated to input and output data. By visualizing the data, the resulting network graph displays 30 nodes and 67 edges (**Figure 10**). Analysis of the graph indicates that the connector is building mass,

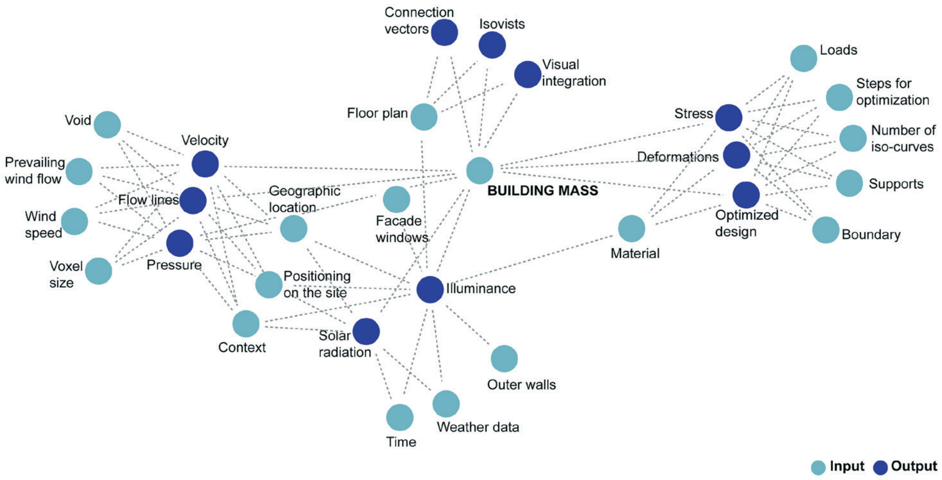


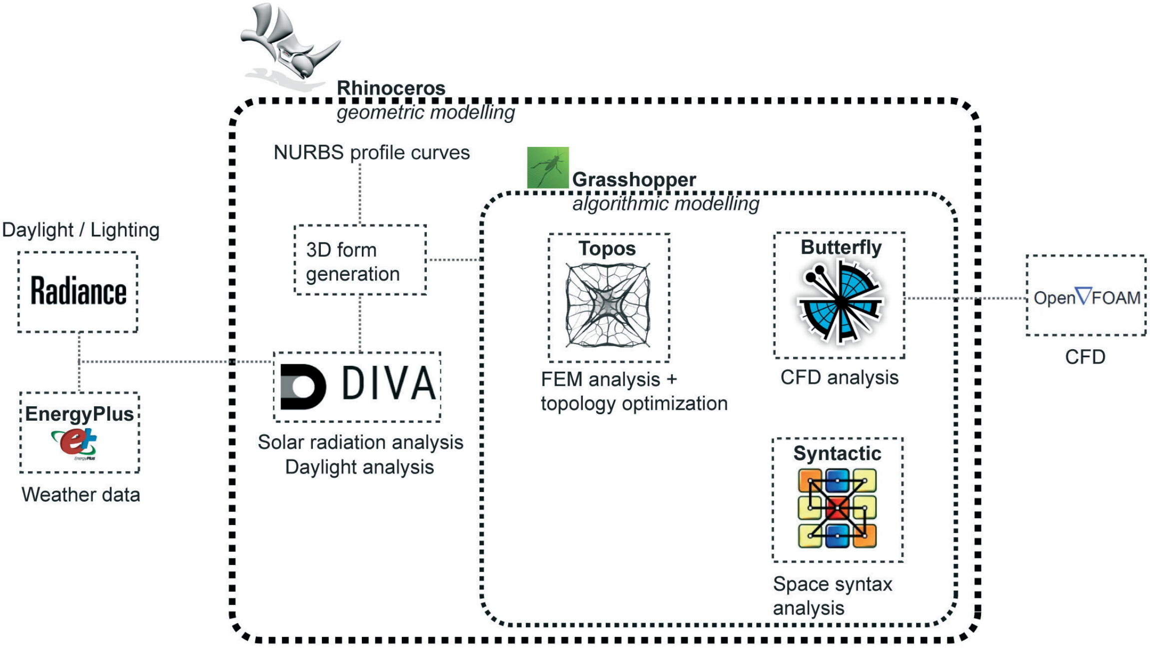
Figure 10. The network graph generated for the data. The connector is *building mass* with the highest betweenness centrality score.

