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Generative Design Approach in the Early Stage of High-Energy Performance Building Design with BIM-Based BEM Process

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Abstract

The design of high energy-performance buildings today increasingly emphasizes the importance of decisions made during the early design stages. In this context, the adoption of Building Information Modeling (BIM)-based Building Energy Modeling (BEM) approaches has been encouraged. This study investigates a generative design approach integrated with BIM-based BEM in the design process of high energy-performance buildings. The proposed method, developed for cold-dry climate conditions, enables architects to generate various building forms during the early design stage, analyze them in terms of energy performance, and identify optimized solutions. Through algorithms developed within the Revit-Dynamo environment, building forms were first generated based on form factor and floor area criteria. Subsequently, window placements and Window-to-Wall Ratio (WWR) values were parametrically defined for façade design. The resulting design alternatives were subjected to energy simulations using Green Building Studio and evaluated based on their Energy Use Intensity (EUI) values. The design options were visualized in a manner that allowed ranking according to the architect's objectives, thereby supporting the decision-making process. The findings indicate that compact forms with low form factors and façade-based window optimizations have a significant impact on energy efficiency. Within this scope, the developed framework emerges as an effective tool for sustainable and data-driven building design at the early design stage.

1. INTRODUCTION

The increasing demand for energy and the growing emphasis on sustainability have made energy efficiency a primary concern in building design. Designing high energy-performance buildings requires the integration of both passive and active design strategies, with early design stages playing a critical role in this process. Traditional design methods often offer limited alternatives during the decision-making process, and in cases where numerical analyses are either not integrated or are applied at later stages, the full potential for energy efficiency cannot be realized. Decisions made in the early design phase significantly influence a building's energy performance. Studies have shown that optimizing building form and orientation can reduce energy consumption by 30–40% [1]. Numerous researchers in the literature emphasize that integrating building performance simulations into the early design stage is essential for achieving high-performance buildings [2]. The application of energy simulations during early design enables the optimization of critical design decisions (such as form, orientation, window-to-wall ratio (WWR), and construction materials) that directly affect building performance [1].

Building Information Modeling (BIM) has emerged as a powerful tool for optimizing the energy performance of buildings during the conceptual design phase. BIM-based energy analysis enables project teams to explore various energy-saving alternatives during the early stages of design—when decisions have the greatest impact on life-cycle costs [3]. Through integration with energy simulation software such as EnergyPlus and IES, BIM allows designers to efficiently assess building performance in relation to factors such as orientation and window dimensions [4]. This approach facilitates the selection of energy-efficient materials and strategies within the framework of green building standards [5]. Studies have

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demonstrated that BIM-based optimization can lead to significant energy cost savings; in one case, a 58.46% reduction in energy costs was achieved over a 30-year period compared to the initial building model [6]. Overall, BIM-based methods offer a time- and cost-effective approach to evaluating and improving building energy performance in the early design stages.

Generative design is an approach that automates and optimizes the design process through the use of algorithms and artificial intelligence. This method enables the rapid evaluation of a large number of design alternatives and the generation of solutions aligned with predefined performance criteria [7]. Particularly in the context of goals such as energy efficiency, the generative design process can achieve optimization in terms of performance metrics such as thermal comfort and energy consumption [8]. The integration of artificial intelligence further advances the generative design process by providing predictive capabilities for evaluating building performance [9]. Compared to traditional and parametric methods, generative design has been identified as the most effective approach for energy-efficient design processes. Automating the design process and optimizing it based on specific criteria not only allows architects to focus on creative aspects but also positions energy efficiency as a fundamental design parameter. The capacity of generative design to produce multiple alternatives and its adaptability to sustainability-focused objectives highlight it as a powerful method for addressing contemporary architectural challenges [10].

In this context, the generative design approach supported by Building Information Modeling (BIM)-based Building Energy Modeling (BEM) offers a significant advantage during the early design phase. While BIM digitizes the building design process and enables the integration of energy modeling and optimization workflows, generative design algorithms allow for the rapid and effective generation of diverse design alternatives. As a result, the impacts of design decisions on energy performance can be anticipated and optimized at much earlier stages of the design process.

The building envelope functions as the primary boundary separating a structure from its environmental conditions, while also exerting formal influence at the urban scale. In this context, the envelope is considered one of the most defining elements of a building. Moreover, it plays a critical role in determining the building's energy performance. Contemporary architectural design processes increasingly consider environmental sustainability; however, a strong focus on improving energy performance can often come at the expense of other architectural values such as aesthetics and functionality [11]. This imbalance may result in building envelopes that are energy-efficient but lack functional adequacy and visual quality, overlooking user needs, spatial quality, and formal coherence. Achieving an appropriate balance is only possible through a holistic application of architectural composition principles throughout the design process.

The form of the building envelope is typically defined during the early design stages and undergoes only limited modifications throughout the remainder of the design process. Due to the time-consuming and complex nature of energy simulations, energy consumption values of buildings are often not calculated during the early design phase. This hinders the ability to evaluate design decisions in terms of energy efficiency. To address this issue, a number of energy-efficient design rules have been developed to guide the design process at early stages [12]. However, while such rules can contribute to the design process, they are generally generic in nature and often fall short when applied to complex building geometries.

