Comfort Assessment of a Fully/Semi-enclosed Courtyard: Case Study of Bahrain Low Rise Villa Housing Model

دراسة نموذج فيلا سكنية منخفضة الإرتفاع في البحرين لتقييم الراحة لفناء مغلق تماما و شبه مغلق

By

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Abstract

The built form industry specifically the residential sector contributes directly on energy consumption and increase of ecological footprint. Bahrain changing built form typology and configuration from introverted to extroverted built forms increased the need of cooling and humidity control measures, by affecting human comfort within the built form. Therefore, extroverted built form contributed to the deteriorating of the environment's comfort level and effected microclimatic conditions. Traditionally, the courtyard built form did not consume excessive amount of energy due to its sustainable microclimatic condition by offering thermal comfort.

A scientific literature review of the courtyard built form and its design parameters that affect the courtyard performance were analyzed. Moreover, Bahrain climatic condition as the context of this study was evaluated to relate to the study.

This study is an evaluation of the microclimatic condition of both the traditional fully enclosed courtyard and the semi-enclosed courtyard and its influence on the comfort level for the courtyard itself and further its influence on the living room as a selected occupied space within the case study house. The fully enclosed courtyard was integrated within an extroverted modular house for Bahrain case study. As the introverted courtyard built form is achieved, openings were integrated in forming two different courtyard shapes. The study varying parameters were: the courtyard shape, opening orientation, and active mode. Those parameters are assessed on thermal comfort, natural daylight penetration, solar exposure, and airflow through simple CFD representation.

Ecotect Analysis computer simulation software was used to simulate the two different courtyard configurations, *Courtyard-T* that represents the fully enclosed courtyard and *Courtyard-S* that represents the semi-enclosed courtyard. *Courtyard-S* presents two shapes *Courtyard-S*-U and *Courtyard-S*-C. Three orientations and not all as the West and East performance are similar were studied for each configuration and shape: North, South, and West. The simulations were carried out in 21^{st} of June and 21^{st} of December representing extreme seasons summer and winter.

The assessments of the results revealed that the fully enclosed courtyard "*Courtyard-T"* mitigates and modifies the courtyard and living room microclimatic conditions. It recorded to have the lowest exposure to solar radiation, lowest solar heat gain, and highest temperature differential within the living room, also highest air temperature differential within the courtyard, and adequate illuminance level and distribution within the living room. The major value of *Courtyard-T* configuration is that it has an opening percentage of 30% in relation to the built form. The living room space extends to 5.2208m in order to maintain the total area. The Northern and Eastern courtyard wall has an additional door and two window openings.

Courtyard-S-U demonstrated poor performance in all assessments. *Courtyard-S*-C resulted in modifying the courtyard and living room microclimatic condition, specifically *Courtyard-S*-C-W, however, it performance was not efficiently as *Courtyard-T*. The major value of *Courtyard-S*-C-W configuration is that it has a opening of $2.25m^2$ oriented on the West. The Southern side of the living room has been deducted to regain the area that was added by the courtyard opening, thus, the courtyard window and door openings shifted 200mm North. *Courtyard-S*-C-W receives lower solar radiation exposure, lower wind speed within the courtyard, best temperature difference within the courtyard compared to the exterior, and the highest hours of thermal comfort. The courtyard configuration, shape, orientation, geometry, and percentage of enclosure affect its performance. As the opening size increases, simultaneously the wind speed within the courtyard increases.

It revealed that percentage of enclosure, opening dimensions, courtyard geometry, courtyard shape, and indoor space geometry manipulates the comfort levels within the built form. Sun and wind distribution and exposure in relation to the courtyard shape and opening size demonstrated plausible explanation to their impact on comfort levels.

Thus, the study concluded that *Courtyard-T* configuration promotes an efficient microclimatic condition, and performs best in modifying temperatures, thermal comfort, and light and air distribution. The study suggests some recommendations for further studies in terms of courtyard performance.

بناء القطاع السكني يساهم بشكل مباشر على استهلاك الطاقة و زيادة البصمة البيئية. فإن تغيير شكل، تكوين،و تصنيف البناء في البحرين من التكوين المنغلق على الداخل الى التكوين المنفتح على الخارج ادى الى ازدياد الحاجة لتدابير رقابة التبريد و الرطوبة التي تؤثر على راحة الإنسان في البناء السكني. القطاع السكني ذو التكوين المنفتح على الخارج ساهم على تدهور مستوى الراحة البيئية و اثر على الحالة المناخية المحلية. تقليدياً، نموذج البناء السكني ذو الفناء الداخلي لم يستهلك كمية زائدة من الطاقة نظراً لحالته المناخية المحلية المستدامة من خلال توفير الراحة الحرارية.

هذه الدراسة مبنية على وثائق علمية عن البناء ذو الفناء الداخلي التي قد تم تحليل اثر التصميم على اداء، فعالية، و تأثير الفناء الداخلي. علاوة على ذلك، في سياق هذه الدراسة تم تقييم الظروف المناخية للبحرين لربطها لهذه الدراسة.

هذه الدراسة هي تقييم للحالة المناخية المحلية لكل من البناء السكني التقليدي ذو الفناء المغلق تماماً و شبه مغلق، و تأثيرهما على مستوى الراحة للفناء نفسها و غرفة المعيشة باعتبارها المساحة المختارة داخل النموذج السكني المدروس للبحرين. تم دمج فناء مغلق تماما داخل احدى الوحدات السكنية النموذجية المنفتحة على الخارج لدراسة الحالة في البحرين. مع تطبيق التحويل السكني الى نموذج سكني ذو فناء مغلق تماما، تم دمج فتحات لتكوين شكلين مختلفين لنموذج السكني ذو الفناء الداخلي. الدراسة لديها معلمات متفاوتة التي و هي: شكل الفناء، توجه الافتتاح، و وضعية العوامل الناشطة. يتم تقييم تلك المعايير على الراحة الحرارية، اختراق ضوء النهار الطبيعي، تعرض للطاقة الشمسية، و تدفق الهواء من خلال تمثيل السائل الحيوي.

تم استخدام برنامج جهاز تحليل محاكاة اسمه اكوتكت لمحاكاة النموذج السكني مع الفناء الداخلي ذو شكلين مختلفيين: فناء-(ت) الذي يمثل الفناء المغلق تماما،و فناء-(س) الذي يمثل الفناء شبه المغلق. فناء-(س) يمثل شكلين و هم: فناء-(س-و) و فناء-(س-ص). تمت دراسة ثلاث توجهات فقط لكل التكوين و الشكل لأن جهة الغرب و الشرق متماثلة الأداء، لذلك تمت دراسة جهة الشمال، الجنوب، و الغرب. نفذت عمليات المحاكاة في ٢١ من يونيو و ٢١ من ديسمبر لأنهما يمثلان اقصى ايام الصيف و الشتاء.

تقييم النتائج كشف ان نموذج السكني ذو الفناء المغلق تماماً الا و هو فناء-(ت) يخفف و يعدل الحالة المناخية المحلية للفناء الداخلي و غرفة المعيشة. لقد سجل بأن لديه ادنى تعرض لأشعة الشمس، ادنى اكتساب حرارة شمسية، اعلى فرق لدرجة الحرارة داخل غرفة المعيشة، و اعلى فرق لدرجة حرارة الهواء داخل الفناء، و المستوى الكافي لدرجة الإضاءة و توزيعها داخل غرفة المعيشة. خصائص تكوين فناء-(ت) هم كالتالي: اولاً ان فتحة الفناء تتكون نسبة ٣٠٪ من البناء، ثانياً تمتد مساحة غرفة المعيشة الى ٥,٢٢٠٨م للحفاظ على المساحة الإجمالية، ثالثاً يحتوي جدار الفناء الشمالي و الشرقي على باب و نافذتين.

فناء-(س-و) اظهر ضعف اداء في جميع التقييمات. اسفر اداء فناء-(س-ص) على تعديل الحالة المناخية المحلية للفناء و غرفة المعيشة، تحديداً فناء-(س-ص-غ) و لكن ليس بكفائة فناء-(ت).خصائص تكوين فناء-(س-ص-غ) هم كالتالي: اولاً الفتحة موجهة تجاه الغرب ذو اتساع ٢,٢٥م^{٢}، ثانياً تم حسم الجانب الجنوبي من غرفة المعيشة للحفاظ على المساحة الإجمالية لذلك تم انتقال باب و نافذة الفناء اتجاه الشمال. القيم الكبرى لفناء-(س-ص-غ) هو انه يتلقى اقل تعرض للإشعاع الشمسي، انخفاض في سرعة الرياح في الفناء الداخلي، افضل فرق في درجة الحرارة داخل الفناء بالمقارنة مع الخارج، و اعلى ساعات من الراحة الحرارية. تكوين الفناء، شكل الفناء، توجه الفناء ،توجه الفتحات، هندسة الفناء، و نسبة الإنغلاق يؤثر في اداء الفناء الداخلي. كل ما يزداد حجم الفتحات تزداد سرعة الرياح داخل الفناء الداخلي.

الدراسة كشفت ان نسبة الإنغلاق، حجم الفتحات، هندسة الفناء، شكل الفناء، هندسة المساحة الداخلية يتلاعب في مستويات الراحة داخل البناء السكني. اظهرت توزيع و تعريض اشعة الشمس و الرياح فيما يتعلق بشكل الفناء الداخلي و حجم الفتحات تفسيراً معقولاً لتأثيرها على مستويات الراحة في البناء السكني.

بالتالي خلصت الدراسة الى ان فناء-(ت) يعزز كفاءة و تحسين الحالة المناخية الداخلية، و تأديته افضل في تعديل درجات الحرارة، الراحة الحرارية، و توزيع الإضاءة و الهواء. تقترح الدراسة بعض التوصيات لإجراء المزيد من الدراسات من حيث الأداء لنموذج البناء السكني ذو الفناء الداخلي.

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I cannot find words to express my gratitude to my beloved husband, Omar, for his unconditional love, endless patience, enthusiastic motivation, and for holding up a mirror to the endless possibilities he sees in me.

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Abbreviations

EF- Ecological Footprint

UNEP-United Nations Environment Programme

CAA- Civil Aviation Affairs

AR- Aspect Ratio

SSI- Solar Shadow Index

IES- Integrated Environmental Solution

CFD- Computational Fluid Dynamics

IESNA- Illuminating Engineering Society of North America

Chapter 1

Introduction

1.1. The World Environmental Assessment

This is the time where biodiversity in relation with the ecosystem are at the spotlight. The time that sustainability is compromised, headlining the forefront issue of environmental, economical, and social magnitudes. The well-being of the planet wealth is at an unsustainable pressure. The rapid human development, economic growth levels, increase in population resulted into a degraded ecosystem that cannot support the human demand, hence producing an unsustainable ecological footprint (EF). Ecological footprint is the level of demand that the human population stresses on the ecological capacity. It evaluates by assessing the measure of biologically constructive water and land zones necessary to produce resources that a populace consumes. According to a report by Living Planet, the unsustainable consumption resulted into a 50% ecological overshoot, in which the humanity's footprint is 2.7gha per person while the planet's biocapacity is 1.8gha per person; thus estimating enquiring 1.5 planets to provide the resources and absorb waste (2010, p.34). Figure 1.1 shows the ecological overshoot in equivalence in amount of plant required. Figure 1.2 demonstrates the EF by component in relation to the total biocapacity that equals to a one planet.

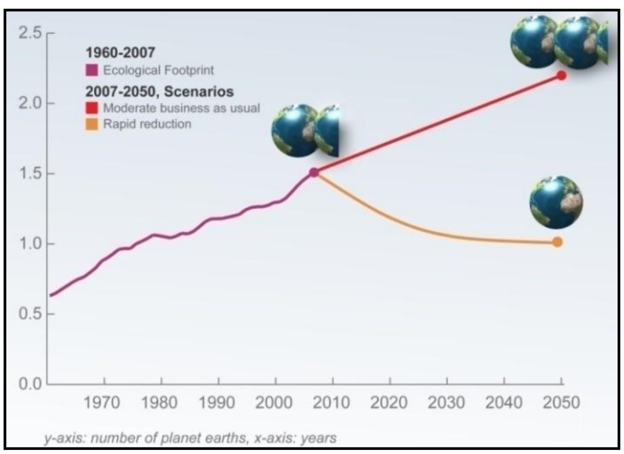

Fig. 1.1. Global ecological footprint (Source: Global Footprint Network, 2010).

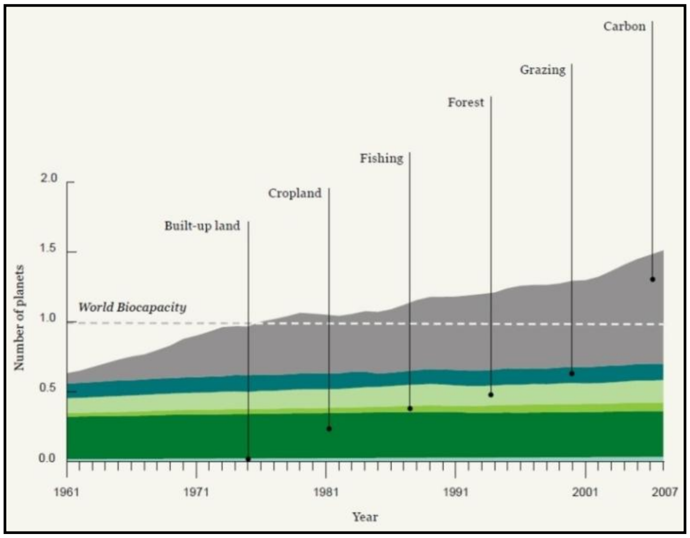

Fig. 1.2. Ecological footprint by component 1961-2007 (Source: Living Planet, 2010).

The unsustainable human development depleted enormous quantity of resources in the other hand offering an enormous quantity of carbon dioxide emissions. By burning fossil fuels, the carbon footprint makes out 54% of the EF and is at constant growth (Global Footprint Network, 2009). The International Energy Agency draws attention to the major contributing sectors to the EF in 2008, electricity and heating, transportation, and the building industry (IEA 2010). The electricity and residential building industry draws attention on the significant impact generated by the building developments as shown in Figure 1.3 and 1.4.

