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COMPUTATIONAL DESIGN FOR FUTURISTIC ENVIRONMENTALLY ADAPTIVE BUILDING FORMS AND STRUCTURES

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Abstract

Introduction: With the rapid development in computational design, both architectural design and representation processes have witnessed a revolutionary change from the analog to the digital medium, opening new doors for adaptability in the architectural design process by leveraging nature concepts in design. The computational design approach starts with the mathematical model definition based on numerical relations and equations, thus, replacing the standard visual representation. **Purpose of the study:** We aimed to integrate computational design technologies to create self-learning buildings that could adapt to environmental challenges and adjust accordingly by collecting data from the surrounding environment via the implementation of sensors. **Methods:** We started with extensive research on state-of-the-art computational design in architecture, followed by the design implementation and the implementation of the architectural design of a building. The design followed a parametric approach to design and strategies. An algorithm was developed with Grasshopper Scripting to generate documents that mimic the growth process of cellular bone structures and adapt that form to a selected project site. To ensure that the generated form is adaptable, we performed multiple analyses, such as sunlight, radiation, and shadow analysis, before selecting the form and finishing its development. The results show that an environmentally responsive form that extends from the surrounding environment is characterized by high levels of adaptability. **Results:** In the course of the study, the effectiveness of computational design technologies in architecture was established.

Keywords: computational design; Grasshopper; parametric design; architecture; adaptive design.

Introduction

Integrating computational design (CD) via parametric architecture has been done with machines mimicking the human mind. The ability to mimic such skills as critical thinking, problem-solving, and decision-making refers to the desired attribute of CD intelligence and its ability to think and make decisions to achieve a specific goal (Choi et al., 2010).

The advancement of technology increases the evolvement of CD to benefit a wide variety of industries (Dimitropoulos et al., 2021). Nowadays, various tools are being developed in the AEC industry that leverage CD to automate tasks and decrease the time of their performing from days to minutes.

This big jump in technology is setting a new standard for the way architecture is practiced. It is taking architectural practices in a direction where it will no longer be optional to upgrade to new design methods (Emaminejad and Akhavian, 2022). Caetano et al. (2020) identified the positive impact of CD on architecture and established that it enables architects to enhance the design process by expanding its conceptual boundaries. Nisztuk and Myszkowski (2017) demonstrated that recent studies still focus on finding accurate and effective computational approaches for the generation of floor plans with less focus on the effectiveness of a particular algorithm or IT solution.

Caetano and Leitão (2020) focused on three aspects: analyzing CD, discussing advancements in CD tools, and presenting architectural projects and events that explored CD. The results showed that technological developments continue to shape architectural theory and practice and, simultaneously, are guided by their needs and aspirations.

In this study, we explore the potential of integrating Artificial Intelligence in architecture to create self-learning buildings that can adapt to future challenges and enhance their performance, and improve the architectural design process using computational design technologies. This paper focuses on two aspects. First, we dive into the subject of CD and how it would serve architecture in a hypothetical scenario.

The second part shows the architectural design process in implementing a building using computational design. By looking at the factors that influenced architecture throughout history, it can be noticed that a new historical event happens every few decades, such as a natural disaster, war, or pandemic, which inspires architects, engineers, and designers to address new design challenges (Hendy, 2020).

This study aims to create a building that uses a system providing innovative solutions for any potential challenge facing the building. Such a system would take advantage of the latest machine-learning technologies. It would merge sensors and bio-digital materials, which work perfectly together to deal with any challenge (Estévez and Navarro, 2017). An example of this would be the challenges that occurred during the COVID-19 era. In this case, the building would adapt by activating social distancing from within the building, which could be done through the communication between the CD cloud system of the building and the robots, which are inside the building. This means the CD would take the necessary actions to adapt and achieve the goal of social distancing (Ahmed, 2021).

Another way to deal with COVID-19 challenges could be by placing an innovative skin on the buildings' interior walls, which does not pick up germs. This can ensure that the spaces are sanitized at all times (Assaf, 2021).

The goal of this study is to create a self-learning building. It would be a building that can adapt and learn from all sorts of aspects of its environment (Cortiços, 2019). For example, if a project is implemented in a particular place, the intelligent building system would be able to study and collect information internally about the culture of that place and adapt itself to that culture. It would use sensors to know the number of people in the building, the time they spend together, the clothes they are wearing, and the actions they are taking.

After some time, it would see patterns and learn from them to predict what will happen in the future (Hutson, 2017). Another example of what the building can learn is the environmental conditions of its site, which can be sensed externally. This means the building would be able to collect and store data about the environmental conditions and energy use of the building.

Based on the data collected, it would decide on the actions needed to reduce the energy use of the building, such as changing the tint of the windows to reduce the amount of heat in the building (Mehra and Sharma, 2019).

1. *Use of technology to enhance building performance*

When it comes to the performance of buildings, new automation systems can be used to control security, comfort, and energy efficiency (Birangal et al., 2015). AI enables buildings to become places driven by real-time data and feedback, communicating with itself like a living organism (Cotrufo et al., 2020).

It creates a system where buildings, smartphones, cars, and public places share to improve living conditions, limit waste and traffic, and increase safety. This would allow the building's AI to predict any challenges that might come up (Alexander, 2020). AI also opens the doors to creating smart homes, living spaces that are complex real-time data-driven living organisms (Pala and Özkan, 2020).

For architects, the challenge is how to use AI to fit it into the design language of the home to improve the lives of the residents (Chua, 2013). With AI, we would be able to tailor the building performance according to the people's needs and have buildings learn, adapt, and respond to the data that they receive from the users (Zhao et al., 2019).