which has the highest betweenness centrality score (0.497) with a degree score of 11. This means that most of the nodes go through building mass to connect other nodes in the network. Investigating the relationships among the nodes and edges in a network graph allows us to interpret how information is transmitted through the system. For instance, the material has the seventh-highest number of connections with a degree score of 4. By comparing the floor plan to the material (both with degree scores of 4), we see that material plays a more significant role in the PBIM because its centrality score is higher. Similarly, all data can be interpreted vis-à-vis their contribution to the design process. Since the architectural design is considered to be an optimization process, in which architects, designers or students determine the importance of parameters and prioritize some of them according to their subjective opinions, the PBIM offers an initial insight into how different design and performance parameters might inform the decision-making process in the early design stage.

Validation

The PBIM is implemented as a pedagogical approach for undergraduate architecture students, with the intent of simplifying the decision-making process in design by extracting only critical parameters. The model is validated by using a different toolset, including the Diva plug-in for Rhino (not only used for the SRA and DA, but also the thermal and glare simulations), the Topos add-on for GH, used for the SA and topology optimization, the Butterfly add-on for GH, used for the WFA, and the Syntactic add-on for GH, used for the SpA. Diva is a comprehensive tool linked to validated environmental simulation engines for daylight and energy use, including Radiance and EnergyPlus. Additionally, Butterfly uses OpenFOAM as a validated software platform for advanced CFD simulations (**Figure 11**). All the tools used in the validation, including Diva, Topos, Butterfly and Syntactic, can be evaluated under Distributed Models since they are all associated with Rhinoceros and GH.

Figure 11. Different toolset used for validation of the PBIM.



Inputs: SRA and DA

- **1** Geographic location
- **3** Weather file (.epw)
- **4** Time
  - date and time
  - start time, end time
  - hour range
  - day
  - hour
- **5** Context geometries
- **6** Building mass
  - Nodes for analysis
  - Distance of nodes / grid
- **8** Window openings
- **9** Floor plan
- **10** Materials
  - Daylighting
  - Thermal materials
- Lighting
  - Electric lighting file
  - electric lighting off
  - detailed electriclighting controls / operation type, lighting power,etc.
- Shading
  - Conceptual Shading controls
  - Blind or operable shading devices
  - No shading
  - Conceptual dynamic shading
  - Detailed dynamic shading
  - Hide dynamic shading
- Sky condition
  - Clear sky with sun
  - Utah colored sky model
  - Clear sky without sun
  - Overcast sky
  - Custom sky
  - Intermediate sky with sun
  - Intermediate sky without sun
- Camera
  - Select camera views
  - Camera type
  - Image quality
  - Image size
  - Camera type
- Set LM-83 sDA control
- Radiance parameters
- Geometric density
- Radiance raytracing par.
- Cumulative sky method
- Daysim-based hourly mth.
- Occupancy schedule
- Target illuminance
- Adaptive visual comfort
- Occupant density
- Equipment power density
- Air changes
- Heating efficiency
- Cooling efficiency
- Cooling-heating setpoint
- Cooling-heating setback
- Natural ventilation

Outputs: SRA and DA

- Daylight Images
- Visualization
- Timelapse
- Radiation Map
- Point-in Time Glare, Annual Glare
- Daylight Grid-based
- Daylight factor
- Point-in Time Illuminance
- Climate-Based Radiation Map
- **20,21** Visual display: falsecolor Irradiance
- **20** Radiation values
  - Solar exposure rend.
  - Min daylight autonomy
  - Photorealistic images
- **21** Illuminance contours
  - Luminance falsecolor
  - Thermal Single-Zone
  - Daysim report