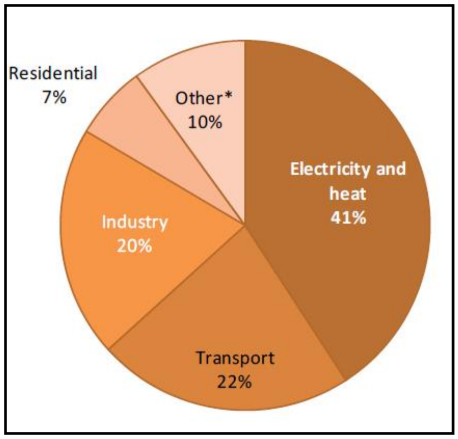

Fig. 1.3. World CO_2 emissions by sector in 2008 (Source: IEA 2010).

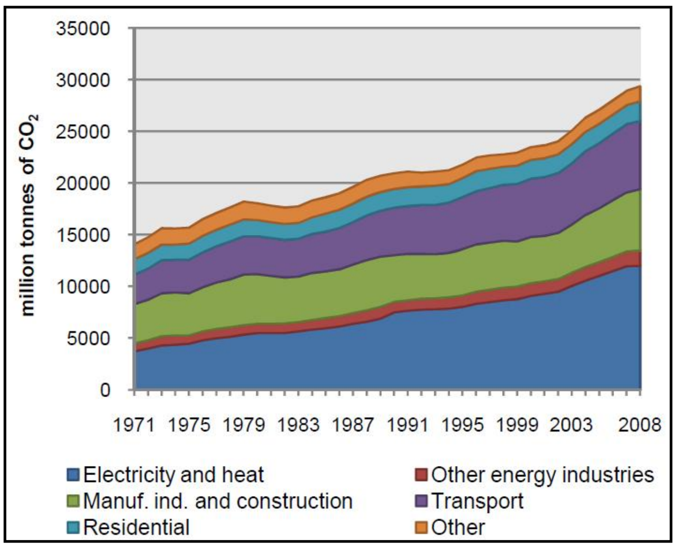

Fig. 1.4. CO_2 emissions by sector (Source: IEA 2010).

The Middle East is from the utmost contributors responsible of carbon dioxide emissions (Figure 1.5 and 1.6). This part of the region in the world is at constant increase of carbon dioxide emissions relating to the upsurge in economic and population growth; thus, the urban development's and construction activities are intensifying.

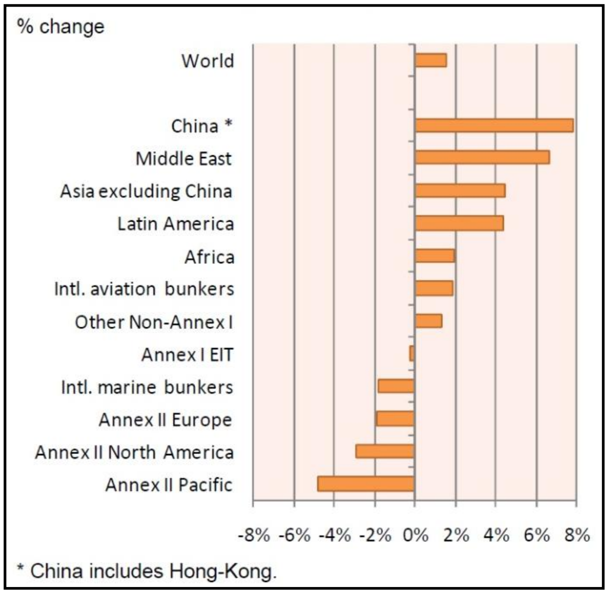

Fig. 1.5. Change in CO_2 emissions by region (2007-2008) (Source: IEA 2010).

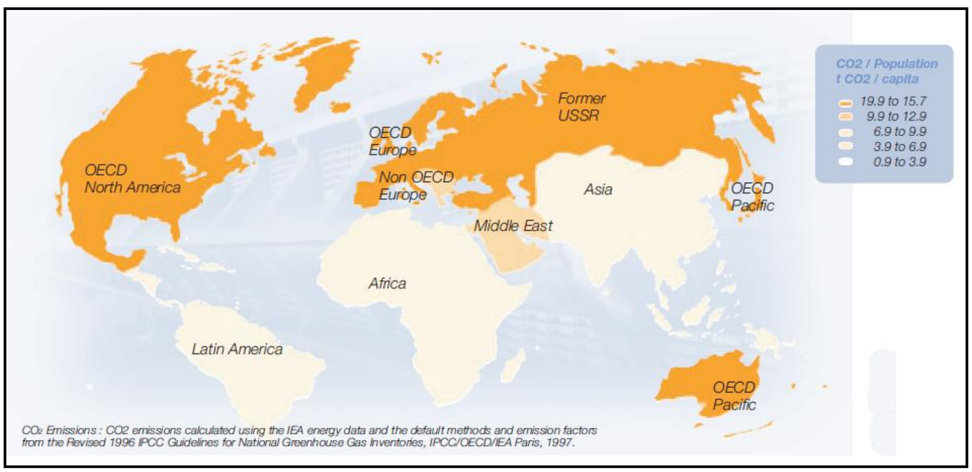

Fig. 1.6. CO_2 emissions per capita (Source: IEA Statistics 2006).

The United Nations Environment Programme (UNEP) reports that the building industry is liable for over 40% of energy usage, one third of the world's greenhouse gas emissions, and carbon dioxide emission through electricity at a growing rate of 1.7% per year of residential buildings (2009, citing Levine et al., 2007). The residential buildings accounts for 23% of electricity utilizations (UNEP 2007). Figure 1.7 previews emissions generated from the building industry growth, and based on the growth rate developing countries such as the Middle East will surpass the developed countries. Drawing the eye specifically to the direct linkage between sustainable deterioration and architecture typologies. This is not to state that other measures and sectors are not putting in hand in the sustainable development such as urban development, vegetation, transportation, waste management, building regulation, and structured roads. It is to state that the sectors contributing to the environmental deterioration of increase of green house gases and resource deployment are in direct link to the architecture development with the attestation of the increase consumption of electricity, heating, cooling, burning fossil fuels, and excavating materials.

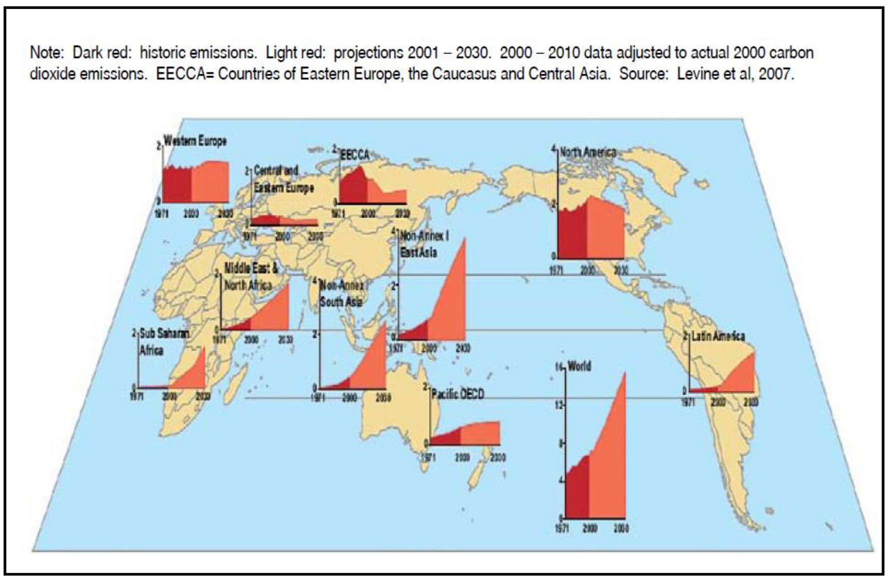

Fig. 1.7. CO_2 emissions from buildings (Including through the use of electricity) (Source: UNEP 2009, citing Levine et al 2007).

The building industry conveys direct responsibility towards the environmental degradation. This is not to argue that the issue facing is only in terms of energy waste and consumption, however, the issue enlarges to humankind discomfort in terms of microclimatic descent. As people rely more on active measures, the implications reflect on the microclimatic conditions of the urban form, such as typology configuration, urban density, and material selection, to name a few.

Architecture development is not only defined in the increase of urban forms and intensifying of construction activities. Architecture development defines and accentuates the change of built form typologies and configurations. Built form typologies links to the influence of passive and active design measures, and the increase of environmental degradation diminishing human comfort and microclimatic conditions. Environmental microclimatic conditions parameters are daylight penetration, direct solar radiation, thermal comfort, airflow, natural ventilation, and shading measures. Built form typology categorizes as two forms: an introverted form and extroverted form. The introverted building form is represented by the inward looking courtyard building. The modernized block units that are outward looking represent the extroverted form.

Vernacular typologies such as courtyard built form are emphasized with passive design that demonstrates the microclimatic effect of altering vernacular forms with modernized forms infused with active measures. By changing the built form typology and configuration, the microclimatic condition of the built form changes affecting on the human comfort in terms of urban heat island and increase need of cooling and heating measures, which then increases in energy consumption and resource waste affecting the overall environmental conditions. Highlighting that passive design measures in terms of archetype configuration and form are vital components in mitigating the environmental microclimatic condition.

However, concurrently it has the highest capability of achieving a significant EF reduction by adhering to climatic, cultural, and environmental identities without compromising living standards. As this was the case before modern architecture and economic revolution, where the built environment responded in a sustainable manner and answered to the climatic, cultural, and functional identities.

1.2.Bahrain Environmental Assessment

Today Bahrain is a significant icon of urban growth in the Middle East. It is developing into a metropolitan cityscape after the United Arab Emirates due to the prompt increase in its economic growth. Globalization reflects directly on Bahrain's urban morphology and archetype typology. The construction industry has thrived and developed with new buildings and manmade island developments naming a few such as the Bahrain Twin Towers, Durrat Al Bahrain, Amwaj Islands, and Bahrain's Financial Harbor. Hence, Bahrain emerged from being a city contoured with internal parameters into steel-framed glass extroverted high-rise buildings operated with excessive air conditioning systems. Table 1.1 demonstrates a comparison between Old Muharraq city and its new extensions providing that the new extension consist of large dwelling developments and different building forms; the old city encompasses introverted courtyard form, while the new extension stresses on the extroverted modernized building form.

Table 1.1. A comparison between old Muharraq city and its extensions (Source: Hamouche, M.B. 2004)

	Area (Hectares)	Density 1: area covered (%)	Density 2: persons/hectares	Density 3: dwellings/ hectares	Housing typology
Old city of Muharraq	340	70	250	+50	Low rise, inward looking (with courtyard)
New extensions reclamation	300	30	50	10	High rise, outward looking (flats)

The economic and construction industry are responsible for causing major environmental issues from the change of building form resulting a deteriorate environmental and microclimatic system such as deterioration of air quality, increase of pollution rates that puts the human health at concern, depletion of natural resources and increase of energy consumption.

As Bahrain's extroverted built form developments are increasing the energy demand are substantially increasing. Figure 1.8 illustrates the escalating consumption of electricity. Bahrain energy consumption divides into four sectors, with the residential industry being the principal of consuming 54% of the sum electricity as shown in Figure 1.9 (Radhi, H. 2009). The population increases simultaneously the urban growth increases, hence heat island effect increases resulting into the increase level of electricity consumption for air conditioning, therefore resulting into such figure of residential electricity consumption. With such rate of energy consumption, carbon dioxide emission production increases, as shown in Figure 1.10. This increase of carbon dioxide emissions is developing into a predicament considering the total area of Bahrain and its population in comparison with other countries. Radhi H. states that 24% of the carbon dioxide production is due to building operation (2009).

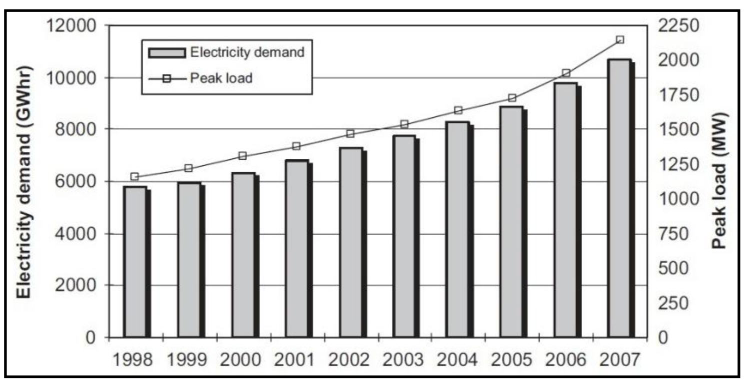

Fig. 1.8. Growth of electricity consumption in Bahrain (Source: Radhi H. 2009).

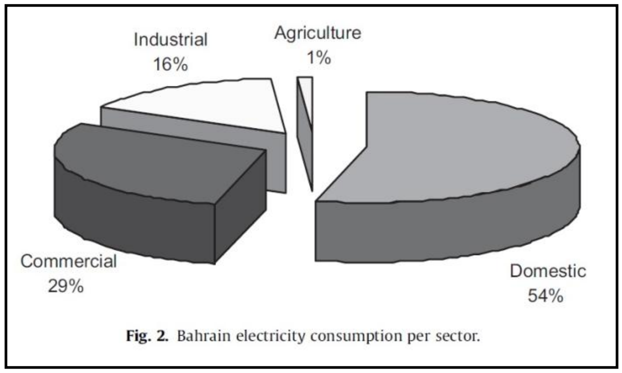

Fig. 1.9. Bahrain electricity consumption per sector (Source: Radhi H. 2009).