AI in buildings takes complete care of residents' comfort and safety and helps with energy and financial savings (Joshi, 2019). AI-based energy management platforms can track usage patterns to create proper conditions for tenants, conserving energy and saving money (Chen et al., 2021). Fig. 1 shows a Nest Thermostat, an excellent example of a system that can adapt and keep the building at a safe and optimal temperature. It can also alert users if the temperature increases to reach a dangerous range. AI devices can analyze data from sensors to monitor leaks or malfunctions. This makes it easier than ever to track the building's performance and efficiency (Oberste-Ufer, 2019).

In addition, building managers can maximize operational efficiency, properly utilize assets, and improve the comfort level of occupants (Rocha et al., 2021).

2. *Use of AI in the architectural design process*

As architects, we start our projects by spending many hours on research to understand the design philosophy of that project and analyze previous similar projects. However, this process takes much time, and here AI comes in (Al-Azzawi and Al-Majidi, 2021). AI can collect and combine limitless amounts of data in little time, make decisions, and give recommendations that ease the architect's research process (Kurtoglu et al., 2009).

The architect can test many ideas and conceptual designs simultaneously without needing a pen and paper, and, as a result, better understand the design philosophy using a faster strategy. We are living in the world where AI has become a tool to leverage the design process. However, it is not convenient

Fig. 1. AI Nest Thermostat device keeping the building at an optimal temperature (Wollerton, 2018)

to automate the entire design process and solely depend on AI as there are always possible errors.

The real advantage of using AI comes from a collaboration between human intelligence and Artificial Intelligence (Wang, 2011). Today, there are many AI engines, such as DeepArt, MidJourney, and DALL-E, which open doors to a wide variety of possibilities that can affect the architectural design process. These engines can visualize anything the user desires. The user (provided that they have some prior knowledge in coding) just needs to type a prompt.

This means that the concept stage in the design process will no longer need to involve sketching the ideas. It can simply be visualized with high quality in seconds (Jaruga-Rozdolska, 2022). Fig. 2 shows images of buildings generated by the AI engine MidJourney in a matter of minutes. These images were obtained by typing a prompt to generate a building in a nature-inspired style. The engine creates four images and allows the user to select the best ones to further create more images and make enhancements. Traditionally, it might take days to manually design and render, but with AI, it can be reduced to minutes.

Fig. 2. An example of images of buildings generated by MidJourney (source: the authors)

3. *Computational design in the architectural design process*

Parametric/Computational Design is a significant field where technology and architecture work together harmoniously and where programming tools have quite an impact on architecture. CD allows us to create a parameter-based system that can generate the desired output, such as forms, structures, and systems, with the ability to control high levels of complexity.

The CD approach to architectural design gives the designer many advantages, such as creating complex structures and having complete control over them, automating redundant tasks, which take a lot of time in the design process, and easily modifying the design at the late stages (Oxman, 2017). Intelligent software like Grasshopper Scripting gives the architect the opportunity to use geometric component-based programming with complex algorithms to generate design variations that follow a specific design vocabulary and offer numerous design options. One of the advantages of using Grasshopper is its ability to control and produce high-quality complex organic geometries (Cubukcuoglu et al., 2019).

Another advantage is that it is supported by a variety of plugins, providing access to external libraries such as Ladybug, thus giving you the opportunity to perform a real-time environmental analysis of your project, which will be demonstrated in Section 2.2.2 below (Roudsari et al., 2013). Another popular CD software is Dynamo. It is a visual programming software created by Autodesk, which can be used with Revit, a BIM software. As opposed to Grasshopper, Dynamo's advantage is not in creating geometries but rather in ensuring data management for the project, which makes it an excellent choice for BIM. Dynamo is a very important tool in the automation of a lot of BIM processes, which increases the efficiency of the design process (Shishina and Sergeev, 2019).

It works on a node-based system. Each node carries a piece of code inside, but instead of writing the code, a node can be dropped easily with a ready-to-use code. These nodes can be connected with wires to be merged into one piece of code that performs a specific function. A full algorithm would usually look similar to the one shown in Fig. 3, where groups of nodes connected perform one or more specific actions. These CD strategies are almost like an architect's own programming language. They can be made even more vital when paired with Virtual Reality (VR) and Augmented Reality (AR) devices, where you would be able to use devices like the Magic Leap to observe your design as if it is built in front of you and make adjustments from a different perspective (Philips, 2020).

Methods

The approach followed in this paper to show the architectural design process for the implementation of the building is divided into three phases. The first phase is the form generation process. In this phase, a concept for an adaptable organism is selected to inspire the form generation strategy. After that, an algorithm is designed using Grasshopper Scripting to generate various adaptive forms. The second phase is the form selection process. In this phase, the forms generated in the previous phase get filtered according to many different analyses, such as structure, radiation, and shadow analysis. The filtration process will help in selecting the most

