PARAMETRIC STUDY AND COMPARATIVE EFFICIENCY OF ISLAMIC GEOMETRIC PATTERNS AS A RETROFIT STRATEGY IN MID-RISE BUILDINGS OF AL AIN CITY, ABU DHABI, UAE

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ABSTRACT
The city of Al Ain (Abu Dhabi, UAE) has a significant amount of mixed-use mid-rise buildings, especially in the city's central district. Because of the harsh arid climate of Al Ain, many of these buildings have high energy demands to accommodate the cooling load. By taking inspiration from the traditional Islamic architectural element, Mashrabiya, this study is concerned with exploring and identifying various, optimal Islamic geometric pattern (IGP) configurations used in cladding systems, with respect to energy consumption, daylighting, and quality views. The main objective of this study is to formulate a repertoire of IGPs that can be used in façade cladding systems that achieve significant reductions in energy consumption, while also providing sufficient daylighting and quality views. After a comprehensive literature review and local climate analysis, ten commonly-used IGPs will be modelled using the parametric software language Grasshopper and applied to the selected building modelled in Rhinoceros 3D, a 3D modelling program. Next, energy, daylight, and view quality simulations will be conducted using different orientations and during different seasons. The modelling process and simulations, along with the obtained results should give stakeholders a catalogue of optimal IGPs to refer to when selecting a passive exterior perforated cladding system. The study should also add to the knowledge of employing vernacular patterns to façade cladding systems in the hopes of strengthening the link to local culture.
Keywords: Islamic geometric patterns (IGPs), Mashrabiya, parametric modelling, Grasshopper, Rhino 3D, passive cooling, perforated screens.

1 INTRODUCTION

There has been growing awareness in recent years regarding the energy consumption and interior environmental comfort of buildings. Because of the harsh arid climate of Al Ain, the built environment has high energy demands to accommodate the cooling load. The energy utilized to power residential and commercial buildings is responsible for more than 70% of the total electricity consumed in the UAE today, and air conditioning is a significant hindrance to reducing electricity consumption [1]. This prompts designers and engineers to consider passive retrofit strategies that maintain thermal comfort and reduce exorbitant usage of air conditioning. To aid in reducing this figure, applications of traditional elements, such as Islamic geometric patterns, have the potential to serve a myriad of purposes; namely as a passive cooling system such as in the original purpose of the traditional Mashrabiya.

2 RESEARCH QUESTIONS AND OBJECTIVES

2.1 Research questions

Many factors have added to the growth of energy consumption in mid-rise buildings in the UAE, specifically the increase in population, the improvement of comfort levels, and the increasing number of electricity-using devices such as air-conditioning, as mentioned previously [1]. Passive cooling techniques control the amount of daylight without the need

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for energy or electricity. Furthermore, common passive cooling devices, such as perforated screens can communicate a sense of cultural identity by incorporating regional Islamic Geometric Patterns (IGPs) and tessellations. This research thesis takes place in Al Ain, UAE, and aims to answer several questions, namely:

1. How have IGPs that have been woven into the built form of Al Ain?
2. How can these IGPs be used in perforated cladding systems retrofitted on the façades of mid-rise buildings?
3. What are the ten most optimal IGP configurations for reducing energy usage and cooling loads?
4. What are the ten most optimal IGP configurations that maintain quality daylight and views?

2.2 Research objectives

The objectives of this study are the following:

1. Assess the status quo of the integration of IGPs in the urban fabric throughout Al Ain.
2. Assess the current condition of mid-rise buildings in Al Ain's city centre and determine a base building that will be improved with a passive Mashrabiya-inspired skin.
3. Model and simulate ten frequently used IGPs on the proposed building and compare results to common shading devices such as overhangs and louvers.

The first objective will be achieved via comprehensive observational tactics. First, a stock of the available IGP Mashrabiya in Al Ain will be documented. As for the second objective, construction documents for a mid-rise structure in Al Ain's central district will be obtained, diagnosed for heating and energy shortcomings, and recreated in the digital environment of Rhinoceros 3D. It is noted that a comparison with other passive cooling methods must be conducted to ensure that the installation of a perforated screen façade will not be detrimental to the environmental quality of the proposed building. After accurate modelling and comparison of the ten selected patterns, the final deliverable will take the form of a catalogue of optimal IGP configurations with a quantitative set of values regarding energy usage, daylighting, and view quality in the context of shading devices.