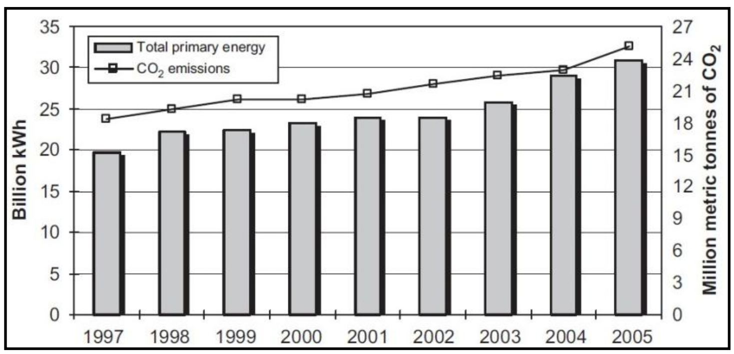

Fig. 1.10. Increase in Co_2 emissions relative to the energy use (Source: Radhi H. 2009).

The population growth is developing into a major source of the increase of carbon dioxide emissions; as the growth persists, pressure will add on the construction industry to provide dwellings, which on the other hand will pressurize the energy demands and natural resources hence increase it. In 2006, Bahrain annual population growth rate is at a 2.2% ranking as having one of the highest annual population growths in the world, as illustrated in Figure 1.11. The population growth threatens the ecological balance and biodiversity.

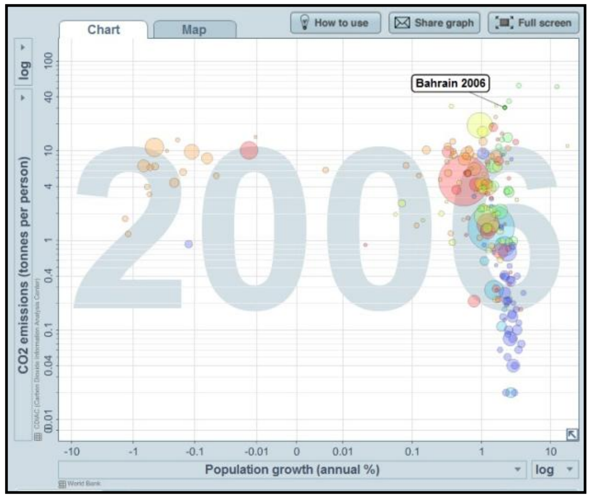

Fig. 1.11. CO_2 emissions in relation to the income per person indicator (Source: http://graphs.gapminder.org/)

These issues are the results and impacts related to the lack of thermal comfort, excessive direct solar radiation, lack of sufficient natural daylight resulting in the need of artificial lighting, lack of adequate airflow and natural ventilation provided from the extroverted built form.

1.3. Residential Building Form in Relation to Microcliamtic Efficiency

Variations in housing typologies are highly influenced by climatic distinction. Architectural building design form respond and alter to adapt into a specific climate as environmental factors influence the internal microclimatic conditions and building performance in terms of consumption and efficiency. Such environmental factors are solar radiation, prevailing wind, humidity, and climatic temperatures. Building form, orientation, opening ratio, and materials reflect in providing a comfortable internal microclimatic condition and energy efficiency. Hence, emphasizing on passive building design to improve the architectural response of the environmental factors, in return to provide an efficient microclimatic building.

However, in such acute hot humid climate of Bahrain, the environmental factors are intense, with extreme solar radiation and high temperatures, that increase the challenge of providing a comfortable internal environment. These conditions increases lighting and cooling demand to endow a contended thermal condition, hence energy demand increases. The building design form and skin is the ultimate boundary that relate and effect between exterior and interior conditions. This relationship defines the balance of adequate penetration of natural light and thermal comfort levels in terms of lighting and cooling within the building interior.

Bahrain residential building forms vary in scale and complexity of design. However, specifically indicating the conventional modular buildings, they are designed in an enclosed extroverted block structure. The structure is in integration with an extroverted courtyard. All openings are allocated at the external walls. Design regulation, opening ratio, leas span, external obstruction, materials such as insulation, and glazing type are standard, however, they are not defined by green design regulations, or studies that identify and assess the appropriate regulation figures and ratios that bestow comfortable internal conditions and efficient building performance. Regulations should alter and assigned by careful studies taking into consideration environmental conditions. The current residential building form are inappropriate in providing comfort from the harsh climate that been influenced from other regions. The current building forms are the result of the rapid economic growth. Modernistic housing typology increases the integration of active systems and reduces the integration of efficient passive systems inspired from traditional concepts along with developing them into contemporary structures.

Courtyard dwelling typology is an old passive design implemented in this region. The Arabian region, in the past, developed courtyard form dwellings to respond and adapt to climatic, cultural, and social conditions. It represents an efficient bioclimatic typology. The courtyard concept employs the courtyard in an introverted central form in a certain orientation that reduces the negative effect of solar radiation and heat gain, producing a comfortable outdoor and indoor climate with pleasant air movement. On the other hand, passive design of introverted fully enclosed courtyards has the capability to improve its performance through further development and studies. The potential of improvement and development may possibly be through changing the form and configuration of a fully enclosed courtyard into a semi-enclosed courtyard typology. Semi-enclosed courtyard typologies may enhance the building performance and its adaptation to Bahrain environmental conditions. This form can augment natural ventilation, diffused natural daylight that increases thermal comfort and decreases heat gain and application of cooling loads.

As the courtyard built form did not comply large amount of energy; provided with the increase of energy consumption and ecological footprint, due to the comfortable, sustainable microclimatic condition it provided, the study will convey around the microclimatic effect of courtyard typological form and configuration. In the following section, each microclimatic affecting factor will be investigated comprehensively.

Design practices have the ability in mitigating and adapting buildings environmentally. Solar radiation penetration can be in control in terms of natural light quality and quantity. Solar penetration can be restricted through the building form, building and opening orientation, opening ratio, opening geometry, shading devices, and material selection. Consequently, control provides comfortable natural daylight that reduces the need of full air conditioning systems at its lowest temperatures. Nonetheless, air movement between and around the building have the ability to mitigate building heat gain from solar radiation by cooling heat down and contain overheat. Design practices can increase adequate air movement between residential buildings and within the building that can reduce the need of cooling loads. Therefore, developing the fully enclosed courtyard passive traditional concept into a contemporary form of semi-enclosed courtyard typology alleviates and represents a better form of bioclimatic typology.

The critical factors considered raise the need to be environmentally contemplated in building developments. By applying measures such as, green building standards, environmental design through design optimization and systematic methodologies the risk is preserve. Building design and configuration contribute to energy consumptions in which it can increase or decrease heat build-up within the building, solar penetration, and comfort. Sustainable building and construction method in terms of design hold back a large impact on the further consequence of energy consumption, and internal comfortable microclimatic environment making sustainable building a must to reduce environmental impacts.

1.4. Aims and Objectives

This thesis study examines and compares the potential of developing the traditional concept of fully enclosed courtyard into a semi-enclosed courtyard housing typology within the hot arid climate context. A proposal of semi-enclosed courtyard will be in comparison to the converted conventional extroverted modular housing into a fully enclosed courtyard. The conventional extroverted housing form will be converted into a courtyard form due to the microclimatic effect that the courtyard form offers. Both will be designed with reference to literature review findings and recommendations to achieve close to realistic results that would act as a guideline for design.

The aim of this research is to analyze the optimum semi-enclosed courtyard configuration within Bahrain's modular residential typology through its suitability, efficient performance, impact, and appropriateness of its environmental features in a hot-arid climate.

The objectives are:

- Assess the effect of thermal and lighting analysis provided from the courtyard to reach an optimum solution into the living room.

- Assess the microclimatic environmental performance of the proposed courtyard in reflectance to the effect of solar radiation and natural ventilation through airflow and temperature measurement as a recreational space.

This thesis site study is specifically located in Al Buhair, Riffa district, identified as a dense residential district. In order to bring about this thesis study, the following factors will be carried out:

- Appraise the courtyard historical, cultural, and social dimensions within this region and its application efficiency.
- Assess environmental conditions that affect the courtyard microclimatic efficiency and its consequence on the indoor environment.
- Acquire design guidelines to draw a conventional fully enclosed courtyard house integrated into the modular housing typology and analyze its microclimatic efficiency.
- Acquire design guidelines to assist the development of the semi-enclosed courtyard model.

The conceptual building environment and block will be tested within Bahrain's climate through the application of computer modeling and simulation software. Results will undergo comparison to present the optimum semi-enclosed courtyard design form. In addition, to present the comparison results between the traditional courtyard and the contemporary semi-enclosed courtyard concepts.

This study is divided into the subsequent chapters:

- Chapter one comprises of introducing the effect of the alteration of the introverted built form and configuration into an extroverted form in Bahrain with regards to the microclimatic condition that subsequently effects the energy consumption and overall environmental condition. The chapter will introduce the research aims and objectives.

- Chapter two will encompass a comprehensive scientific literature review of the built form, environmental and design parameters effecting the microclimatic performance of the courtyard.
- Chapter three explains the study proposal in terms of parameters and assessments, comparing different types of methodologies and software to perform similar studies with regards to their limitations and advantages. Additionally, describing the selected methodology and software to perform the research assessment.
- Chapter four describes the simulation methodology steps from Bahrain climate analysis, computer model set-up and validating the process decisions.
- Chapter five will provide an extensive analysis of the simulation results discussing the findings to identify the advantages and disadvantages of the built form performance.
- Chapter six will conclude a summary of the findings providing recommended guidelines for future research.

Chapter 2

Literature Review

Introduction

Apprehensions regarding global warming and the limitation of natural renewable sources increase the demand of considering solutions that vernacular architecture promotes in modifying indoor and outdoor environment. Vernacular architecture narrates environmental architecture principles as it capitalizes on the exploitation of natural energy through developing architecture in harmony with the environment and people. Modern architecture practices amplify overheating building interiors due to solar radiation through the lack of passive design measures in the building envelope and opening. Nonetheless, relying heavily on artificial ventilation, natural ventilation enhancements are disregard through the design of built forms and urban forms layouts. The airflow pattern within and around the building effects the indoor air temperature. Therefore increasing overheat and uncomfortable indoor and outdoor environment. Passive design strategies of vernacular architecture endorse natural ventilation with adequate air movement and reduction of solar radiation. A local vernacular architecture model is the courtyard housing design. The employment of courtyards in vernacular architecture is due to the auspicious microclimatic condition it develops. In general, the courtyard element is designed to promote airflow pattern movement surrounding and within the built form, and adequate percentage of solar radiation and shade that modifies the indoor and courtyard environment. This review will focus on scientific studies influencing courtyard design on the thermal, solar radiation and airflow performance in the traditional introverted courtyard and interiors in order to develop the form into a functional semi-enclosed courtyard.

2.1.Bahrain Location & Climate

Kingdom of Bahrain is located in the Arabian Gulf, Figure 2.1. It is a borderless country. It lies between 26°00' North latitude and 50°33' East longitude. It situates at the East coast of Saudi Arabia with a distance about twenty-four kilometers, and

Qatar is at the South with a distance of twenty-eight kilometers. It is a collection of 33 islands, the largest island Bahrain is connected to Muharraq and Sitra with bridges. According to Civil Aviation Affairs of Bahrain (CAA) The total area is about 770 square kilometers; however, the largest island itself is 586.5 square kilometers (CAA 2011). Bahrain from East to West is about sixteen kilometers at width, and from North to South is about forty-eight kilometers at length. The highest point on Bahrain is the Jebel Al-Dukhan with 134 meters above sea level. The island surrounds with shallow inlets of water.

The study is specifically located in Al Buhair in East Riffa district. It is part of the Central Governorate. It is a dense residential area, with several commercial units making a productive community.

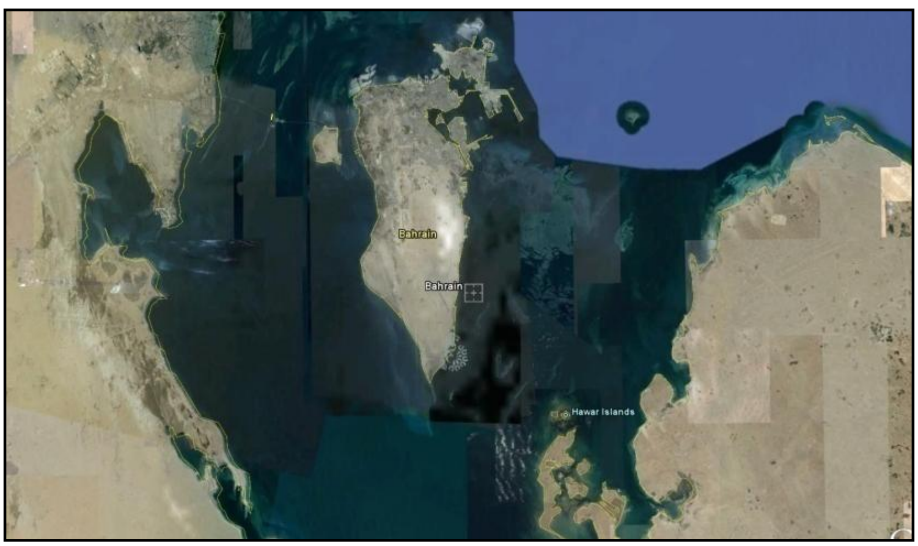

Fig.2.1. Aerial view of Bahrain (Source: Google Earth).

Generally, the climate of Bahrain is hot and arid with high humidity levels. It has two distinctive seasons; a temperate winter and an intense hot summer. During the summer season, the temperature average reaches 40^{o}C to 48^{o}C. High levels of humidity and extreme heat increases discomfort. Winter season is short with temperature ranging from 10^oC to 20^oC. During the winter season, humidity rises over 90%.

2.2.Bahrain Housing Modules

Bahrain's modular housing units are westernized in their architectural design characteristics. They are structured through strict building regulations and specifications.