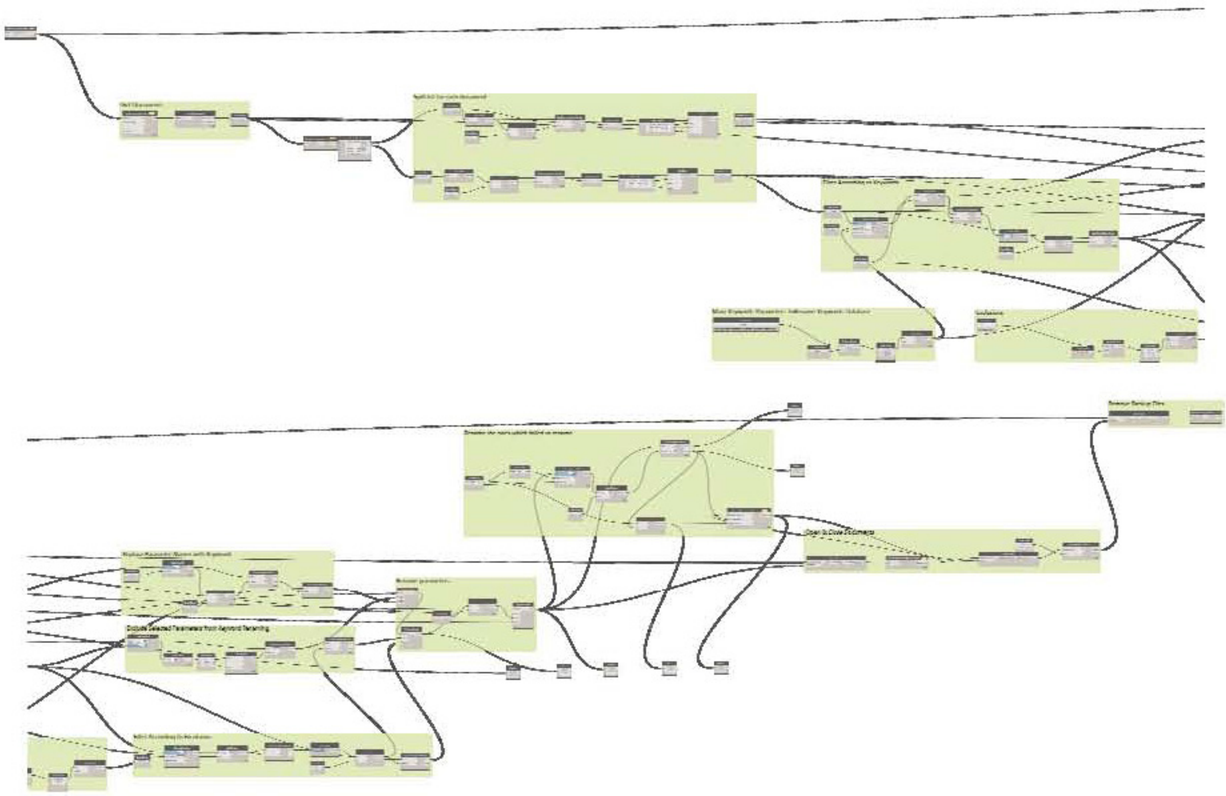


Fig. 3 shows an example of an algorithm design in Dynamo. As seen from Fig. as well as Fig. 5, which is a Grasshopper algorithm, the way these tools work is similar to coding but more convenient

environmentally responsive form. In the third phase, the final selected generation is developed further to finalize the design and ensure a more ecologically responsible approach.

1. *Phase 1: Form generation process*

1.1. Concept development

The basis of this project was adaptation. The research interests lie in form finding, form optimization, architectural facades, skin, and other geometrical explorations using computational tools such as Rhino and Grasshopper. When we look at nature, we can see a lot of naturally adaptive forms and processes. This makes nature the mother of inspiration for adaptive designs. We followed the natural process of adaptation, combining parametric modeling and CD modeling to explore avant garde bio-inspired concepts. We also aimed to take a concept from idea to form and visually present it in a convincing rendering. It was planned to use growth as a generative tool to create unexpected forms that resemble those found in nature and organisms.

In the course of the study, we used Rhinoceros paired with Grasshopper + plugins to obtain biomorphic designs. We tried to use computational tools and strategies to create complex forms morphing and mimicking the growth of bone cellular structures, which are shown in Fig. 4. The goal was to bio-mimic the process of growth in these organisms that causes them to evolve into an adaptive structure. These organisms grow in a way that produces voids of different sizes in structures.

In architecture, such voids could help create different-sized patios that would allow sunlight to go into the building to reach the internal spaces and wind to flow and naturally ventilate the building, thus making an environmentally responsive form. These

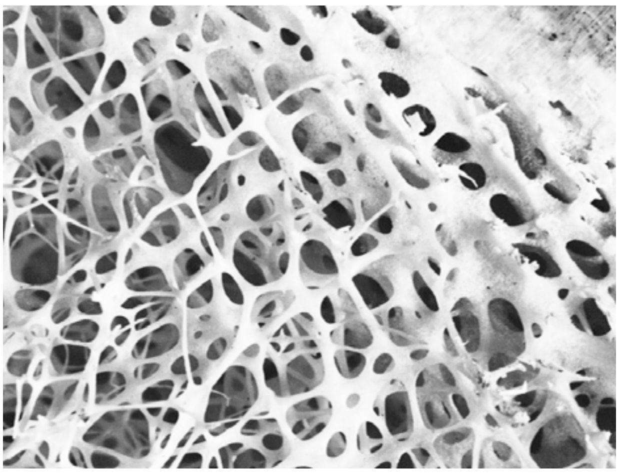


Fig. 4. Cellular structures' growth pattern (Naboni and Kunic, 2017)

structures also could melt into each other forming bridges between the different cells. The formed bridges would connect functions on different levels (Chen et al., 2015).

1.2. Grasshopper script design

To generate architectural forms that mimic the growth of bone cellular structures, intelligent CD technology and component-based programming tools such as Grasshopper were used in the design process. This design technology allowed for developing an algorithm creating a system that can generate complex forms based on logic.

The CD tools and principles were used to design a Grasshopper definition that can generate adaptive forms bio-mimicking the natural process. The Cocoon plugin was applied in the process since it helps generate organic forms that connect masses by melting them into each other. As shown in Fig. 5, the main component is called the Cocoon, which is the script's core. The Cocoon generates the form based on the inputs, which are shown on the left side and called Charges.

These charges include three input parameters.