Inputs: WFA

- **6** Geometry
  - Wind-tunnel
  - Wind tunnel parameters
- **16** Wind direction
  - Wind vector
- **17** Wind speed
  - Reference height for wind velocity
- **5** Landscape: an integer between 0-7 from sea to chaotic
  - MeshParams
  - Cell size in xyz
  - grad XYZ
  - locationinmesh
  - globrefinelevel
- **18** Mesh
  - BlockMesh
  - snappyHexMesh
  - chekMesh
  - snappyHexMeshDict
  - grading XYZ
  - multigrading
  - segment grading
  - load mesh
  - load points
- **19** Boundary
  - Inlet boundary
  - inlet flow-rate boundary
  - outlet boundary
  - wall boundary
- Boundary conditions
  - Calculated
  - EpsilonWallFunction
  - FixedValue
  - KqWalFunction
  - NutkWalFunction
  - ZeroGradient
- Turbulance
  - Laminar turbulance model
  - LES turbulance model
  - RAS turbulance model
- Recipe
  - Heat transfer recipe
  - steady incompressible recipe
  - relaxtion factors
  - residual control
- Solution
  - solution parameters
  - controlDict
  - function object

Outputs: WFA

- Solution
  - loadprobes
  - loadprobesvalue
  - plotresiduals
    - time range
    - curves
    - residual line colors
  - residualFields
  - residualvalues
- **25** preview geometry
- **26** velocity
- **27** pressure

Inputs: SA

- **6** Domain properties
- **10** Material properties
  - Young module
  - Poisson factor
- **11** Boundary
  - Boundary conditions
  - Boundary domain
  - Boundary properties
- **12** Loads
  - Linear load
  - Point load
  - Surface load
  - Volume load
- **13** Supports
- **14** Model resolution
- **15** Optimization iteration
  - Subdivision threshold

Outputs: SA

- Boundary cond.data
- Element data
- Node data
- Iso mesh
- Voxel mesh
- Preview densities
  - Density
  - Compliance
  - Sensitivity
- **22** Geometry preview
- **23** Principal stress
- **24** Deflections

Inputs: SpA

- Functional spaces
- Area values
- **9** Spatial connections

Outputs: SpA

- **28** Graphs
  - Spatial properties
- **30** Integration
  - Topo. shortest paths
  - Bubble diagram

Table 4. Critical input and output parameters in the PBIM, indicated with numbers from 1 to 30, are associated with parameters in the validation.

Critical input and output parameters identified in the PBIM (shown in **Table 2** and **Figure 9**) are associated with those extracted by the toolset in the validation (**Table 4**).

Table 5. Comparison of the parameters used in the PBIM and the validation.

	PBIM (Input and output parameters)	Validation (Input and output parameters)
SRA	1, 2, 3, 4, 5, 20	1, 3, 4, 5, 20
DA	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 21	1, 3, 4, 5, 6, 8, 9, 10, 21
SA	6, 10, 11, 12, 13, 14, 15, 22, 23, 24	6, 10, 11, 12, 13, 14, 15, 22, 23, 24
WFA	1, 2, 5, 6, 16, 17, 18, 19, 25, 26, 27	5, 6, 16, 17, 18, 19, 25, 26, 27
SpA	6, 9, 28, 29, 30	6, 28, 30

Different software platforms may use various terms to describe the same or similar content. For instance, some tools may, for example, indicate building mass as “geometry”, context as “context geometries” or “landscape”, and façade windows as “window openings”. Thus, parameters were categorized according to the interpretation of their meanings. Since more comprehensive tools, including Diva and Butterfly, were used in the validation, a significant amount of input and output parameters existed that generally require expert knowledge for their interpretation. Table 5 indicates the comparison of the input and output parameters provided in the PBIM and the validation.