The housing unit consist of ground and first floor within a plot area of $102.4m^2$.The plot size of the units vary from type to another however, the most common housing unit footprint is 8mx12.8m without the boundary wall, and with the boundary wall is 11mx24m. The height of the housing unit is 6.34m without the roof staircase, and the total height with the roof staircase is 10.56m. The ground floor level and first floor level each are 3.17m. The orientation of the unit is dependent on its site location. The common window opening dimensions for the rooms are 1.2mx1.3m, the kitchen is 1.1mx1m, and the bathrooms are 0.6mx0.8m. The ratio of openings on the housing facade varies from unit to another; however, the model in use is a common typical housing model.

According to the ministry of housing, the housing projects standard specifications are as follows:

- Walls: are usually 200mm block work plaster and paint. The external walls have Stone-face paint, and the internal walls have 2 coats of vinyl Emulsion paint.
- Floor: it is concrete screed and is finished with ceramic tiles.
- Roof: it is usually a precast concrete slab. The insulation used for the roof is waterproofing system insulation, and extruded polystyrene insulation.
- Ceiling: suspended ceiling with gypsum.

- Insulation: for the roof, a protective waterproofing coating that covers the polyurethane foam base and covers the concrete or block work base screed and membrane that are laid on the waterproofing coating.
- Glazing: a double glaze.
- Pavement: the exterior non-built area surrounding the house is sand.
- Door: the external door is aluminum and the internal doors are wood.
- Window: the frames are aluminum.

Therefore, the study will apply the specified materials from Bahrain's Ministry of Housing. Nonetheless, the built area, openings and opening ratio, and height will also be in application in the study.

2.3. History of Courtyard Housing

Courtyard is an element in the architectural language that is communal throughout the history of many urban civilizations. Courtyard form integrated into man's dwellings is encounter in the ancient civilizations dating back to 3000BC (Edwards et al. 2006). Courtyard housing is located from the Bronze period of Greece, throughout the Classical period into the Hellenistic and Roman period, which then proliferated through the Americas, Europe, Africa, Middle East, and the Far East evolving from a civilization to another; Bronze age Mesopotamian, Egyptian-Sumerian, Indus valley, Asia minor, and the Mediterranean (Meir I. A. et al., 1995). Figure 2.2 illustrates the proliferation of the courtyard housing. The Arab nomads have applied the courtyard concept in the desert by surrounding a central open space with their tents to provide their cattle with security and shelter.

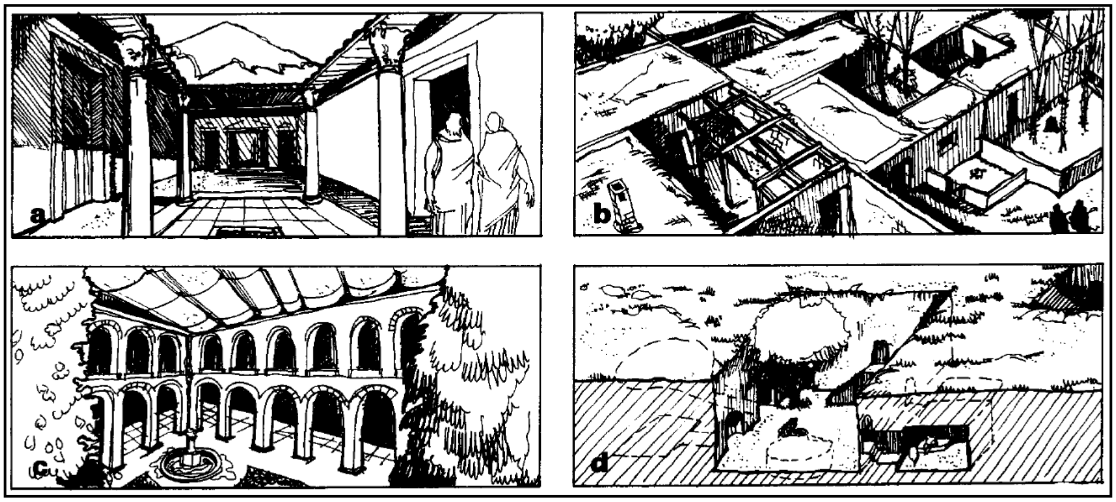

Fig.2.2. Courtyard dwellings: (a) Greece, (b) Mongolia, (c) Spain, (d) North Africa (Source: Meir I. A. et al., 1995).

Through history, courtyard form is evidentially in having a symbiotic affiliation in the Middle Eastern society where a surviving number of courtyard housing dating back to pre-Islamic and Islamic periods are located. Courtyard housing form is fully enclosed which is known as the traditional design of the courtyard. Examples of such buildings are Chogha Zanbil from 1250 BC in Iran, Susa palace of Dario that goes back to the Achaemenid dynasty from 550 BC in Iran, Jami Fahraj Mosque from the 8th AD, Al Fustat which have been excavated dating back to 8th to 9th century AD in Egypt, Mosque of Uqba in Tunisia dating back to 670 AD, and Bayt Al-Badr in Kuwait from 1840 (Edwards et al. 2006).

The courtyard housing archetypal form may differ from an area to another but it remains a universal form, Figure 2.3. The early courtyard housing of Egypt dating back to the 8th and 9th century AD have influenced the Maghreb (the western; Tunisia, Morocco, Algeria, and Andalusia) courtyard housing. They developed regular square-rectangular courtyard surrounded with symmetric rooms and t-shaped reception rooms.

Fig.2.3. A view of Riyadh old urban fabric (Source: Edwards et al. 2006).

The courtyard element is an emergence of socio-cultural and environmental attributes. It is a concept applied in various built forms worldwide considering the main concept and role behind its application. However, in the Middle East, the Islamic architecture developed courtyard housing as a crucial typological element that satisfies the necessity of having an exposed area and a microclimatic moderator. As a characteristic of having a hot and warm climate, a central courtyard modifies the microclimate of the house through its passive cooling technique by the air patterns allowing cool breeze, provides adequate daylight, protection from dust, and privacy. Therefore, contended outdoor activities are performed within the private courtyard dwelling including playing, working, gathering, cooking, and sleeping during extreme weather conditions. Hence, the courtyard element became an important feature within the Arab residence.

Courtyards evolved from a single storey into a double storey, and from a fully residential block into a "taberna"; which is the commercialization of a residential space, and into an "insula", which are apartment blocks. Those tendencies shifting of format of moving from a residential into a "taberna" and "insula" is due to economic crisis, oil boom, and population growth. Hence, courtyard housing reduced with the increasing of apartments.

Through colonization periods, courtyards have been adopted as a social space rather than a climatic regulator. Housing forms have conformed to the European standards into developing the courtyard house into a villa. The oil boom and population growth with area limitation modern architecture canceled out courtyard housing depending on mechanical ventilation systems and artificial lighting. Thus, enclosed courtyard housing or semi-enclosed courtyard concept have not been further studied or developed to accommodate the present day's needs.

Nonetheless, courtyards developments in European and American metropolis have an ancient origin. Examples exist back to Imperial Rome and Renaissance. In Europe, the courtyard forms have been formalized in the nineteenth century. Courtyards occurred in medieval cities, yet they were usually in random shapes. As the city fabric were devoid of adequate light and urban ventilation space due to the increase of population and building structures leading to the epidemics of illnesses. The courtyard form offered some advantages, not only that it was responsive to the environmental conditions; it served the need to exploit wind, air, and solar exposure through the courtyard and the dense structures which promoted sanitary order that is vital for the public health. Moreover, it was economical to build hence, serving the lower, middle, and upper class in terms of efficiency, aesthetic, and land utilization. Orientation of the courtyard differed according to need, as in Germany solar exposure was the priority, while Scotland priority was urban ventilation (Edwards et al. 2006). By the nineteenth and twentieth century, the courtyard form in Europe and America were being exchanged by new architectural form of developments.

2.4.Types of Courtyards

Courtyards have been developed into various forms. Those forms sector into fully enclosed and semi-enclosed courtyards. They represent the extent of courtyard enclosure inserted into the building mass. The fully enclosed courtyard is the traditional courtyard design that encloses from all four sides and is vastly in use for residential built forms. However, the semi-enclosed courtyard is very rare, it has few openings; differing into the extent of openness, and is in use for various built forms in large scale not as a housing unit. An apparent example of a semi-enclosed courtyard is the plaza or also known as the piazza where couple of buildings surrounds an open space and has openings within them. Nonetheless, courtyards also differ into their position as being the central space of the building or at the side of the built form.

Moreover, historical courtyard housing demonstrated the integration of more than a single courtyard within a dwelling, Figure 2.4 and 2.5. Multiple courtyards provide privacy for the family and extend the dimensions of security. There are various types of multiple courtyards. The rural housing have multiple courtyards in which one is designated for the family, while the other which is called the annexes designated as a stable, area for farming equipment and tools. In addition, there might be an additional courtyard for cooking. However, another type of multiple courtyards within the urban society, the innermost courtyard is for family members offering a private space where females are unobserved, and the outermost courtyard usually by the entrance and men reception area or majilis that is designated for male guests.

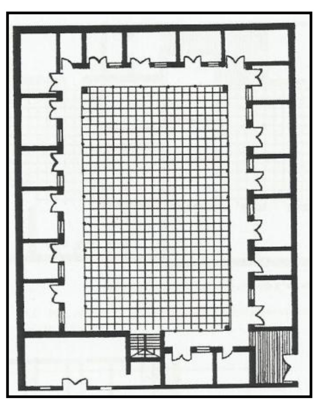

Fig.2.4. A plan of a single-courtyard (Source: Edwards et al. 2006).

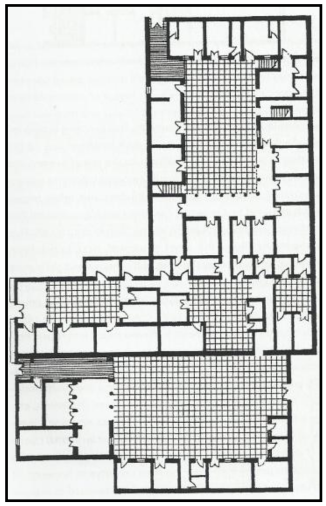

Fig.2.5. Bayt al-Badr floor plan showing its multiple courtyards (Source: Edwards et al. 2006).

2.5. Social and Cultural Dimensions

Architectural design is a sculpture of the cultural and social life of the people. Behavioral factors are a significant element that effects the formation of people's culture and its application in design. There are interaction of various forces that influence the layout of the archetypal built form such as change in periods, different ideas, and attitudes of the society towards certain elements such as privacy. Each society through history developed a built environment that fits their needs. The development of the courtyard expresses social values and satisfies climatic and functional needs. Courtyards configure into various shapes and forms depending on an environment to another and behavioral factors. The variety in form and control of exposure reflects the society's behavior that influences the built form design and layout.

In the traditional Arab and Islamic cities, social, behavioral, and cultural factors in terms of privacy and security expresses within the building layout. Privacy is a fundamental socio-cultural factor that articulates the society's values and behavior in physically shaping the built form and order of spaces. In the Arab region, women require privacy from the visual intrusions of the public. Therefore, cultural and social roots focus on the segregation among public and private lives allowing women to maintain their privacy. The enclosed courtyard transpires as the women domain as it encloses all activities in a private form to reduce social stress.

In addition, the European courtyard shares this similarity with the Middle East. Both traditions and social structures of the European and Middle Eastern typologies expressed gender division as a domestic territory. The courtyard in Europe was a space for women and children separating them from the masculine frame of men (Edwards et al. 2006). Zoning were crucial due to the need of privacy. The kitchen, bedroom, and bathroom looked across the inner courtyard, while public rooms looked toward the street. Men occupied the street and the rear courtyard.

Privacy reflects a paramount influence on the enclosed courtyard introverted spatial organization, facade, openings, and entrance treatment. By the means of having an introverted enclosed courtyard the spatial organization of rooms open toward the central courtyard, thus giving spaces their privacy, Figure 2.6.

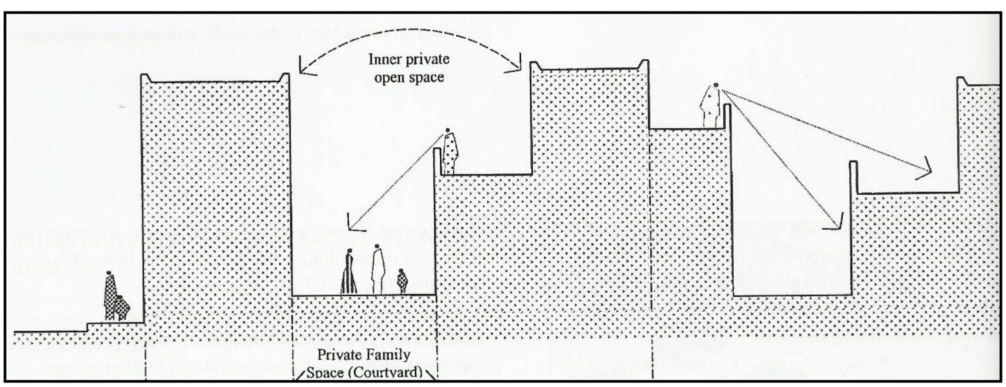

Fig.2.6. A section through adjoining houses showing how setbacks maintain privacy between them (Source: Edwards et al. 2006).

Moreover, the increase amount of courtyards, space configuration of the men's reception area "majilis" by the guest entrance, and segregating the courtyards between family area and guest area controls the private domain without compromising the guests comfort and entertainment. The control of exposure reflects through the housing facade by having a solid external envelope with minimal openings that are above eye level preventing passers from visual access. Within the courtyard, spaces looking into it have appropriate size of openings for light penetration. The location of the entrance and the opening points protects the housing components from direct sight through the application of the "bent entrance" principle, Figure 2.7. The bent entrance principle is shifting the entrance from the courtyard axis and placing a wall parallel to the entrance by shaping the passageway from the entrance to the courtyard and spaces.