The first parameter is the site-surrounding blocks shown in Fig. 6. Using the site surroundings as a parameter guarantees a form specifically tailored to the selected site. The second parameter is the connection lines including the connection to the surrounding blocks, the entrances to the site, and the overall circulation pattern. Using those as a parameter helps in defining the mobility and circulation path of the building. To generate a final form, the volume of the function was used as the third input.

It was used as an input parameter instead of the area of each function to generate 3D forms, not 2D patterns. Finally, the last component on the right is the Smooth component which is used to smoothen the connection between the masses.

2. *Phase 2: Form selection process*

2.1. Experimental studies

The approach followed to generate an adaptive, environmentally responsive form was subject to experimental studies. In this phase, tens of experimental studies are generated and filtered by analyzing and selecting the most adaptive form. To achieve this, the Grasshopper definition was developed further by using the Millipede plugin. This plugin gives an opportunity to analyze the structure of each generated form and provides essential values such as maximum deflection, weight, yield, bending moment, and more.

The generation process for all the experimental studies was implemented using the Grasshopper Galapagos tool. It is an Artificial Intelligence tool in Grasshopper that changes the selected parameters to find the best solution which maximizes or minimizes a selected value. In this case, the value that was selected to be minimized is the maximum deflection of each form, which was calculated with the Millipede components.

The parameters that were altered to change the form were the radius and the position of each Cocoon charge assigned to the site-surrounding blocks and connections. Fig. 7 shows the best 24 generated results of experimental studies with the Galapagos tool.

2.2. Selection analysis.

At this stage, we analyzed the results of experimental studies generated at the previous stage. Fig. 8 shows all the structural analyses for the generated forms. The colors show the distribution of deflection around the form; the red color shows the high-deflection areas, and the blue color shows lower amounts of deflection distribution.

The filtration process will depend on the forms with the lowest maximum deflection, deflection distribution