Some exceptional parameters did not overlap with those in the validation. For instance, students needed to identify the positioning of their buildings during their design process. For the validation study of the SRA and DA, (2) positioning on the site was not provided as a separate parameter. However, it is identified already by selecting building mass in the 3D modelling environment. (7) Outer walls were also not selected as an additional parameter for the DA; instead, they were evaluated along with the building mass. Nodes for analysis parameters in the validation study cover the selection of surfaces according to the assigned layers, including the outer walls or floor plans. Similarly, for the validation of the WFA, (1) geographic location and (2) positioning on the site were not assigned separately, as they were directly associated with wind speed and direction. Students identified these parameters in their design processes by considering the location and orientation of the buildings. For the validation of the SpA, (6) building mass and (29) isovists were not required. Due to the capabilities of the software used in the validation, the outline boundary of the plan was not necessary; instead, the relationships of the spaces in the plan as graph networks were identified. Parameters indicated for the SA in the PBIM significantly overlapped with the validation.

By evaluating the validation study, the Sensitivity Rate (SR) is specified. Here, the number of positives (i.e., overlapping parameters of the PBIM with the validation) are divided by the sum of negatives and positives (i.e., the total number of parameters in the PBIM) as follows:

$$SR = \frac{\text{number of positives}}{\text{number of positives } + \text{ number of negatives}}$$

An SR is calculated for each performance computation method (**Table 6**). According to the evaluation, the SR of the SA has the highest percentage. Due to differences in software features and the interpretation of the parameters used in the PBIM and the validation, SRA, DA, WFA and SpA obtain some excluded parameters. As a result, the average SR value is calculated as 80.8 %.

Table 6. Calculation of the SR.

	PBIM (Total number)	Validation (Number of positives)	SR (Number of positives / total number)
SRA	5	4	4 / 5 = 0. 8 (80%)
DA	11	9	9 / 11 = 0. 82 (82%)
SA	10	10	10 / 10 = 1 (100%)
WFA	11	9	9 / 11 = 0. 82 (82%)
SpA	5	3	3 / 5 = 0. 6 (60%)
			Average: 80,8%

Discussion

Use of performance computation methods assisted students in terms of their decision-making process by increasing their awareness of performance issues. The results underlined, how different performance issues may inform their conceptual design decisions, by creating feedback loops between the geometric, algorithmic and analytical models. By the use of case studies, only the critical inputs and outputs are identified. To assess the level of reliance of the proposed approach on the tools, the model is validated by using a different toolset. Through the validation study, the Sensitivity Rate (SR) is specified for each performance computation method. Due to differences in software features and interpretation of the parameters used in the PBIM and the validation, the average SR value is calculated as 80.8 %, which is a high percentage and underlines the reliance of the PBIM.

The main difficulties encountered in the process were the complexity of the tasks undertaken and the use of different software tools for various performance computations. Additionally, students did not obtain experience in terms of integrating performance criteria to their design projects in the early design stage by the use of CD and explore options in conceptual design informed by performance previously. Interpretation and integration of data to the design projects took in-depth critique sessions and required additional research, to recall the existing knowledge of architecture students on building science/technology courses and extend their knowledge by increasing their awareness on PBD.

Because PBIM is a comprehensive method that applies 11 different tools, the model can be developed in the future to implement a single algorithmic and analytical modelling tool that will simplify the process. Additionally, the content of the PBIM may be extended towards including other types of performance computation methods, such as energy, thermal, acoustics and/or fire performance.

CONCLUSION

The architectural design process is complex, requiring various issues to be considered integrally. Architects and designers need to have specific expertise in undertaking and interpreting the results of performance analysis, which has typically drawn heavily on engineering or other technical knowledge. Integration of knowledge taught in different types of courses in architectural curricula, such as architectural design, building science and technology-related courses, is thus critical. A new approach for architectural design education is necessary to integrate design with performance parameters, by increasing architecture students' awareness, and competencies with CD and PBD.