Buildings, as structures with long life cycles and high levels of energy consumption, play a critical role in environmental sustainability. In this context, the form of the building envelope has a direct and decisive influence on its energy performance [13], [14]. Therefore, relying solely on general design guidelines does not constitute a sufficient strategy for the development of energy-efficient building envelopes.

The building envelope shaping approach presented in this study is based on two fundamental principles: first, the theoretical and practical significance of architectural composition principles in the design process; and second, the instrumental role of energy simulations in achieving energy-efficient design. The primary motivation behind this research arises from the need to quantitatively reveal the impact of formal design decisions on energy performance. In doing so, it provides designers with the opportunity to revise and improve building envelope forms when energy performance expectations are not met. Generative design systems are defined as models based on a set of computational rules designed to produce alternative design solutions [15], [16], [17]. These systems not only ensure the intended formal diversity but also encode predefined design constraints to guide the design process. Accordingly, through a well-structured rule set, generative design systems can offer formal variation while maintaining stylistic coherence and design language consistency. This dual capacity supports creative freedom while ensuring design integrity.

Unfortunately, the traditional design process is largely incompatible with the use of complex generative design systems such as shape grammars. In scenarios where only a single design output is pursued, alternative designs may be considered, but a formally defined design system is typically not established. However, exploring design diversity through a well-structured design system necessitates the construction of that system, and if only one output is ultimately required, the benefits of such an exploratory process may not justify the effort involved. With some exceptions, the practical application of generative design systems—particularly shape grammars—is generally limited to contexts in which multiple outputs are needed, such as mass housing production and customization scenarios [18], often in conjunction with prefabricated building systems.

This study aims to investigate how generative design approaches can be employed to generate design alternatives in the early stages of high-energy-performance building design by integrating BIM-based BEM methods. The integration of BIM-based energy simulations with generative design algorithms will be explored, and new strategies will be developed to enhance energy efficiency in architectural design. The findings will serve as a guide for architects and engineers in optimizing design processes and contributing to sustainable building design.

1.1.BIM base BEM

Building Information Modeling (BIM) can facilitate the evaluation of building energy performance in the early stages of the project process, thereby enhancing the impact of design decisions on energy efficiency and cost [19]. In this regard, BIM-based Building Energy Modeling (BEM) methods have become increasingly popular and have emerged as an adaptable approach to integrated design processes [2]. Building energy simulations play a critical role in reducing energy consumption [20]. However, existing energy simulation tools are time-consuming due to the need for manual data entry, and they have a high likelihood of errors. Additionally, in cases of missing data, experts may be forced to use hypothetical values, which can lead to inconsistent results [21]. The integration of BIM-based BEM can eliminate the manual modeling process, making energy analyses more efficient and reliable. However, overcoming current software and workflow challenges is necessary to achieve full integration. The BIM-based BEM process consists of various components that contribute to the overall workflow [22]. An overview of the BIM-based BEM process is shown in Figure 1.

Figure 1: *Overview of the building information modeling-based building energy modeling process*

The integration of Building Information Modeling (BIM) and generative design has emerged as a promising approach for achieving high energy performance in building design [23]. Generative design is an iterative, rule-driven process based on algorithmic and parametric modeling, which allows for the automatic exploration and optimization of design possibilities by defining a high level of constraints and objectives. When combined with BIM's ability to create, record, and manage digital information about a building throughout its lifecycle, this approach can facilitate the constructability of generative design solutions and enhance the capabilities of BIM in the early stages of design [8].

In the study conducted by Utkucu et al. (2023), the multi-criteria optimization of building performance was addressed through an integrated design approach based on Building Information Modeling (BIM).

The study proposes a three-phase interdisciplinary design process—conceptual, schematic, and detailed—through the integration of various analysis tools, such as energy simulation and computational fluid dynamics (CFD), with the BIM platform. The method emphasizes data sharing and interoperability between software during the 3D modeling process, achieving up to 75% energy savings in a two-story residential building case study and enabling the building to achieve an "A" energy class rating [24]. However, the study does not cover the early stages of the design process or the generation of alternatives regarding the building form.

One of the key advantages of generative design is its ability to manage an increasing number of variables and parameters using computational power. This approach can offer significant benefits in early-stage high-energy-performance building designs by allowing designers to test multiple and complex alternatives [25]. The decisions made at this stage can have a significant impact on the environmental performance of the building.

1.2. Generative Design Systems

Generative design systems fundamentally encode the transformation of design forms using algorithms and mathematical rules. These systems simplify the design process significantly by offering different options and enabling the exploration and evaluation of various alternatives [26]. The use of real computation and digital technologies helps designers enhance their ability to develop new and effective design processes [16]. Generative design systems are defined as mechanisms and processes that provide opportunities to generate unexplored forms.

Generative design processes generally follow and repeat four steps: Representation, Production, Evaluation, and Feedback. These operations are based on an input-output relationship. Cagan (2005) explained that the representation phase involves defining the design problem and assists in generating suitable techniques. Production encompasses the performance of the entire mechanism and its components. Evaluation represents the testing phase of the system, demonstrating how successfully the relationship between the objectives and constraints is achieved. Additionally, feedback is the final step in which design improvements are provided for the next phase [27].