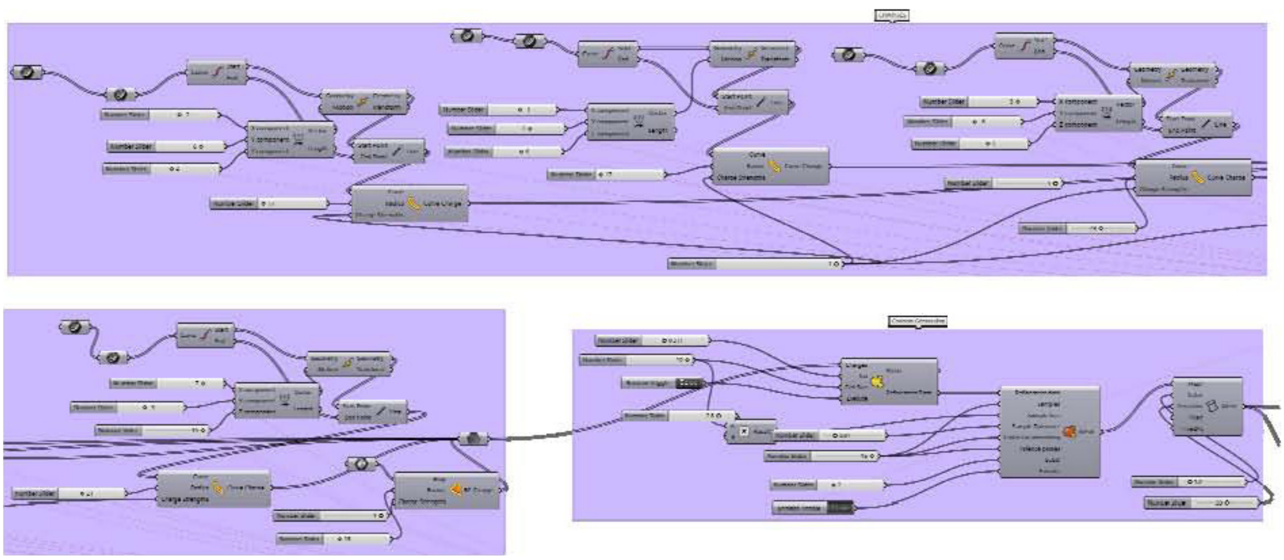


Fig. 5. Grasshopper algorithm designed to generate building forms

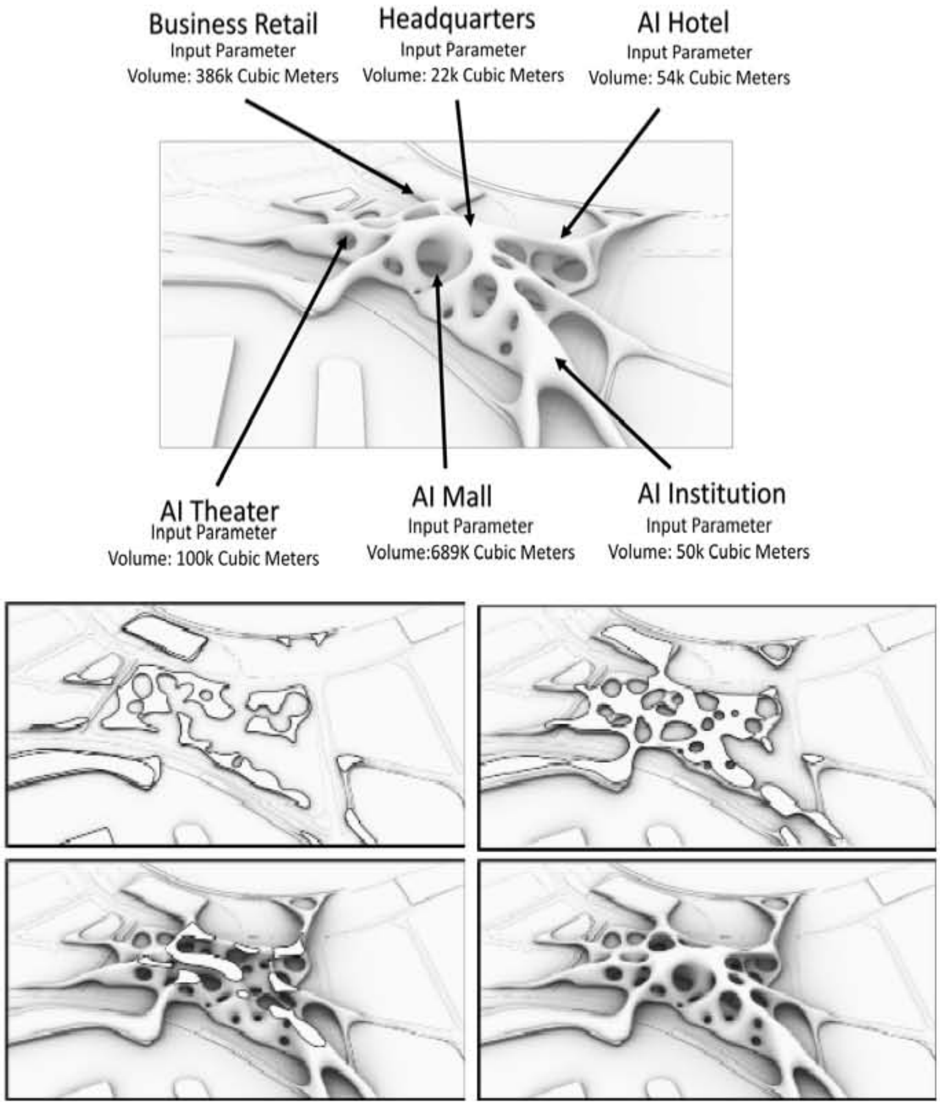


Fig. 6. Site surroundings and volume of each function as the parameters defining how the building will look like

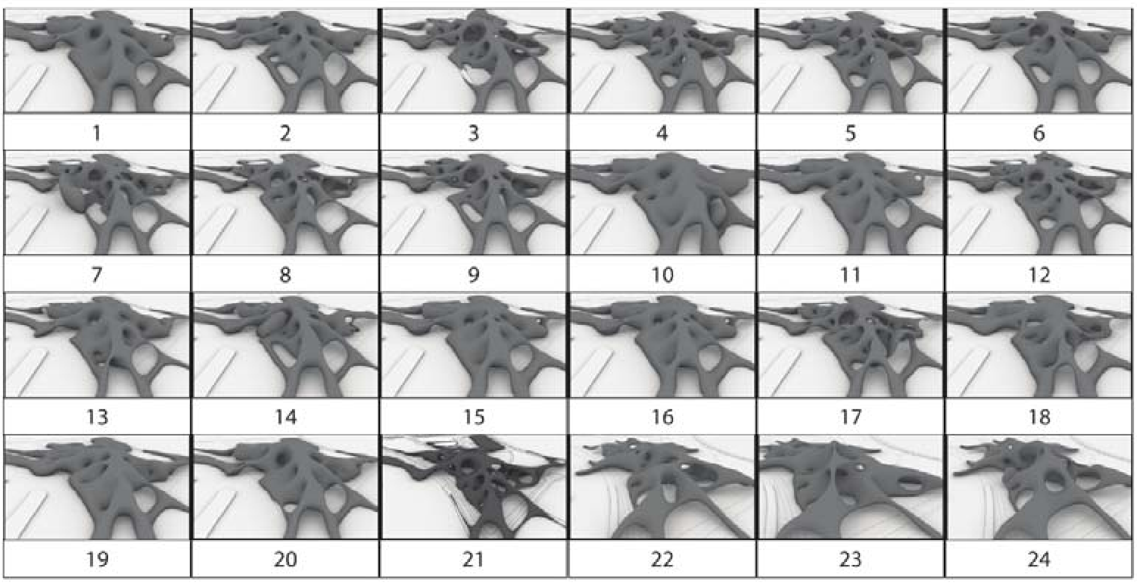


Fig. 7. Experimental studies performed in the process of generating the best form

pattern, density of the structure, and availability of errors in the form. According to these criteria, the best four forms are generations 21, 22, 24, and 24, with the minor deflection in all the experiments.

In addition, as seen from the colors, their deflection distribution pattern is acceptable. It can be noticed that all four of these generations are very similar, which makes sense since they have similar performances. These four forms then went through shadow and radiation analysis to select the most adaptive final form. Fig. 9 shows the shadow analysis for the four selected forms. It can be seen from Fig. 9 that the best selection would be generation 21.

Since this selection has more considerable curvature, it provides a more extensive surface area towards the side of the Sun's movement. It casts shadows for a longer time of the day, with only one hour of direct sunlight hitting the internal part of the building. Fig. 9 also shows the radiation analysis for the same four generations (Maksoud et al., 2022). Similarly, the same selection performed the best in terms of radiation on the internal part of the building with a value below 467.98 kWh/m^2, which makes sense since this form will have the least amount of direct sun exposure. The performed analysis helped in selecting the most environmentally responsive form.