3 LITERATURE REVIEW

3.1 Relevant works

Hassan Fathy is considered the father of all published studies of Mashrabiya [2], as he is responsible for conducting many influential studies of all traditional Arab architectural elements. With the emergence of advanced designing tools such as parametric modelling, Luigi Giovannini's work developing the shape variable Mashrabiya (SVM) has risen to prominence [3] in the field of Mashrabiya studies. Similarly, Bagasi and Calautit [4] and Bagasi et al. [5], have conducted numerous comprehensive studies on Mashrabiya as a passive cooling technique.

3.2 Mashrabiya as natural ventilation

A Mashrabiya is a form of projecting oriel window on the top levels of a structure that is encased with carved wood latticework. It was once used to capture and passively chill the wind by placing containers and basins containing water in it to create evaporative cooling.

Its namesake stems from the Arabic term "yashrab" meaning "drink". The traditional Islamic window element is used to wrap entire buildings as an ornament system, serving as a local identity feature and as a sun-shading device for cooling. Designers have recently transformed the vernacular wooden element into adaptive and responsive daylight systems, such as in the case of Al Bahar Towers (Fig. 2) or the Louvre Museum in Abu Dhabi, UAE [6]. Mashrabiya differ based on the pattern used, level of enclosure, thickness, and material among other factors.

Akçay and Alotman [7] highlight the lack of original criteria for the re-evaluation of traditional architectural elements. Their study focuses on the Mashrabiya and they formulate a general theoretical framework in order to establish a consistent set of functions, parameters, and patterns for the revived versions of contemporary Mashrabiya. It is explained that on top of the ornamental and aesthetic qualities, Mashrabiya establish a sense of privacy and environmental purposes such as lighting, heat, and airflow control. The study then goes on to closely analyse four examples of contemporary Mashrabiya application: Mashrabiya House in Palestine, Masdar City (Fig. 3) and Al Bahar Towers in UAE, and Birmingham Library in the United Kingdom. Ultimately, the study calls for a halt to misconceptions regarding the implementation of Mashrabiya and suggests that project coordinators should have a complete understanding of the environmental functions of Mashrabiya.

Bagasi and Calautit [4], investigating the effect of different passive cooling strategies on indoor thermal environment, with an emphasis on Mashrabiya (Fig. 1), found that even though closing a Mashrabiya constricted the entry of airflow, it also sufficiently shields from direct sunlight during noon times. The author suggests Mashrabiya are efficient in delaying the heating effect of a room for up to 4 hours, while opening a Mashrabiya only delayed the heating effect by three hours. It is also recommended that scholars further study the impact of various configurations of Mashrabiya on indoor thermal comfort that were not covered in their case study, which took place in Jeddah, Saudi Arabia. Additionally, the author suggests studies on the effect of Mashrabiya on individual occupancy comfort by means of either modelling and simulations or field surveys.

Ashour [8] proposes a method for breaking down and deciphering the vocabulary of Islamic architectural heritage and integration (Fig. 4) into the built environment. His study suggests that designers should acknowledge the interconnected and complimentary values of vernacular components; which should enable designers and engineers to effectively perceive and comprehend these components and implement them into their designs. In a study by Abdelkader and Park [9] that discusses the contemporary applications of the traditional Mashrabiya, it is emphasized that while modern Mashrabiya tend to act as a shading device through static or dynamic active skins, it neglects other environmental factors, for instance, natural ventilation, which is the main principle in the traditional Mashrabiya.