Generative design algorithms systematize the design process, allowing human designers to explore their creative space more deeply. In this context, shape grammar enables the generation of solutions with rapid and formal diversity by transforming specific design rules into a computational framework. These methods support users in making effective design decisions without the need for interdisciplinary knowledge [14]. In his doctoral thesis, Boumaraf (2022) categorizes generative design methods into nine systems: Algorithmic Systems, Shape Grammar, L-Systems (Lindenmayer Systems), Cellular Automata Systems, Genetic Algorithm Systems, Voronoi Systems, Subdivision Systems, Topology Optimization Systems, and Swarm Behavior Systems [28].

A shape grammar-based parametric design system is a proposed method for achieving flexible designs while maintaining architectural composition principles. The unique characteristics of shape grammars offer the opportunity to explore meaningful design diversity [29]. The basic components of shape grammars, as shown in Figures 2 and 3, are form rules that define the spatial transformation of a geometric shape. These rules consist of two components: the Left-Hand Side (LHS) and the Right-Hand Side (RHS); the RHS represents the transformed version of the LHS. Shape grammars begin with a specific set of forms, symbols, and transformation rules, and require an initial form in which at least one rule matches the LHS. The rules continue to be applied by iteratively transforming the shapes. Five common types of transformations are defined in the literature: addition, subtraction, division, modification, and displacement. These transformations allow for the generation of new forms by either maintaining or altering the structure of the original shape, enabling the productivity of shape grammars [14].

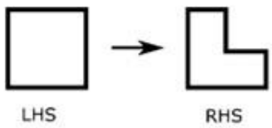

Figure 2: *A common shape rule that includes LHS and RHS shapes [14]*

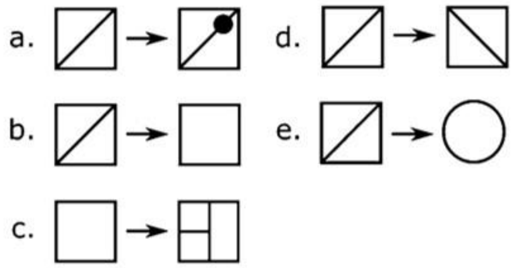

Figure 3: *Examples of shape rules based on different types of transformations: (a) addition, (b) subtraction, (c) division, (d) permutation, and (e) substitution [14]*

1.3. Generative Design and BIM Integration

Generative design is the process of automatically generating a multitude of alternative solutions through computer software to achieve specific design goals. In this process, designers define certain parameters (such as material types, building height, cost constraints, etc.), and the software generates various design options that align with these parameters. Thanks to generative design, multiple alternative design solutions can be produced simultaneously, with optimized solutions based on performance criteria (such as energy efficiency, cost-effectiveness, structural durability, etc.), offering more innovative and unconventional design options compared to traditional design methods.

The integration of generative design with Building Information Modeling (BIM) combines the advantages of both technologies, enabling the creation of smarter and more efficient design processes. In this way, alternative design solutions generated through the generative design process can be directly integrated into BIM models for visualization and analysis [30]. While generative design presents optimized solutions based on performance criteria, these solutions are detailed using the BIM model. BIM ensures that all project stakeholders work on the same model, while the generative design process provides more coherent and optimized design solutions based on inputs from various stakeholders [28]. The integration of generative design and BIM facilitates the realization of more innovative, efficient, and sustainable projects in the construction and architecture sectors. This integration contributes to the successful completion of projects by enabling better decision-making from the early stages of design.

2. METHOD

BIM-based BEM (Building Energy Modeling) technologies provide an opportunity to compare design options and create the best solution to improve the building's ecological footprint. However, as observed in this research, design experts are still striving to reorganize their processes in order to maximize the benefits of these technologies. In this article, a BIM-based BEM framework, suitable for the early stages of the design process, is proposed to facilitate and systematize information sharing. In the first step, an algorithm suitable for our purpose is created using Revit-Dynamo. Dynamo parametric programming, Revit-Dynamo interaction commands, and built-in mathematical operations are used to control decision variables. The program modules have the ability to capture decision variables from model components and establish connections between them. Complex information is flattened into parallel control modules that can globally regulate the model with less human intervention by altering decision variables. The interface between the building model and simulation tools can be connected through Python programming, which enables real-time data interaction between Dynamo open-source packages, the modeling platform, and the simulation platform. In the proposed process, Green Building Studio (GBS) is used to simulate energy consumption.

The proposed framework has been developed to support sustainable building design in the early design phase by integrating a generative design approach within the BIM-based BEM environment. It aims to generate, analyze, and optimize different design alternatives in terms of energy performance. During the conceptual design process, the primary objective is to automatically generate high energy-efficiency building forms and then determine parameters such as window placement, size, and opacity/transparency ratio for the building envelope design. The workflow developed within this scope offers a systematic approach that integrates energy-efficient design criteria with the generative design process.

In the first phase, performance criteria such as form factor and total floor area are defined to guide the design process. Subsequently, alternative building forms are parametrically generated in the Revit-Dynamo environment within the framework of shape grammar rules. The most optimal form is selected by targeting the minimum form factor and maximum floor area. In the second phase, building envelope design alternatives are created to achieve the lowest possible Energy Use Intensity (EUI). In this context, variables such as window position, size, and transparency ratio are parametrically defined. The resulting geometries are converted into gbXML format to be compatible with energy simulations and transferred to BEM software. Based on energy analyses performed with climate and location data, the form with the highest energy efficiency is identified, and the optimum design is selected. The process is iteratively repeated if necessary, and based on the findings, the design process either moves to the next phase or undergoes further optimization.