3. *Phase 3: Form development process*

3.1. Skin and structure development

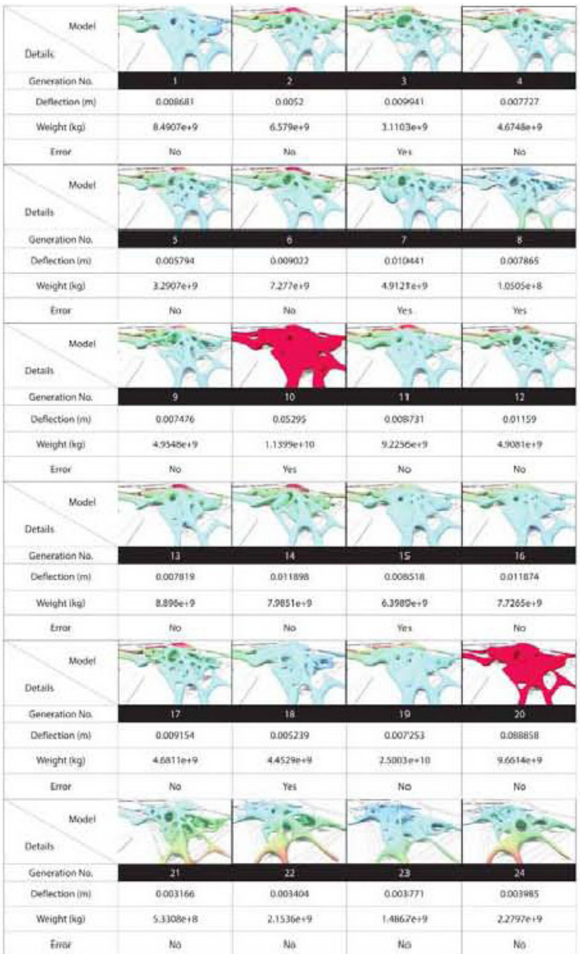
After selecting the most adaptive form, we developed it into a finalized form. At this stage, another Grasshopper definition was designed to generate the skin and the structure of the building. As you can see in Fig. 10, this definition uses the Weaverbirds plugin, which helps in generating triangle-shaped panels forming the geometry of the form.

It also helps in generating the structural members that are supporting these panels. The skin that is used for the building is smart skin. It can sense the Sun's heat using CD and change the tint of the glass when the heat increases and decreases. The panels that are facing the Sun moving from the south will be filled with solar PV panels to generate energy for the building. As for the rest of the panels that are facing the other sides, they will be filled with smart glass, which helps bring diffused light into the building. (Abdalla, S.B et al., 2022)

Results and discussion

1. *Adaptive expansion system using CD*

The final form of the building was produced after finishing the form development, shown in Fig. 11. As seen from the Figure, the strategy of using CD in the design process helped in creating an elegant



Generation No.	Deflection (m)	Weight (kg)	Error
1	0.008681	8.4907e+9	No
2	0.0052	6.579e+9	No
3	0.009941	3.1103e+9	Yes
4	0.007727	4.6748e+9	No
5	0.005794	3.2907e+9	No
6	0.009022	7.277e+9	No
7	0.010441	4.9121e+9	Yes
8	0.007865	1.0505e+8	Yes
9	0.007476	4.9548e+9	No
10	0.05295	1.1399e+10	Yes
11	0.008731	9.2256e+9	No
12	0.01159	4.9081e+9	No
13	0.007819	8.896e+9	No
14	0.011898	7.9851e+9	No
15	0.008518	6.3989e+9	Yes
16	0.011874	7.7265e+9	No
17	0.009154	4.6811e+9	No
18	0.005239	4.4529e+9	Yes
19	0.007253	2.5003e+10	No
20	0.088858	9.6614e+9	No
21	0.003166	5.3308e+8	No
22	0.003404	2.1536e+9	No
23	0.003771	1.4867e+9	No
24	0.003985	2.2797e+9	No

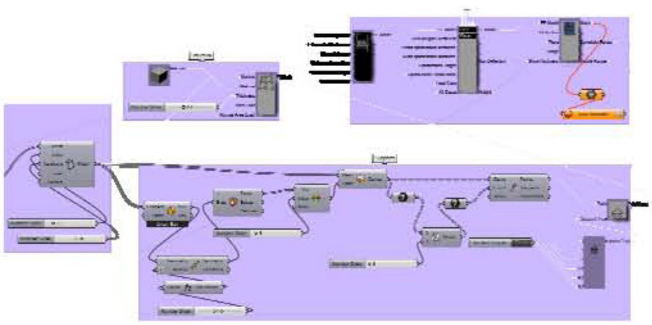


Fig. 8. Algorithm and results of the structure analysis

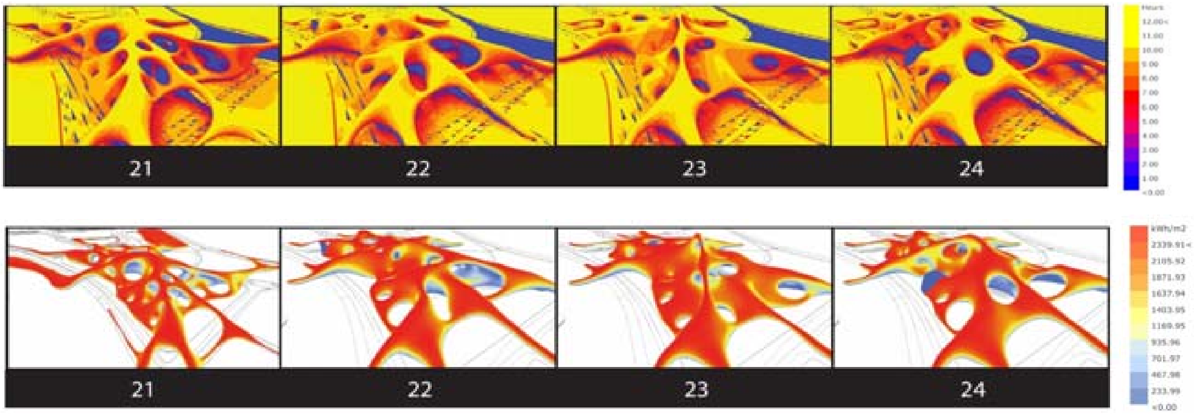


Fig. 9. Shadow and radiation analysis for the best four generations

originally looking building adapted to the site. The obtained final design looks futuristic, and some might argue that it’s not buildable. However, CD tools provide more strategies for us in the digital fabrication of such designs.