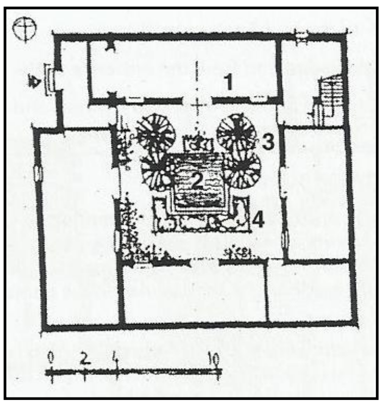

Fig.2.7. Bent entrance in Beit-Radwan, Marrakesh (Source: Edwards et al. 2006).

From the beginning of the application of courtyards, the social demand of privacy reveals a synchronized relationship of expression between the built environment architectural form and the occupants dressing, Figure 2.8. It demonstrates the application of layers in which the exterior is completely veiled to emphasize protection.

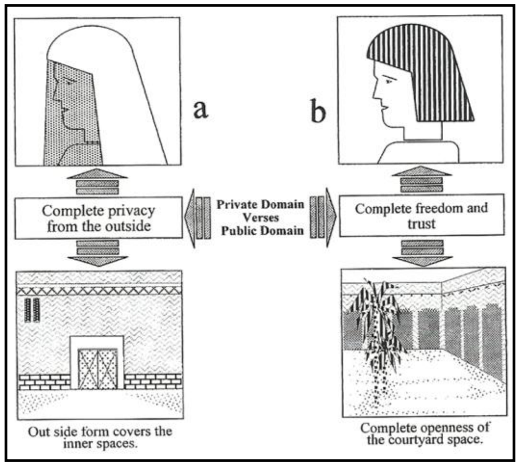

Fig.2.8. (a) Private domain (b) Public Domain (Source: Edwards et al. 2006).

However, by the shift of time and development, women exposure has increased to the outer shell of the society through their education, working habits and change in lifestyle where women socialize with men. At the old period of time where enclosed courtyards are required women were enclosed into their domestic built environment and only men represent the labor sector. Present housing units demonstrate the amount of exposure each family or society reveals through the structure in terms of windows on the exterior envelope, the height of the fence, design of the envelope, and interior spatial organizations. Therefore, through periods, civilizations social values and needs have altered due to globalization and developments of the mind and society reflecting on the built form. Hence, revitalizing the enclosed courtyards into semi-enclosed courtyard housing meets the society's demands without compromising their values.

Traditional enclosed courtyard form posses a significant meaning however, revitalizing it concept with significant changes and development will satisfy modern needs and environmentally function. Therefore, it is clear that people's values, lifestyle, and beliefs developed a behavior that shaped the human built environment linking the social and spatial orders.

2.6.Design Guidelines and Principles

2.6.1.Form, Geometry & Configuration

Fathy states that by simple analysis it's understandable how the courtyard form became adopted by Arabs due to the desert climate where it's natural to narrow and orient the streets to seek shade and avoid hot desert wind by closed vistas (Ratti et al. 2003).

Form, geometry, and configuration of a courtyard affect its environmental performance. Courtyard form integrated into the built environment is various in shapes such as square, rectangular, circular, and polygonal. However, the old city fabrics convey the rectangular or square shape as the traditional form of courtyard. Other shapes are rarely applied and may be influenced by the plot and topography. An example of a circular courtyard is the Samba village in Africa, Figure 2.9.

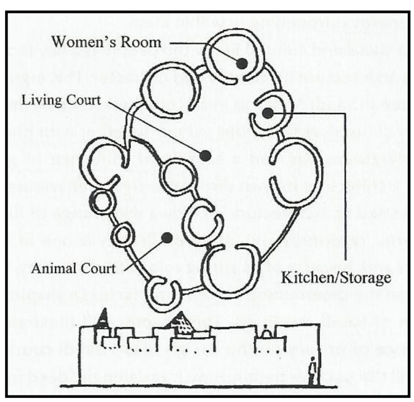

Fig.2.9. Samba Village (Source: Edwards et al. 2006).

The geometrical proportions in terms of width, length, height, aspect ratio, and solar shadow index of the courtyard changes the microclimatic properties of the courtyard and its effect on the surrounding interiors. Adequate accessibility of solar radiation, shading percentage, and effective air movement are by appropriate courtyard proportions.

Ratti, Raydan, and Steemers have been reviewing Leslie Martin and Lionel March archetypal built forms effect on the environmental performance findings done in the 60's (2003). The built form was represented as a series of urban arrays of two archetypical building form; the courtyard, that represents the old form and the pavilion, which represent modern architecture. From the original research findings, Martin and March comparison between courtyard and pavilion urban array, both with the same site coverage of 50%; 25 courtyard forms and 49 pavilions, and both maintaining the same height and total floor area, Figure 2.10. Observations illustrated that both forms can sum up to the same floor area and internal room depth, however, the courtyard have placed the same floor space in a similar building depth on the contrary requiring one-third of the pavilion height. As the Fresnel diagram, Figure 2.11 demonstrates the concept of square geometry of each annulus having an equal area (Ratti et al 2003).

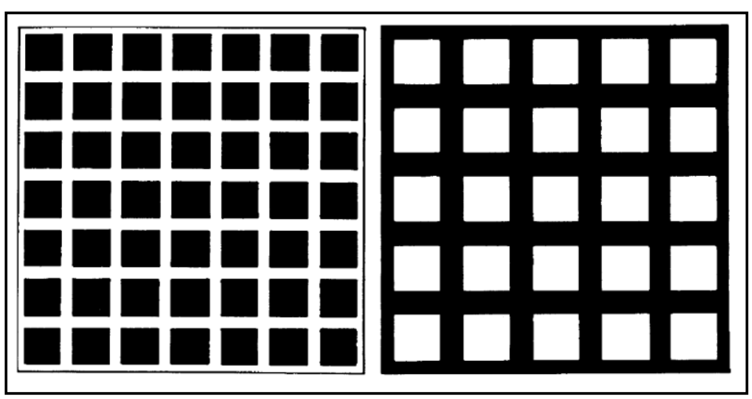

Fig.2.10. Two archetypal urban patterns, based on pavilions and courts (black represents buildings) with the same site coverage, building height, and total floor space (Source: Ratti et al. 2003).

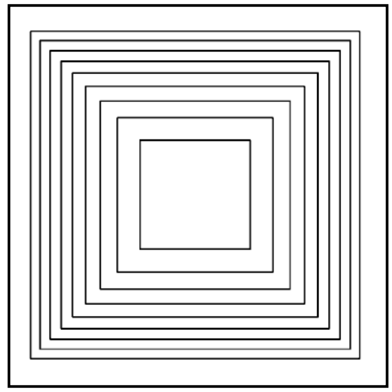

Fig.2.11. Fresnel's diagram: all concentric squared annuluses have the same surface area, which is also equal to the area of the centre square (Source: Ratti et al. 2003).

Muhaisen (2006) have studied the courtyard geometrical proportion parameter in relation to its effect on the courtyard thermal performance, shading, and exposure. The study took over four different locations: Kuala Lumpur, Cairo, Rome, and Stockholm representing different climatic conditions. Cairo represents the hot dry climate. The climatic condition highlights its relation to the geometric form of the courtyard, in terms of courtyard height and ratio in courtyard performance by varying solar exposure and shading to the sun's position in each different country. The study was carried out on the two extreme days, June 21st and December 21st representing the summer and winter solstices at 14:00.

The investigated proportion parameters are examined by a ratio of floor perimeter to height represented by R_1 and width to length represented by R_2 (2006). R_1 ratio represents the ratio of the courtyard floor perimeter P to the height H (P/H), ranging from 1 to 10. R_2 ratio represents the width to length (W/L), ranging from 0.1 and 1. To represent realistic dimensions, the study the minimum width is 1m. As an example, courtyard ratio of R_1 is 1 and R_2 equal to 0.1 demonstrates that it has a height of 22m and 1m in width and 10m in length.

All the forms considered has a constant wall surface area to an area of 282m^2 regardless of the courtyard form proportion. The constant wall surface area is the internal wall surface area of the courtyard. It is heavily considered due to the effect they carry on the thermal performance comparing to ground or exterior wall surface.

In this section, Muhaisen study will record the efficient geometric courtyard ratio in a hot arid climate of Cairo. The study will be further elaborate within the solar radiation exposure and shading section to relate best the geometric effect on the courtyard performance.

As the wall areas are equal, the sunlit area and shading on the walls are taken as a percentage of the total unit area of the walls. The shaded area decreases when R_1 reaches 1 as it's the shallowest form. In Cairo, by ranging R_1, R_2 value alteration does not have an effect, as it would produce an equal amount of wall-shaded area. The percentage of shading decreases rapidly when R_1 increases from 1 to 5. The most efficient values for the hot dry climate in summer and winter of R_1 range between 4 and 8 with 4 representing the deep form and 8 the shallow form. Efficient values of R_2 are between 0.3 and 0.8, Figure 2.12.

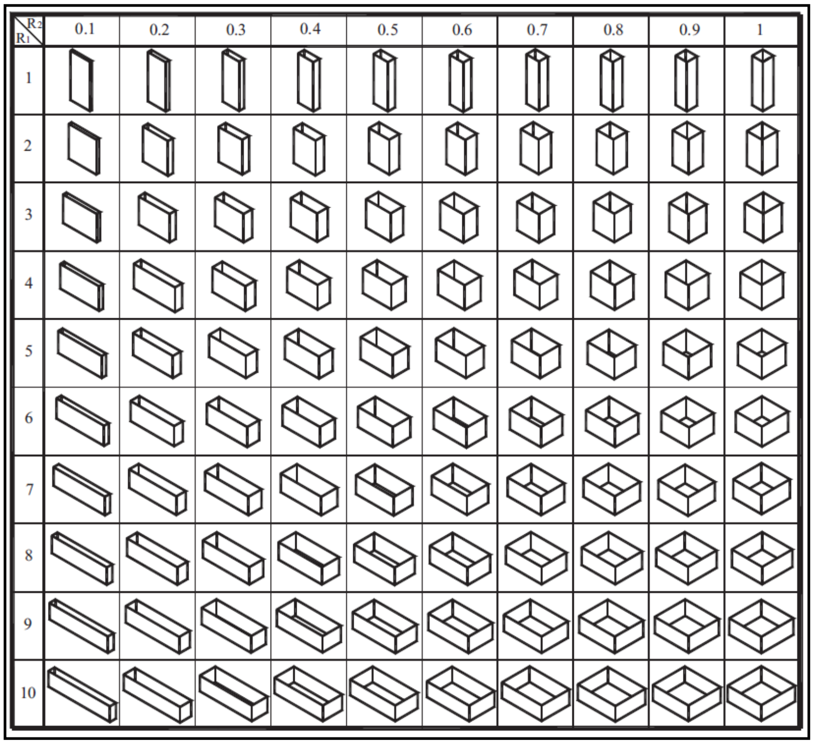

Fig.2.12. Rectangular courtyard forms relation between R1 and R2 ratio (Source: Edwards et al. 2006).

Koch-Nielsen draws a recommended width of the courtyard that ranges from x to 3x, having x the courtyard height, Figure 2.13 (2002, p. 57). Moreover, Laffah states that the common proportions of width to length are 1:1:8 and 1:3:6 (cited in Edwards et al 2006, p.149). Another factor is the courtyard area percentage in relation to built area where it is suggested that 25%-30% of the plot is to be open (Reynold 2002, p. 177).

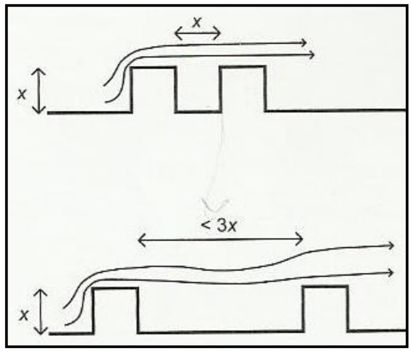

Fig.2.13. Width to height relationship (Source: Koch-Nielsen 2002).

Reynolds defines courtyard exposure into two parametric factors, which are aspect ratio (AR), and solar shadow index (SSI)(2002, p.16 & 17). Aspect ratio is the degree of exposure to the sky, therefore the higher the aspect ratio the greater exposure of the courtyard to the sky, hence more solar radiation. AR is calculated as follows (Reynold 2002):

$$\textbf{Aspect Ratio} = \frac{\textbf{area of the courtyard floor (m}^2\textbf{)}}{\textbf{(Average height of surrounding walls)}^2} \quad \textbf{(2.1)}$$

Solar shadow index refers to winter sun exposure, where by having a high SSI less winter sun reaches the South wall and floor perimeter, hence deeper walls. SSI us calculated as follows (Reynold 2002):

$$\textbf{Solar Shadow Index} = \frac{\textbf{South wall height (m)}}{\textbf{North-South floor width (m)}} \quad \textbf{(2.2)}$$

Ratti et al. have studied the environmental performance of three realistic urban forms in a hot-arid climate of Marrakesh (2003). All built forms have the same built volume, within different forms. The three urban forms are a courtyard, which is a real prototype, pavilion 1, which replaces each courtyard with a block, pavilion 2 integrates four courtyard forms into one block. Figure 2.14 represents the three urban forms. The building height is calculated by preserving the total built volume. The studied parameters are surface to volume ratio, shadow density, daylight distribution, and sky-view factor. The sky-view factor is the measure of openness of the urban form to the sky. Hence, these factors address solar radiation and thermal comfort. Ratti et al. observed the study through computer imaging.