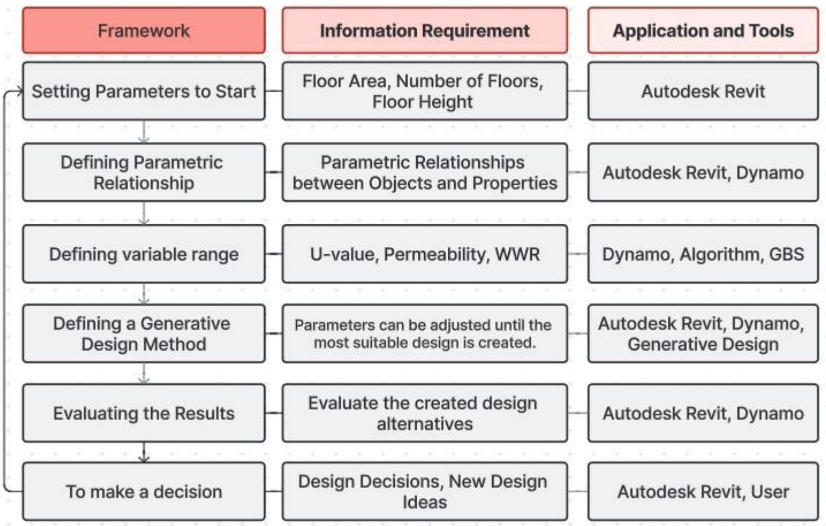

Figure 4: *The proposed framework process and the tools and practices used in the process*

The algorithm developed on the Dynamo platform is designed to support Generative Design processes. The inputs of the algorithm consist of various parameters that define the building form. These parameters enable the design to be optimized in accordance with both geometric and performance criteria. The outputs of the algorithm are evaluated based on performance-driven objectives such as maximizing floor area and minimizing form factor. During the building form generation process, shape grammar rules are applied to establish a systematic design language. These rules provide fundamental principles for generating and optimizing building geometry. As a result, the algorithm functions as a design tool aimed at producing building forms optimized for both aesthetics and energy efficiency.

The form factor is a term used to assess the impact of a building's design on energy efficiency and heat transfer. It measures how the shape, proportions, and external surface of a building influence its energy performance. A simple formula for calculating the form factor is expressed as follows:

Form Factor (F) = Surface Area (A) / Volume (V)

- Form Factor (F) reflects the effect of a building's shape and proportions on energy efficiency.
- Surface Area (A) refers to the total area of the building's external envelope.
- Volume (V) indicates the internal volume of the building.

This simplified form factor equation is useful for understanding how the compactness and shape of a building affect its energy performance. A higher form factor represents a smaller internal volume relative to the external surface area, which can increase energy loss. Conversely, a lower form factor indicates less external surface area relative to the internal volume, contributing to improved energy savings. The form factor is utilized in the optimization of building design and in the assessment of strategies for enhancing energy efficiency. A well-designed building may exhibit a lower form factor, thereby supporting energy conservation.

The 12-square grid system, defined as the starting point, establishes a fundamental framework for the design process. Within this system, rules are defined for generating shape variations, such as the positions of squares, points of connection, as well as subtraction and addition operations. However, the rule prohibits two squares from joining at only a single point. By integrating these rules into algorithms, a systematic generation of diverse forms can be achieved automatically. Additionally, a parametric control mechanism is implemented to allow greater flexibility in shaping the design. At this stage, parameters such as size, height, and number of squares are incorporated into the algorithm, enabling the creation of diverse variations that are both aesthetically and functionally distinct. This process facilitates the systematic development of the design and allows for the controlled generation of complex structures.