For example, each of those panels that make the skin of the building can be easily tracked with Grasshopper to produce a report with all the pieces required to build this using manufacturing and assembly data.

The story does not end here because a new analysis must be made to test the performance of the final building after its development and check if the building is environmentally responsive.

To analyze the performance, a new Grasshopper algorithm was developed using the Ladybug plugin, which is shown in Fig. 12.

The table in Fig. 12 shows the results of the analysis that was generated from the algorithm. As seen from the Table, the total radiation per year is 161.36 kWh/m^2. To know if that is a good result, it can be compared to the Emirates GBC BEA Project from the Emirates GBC 2020 Green Building Market Brief, which is shown in Fig. 13.

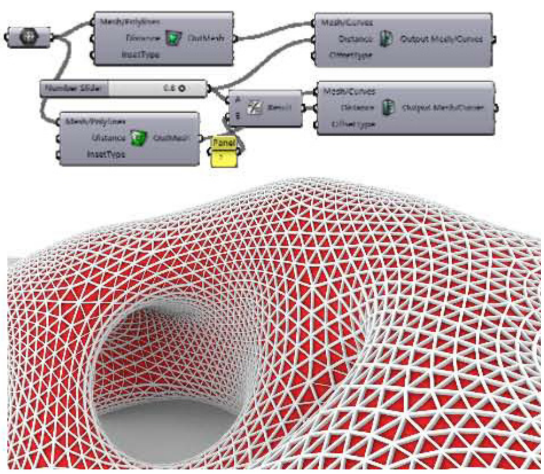


Fig. 10. Skin and structure of the building

Fig. 13 shows that the best performers in terms of radiation are the buildings that have less than 171 kWh/m^2 for hotels, 193 kWh/m^2 for resorts, 92 kWh/m^2 for schools, and 378 kWh/m^2 for malls (Emiratesgbc.org, 2020). Fig. 14 shows that a significant part of this building is a CD Mall, and there are some parts of the building that act as a CD Hotel and CD Institute. (Mushtaha, Emad et al., 2022)

When comparing our results to those of the BEA project, it can be concluded that the building is considered a best performer when it comes to the mall and hotel and a median performer when it comes to the institute. These results prove that the building generated by CD is, in fact, environmentally responsive.

In addition, it can be noticed from Fig. 12 that the PV panels placed on the south façade provide 368,070.02 kWh per year, which is 12% of the building’s energy.

2. *Adaptive expansion system using CD*

CD has many potentials in design. At this stage, a CD engine called Deepart.io was used to predict the future expansion of the building on the project’s site and in the city of Dubai. This is a global CD engine that has been used by international universities like MIT & organizations like AA in London. It can alter a picture based on a given style, which acts as a parameter controlling the output. So, a picture of the site was uploaded as an input with another picture of one of the experimental studies, as shown in Fig. 14.

The CD engine was able to study the style of the building and produce an output showing how the entire site would look when filled with this form. In architectural terms, this CD engine could predict future expansion of the building based on its information as a parameter. This makes architecture no longer about one building; it is rather about an adaptive system that can be applied in any location. By changing the picture of the site to a picture of a different site, the CD engine will adapt the form to the new site and produce a different result.

Conclusion

CD technologies not only enhance the efficiency of the design process but also help create adaptive

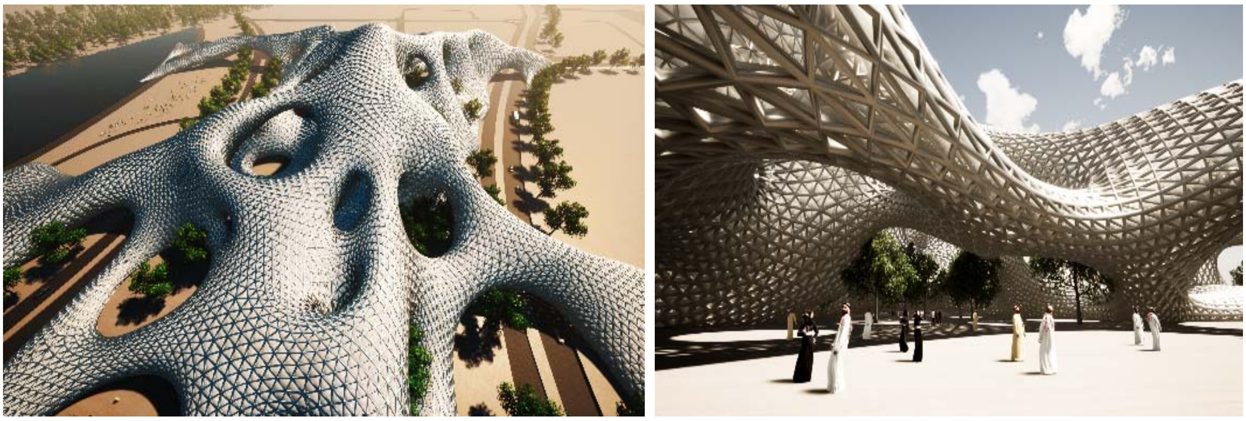
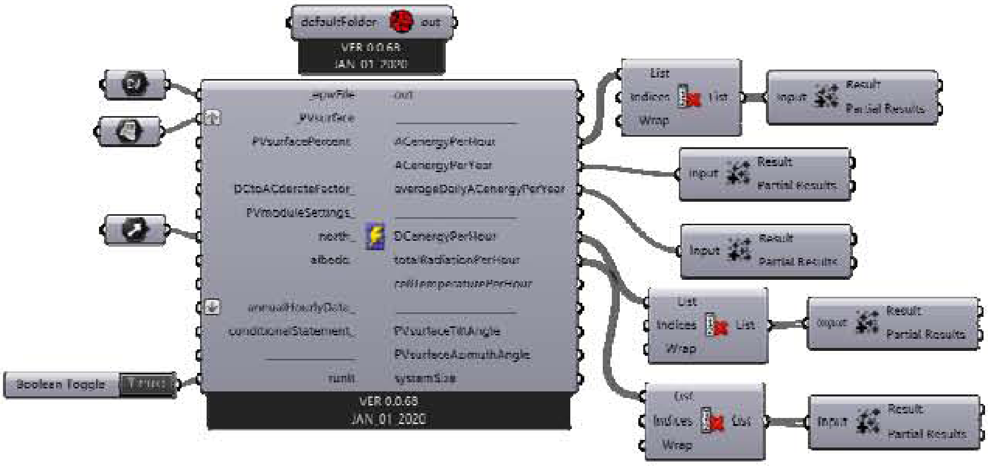