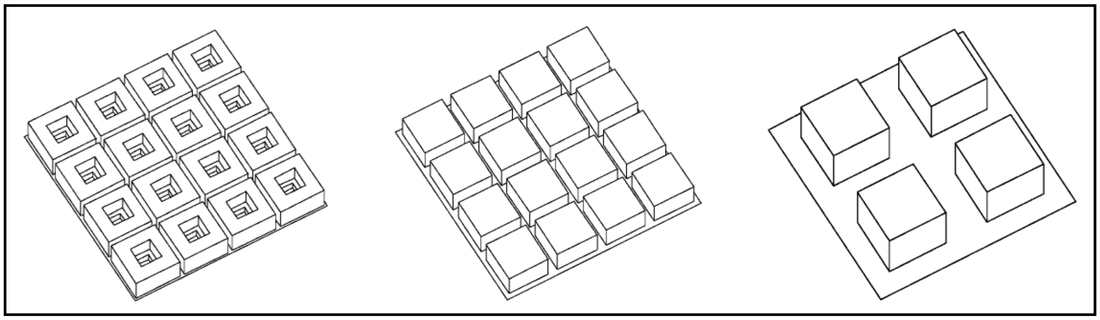

Fig.2.14. Axonometric representation on a 67.5mx67.5m site of traditional Arabic courtyard (left: three floor courtyard) and of two pavilion structures (middle: micro-pavilion, three floors; right: pavilion, six floors) (Source: Ratti et al. 2003).

The factor of surface to volume ratio results show that the courtyard has the highest surface to volume ratio of 0.58 comparing to the pavilions. Thus, the courtyard is exposed to heat loss in winter, and heat gain in summer, therefore the form will not perform thermally well. By having a maximum surface to volume ratio, the courtyard acts as a heat sink and reradiates the heat indoors. Representing the relation, that the thermal mass having a positive effect on the thermal performance of the courtyard.

The sky view factor results interpret that the courtyard form has the least sky view factor with a 13.5^{o}C temperature. Ratti et al. (2003) acquainted that in a hot arid climate context, night and day temperature variations must be taken into consideration. As also, radiating temperatures affect thermal comfort. Therefore, concluding that low sky view factor are beneficial in such climate, since low sky view factor insure an increase in shading and reduction of reflection resulting thermal comfort between the open spaces of the courtyard.

Hence Ratti et al. study concludes that the climate, built form type, geometry, and proportion can change the built form performance and adopt within the climate context.

Therefore, confirming Muhaisen theory that a high aspect ratio (wide and shallow) form performs as a sun collector, while a low aspect ratio (narrow and deep) performs as a sun protector in hot and dry regions hence enhance cooling resulting into a better environmental performance than an extroverted unit block form.

Configurations of courtyard forms are in relation with several factors, such as the urban fabric, orientation, and climatic properties. In hot arid climates, influence the urban fabric, as the built form is dense and compact reducing surface areas to be in exposure to high solar radiation and provide maximum shading. In addition, courtyard house epitomizes with an introverted form that avoids solar heat gain, hence providing adequate daylight penetration and shading levels. Modern housing units differ in utilizing extroverted courtyard application in hot arid climate, therefore exposing the unit to excess solar heat gain. However, configuration should enhance cool air movement and develop efficient ventilation through the utilization of the courtyard configuration and compact urban fabric, nonetheless, avoiding dusty wind.

Hakmi (2006, cited in Edwards et al 2006, p.187 & 201) worked on evolving the traditional courtyard concept into the modern architectural character. He developed a variety of possible contemporary configurations for a single-family courtyard dwelling that function efficiently towards the local climatic and cultural needs, Figure 2.15.

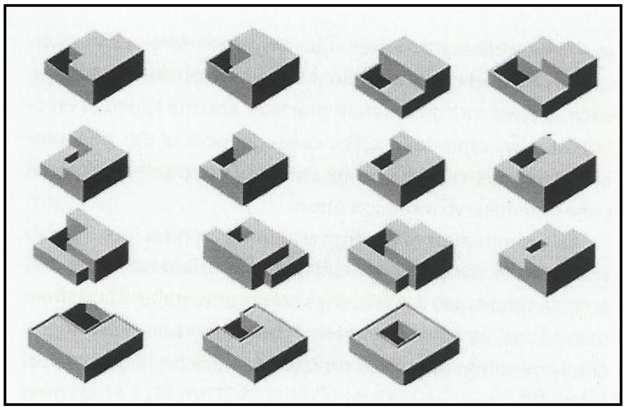

Fig.2.15. One and two storey courtyard layouts (Source: Hakmi 2006, cited in Edwards et al 2006).

He concluded that:

- Combining features of modern architecture with traditional courtyard form generates innovative and functional built environment.
- The European urban system in terms of detached and row residential units that enquire setbacks does not correspond to courtyard housing foundation where a compact urban fabric is required.
- Dimensional plots of 12 x 12m to 14 x 14m are the optimum size to adopt a courtyard form.
- Providing a central courtyard with at least closed three sides allows the courtyard to provide with effective daylight and ventilation.

2.6.2.Orientation

Built forms interaction respectively to solar angle and prevailing wind direction is the fundamental basis of orientation. Although there are conflicts between efficient prevailing wind orientation and solar orientation that must be taken into consideration and in detailed analysis for each site. Additionally, manipulation of the urban fabric alignment in terms of streets and plot shape delivers effective orientation. As referred to earlier vernacular narrow streets and compact form layout minimizes solar exposure and increase shading effect, hence shading East and West facades of the North-South oriented streets.

Koch-Nielsen (2002) states that in the case of latitudes closer to the equator such as Bahrain, the sun has a high altitude, the North, and South facing vertical surfaces receive minimum solar radiation. Therefore orienting large exposed surfaces North-South. East and West vertical surfaces receive excess heat gain due to the intense solar radiation during morning and afternoon periods, which can be contained through increasing glazing characteristics, thermal mass and insulation properties. Horizontal surfaces are the most exposed to intense solar radiation.

Along the line of Muhaisen's (2006) earlier study of the geometrical courtyard form relation to the environmental performance in different climatic regions, Muhaisen have studied the effect of the change of orientation. As the internal walls are constantly vertical, the orientation would alter the azimuth angle of the single surfaces. Resulting in having some walls constantly in shade and others exposed to the solar radiation, affecting the thermal performance. Orientation concerning climatic conditions and location affects the experience of maximum shaded area in summer and minimum in winter. Therefore, Muhaisen studied the effect of orientation by rotating the courtyard.

The simulation investigated on the courtyard ratio of R_1 is 5 and R_2 is 0.5. The simulation hours were from 7:00 to 17:00 with an hour intervals. The alteration of the orientation angle was from 0^{o} to 90^{o} in 10^{o} steps, studying the daily performance in winter and summer. Minimum shadows are generated when the courtyard is oriented along the East-West axis, and as the angle increases the shadow range increases.

Muhaisen concluded that in the hot arid region, orienting the courtyard long axis between the North-South axis and the Northeast-Southwest determines effective courtyard performance within all seasons of the year (2006). Figure 2.16

demonstrates Muhaisen theory as the sun direction for the regions located by the equator, the sun passes overhead resulting the east and west walls receiving the most amount of solar radiation.

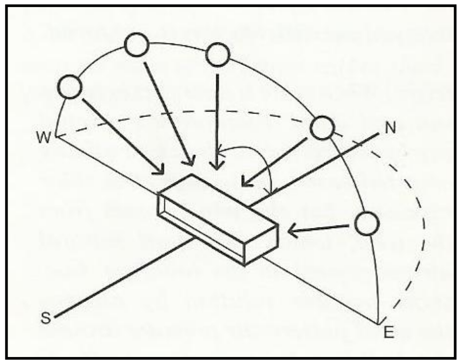

Fig.2.16. Sun path on a longitudinal North-South courtyard (Source: Koch-Nielsen 2002).

Regarding wind determined orientation to maximize natural ventilation and cool air movement, is by orienting the windward side of the building perpendicular towards the wind. Orienting the building and the openings at a 45^{o} towards the wind direction increases air velocity, which enhances the air movement within the building (Koch-Nielsen 2002, pg.45). Figure 2.17 demonstrates the improvement of air distribution by the suction effect.

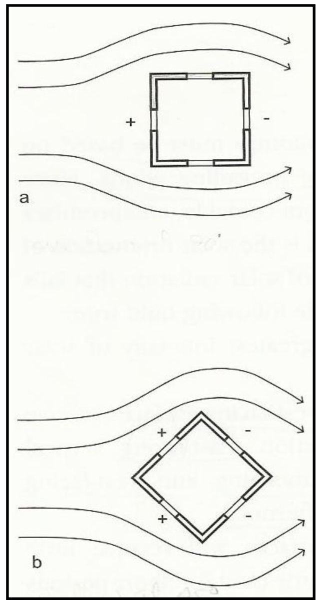

Fig.2.17. Wind orientation to increase airflow pattern (Source: Koch-Nielsen 2002).

2.6.3.Openings

Courtyard opening size and location enhances the climatic effect as it is in direct relation to light penetration, air movement, and heat gain. Locating openings affect the structure energy use, heat gain, and loss. Openings that are at a risk of receiving high solar radiation are to be limited. Courtyard housing external envelope distinguishes with small, above the eye level openings, while the courtyard surrounding spaces distinguishes with bigger openings for adequate light penetration without heat gain, direct solar radiation, and glare.

Regarding ventilation, opening arrangements can optimize cooling, air movement, and cross ventilation. The average interior air velocity, the volume of air flow, and the route of air flow within a courtyard, or an enclosed space is dependable on the location and the size of the opening. By having two openings on opposite walls, a small opening on the windward surface and large openings on the leeward surface, higher air velocity generates. Figure 2.18 shows the effect of air distribution and speed due to variation in opening size. Having openings in adjacent walls with an oblique wind direction air distribution increases with the increase of turbulence. Hence, it encourages air mixing and efficient cooling effect within the space. On the other hand, having variation in height on the opposite walls develops effective distribution of air in the occupied zone. Figure 2.19 shows a vertical section of air speed and distribution due to various opening positioning. Not all openings should be located near the floor or ceiling because such action prevents an occupied zone to have its maximum air velocity. For higher air velocities, some openings should be located mid height, or with a combination of high and low openings. Fig 2.20 presents the difference of interior air velocity and distribution due to opening locations.

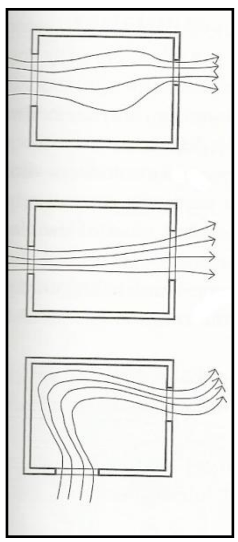

Fig.2.18. Variation of air speed and wind distribution due to openings different sizes and location, horizontally (Source: Koch-Nielsen 2002).

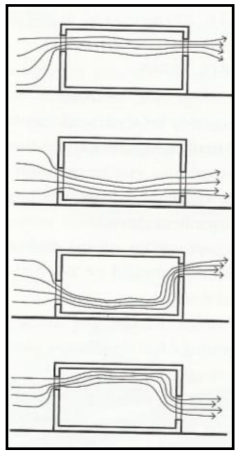

Fig.2.19. Variation of air speed and wind distribution due to openings different sizes and location, vertically (Source: Koch-Nielsen 2002).

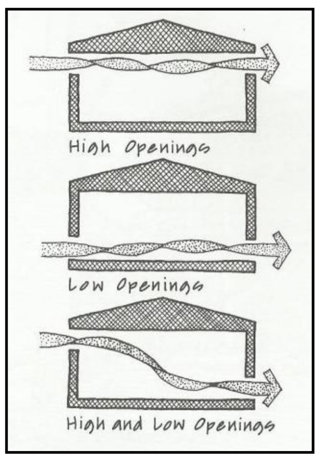

Fig.2.20. Variation of interior air velocity distribution due to the different opening locations (Source: Brown et al. 2001).

2.7. Environmental Dimensions

2.7.1.Solar Radiation, Daylight and Shading Analysis

The courtyard proportions and exposure affects the courtyards admittance and control of solar radiation, natural daylight within the internal spaces, and shading coverage.

Experiencing solar radiation extents on an exposed area depends on the latitude, altitude of the sun, cloud coverage, the building orientation towards the sun, and the aspect ratio of the courtyard. As the sun altitude increases, simultaneously solar radiation intensity increases. Cloud coverage affects heat transmittance, where in the case of Bahrain; the absence of clouds allows heat to be in a long-wave radiation form. Three different types of solar radiation affect the amount of heat transmitted into the building, which are direct solar radiation, diffused solar radiation, and reflected solar radiation. Radiation affects directly the thermal comfort of the building through heat gain. The ways that radiation develops heat gain effect are through absorbed radiation that access directly from openings, heat exchange process by radiation absorbed by the external building envelope surfaces and transferred into the internal surfaces.

With reference to Muhaisen study earlier, he has studied various effects of sunlight and shade on circular, polygonal, and rectangular courtyard geometrical forms through IES computer simulation program. However, focus is on Muhaisen studies on rectangular courtyard forms as it represents the traditional form. Muhaisen (2006) has examined exposure and shading on four different climatic conditions with the use of two ratios in order to obtain the optimum sunlit area in winter and wall shaded area in summer. These ratios are expressed as R1, which is from 1 to 10, and R2, which is from 0.1 to 1 and defined as follow (Muhaisen 2006):

$$R1 = \frac{\textbf{floor area (m}^2\textbf{)}}{\textbf{height (m)}} \quad (2.3)$$

$$R2 = \frac{\textbf{width (m)}}{\textbf{length (m)}} \quad (2.4)$$

In the case of climate relation, Cairo represents the hot arid climate. The study examined the effect of height on the shading performance. To test the effect of height variation on the shading conditions of a rectangular courtyard a reference model was taken was taken with a R2 of 0.5 and a 3 meter high building. The test was against different height ranging from one to five storeys in summer and winter respectively, figure 2.21.