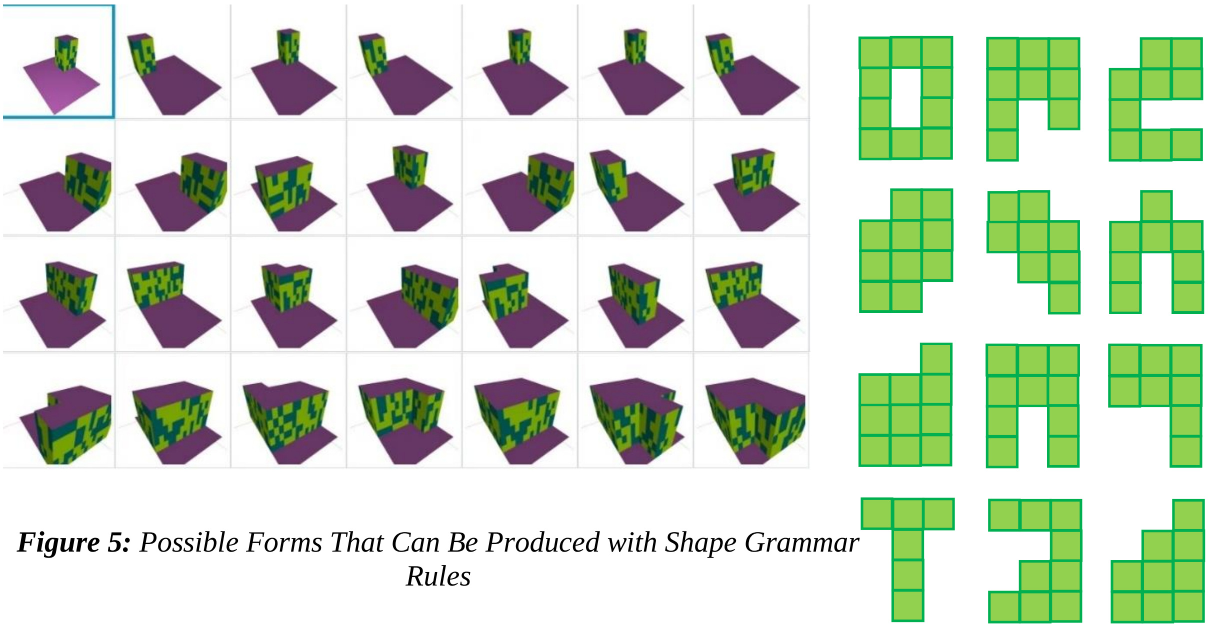

Figure 5: *Possible Forms That Can Be Produced with Shape Grammar Rules*

At the end of this phase, various building forms are systematically analyzed to determine the most appropriate form in line with performance goals. During this analysis process, different formations are compared based on key performance parameters such as form factor and floor area. The comparisons are carried out using criteria such as energy efficiency, material usage, and structural integrity. This stage of the design process not only meets performance requirements but also takes broader objectives into account, including sustainability and economic efficiency. Ultimately, the design alternatives that offer the most efficient outcomes are evaluated, and the optimal option in terms of building form is selected. Based on this selection, the design process advances to the next phase. This process is supported by a holistic approach that aims to maximize the impact of early-stage design decisions on overall building performance.

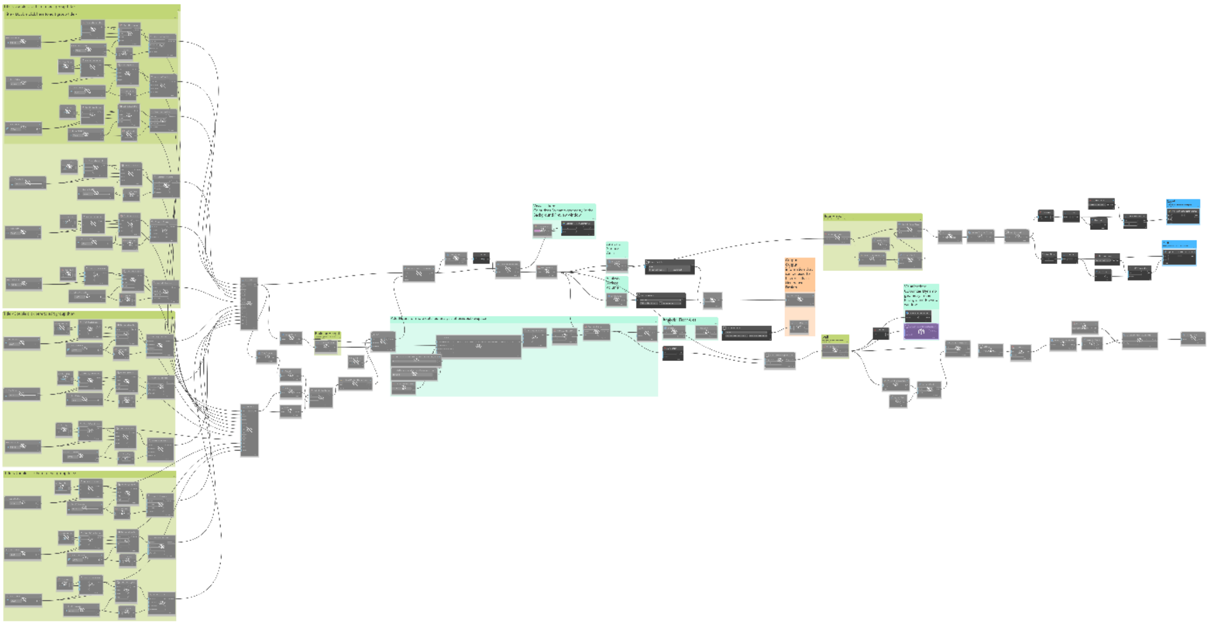

Figure 6: *Developing Form Grammar Based Algorithms for Generative Design*

This algorithm developed in Dynamo constitutes the first phase of the proposed process and applies generative design using a shape grammar approach for building form optimization. The algorithm comprises stages including the generation of building geometry, the creation of form variations, and the analysis of these forms based on defined criteria. Figure 6 illustrates the algorithm developed within the Dynamo environment. The algorithm consists of the following main components:

a) Shape Grammar Rules (Left Section – Green Areas) The components at the beginning of the algorithm include rule definitions that govern the creation of the building form. These components are composed of modules that define the shape grammar rules and include input parameters for generating alternative form variations.
b) Geometry Generation (Central Section – Grey Modules) In this section, various form variations are generated according to the shape grammar rules, leading to the formation of the building mass. While deriving possibilities for alternative forms, building components (walls, floors, roofs) are modeled and prepared for the analysis process.
c) Performance Analysis (Right Section – Blue and Orange Areas) The generated building forms are evaluated by analyzing the surface area-to-volume (SA/V) ratio and floor area. Surface area and floor area calculations are conducted, and the results are compared to identify the optimal form variations.
d) Optimization and Outputs (Far Right Section – Purple and Red Areas) The outputs of the generative design process are analyzed to select the most suitable building form. Alternatives with optimal form factors and maximum floor areas are identified. Finally, parametric analyses of the final model are completed, and the design outputs are produced.