3.3 Islamic geometric patterns (IGPS)

Islamic geometric patterns (IGPs) are one of the three major forms of Islamic ornament, which tend to avoid using figurative images, as it is forbidden to create a representation of an important Islamic figure according to the holy scripture Quran. IGPs are often built on combinations of repeated squares and circles, which may be overlapped and interlaced to form intricate and complex patterns, including a wide variety of combinations. In Islamic culture, seemingly infinite patterns are believed to be the bridge to the spiritual realm and an instrument to purify the mind and the soul. The repetitive, complex geometric designs in Islamic ornamentation give the impression that even the smallest element of pattern plays an

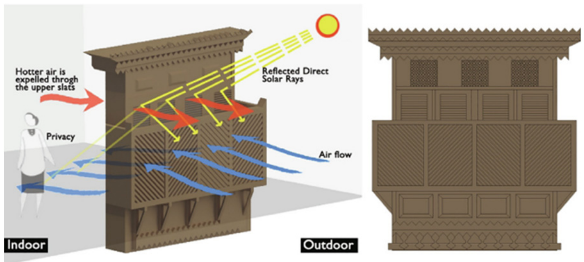


Figure 1: Mashrabiya function diagram [4].

Figure 2: Al Bahar Towers, Abu Dhabi, UAE [6].

Figure 3: Terracotta Mashrabiya in Masdar City, UAE [7].

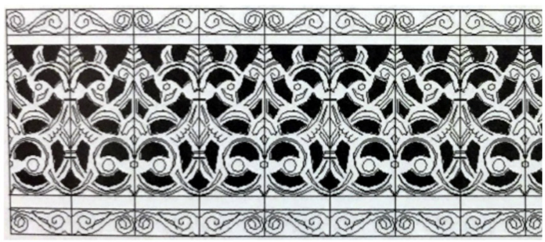


Figure 4: Early Mashrabiya pattern [8].

intentional role in the infinite repetition of the whole. IGPs are commonly categorized based on the number of "points" the base geometry consists of.

A study by Khamjane and Benslimane [10] with a primarily mathematical approach aimed to construct, within the fundamental region, the minimal key information needed to generate a particular symmetry type of IGPs (Fig. 5). The constructed template motif depends on the symmetry group, creating the unit motif. A Java application called Lmaâlem is constructed as a result of the study. The usage of such an application can yield patterns that would not be achievable using a pure polygons-in-contact approach. For example, rosettes that do not come into contact with each other are now possible to generate. The method is easily implemented compared to existing generative methods, and this insightful study has revealed a method of generating endless possibilities of IGPs.

Elmoghazy and Afify [11] discuss the progress of the presence of patterns in architecture from the 20th century until modern time (Fig. 6), while also navigating the meaning and importance of using patterns. After conducting a thorough SWOT analysis, it is highlighted that further research is needed in regards to patterns' role in defining the image of a city and should be analysed in the form of a comparative analysis between the perception of architects and inhabitants.

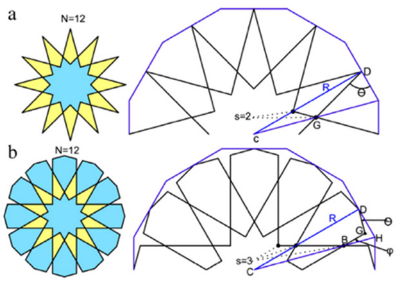


Figure 5: Twelve ray star parameters [10].

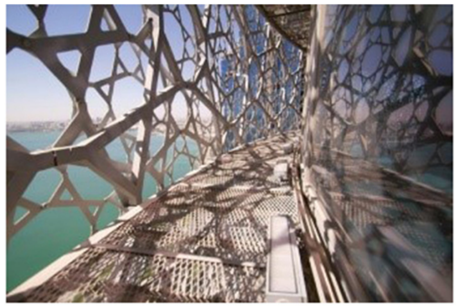


Figure 6: Doha high-rise office tower [11].

3.4 Adapting IGPS into a façade

The usage of technology in design applications has grown tremendously in recent years. One of these developments includes the widespread use of visual programming languages. A visual programming language allows users to create programs by interchanging program elements visually rather than by detailing them textually. The most common visual programming language used in Mashrabiya studies is Grasshopper, a visual programming language that operates within the Rhinoceros 3D computer-aided design (CAD) application. Grasshopper has a myriad of plug-ins that can be used for diverse functions, such as pattern generation, energy analysis, and daylight simulation.