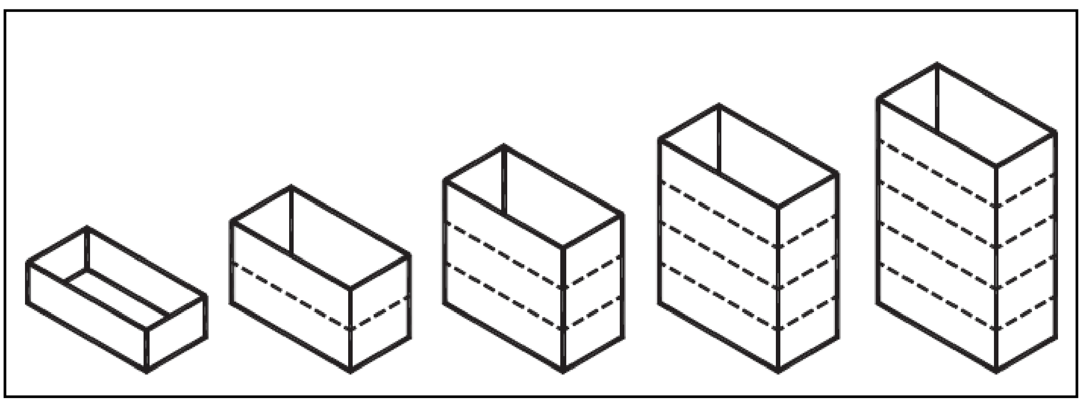

Fig.2.21. Investigated heights of the courtyards building (Source: Muhaisen 2006).

Results demonstrated that increase in the number of storey, simultaneously increases shaded area. Yet, as the sun altitude increases, the relation of height increase and shaded area decreases. As the case in Cairo where the average rate of increasing shadow due to increasing height in summer in 2.5% and winter -7.5%, Table 2.1.

Furthermore, he states that the optimum performance of courtyard in terms of shade and exposure during summer and winter season is achievable at the height of two storeys, Table 2.2. The wall surface areas are equal, the sunlit and shading area on the walls are taken as a percentage of the total unit area of the walls. The percentage of shading decreases when R_1 increases from 1 to 5. As stated earlier, the optimum ratio values during the whole year of R1 ranges between 4 and 8, while R2 ratio values ranging between 0.3 and 0.8. He concluded higher courtyard transforming the courtyard into a deep courtyard form provides more shading. The geometrical shape has greater influence in summer than winter. Consequently, courtyards with deep forms provide less solar gain and more shadow in hot climatic regions, hence performs efficiently.

Muhaisen (2006) states that the courtyard can be an efficient modifier to the climatic condition when proportioning the courtyard form to ensure adequate shading within the summer conditions to decrease cooling needs and solar radiation within the winter to increase warmth. Therefore, understanding the link between geometry and environmental performance.

Table 2.1. Average rate of increasing the shaded area and decreasing the exposed area due to increasing height by one storey (Source: Muhaisen 2006)

Kuala Lumpur		Cairo		Rome		Stockholm	
Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
4.3%	−6%	2.5%	−7.5%	3.4%	−6.6%	6.3%	−1.3%

Table 2.2. Reduction percentage in the maximum achievable shaded and sunlit area (Source: Muhaisen 2006)

Building height	Kuala Lumpur		Cairo		Rome		Stockholm	
	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
One storey	17	0	10	0	14	0	25	0
Two-storey	14	5	8	14	11	16	19	3
Three-storey	10	11	6	23	7	22	13	4
Four-storey	6	18	3	27	4	25	6	5
Five-storey	0	24	0	30	0	26	0	5

Another study review conducted by Meir et al. (1995) undertook a study on the internal shading in summer on two courtyards in a hot arid climate. The courtyards are identical in shape and treatment, however are different in orientation: South and West, Figure 2.22. The length to width ratio (L/W) is 3.8, and height to width ratio (H/W) is between the ranges of 0.47 to 0.56.

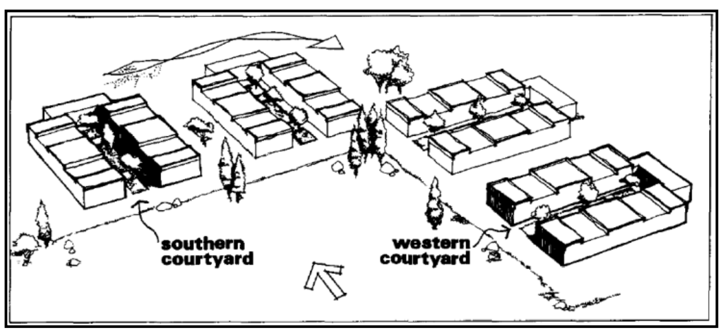

Fig.2.22. General layout of the monitored courtyards' area (Source: Meir et al. 1995).

They concluded that direct solar radiation reaches the South-facing courtyard during morning and late afternoon hours much less than the West-facing courtyard, Figure 2.23 and 2.24. However, trapped solar radiation and inadequate ventilation of the courtyards resulted overheating, irrespectively to orientation, thus, affecting the thermal behavior.

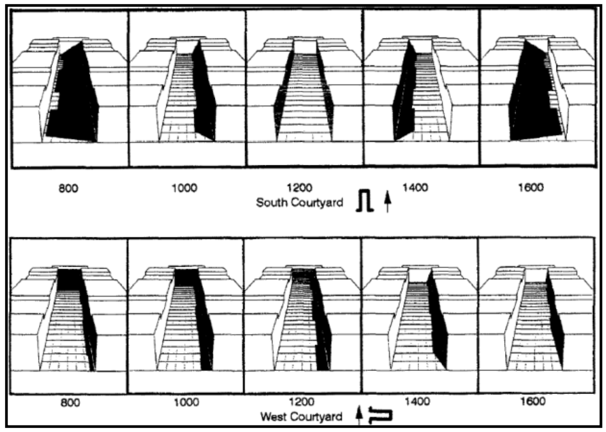

Fig.2.23. Internal shading of surfaces in courtyard of different orientation in August (Source: Meir et al. 1995).

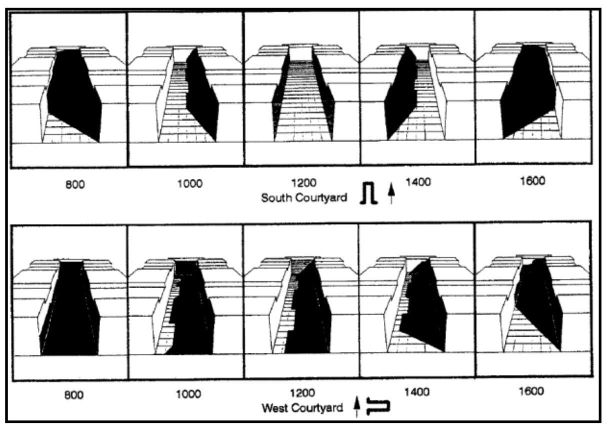

Fig.2.24. Internal shading of surfaces in courtyard of different orientation in December (Source: Meir et al. 1995).

Referring back to Ratti, Raydan, and Steemers study on the three urban forms; courtyard, pavilion 1, and pavilion 2, in the hot-arid climate of Marrakesh, the building form presents interesting results regarding shadow density and daylight distribution (2003). Shadow density is taken in the street, while daylight values are an average of all ground surfaces. Results concerning the shadow density and daylight distribution parameter the courtyard recorded to have the highest value of shadow density. However, overshadowing relates to low direct daylight. Hence, the courtyard has the lowest daylight distribution of 15%. However, by taking the courtyard alone, observations record that the daylight factor is 19% in the courtyard, while in the street its 10%. Therefore, daylight is effective through the courtyard.

Thapar and Yannas performed a study of how the urban form affects the microclimatic conditions within various site locations in Dubai, a climate that is very similar to Bahrain. The study was to analyze the microclimate urban form of Deira, Bastakia and Dubai Marina in July 2007 (Thapar et al 2008). The study is divided into a three states: a compact low-rise courtyard, a mid-rise, and a high-rise building form. The study is based on on-site measurements and supported with further software simulation investigation and validation. The parameters investigated are the built form performance, the presence of vegetation, the presence of water bodies; all effecting the thermal comfort of the urban space.

Each form has a different shading effect for similar built volumes, as Figure 2.25 shows that a dense development of a courtyard block provides a well-shaded area. The shadow cast area increases from the function of the built form; the high-rise tower has the least shadow cast, while the dense courtyard has the highest shadow cast.

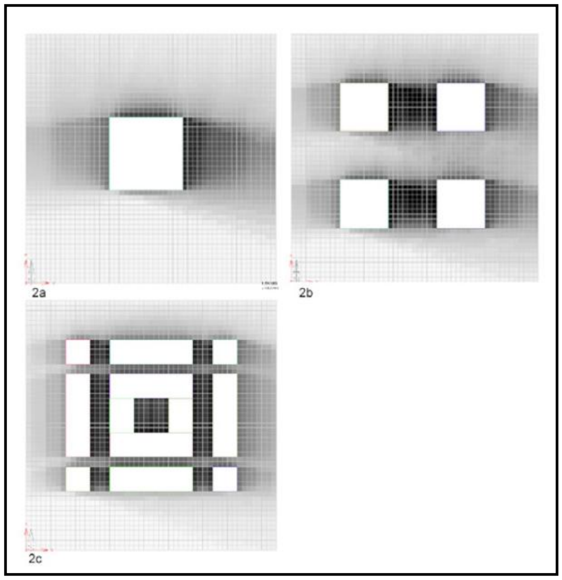

Fig.2.25. The area of shadow cast on the ground increases for a constant built volume (of 57,120m^3) as a function of builr form from (a) a 63.5m high tower, (b) 35.7m high blocks, (c) 21m courtyard blocks (Thapar et al. 2008).

By the analysis of the case studies, in hot arid climate of Bahrain, sunlight projection should be towards the South longitudinal elevation that takes in large amounts of heat in winter and less amount in summer period, hence benefiting of solar gain in winter. A rule of thumb, avoiding heat gain by shading provides thermal comfort. Therefore, the introverted form of courtyard reduces exposed surfaces to solar radiation and increases shade. However, the geometrical proportion of the courtyard must be accurate to develop adequate shade and daylight. Narrow and deep courtyards oriented in the East-West direction and elongated in the North-South direction work well in hot arid climatic conditions in which they provide shade from the low-angle sun in the morning and afternoon period. As the courtyard is in shade for most of the day, it will gain heat less and lose heat by outgoing radiation more.

As for adequate daylight admittance within the internal spaces, the daylight factor performs as a guideline. The daylight factor is the ratio between the daylight within an internal space and external at the same time. Daylight coincides with the heat of the sun. Therefore, hot arid climate benefits from low daylight factor. For deeper daylight penetration, window dimensions ought to be large relative to the floor area, hence higher daylight factor that do not comply for hot arid climates. When the distance into the room from the courtyard edge exceeds 2.5 times the height of the opening, daylight is less that increases the need of electrical lighting. Figure 2.26 is a diagram demonstrating that the distance in the internal space that exceeds 2.5 times the height of daylight opening, there will be little daylight.

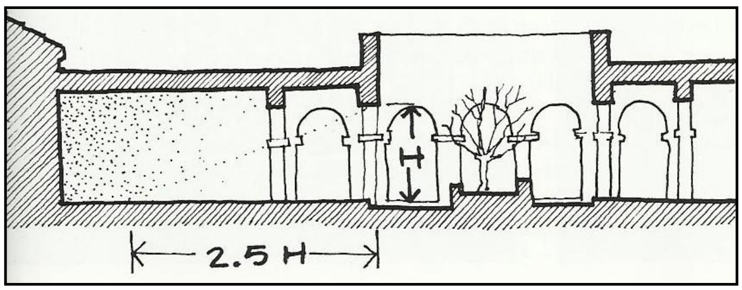

Fig.2.26. Daylight penetration from window in relation of window height to the floor area (Source: Reynold 2002).

The Illuminating Engineering Society of North America (IESNA) lighting handbook has developed codes and standards for indoor spaces in order to provide a healthy visual environment. They recommend illuminance for specific visual tasks. Controlling daylight provides in controlling light distribution, light quantity, and absorbed heat gain. Glare causes discomfort, reduces task visibility, and hinders occupant's visibility. Glare can be direct or reflected. Lighting design depends on the occupant needs, and activities. The living room activity level selected is sedentary and light, as it is a place for relaxation and light activities. The living room space includes flexibility of activities ranging from simple to medium tasks. Natural daylight should provide general lighting for a range of various activities. The IESNA recommends an illuminance level between 200-300 Lux for a permanently occupied area with a visual task set as moderately easy; such as relaxation, dining, crafts, reading, and entertainment such as playing the piano or table games (Rea M.S., 2002).

Courtyard form may reduce sunlight penetration and glare according other factor such as surface color. As the courtyard admits, reflects, and absorbs light, light surface color and material may reflect substantial quantity of light towards the walls and ceiling that may produce glare. In order to reduce glare within the internal surfaces, surfaces around the window opening must mediate between the dark surfaces and bright window.

2.7.2.Airflow and Ventilation Analysis

Air movement and pattern into the built form affects the thermal comfort, heat loss, and heat gain through the building envelope. Courtyard built form is an effective passive strategy for cooling in hot arid climatic regions as they characterize with large diurnal temperature swing. A virtue of the courtyard design is that cold breeze is available regardless of wind direction as the wind will pass over and create low pressure in the courtyard. Exposed areas to the sun and shaded areas are different in air density that causes air circulation between the interior courtyard and exterior space, and between the interior courtyard and interior space of the building.

Natural ventilation and airflow is achievable in two forms; cross ventilation and stack effect. Cross ventilation is a wind-generated pressure difference by air movement from the opening across the space. The stack effect is a temperature-generated pressure difference by hot air rising toward the top opening allowing cold air to settle at the bottom.

Due to solar radiation, daytime hours the courtyard heats up quickly creating a stack effect due to temperature differences. However, the stack effect will only be effective when outside temperatures are cooler than inside with a minimum difference of $1.7^{o}C$

(Kwok and Grondzik 2007, p. 145). On the other hand, another mean to increase the stack effect is by increasing the courtyard height and by increasing the distance between high and low ventilation openings. It is in recommendation that the openings are at different heights with an area for the inlet and outlet not less than 3-5% of the floor area (Koch-Nielsen 2002, p.126). Cross ventilation increases by large opening leeward surface and small opening on the windward surface. In addition, wind would increase within the courtyard and cross ventilation would increase by orienting the courtyard 45^{o} from the prevailing wind.