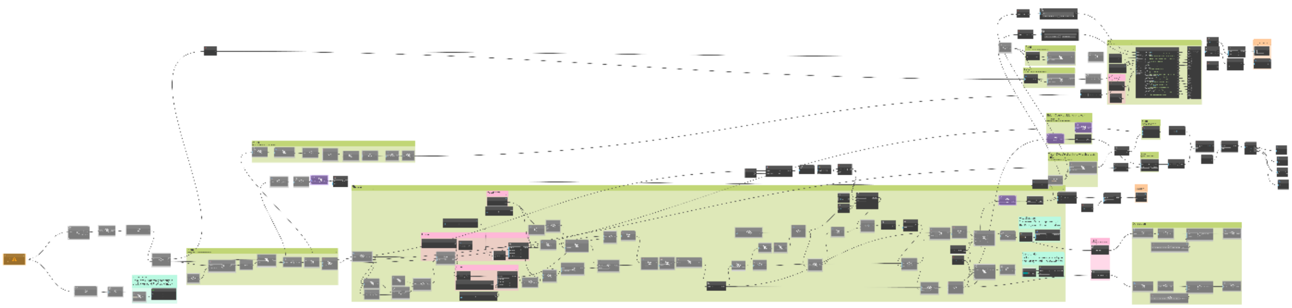

Figure 7: *Developing EUI and WWR Based Algorithms for Generative Design*

In this algorithm, a BIM-based generative design approach was developed to optimize building envelope parameters in terms of energy performance during the early design phase. The proposed method is structured around a visual algorithm that integrates parametric modeling, energy simulation, and optimization processes using Revit and Dynamo software (Figure 7). The process consists of three main stages: parametric modeling, energy analysis, and optimization. The structural components and operational logic of the algorithm are outlined below:

a) Input Parameters (Left Section) The nodes located on the left side of the algorithm represent the parametric inputs used in the generative design process and play a fundamental role in defining the design space. These parameters include variables that directly influence design decisions such as window-to-wall ratio, window placement, opaque/transparent surface ratio, and location data. Minimum and maximum value ranges are defined for each parameter to constrain the algorithm's search space, thereby enabling the generation of valid design alternatives based on both geometric and performance-based criteria.

b) Parametric Modeling and Geometry Generation (Central Section) In the central section of the algorithm, the defined parametric inputs are processed to generate various façade configurations and window placement alternatives. This process is guided by a set of rules that direct the façade design, wherein the applied rule sets—similar to the shape grammar approach—govern window sizing and positioning.

c) Energy Calculations and EUI Evaluation: In the middle and right sections of the algorithm, energy performance analyses are conducted for each generated design variation. Within this scope, performance indicators such as total heating and cooling loads, thermal energy demands, and Energy Use Intensity (EUI) are calculated. During the analysis, the geometric data generated in Revit are converted into gbXML format and transferred to the Green Building Studio energy simulation platform, where they are evaluated together with climate data. This integration enables the calculation of EUI for each design variation.

d) Optimization Process (Lower Right and Mid-Right Sections) In the lower right section of the algorithm, the design variations are analyzed and compared according to energy performance criteria. At this stage, a genetic algorithm optimization technique is applied to determine the window configuration and envelope design with the lowest EUI. The optimization operates iteratively, generating new variations in each cycle based on previous results to enhance performance. In this way, the algorithm systematically and data-drivenly identifies the most suitable solution aligned with the design objectives.

e) Visualization of Results and Output (Far Right Section) The outputs of the algorithm are presented through a visual analysis panel that displays the optimal design variation graphically and enables automatic data transfer to the Revit environment. The user can comprehensively evaluate the selected optimal solution in terms of both numerical performance data and geometric features. Through this integration, the design process is driven not only by visual aesthetics but also by energy performance-based criteria, thus enabling a data-informed and integrated decision-making process.

2. RESULTS AND DISCUSSION

Table 1 presents the input parameters defined for the execution of the developed generative design algorithm, along with their respective minimum and maximum value ranges. These parameters comprehensively describe the geometry and physical characteristics of the building, including Energy Use Intensity (EUI), floor area, thermal transmittance coefficients (U-values) of building components, window opening ratios, number of floors, and floor height. Additionally, environmental and system-related variables that influence energy performance—such as solar heat gain coefficient (SHGC), Window-to-Wall Ratio (WWR), lighting power density, and equipment power density—are also included. These data constrain the algorithm's search domain and constitute the numerical inputs required to generate optimized design solutions. This ensures both the validity of the design variations and the reliability of the energy simulations. Furthermore, this study specifically focuses on a four-story residential building located in Ankara, Turkey.