Wagdy and Fathy [12] conducted an analysis in the context of a classroom (Fig. 7) in Cairo, Egypt. Different combinations of five unique screen parameters were computed. This process created 1600 different screen configurations. In terms of analysis tools, Radiance, DIVA-for-Rhino, and Daysim were used for highlighting the optimal configuration. The study revealed that louver count had no significant effect, even more so in the instance of high screen reflectivity (80%). In a study conducted by Mohamadin et al. [13] Grasshopper is used to generate IGP parametric variations. DIVA-For-Rhino was used for daylight analysis in tandem with Radiance and Daysim, and Design-Builder using EnergyPlus was used for thermal load simulations. The study achieved the required daylight levels with a significant reduction of energy consumption levels of the cooling load.

In a study by Giovannini et al. [3] exploring overheating and visual comfort issues in the UAE, the Shape Variable Mashrabiya (SVM) (Fig. 8) was designed and simulated into an office building in Abu Dhabi. A daylight analysis was implemented using DIVA-for-Rhino, the global energy demand was modelled, and three different user behaviour profiles were implemented in Daysim, a daylight simulation program. The proposed SVM minimized overheating issues and visual comfort is improved in regards to glare control, although at the expense of losing view to the outside environment in the relatively closed configuration.

4 METHODOLOGY

4.1 Climate of Al Ain

The climate in Al Ain is considered a desert climate with minimum rainfall. Based on the latest climate analysis graphs of the weather in Al Ain using the graphics-based computer program Climate Consultant, Al Ain has an average temperature of 28°C which is considered

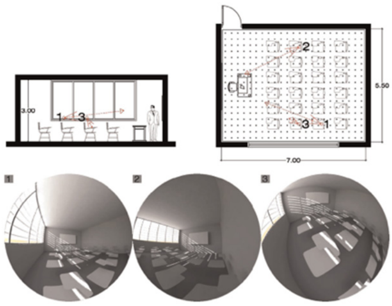


Figure 7: Floor plan and camera positioning of classroom [12].

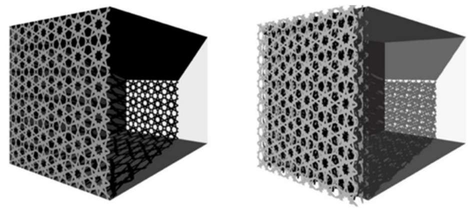


Figure 8: Floor plan and camera positioning of classroom [12].

above the comfort level. The favourable wind comes from north to west which carries a cool lightweight wind with a breeze, and the unfavourable wind comes from the north side which carries dust and has a hot breeze. Al-Ain has high levels of solar radiation and illumination but the humidity level is low which results in low levels of rainfall. Al-Ain has a unique microclimate in contrast to the larger, more humid coastal cities in the UAE. Throughout antiquity, several factors attracted civilization to Al Ain including the availability of groundwater, oases for dates, low humidity, and the role of Al Ain as a transit point between inland areas and the Arabian Gulf.

4.2 Mid-rise buildings in Al Ain

Al-Ain is known for its combination of modern and traditional infrastructure. In contrast to the towering skyscraper typology that is abundant in Abu Dhabi and Dubai, the city has implemented a policy of maximum permissible building height of four storeys including the ground floor, established by the founder of the country, Sheik Zayed, to maintain the city's cultural essence. According to the architectural guidelines published by the Abu Dhabi Urban Planning Council [14], the buildings facing the main streets and the city centre of Al Ain are the most densely developed with the tallest buildings, falling under the category of "mid-rise" buildings. Generally, these buildings consist of retail on the ground floor with residential floors and/or offices stacked above.

4.3 Tools and resources

4.3.1 Rhinoceros 3D

Rhinoceros, commonly referred to as Rhino or Rhino3D, is a computer-aided design (CAD) software developed by Robert McNeel & Associates that allows users to navigate a multitude of three-dimensional features including volume generation and design. Rhino3D manipulates non-uniform rational b-splines, or NURBS, to allow users to realize concepts and designs [15].

4.3.2 Grasshopper

Grasshopper is a visual programming language that operates within the Rhinoceros 3D application. Grasshopper is mainly used to create generative algorithms in the form of boxes and arrows; boxes are treated as entities, connected by arrows that represent relations. Similar to its parent application Rhinoceros 3D, Grasshopper is a highly versatile program that has a large number of plug-ins that can be used for a large number of purposes [16].