The PBIM aims to generate a framework that incorporates different types of performance issues into the conceptual design to improve the decision-making process of architecture students by extracting only the critical parameters. The case studies analysed in the paper have underlined that environmental, structural and spatial performance can be linked to design in the early design stage by generating feedback loops between the geometric, algorithmic and analytical models employed. In this way, students can gain knowledge to interpret design and performance parameters at this crucial phase in the process.

Additional studies should be done not only towards better integration of architectural design with performance issues in architectural education, but also towards improved computational design and thinking skills of students. Architectural design curricula widely implemented should be re-interpreted in order to respond to the required future skills of architecture students. Thus, alterations should be made by affecting the ways how architecture students may design and think.

ACKNOWLEDGEMENTS

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BIBLIOGRAPHY

AISH, R., FISHER, A., JOYCE, S., MARSH, A. (2012) Progress Towards Multi-Criteria Design Optimisation Using Designscript with Smart Form, Robot Structural Analysis and Ecotect Building Performance Analysis, *Proceedings of ACADIA Conference*; 47-56.

ARAYICI, Y., FERNANDO, T., MUNOZ, V., BASSANINO, M. (2018) Interoperability Specification Development for Integrated BIM Use in Performance based Design, *Automation in Construction,* 85, 167-81.

AYNSLEY, R., M. (1999) Shape and Flow: The Essence of Architectural Aerodynamics, *Architectural Science Review,* 42(2) 69-74.

BILGIN, H., FRANGU, I. (2017) Predicting the Seismic Performance of Typical R/C Healthcare Facilities: Emphasis on Hospitals, *Int J Adv Struct Eng* 2017(9), 277–92.

BLOCKEN B., CARMELIET, J. (2004) Pedestrian Wind Environment around Buildings: Literature Review and Practical Examples, *Journal of Thermal Envelope and Building Science,* 28(2) 07-159.

CELANI, G., VAZ, C. E. V. (2012) CAD Scripting and Visual Programming Languages for Implementing Computational Design Concepts: A Comparison From a Pedagogical Point of View, *International Journal of Architectural Computing* 1(10) 121-37.

COLAKOGLU, B., YAZAR, T. (2007) An Innovative Design Education Approach: Computational Design Teaching for Architecture, *METU Journal of the Faculty of Architecture,* 24(2) 159-68.

DIMCIC, M. (2011) *Structural Optimization of Grid Shells Based on Genetic Algorithms,* unpublished Ph.D. Dissertation, Institute of Building Structures and Structural Design, University of Stuttgart.

EKICI, B., CUBUKCUOGLU, C., TURRIN, M., SARIYILDIZ, I.S. (2019) Performative Computational Architecture Using Swarm and

Evolutionary Optimisation: A Review, *Building and Environment*, 147, 356-71.

FISHER, A. (2012) Engineering Integration Real-Time Approaches to Performative Computational Design, *Architectural Design*, John Wiley & Sons Ltd., 82(2) 112–17.

GURER, E., OZKAR, M., CAGDAS, G. (2015) A Hermeneutical Sketch of Design Computation, *METU Journal of the Faculty of Architecture*, 32(1) 165-83.

GURSEL DINO, I. (2012) Creative Design Exploration By Parametric Generative Systems In Architecture, *METU Journal of the Faculty of Architecture* 29(1) 207-24.

HENSEL, M., MENGES, A. (2008) Inclusive Performance: Efficiency versus Effectiveness, *Architectural Design* 78(2) 54-63.

HENSEL, M. U., SØRENSEN, S. S. (2014) Intersecting Knowledge Fields and Integrating Data-Driven Computational Design en Route to Performance-Oriented and Intensely Local Architectures, *Footprint, Dynamics of Data-Driven Design*, Autumn 2014; 59-74.

HILLIER, B., HANSON, J. (1984) *The Social Logic of Space*, Cambridge University Press: Cambridge.

HOLZER, D. (2016) Design Exploration Supported by Digital Tool Ecologies, *Automation in Construction*, 72, 3–8.