Table 1: *Input Parameters and Value Ranges Defined for the Proposed Algorithm*

Parameters	Unit	Min	Max	Parameters	Unit	Min	Max
EUI target	kWh/ m²	80	120	Number of floors	-		4
Floor area	m²	200	300	Height	m	3	3.6
Upper window space from each floor	m	0.6	0.8	WWR	%	10	50
Lower window space from each floor							
Ground floor space of the building	m	0.6	0.8	Solar gain factor	W/m²	180	200
Ground from the roof of the building							
Lighting power	W	4500	5000	Device power	W	2800	3000

The building envelope components used in this study were designed in accordance with the high-performance thermal insulation criteria established by the Passive House Institute. The exterior walls feature a multi-layered construction system, with each layer's thermal properties and material composition detailed in Table 2. The thermal transmittance coefficient (U-value) of the exterior wall, calculated in accordance with ISO 6946, was determined to be U = 0.13 W/m²K. This value is suitable for minimizing energy losses in cold and dry climatic conditions. For windows, a U-value of 0.85 W/m²K was adopted. This window performance rating contributes to enhancing overall building energy efficiency by providing high levels of insulation.

Table 2: *Thermal properties of the external wall.*

Wall	Layers	Thickness (mm)	Thermal Conductivity [W/(m·K)]
	Interior finishing (plaster)	10	0,8
	Gypsum fibreboard	25	0,36
	Insulation (Rockwool)	50	0,033
	Concrete wall	250	2,3
	Adhesive	10	0,16
	Insulation (Rockwool)	200	0,035
	Basecoat	6	0,16
	Exterior finishing (plaster)	10	0,8

Based on the initially defined parametric inputs, the algorithm is capable of generating a total of 4,096 different building form alternatives. However, this extensive solution space was narrowed through predefined design constraints to identify the most energy-efficient solutions. Within the scope of these constraints, alternatives with a minimum form factor and maximum floor area were prioritized. As a result of the preliminary filtering process, only 10 forms were deemed suitable for energy performance analysis (Figure 8). This approach facilitates a more efficient evaluation of design alternatives, enabling optimal use of computational resources and supporting more accurate decision-making during the early design phase.

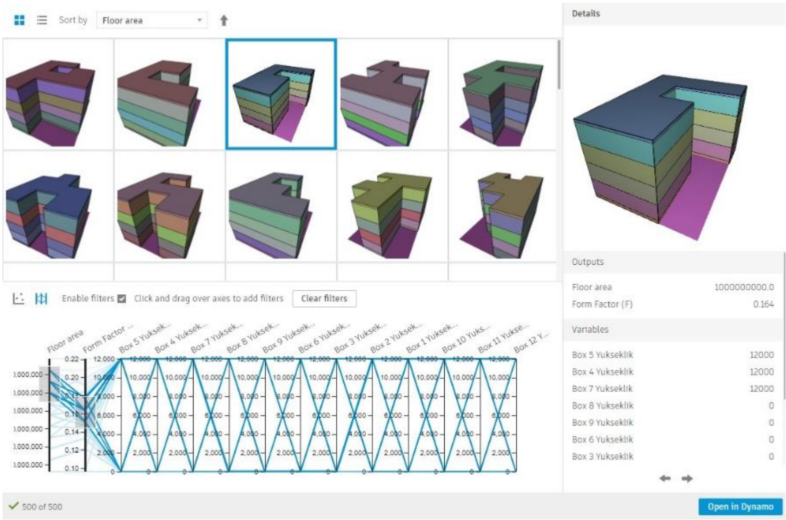

***Figure 8**: Visual and Numerical Analysis of Building Masses Generated Through the Generative Design Process Based on Form Factor and Floor Area.*

The interface developed in this study enables both visual and numerical comparison of alternative building masses generated during the generative design process. Each variation is analyzed based on key performance indicators such as form factor and floor area, allowing systematic selection of solutions that meet predefined criteria (e.g., low form factor and maximum floor area). This transforms the design process from an intuitive approach into a data-driven, rapid, and optimized decision-making framework. The ability to visually monitor selected solutions and directly integrate them into the BIM environment (Revit) supports a holistic and performance-oriented design methodology.

In the second stage, the selected optimal building form—identified through the first algorithm—was integrated into a second algorithm to refine façade design. In this phase, window positions and opening areas were defined for each façade, and corresponding WWR (Window-to-Wall Ratio) values were applied. These ratios were determined based on national standards (TS 825, BEP Regulation) and current literature addressing energy efficiency in cold and dry climate conditions. Table 3 presents the proposed WWR ranges for each façade orientation and summarizes the reference values underpinning the algorithm's decision parameters.

Table 3: WWR Values Suitable for Cold-Dry Climate Conditions

Facing Direction	**WWR**	**Facing Direction**	**WWR**
North	%10 – %25	East	%15 – %35
South	%30 – %60	West	%15 – %35

The Generative Design process was carried out using Autodesk Revit software. A genetic algorithm was employed in the production of design options, with the algorithm's initial parameters defined as follows: a population size of 100, a generation count of 20, and an initial seed value of 1. These parameters were selected to ensure sufficient diversity within the solution space and to explore various design possibilities. Figure 8 presents the data frames and interface presented to the user as a result of the optimization process. In this interface, the energy performance of the designs was analyzed based on variations in window placements and WWR (Window-to-Wall Ratio) across different façades. The 3D models shown in the visual represent different design alternatives, each with different window ratios. This allows the user to visually compare and assess alternative solutions in terms of energy efficiency.