4.3.3 Parakeet

Parakeet is a Grasshopper plugin that specializes in algorithmic pattern generation. It consists of an adaptable approach that generates geometrical and natural patterns and networks. Parakeet features categories such as pattern generation, curve, surface, and Escher among several others [16].

4.4 Methodology

To achieve the aforementioned research objectives, the following steps (Fig. 9) will be taken to identify the most optimal IGP configuration in the use of façade shading screens. A literature review will inform and guide the study by giving critical information regarding the cultural and historical significance of the Mashrabiya. The literature review will also inform the study regarding alternate passive shading devices, while also providing benchmark values in energy reductions, daylight quality, and view quality. After obtaining relevant construction documents from the Al Ain Municipality such as floor plans, elevations, and section drawings, a mid-rise building in the city centre will be modelled in the three-dimensional modelling software Rhino 3D, with an emphasis on accurately portraying the current shading system applied. Subsequently, ten different IGP tessellations will be scripted and modelled in Grasshopper using the plug-in Parakeet, with various parameters including pattern density, thickness, spacing, and form in mind. After a thorough climate analysis of Al Ain, simulations of daylight quality will be conducted using DIVA-for-Rhino and validated using EnergyPlus. Subsequently, energy simulation and view quality evaluation will be performed using EnergyPlus and a comparison with the base case will be produced. The various IGP configurations will be compared to passive shading devices such as louvers, overhangs, and canopies. Finally, the performance of the different IGP configurations will be assessed and presented in the form of a catalogue of patterns ranked in order of optimal performance with respect to energy usage, daylight availability, and view quality. Different orientations and during different seasons will be analysed to identify the overall year-long effect of the proposed IGP configurations.

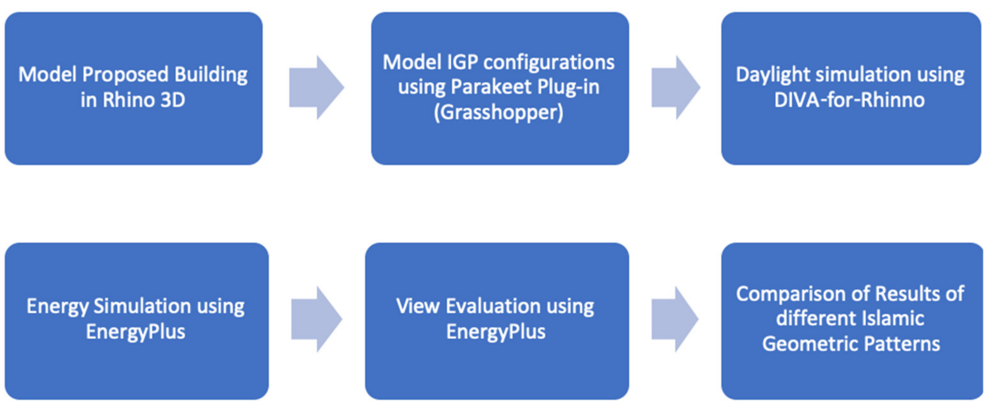


Figure 9: Proposed methodology.

5 PRELIMINARY RESULTS

The primary assessment tools established in the methodology of this research are Ladybug and Honeybee, which are two Grasshopper for Rhinoceros environmental analysis plugins. Ladybug creates site-specific climate analysis visualizations and graphs by combining geometric features in Rhinoceros and the parametric functionality of Grasshopper with unrestricted weather information from EnergyPlus (.epw files). Honeybee integrates Rhino geometry and Grasshopper capability with complex energy modelling and simulation software like Radiance, Daysim, EnergyPlus, and OpenStudio (Figs 10 and 11). Prior to attempting the scripting of the energy simulation, the supplementary scripts for incident radiation, the psychometric chart, direct sun hours, and wind rose were ran using the available weather data for the city of Al Ain, Abu Dhabi, UAE. Ladybug and Honeybee offer a plethora of different environmental analysis tools that may potentially be implemented later in the study (Figs 12 and 13).