HORVAT, M., BRUNO, L., KHRIS, S., RAFFAELE, L. (2020) Aerodynamic Shape Optimization of Barriers for Windblown Sand Mitigation Using CFD Analysis, *Journal of Wind Engineering & Industrial Aerodynamics,* 197 (2020) 104058.

HRASKA, J. (2018) New Daylighting Metrics, VII. Lighting Conference of the Visegrad Countries (Lumen V4).

JAKUBIEC, J., A., REINHART, C., F. (2012) Overview and Introduction to DAYSIM and Current Research Developments, Massachusetts Institute of Technology, Building Technology Program. [https://www.radiance-online.org/community/workshops/2012 copenhagen/Day1/Jakubiec/jakubiec,reinhart_radiance-workshop-presentation_daysim.pdf]

KATO, J. (2010) *Material Optimization for Fiber Reinforced Composites Applying a Damage Formulation*, unpublished Ph.D. Dissertation, Institute for Structural Mechanics, University of Stuttgart.

KAZAKIS, G., KANELLOPOULOS, I., SOTIROPOULOS, S., LAGAROS, N., D. (2017) Topology Optimization Aided Structural Design: Interpretation, Computational Aspects and 3D Printing, *Heliyon,* 3.

KORMANIKOVA, L., ACHTEN, H., KOPRIVA, M., KMET, S. (2018) Parametric Wind Design, *Frontiers of Architectural Research,* 7, 383–394.

KVAN, T., MARK,E., OXMAN, R., MARTINS, B. (2004) Ditching the Dinosaur: Redefining the Role of Digital Media in Education. *International Journal of Design Computing.*

LI, S., LIU, L., PENG, C. (2020) A Review of Performance-Oriented Architectural Design and Optimization in the Context of Sustainability: Dividends and Challenges, *Sustainability,* 12(4), 1427.

LOFTNESS, V., LAMAND, K.P AND HARTKOPF, V. (2005) Education and Environmental Performance-based Design: a Carnegie Mellon perspective, *Building Research & Information*33(2); 196–203.

MACKEY, C. ROUDSARI, M., S. (2018) The Tool(s) versus the Toolkit, *Humanizing Digital Reality*, Springer Nature Singapore Pte Ltd.; 93-101.

MADENCI, E., GUVEN, I. (2006) *The Finite Element Method and Applications in Engineering Using ANSYS*. New York: Springer; 1 -3.

MAHDAVI, A. (1999) A Comprehensive Computational Environment for Performance based Reasoning in Building Design and Evaluation, *Automation in Construction*, (8) 427–435.

MAHDAVI, A. GURTEKIN, B. (2004) Generating the Design-Performance Space via Simulation and Machine Learning, *Journal of Architectural and Planning Research*, 21(4), 350.

MALENDOWSKI, M., GLEMA, A. (2017) Development and Implementation of Coupling Method for CFD-FEM Analyses of Steel Structures in Natural Fire, *11th International Conference on Modern Building Materials, Structures and Techniques, MBMST 2016,* Procedia Engineering 172 (2017); 692 – 700.

MALKAVI, A. (2004) Developments in environmental performance simulation, *Automation in Construction, (13)* 437– 445.

MALLORY-HILL, S., PREISER, W. F. E., WATSON, C. G. (2012) *Enhancing Building Performance*, Wiley-Blackwell, ISBN: 978-0-470-65759-1.

NATANIAN, J., ALEKSANDROWICZ, O. (2018) Environmental Education of an Architect: The Case of Final-Year Design Studio at the Technion, Israel, *Archnet-Ijar*, 12(1) 356-366.

NEGENDAHL, K. (2015) Building Performance Simulation in the Early Design Stage: An Introduction to Integrated Dynamic Models, *Automation in Construction,* (54) 39–53.

NOURIAN,P., REZVANI, S., SARIYILDIZ, S. (2013) Designing with Space Syntax: A Configurative Approach to Architectural Layout, Proposing a Computational Methodology, *31st eCAADe Conference Proceedings*, Delft University of Technology.