Fig. 11. Final form of the building after the development stage



	AC Energy per year (kWh)	Average Daily AC Energy per year (kWh/day)	DC Energy per year (kWh)	Total Radiation per year (kWh/m²)	Total Radiation per year (kWh)
Final Result	322924.56	884.72	368070.02	161.36	2689300

Fig. 12. Algorithm and results of the energy use

BEA RESULTS – Energy Use in Dubai Hotels, Malls and Schools

	Best Performers	Median	Worst Performers
Hotels	< 171 kWh/m².year	249 kWh/m².year	> 414 kWh/m².year
Resorts	< 193 kWh/m².year	334 kWh/m².year	> 444 kWh/m².year
Schools	< 92 kWh/m².year	134 kWh/m².year	> 233 kWh/m².year
Malls	< 378 kWh/m².year	465 kWh/m².year	> 580 kWh/m².year

Fig. 13. Emirates GBC BEA Project from the Emirates GBC 2020 Green Building Market Brief

and environmentally responsive designs. The studies on the effects of these technologies in architecture consisted of two parts. The first part focused on studying how CD could enhance building performance and analyzing some hypothetical scenarios of how it might be implemented. The second part focused on the implementation of the architectural design of a building.

This process used CD technologies to enhance the architectural design process and create more adaptive designs. This stage included three phases:

Phase 1: Using CD tools such as Grasshopper Scripting to design a script that can generate different kinds of adaptable forms.

Phase 2: Performing experimental studies and selecting the best form based on structure, shadow, and radiation analysis.

Phase 3: Developing the skin and the structure of the building, which consisted of triangular panels filled with PV panels from the south and smart glass from the other sides.

After those phases, further analyses were conducted to test the final performance of the building.

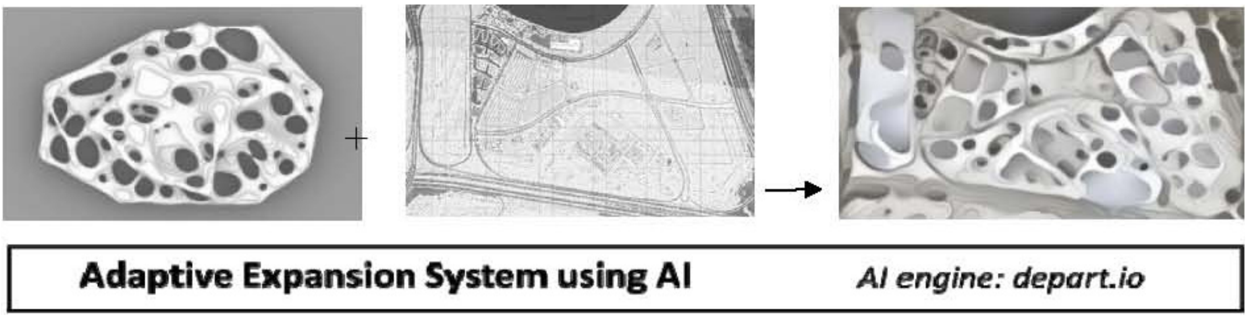


Fig. 14. Using AI to predict the future expansion of the building

The radiation analysis resulted in 161.36 kWh/m^2, which was compared to the values of the Emirates GBC BEA Project from the Emirates GBC 2020 Green Building Market Brief to prove that the resultant form is, in fact, environmentally responsive.

Another analysis was done to test the performance of the PV panels in producing energy for the building, which showed that the PV panels cover 12% of the building's energy.

A CD engine was then used in developing an adaptation system for the building. In conclusion, this research explored the potential of using CD and its technologies in architecture. With the results that showed how the technology helped in creating an environmentally responsive design, it is obvious that these technologies are powerful strategies to be considered and implemented in architecture.

The implementation of CD technologies in architecture starts from the beginning of the design process all the way to the functionality of the actual building. Dubai, being one of the most competitive cities regarding technology, has enormous potential to implement a project like this.

The significant limitation in this field is the scarcity of expertise in CD technology, which makes implementation expensive.

Finally, design and technology are increasingly becoming more connected to each other; it will open doors for new areas of research and redefine how future architecture will look like.

Acknowledgments

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