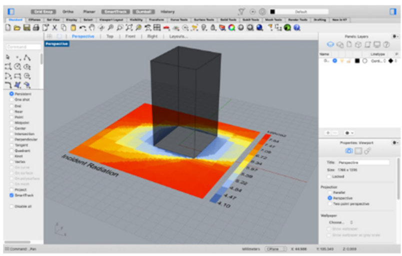


Figure 10: Incident radiation study.

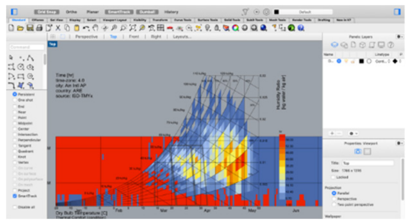


Figure 11: Psychometric chart for Al Ain, UAE.

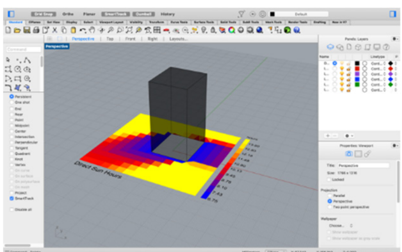


Figure 12: Direct sun hours.

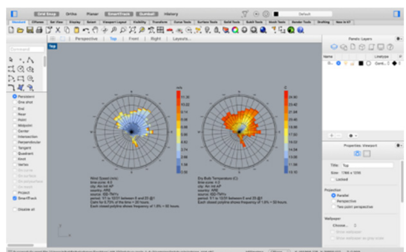
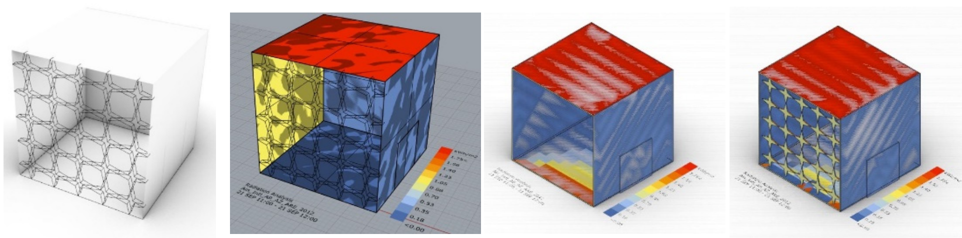


Figure 13: Wind rose.

Following the rudimentary studies conducted, the next step was the write and run an operation radiation analysis script on a simplified rectangular volume with one face removed in order to understand the process of applying the IGP Mashrabiya onto the case study building’s apertures or potentially façade. For the sake of uniformity, the basic Star Pattern I extrusion script was utilized as a buffer between the glazing and direct sunlight exposure. When scripting the radiation analysis, several challenges arose, particularly with the generative cumulative sky matrix component. The first step of the script included specifying the analysis period parameters, specifically the starting month, day, and hour to the end month, day, and hour. The climatic and solar data was imported from the Al Ain-based EPW file and the base model was the input Brep for the analysed geometry. Following the insertion of minute elements such as the north vector, grid size, and distance from base, the script returned the figures displayed below. The trial was unsuccessful; as the geometry of the IGP screen was not detected by the script. After closer consideration, it was apparent that more information regarding the context of the building was needed; this trial also clarified a different approach was needed in order to ensure the IGP is interpreted by the software as a shading device. A secondary attempt verified that the primary source of conflict was the geometry of the IGP. After converting the intitial star pattern into an additive configuration that was properly fitted within the frame boundaries, the script was able to read the pattern as an element of the geometry, thus returning more informative results. Fig. 14 illustrates the operation of the script. Fig. 14(a), 14(b) and 14(c) shows the model without the Mashrabiya as opposed to Fig. 14(c) which contains the Mashrabiya.



(a) (b) (c) (d)

Figure 14: Grasshopper radiation analysis (with and without Mashrabiya screen).