WINEMAN, J. D., PEPONIS, J. (2010) Constructing Spatial Meaning: Spatial Affordances in Museum Design, *Environment and Behavior*, 42(1) 86-109.

OXMAN, R. (2008). Digital Architecture as a Challenge for Design Pedagogy: Theory, Knowledge, Models and Medium. *Design Studies*, (29) 99-120.

OXMAN, R. (2009) Performative Design: A Performance-based Model of Digital Architectural Design, *Environment and Planning B: Planning and Design*, (36) 1026-1037.

PAULE, B., BOUTILLIER, J., PANTET, S., SUTTER, Y. (2018) A Lighting Simulation Tool for the New European Daylighting Standard, *Proceedings of BSO 2018: 4th Building Simulation and Optimization Conference,* Cambridge, UK: 11-12 September 2018.

REINHART, C., F., & LOVERSO, V., R., M. (2010) A Rules of Thumb-based Design Sequence for Diffuse Daylight, *Lighting Research and Technology*, 42(1) 7–31.

REINHART, C., F., HERKEL, S. (2000) The Simulation of Annual Daylight Illuminance Distributions – A State-of-the-Art Comparison of Six RADIANCE-based Methods, *Energy and Buildings,* 32(2) 167-187.

REINHART, C., F., WIENOLD, J. (2011) The Daylighting Dashboard _A Simulation-based Design Analysis for Daylit Spaces, *Building and Environment*, 46(2) 386-96.

ROUDSARI, M., S., & PAK, M., (2013) Ladybug: A Parametric Environmental Plugin for GH to Help Designers Create an Environmentally-Conscious Design, *13th Conference of International Building Performance Simulation Association,* Chambery, France, August, 26-28, 3128-35.

SHARPE, T. (2019) Ethical Issues in Domestic Building Performance Evaluation Studies, *Building Research & Information*, 47(3) 318-29.

SØRENSEN, S. S. (2015) Non–Standard Informed, En Route to Performative, *Architectural Design*. John Wiley & Sons Ltd., 110-115.

TANG, M., ANDERSON, J., AKSAMIJA, A., HODGE M. (2012) Performative Computation-aided Design Optimization, *Arcc Journal*, 9(1) 62-7.

TU, J., YEOH, G., H., LIU, C. (2013) *Computational Fluid Dynamics A Practical Approach Second Edition*, Elsevier, Butterworth-Heinemann, 1-5.

XIE.Y. M., FELICETTI, P., TANG. J. W., BURRY, M. (2005) Form Finding for Complex Structures using Evolutionary Structural Optimization Method, *Design Studies,* 26(1) 55-72.

XIE, Y. M., ZUO, Z.H., HUANG, X., TANG, J.W., ZHAO, B., FELICETTI, P. (2011) Architecture and Urban Design through Evolutionary Structural Optimisation Algorithms, *International Symposium on Algorithmic Design for Architecture and Urban Design,* Tokyo, March 14-6.

YAZICI, S. (2013) Performance based Pavilion Design: A Dialogue between Environmental and Structural Performance, *Proceedings of the 31st eCAADe Conference;* 127-36.

YAZICI, S. (2020) Rule-based Rationalization of Form: Learning by Computational Making. *International Journal of Technology and Design Education,* 30(3) 613-33.

ZHANG, Q., ZHAO, Z., CHEN, J., FAN, F., SHEN, S. (2020) On the Static Properties and Stability of 800m Long-span Mega-latticed Suspension Structures, *Structures*, (23) 139–51.

ZHANG, Z., DONG, S., FU, X. (2007) Structural Design of a Spherical Cable Dome With Stiff Roof, *International Journal of Space Structures,* 22 (3) 45-56.

ZUO, Q., LEONARD, W., MALONEBEACH, E. E. (2010) Integrating Performance-based Design in Beginning Interior Design Education: An Interactive Dialog between the Built Environment and its Context. *Design Studies*, 31(3) 268-87.