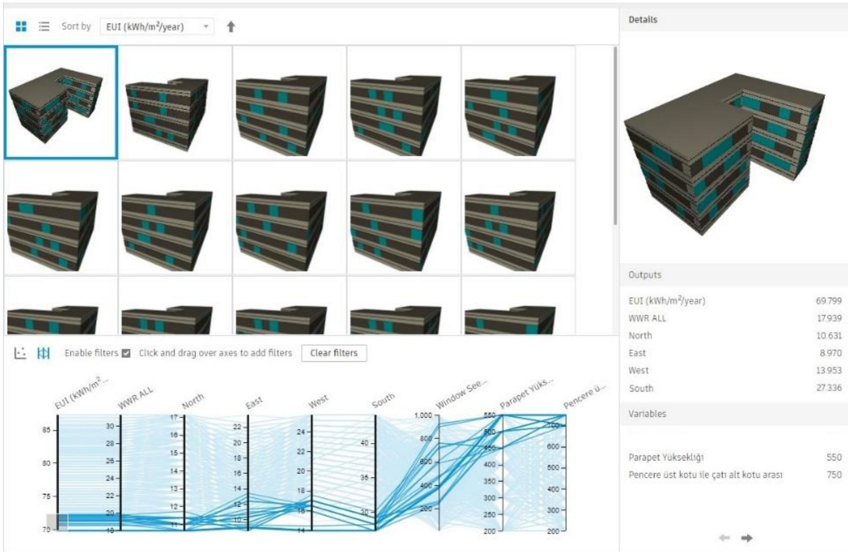

Figure 9: *User interface visualizing the energy performance of design alternatives generated through the generative design process, along with façade-based WWR values and geometric variables.*

For each alternative design, the system calculates and presents data such as Energy Use Intensity (EUI), Window-to-Wall Ratio (WWR) for each façade, Total WWR, the distance between the top of the window and the bottom of the roof, and parapet height. When the user selects any of the generated solutions, they can view all of these data in detail. Additionally, the system provides flexibility for architects to define sorting criteria based on the design goals. The ability to sort the data allows for the comparison of design scenarios with different priorities, enabling the user to easily identify the solution that best aligns with their criteria. Table 4 presents the alternative designs sorted in ascending order based on EUI values, with the solution having the lowest EUI value positioned at the top. This facilitates a direct comparison of energy performance across different design alternatives.

Table 4*: Output data of design alternatives created using the Revit Generative Design interface.*

EUI (kWh/m²/Year)	**WWR All**	**North WWR**	**East WWR**	**South WWR**	**West WWR**	**Upper window space from each floor (mm)**	**Lower window space from each floor (mm)**
69.799	17.939	10.631	8.970	27.336	13.953	550	750
70.593	18.547	10.991	9.274	28.263	14.426	500	750
70.593	18.687	10.631	10.963	27.336	15.946	550	750
70.930	18.805	10.991	9.274	28.263	16.486	550	700
71.266	19.062	10.991	10.304	28.263	16.486	500	750
71.387	19.155	11.351	8.514	29.189	17.027	450	750
71.426	19.185	10.631	12.956	27.336	15.946	550	750
71.602	19.320	10.991	11.334	28.263	10.486	500	750
71.735	19.421	11.351	9.578	29.189	17.027	450	750
71.939	19.578	10.991	12.365	28.263	16.486	550	700

Upon reviewing the data, it is observed that higher WWR (Window-to-Wall Ratio) values are applied, particularly on the south façade. This approach is an appropriate design strategy for maximizing passive heat gains in cold and dry climatic conditions. On the other hand, lower WWR values were preferred for the north, east, and west façades, aiming to limit heat losses and enhance energy efficiency. This approach highlights the impact of façade-specific strategies optimized for climatic conditions on overall energy performance.

3. CONCLUSION

This paper highlights the novelty of our work by focusing on the generative design algorithm developed for BIM projects. By testing this methodology, a new approach has been presented that allows architects to evaluate various design solutions at the conceptual level. This early evaluation helps architects determine the most optimal design option from the outset, leading to time and cost reductions in later stages of the design process. This aspect of the research has practical implications for decision-making in architectural practice and building design. However, it is important to acknowledge certain technical limitations in the study. The algorithm we developed specifically evaluates shapes formed by a combination of 12 grid cells, excluding other complex structural shapes from the evaluation process.

The developed methodology offers architects alternatives based not only on visual aesthetics but also on energy efficiency performance criteria. With the help of parametric algorithms and energy simulation tools developed within the Revit-Dynamo environment, different building forms and façade designs were systematically analyzed to determine optimal solutions. Analyses conducted under cold-dry climate conditions demonstrated that the preference for higher Window-to-Wall Ratios (WWR) on the south façades positively influenced passive heat gains and energy consumption. On other façades, lower WWR values were used to limit heat losses. Additionally, the effects of geometric parameters such as form factor and floor area on energy performance were quantitatively shown, confirming that more compact building forms lead to higher energy efficiency. In conclusion, this research demonstrates that integrating generative design in the early design phase offers a powerful method for developing sustainable and energy-efficient building solutions. The developed methodology presents decision-makers with a systematic and data-driven design process, with the potential to establish a balanced relationship between architectural quality and energy performance.

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