The next natural step is producing a functional script for an energy simulation to serve as a benchmark to compare the final results to. This simulation was conducting using a grasshopper script that provides values for estimated energy consumption due to cooling, heating, lighting, electrical equipment, and the process load. It was critical to ensure Radiance, OpenStudio, and EnergyPlus were properly running in order to achieve an output. OpenStudio is an inter-platform software suite that enables whole-building energy modelling with EnergyPlus and comprehensive daylight analysis with Radiance. OpenStudio is a community development, expansion, and private market adoption open source initiative. After creating a basic model in Rhino, with and without attached sample IGP Mashrabiya screens, the use of several OpenStudio-based components lead to the following energy consumption results: Cooling accounted for 302.66 kWh/m^2, heating accounted for 15.56 kWh/m^2, lighting accounted for 3.4 kWh/m^2, and process load accounted for 22.06 kWh/m^2. Immediately, it is apparent these results diverge from the real-time consumption, as little to no energy is needed for heating and electricity consumption from lighting is expected to be significantly higher due to the mixed-use nature of the building. Nonetheless, this basic script highlighted to large percentage of energy the cooling load requires for occupancy (Fig. 15).

6 EXPECTED RESULTS

According to the 2030 Al Ain Urban Structure Framework plan [17] released by the Abu Dhabi Urban Planning Council, Al Ain suffers from a "loss of distinctive regional architecture, replaced with poor quality new architecture". Additionally, the framework plan has stated that there is a "lack of shading and amenity in the public realm". The results of this thesis aim to mitigate both of the aforementioned issues with a well-organized collection of

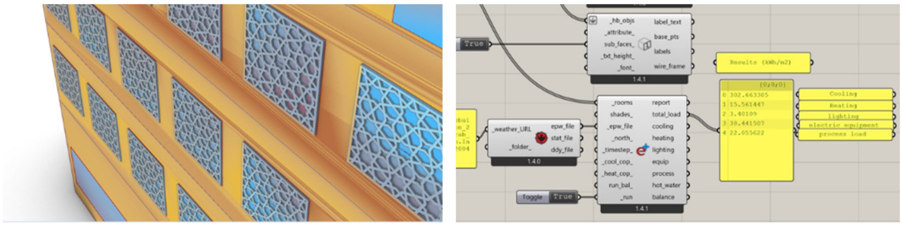


Figure 15: Basic energy simulation results.

Islamic geometric pattern configurations for government contractors to refer to when implementing passive shading techniques. The proposed list of pattern configurations will be designed not only to be applied to new constructions, but also to building retrofit initiatives to revitalize the existing infrastructure with modern, yet traditional qualities. This study also aspires to add to the field of Mashrabiya studies as well as passive shading devices by conducting the study in the context of Al Ain, UAE, a cultural epicentre of the region. The study will also showcase the efficiency of using parametric design software when approaching complex geometric forms. Overall, the results should give designers, engineers, contractors, and government officials an environmentally-friendly option for shading their mid-rise structures and projects.

Obtaining construction documents from the Al Ain Municipality may perhaps prove to be challenging, due to the sensitive nature of the documents. Nonetheless, the proposed building can certainly be modelled based purely on observation, however, obtaining the construction documents will expedite the process as well as guarantee a higher level of accuracy. Another challenge is the learning curve for fluency in the parametric design software, however, UAEU has a plethora of available resources, tutors, and experts to aid in learning the programs to a high degree of proficiency.

7 CONCLUSION

In conclusion, the mid-rise buildings in Al Ain are severely due for a re-evaluation and retrofit strategies using more environmentally-aware techniques to protect occupants from the regional harsh arid climate. These structures commonly have high energy demands to accommodate the frequent air conditioning use. Furthermore, many mid-rise buildings in Al Ain's city centre do not align with the rich and long-established cultural motifs available elsewhere throughout the city, a problem that has been acknowledged by the Abu Dhabi Urban Planning Council [17]. Revisiting lessons of the past, specifically the application of Mashrabiya as a passive shading technique, this thesis strives to identify a repertoire of several optimal Islamic geometric pattern (IGP) configurations to be applied to mid-rise building cladding systems to attain considerable reductions in energy consumption while maintaining daylight quality and view quality. Numerous simulations will be administered, including an energy simulation, daylight simulation, and view quality simulation, and the most optimal IGP configurations for the variables mentioned will be compiled into an easy-to-read catalogue for stakeholders to console when making decisions regarding retrofitting the exterior of mid-rise buildings in Al Ain.

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