NNVE/Normalizing Numerical Values in Excel (2020) [https://lovespreadsheets.medium.com/normalizing-numerical-values-in-excel-a0eeed827a5b] Access Date (15.05.2021).

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Anahtar Sözcükler: Hesaplama; başarım-tabanlı tasarım; erken tasarım aşaması; karar-verme; mimarlık eğitimi.

MİMARİ TASARIMDA BAŞARIM -TABANLI BAĞLANTILI MODEL (BTBM): ERKEN TASARIM AŞAMASINDA ÇEVRESEL, YAPISAL VE MEKANSAL PARAMETRELERİN DEĞİŞİMİ

Bu makale, öğrencilerin karar-verme sürecini iyileştirmek için farklı türdeki başarım konularını kavramsal tasarıma dahil eden bir çerçeve oluşturarak, bunun mimarlık eğitimi bağlamındaki uygulanabilirliğini gösteren bir model sunmayı amaçlamaktadır. Önerilen Başarım -tabanlı Bağlantılı Model (BTBM), kavramsal fikirlerin incelendiği erken tasarım aşamasında, mimarlık eğitiminde tasarım, bina bilimi ve teknolojisi dahil olmak üzere, farklı ders türlerinde öğretilen bilgileri bütünleştirerek, acaba tasarım ve başarım parametreleri birlikte değerlendirilebilir mi, sorusunu irdelemeyi amaçlamaktadır. İlgili pedagojik yaklaşım, tasarım modelinin oluşturulması, güneş radyasyonu ve gün ışığı analizi, yapısal analiz, rüzgar akışı analizi ve mekansal analizler dahil olmak üzere başarım hesaplaması için seçilen yöntemin uygulanması ve kritik başarım parametrelerinin belirlenmesiyle tasarım modelinin yeniden oluşturulması olmak üzere üç aşamadan meydana gelmektedir. Veriler, vaka çalışmaları tarafından yönlendirilen, süreç analizi yöntemiyle toplanıp görselleştirilerek bir ağ grafiği oluşturulmaktadır. Daha sonra parametrelerin mimari tasarım sürecine olan ayrı ayrı katkılarını değerlendirmek için, grafiğin derece ve merkeziyet değerleri belirlenir. BTBM, her çalışma için Hasassiyet Oranının (HO) hesaplanmasıyla doğrulanmaktadır. Önerilen model, tasarım ve başarım parametrelerinin bütünleşik olarak değerlendirilmesiyle, öğrencilerin başarım analizine ilişkin karar-verme süreçlerinin geliştirilmesini sağlamaktadır.

THE PERFORMANCE-BASED INTERLINKED MODEL (PBIM) IN ARCHITECTURAL DESIGN: EXCHANGING ENVIRONMENTAL, STRUCTURAL AND SPATIAL PARAMETERS IN THE EARLY DESIGN STAGE

The paper aims to present a model that generates a framework for incorporating different types of performance issues into the conceptual design to improve the decision-making process of students by extracting only the critical parameters and demonstrate its applicability in the context of architectural education. The proposed Performance-based Interlinked Model (PBIM) seeks to address the question of whether design and performance parameters can be evaluated together in the early design stage, where conceptual ideas are explored, by integrating knowledge taught in different types of courses in architectural education, including design, building science and technology. The salient pedagogical approach consists in three stages—namely, generating the design model, applying the selected method for performance computation—including solar radiation, daylight, structural, wind flow and spatial analyses—and regenerating the design model by extracting critical performance

parameters. Data is collected via a process-analysis method driven by case studies, and a network graph is generated that visualizes the data. The degree and centrality values of the graph are then extracted to assess the individual contribution of the parameters in the architectural design process. The PBIM is validated by calculating the Sensitivity Rate (SR) for each study. The proposed model enables the integrated evaluation of design and performance parameters and the enhancement of students' decision-making process concerning performance analysis.

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