Orientation and built form configuration effects air movement by the creation of eddy zones, Figure 2.27. Nevertheless, courtyard sizing for ventilation and placing openings affects the wind speed percentage within the courtyard. Figure 2.28 demonstrates that wide courtyards have high wind speed in percentage, yet by increasing the length of the courtyard the wind percentage also increases. Narrow and tall courtyards create wind shelter.

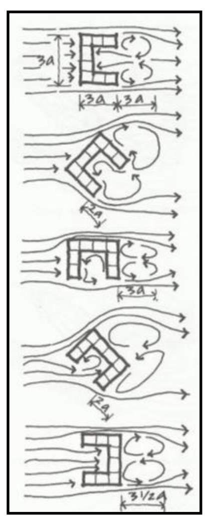

Fig.2.27. Configuration and orientation effect (Brown 1985).

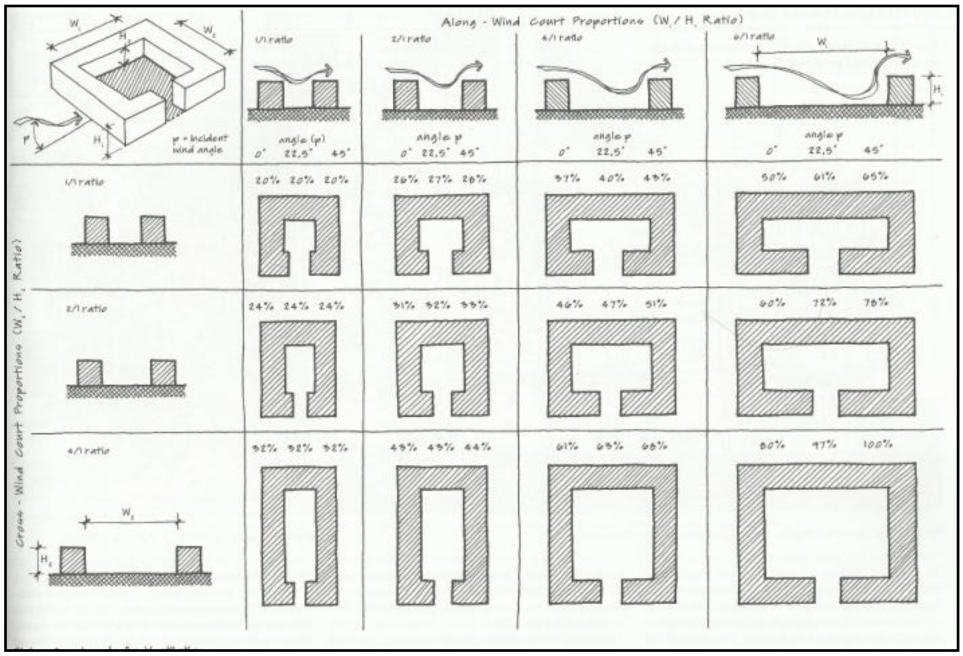

Fig.2.28. Sizing courtyard for ventilation (Brown 1985).

A wind catching strategy by Giovani is raising the height of the downwind courtyard wall (cited in Reynold 2002, p.90). As the wind moves across the lower roof and courtyard opening, it will strike the high wall causing the wind to move over and creating a down draft that can be enhanced by a lower outlet.

A study by Sharples and Bensalem (2001) was taken to compare airflow rates in atrium and courtyard building. Six different pressure regimes were examined by a wind tunnel study, Figure 2.29. The six case models were:

- Open courtyard with positive pressure
- Atrium pitch roof with no openings driving positive pressure

- Atrium pitch roof with small openings in the leeward side causing negative suction pressure
- Atrium pitch roof with large openings in the leeward side causing negative suction pressure
- Atrium pitch roof with small openings in the windward side causing positive pressure
- Atrium pitch roof with openings on both leeward and windward side causing both negative and positive pressure.

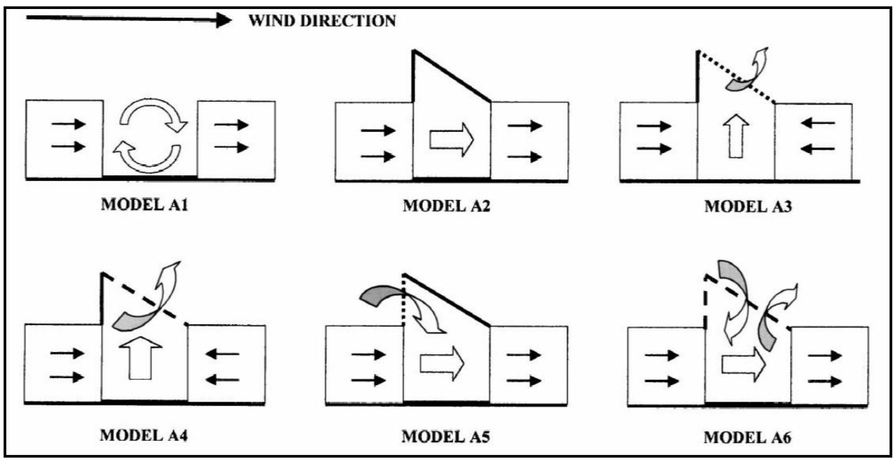

Fig.2.29. Courtyard and atrium roof ventilation strategies used in the study (Sharples et al. 2001).

They concluded that the open courtyard have weak ventilation performance, while the best is when the roof openings are positioned perpendicular toward the wind facing negative suction pressures regimes. On the other hand, by placing the building 45^{o} perpendicular to the wind, the effect of all models become relatively similar.

Al-Hemiddi and Al-Saud (2001) performed an experiment that asses the cross ventilation effect on the thermal performance of the courtyard housing in Saudi Arabia, Figure 2.30.

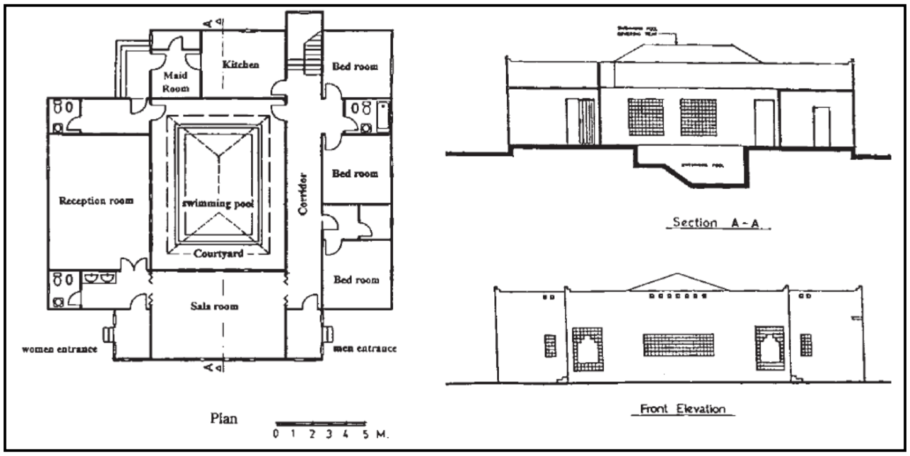

Fig.2.30. Plan and section of the courtyard house in Saudi Arabia (Al-Hemiddi et al. 2001).

The experiment was conducted in six phases, as follows:

- Not ventilated courtyard
- Only inner windows toward the courtyard are open
- Only outer windows are open during night hours
- Outer and inner windows are open
- Outer and inner windows are open, but the courtyard is covered during the day
- Outer and inner windows are open, but the courtyard is covered during the night

The measurements concluded that the courtyards internal temperatures did not exceed the external temperatures, enforcing the fact that cross ventilation significantly cools the internal spaces. In addition, the fifth phases reported to be the best due to its largest time lag for maximum temperatures, Figure 2.31.

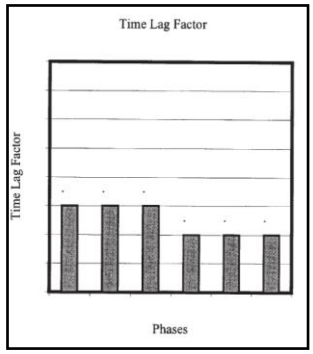

Fig.2.31. Fifth phase is the best for its largest time lag for maximum temperatures (Al-Hemiddi et al. 2001).

Another study been performed to investigate courtyard passive cooling effect of natural ventilation in minimizing indoor overheating. The study was on a single-storey high mass building; however, it is in a warm humid climate by Rajapaksha, Nagai and Okumiya (2003). An internal courtyard was integrated, and indoor airflow patterns were controlled through the composition between the courtyard and envelope openings. Indoor airflow patterns effects the heat exchange between indoor air and the building thermal mass. For this study, Computer Fluid Dynamics Analysis (CFD) was in use. The study compared two cases, Figure 2.32. The first case, the building ventilates only by the courtyard and all openings on the envelope are closed during daytime. The second case, openings on the longitudinal axis are open during daytime. The study identifies that when the courtyard acts as an air funnel discharging indoor air to the sky by openings in the envelope, rather than a suction zone, it modifies indoor thermal conditions.

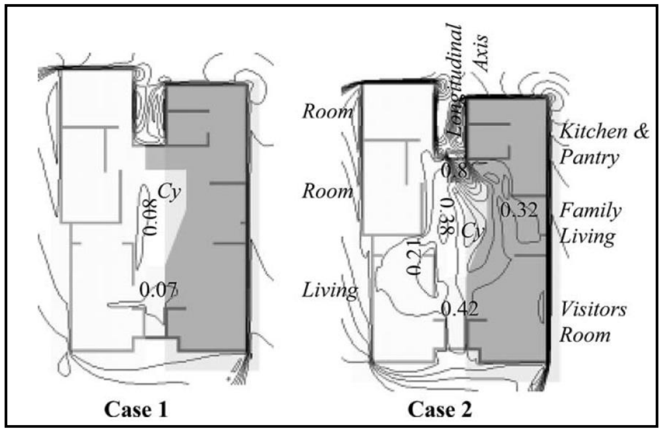

Fig.2.32. Simulated airflow patterns at human body height 1.1m (Rajapaksha et al. 2002).

Furthermore, referring back to Thapar and Yannas study of the three different urban form effect on their microclimatic condition in Dubai. They have analyzed the airflow effect of the urban form of Dubai Marina (high-rise), Deira (mid-rise), and Bastakia (low-rise) in July 2007 (2008). Bastakia consisted of compact courtyard form. The study simulated the forms as a fixed built volume using Envi-met software to run air temperature and air flow. Results in Figure 2.33 shows that the courtyard block has the coolest airflow with the courtyard as the coolest area. However, the wind speed was lowest and the East and West sides were warm. This may have been due to the high level of shading effect of the courtyard form. Nevertheless, the courtyard managed to reduce the humidity levels.

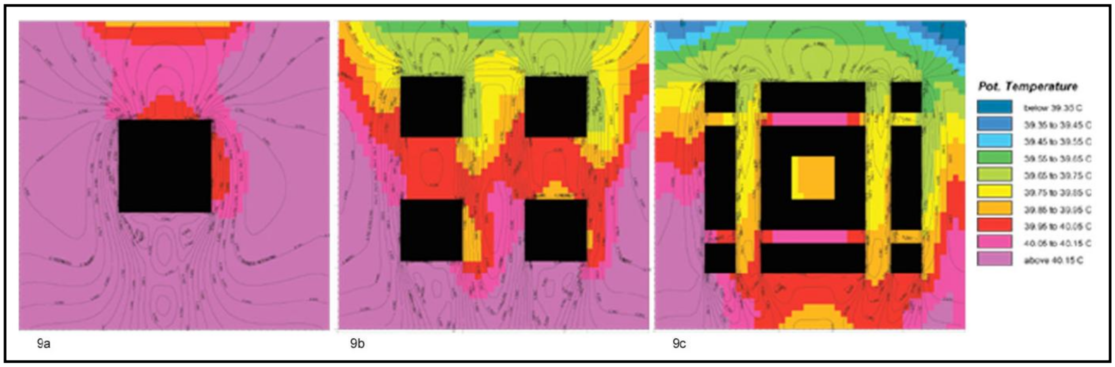

Fig.2.33. Envi-met predictions of air temperatures for 2.00pm on a July day around a constant built volume (of 57,120 m^3) on a 100x100m site as (a) a 63.5m high tower, (b) 35.7m high blocks, (c) 21m courtyard blocks (Thapar et al. 2008).

Regarding natural ventilation and cooling, ventilation needs to be controlled, requiring that directing air movement to pass over warm surfaces. Ventilation openings should be flexible in operation and may be located at different height for stack effect and differing sizes to maximize suction effect. The use of mechanical ventilation may be unavoidable in hot arid climates, as it assess the removal of heat gain A combination option may be in use where natural ventilation is in use in certain period of the year (winter), and active means are in use in other period of the year (summer). Mechanical ventilation affects the thermal conditions within the internal space and is not affected by any lighting systems or strategies.

2.7.3.Thermal Analysis

The integration of a courtyard within the built form functions as a thermal mediator between indoor and outdoor spaces. The building envelope responds to various external conditions such as solar radiation, heat gain, and release of heat radiating within the building. Thermal control and comfort in a courtyard dwelling is achievable by considering many strategies such as effective ventilation and airflow patterns, efficient daylight level admittance and absorbance, orientation, built form configuration, thermal mass, high surface area to volume ratio, intermediate spaces, and material selection. All factors effect thermal comfort within internal spaces and within the courtyard.

Intermediate spaces in the courtyard such as loggia, which is known traditionally as Liwan, act as thermal barriers protecting inward-facing walls from direct solar radiation and heat gain. Heat gain can be avoided by obtaining effective balance between surface exposure to solar radiation and shadow. Moreover, natural ventilation assesses in the heat gain process and heat loss. With adequate natural ventilation, heat will be releases substantially resulting thermal comfort.

The building ability to store and release heat is relevant to the building volume, where as the rate to lose or gain heat refers to surface area. Therefore, there is the surface area to volume ratio that indicates the rate that the building heats up and cools down. To obtain this ratio, divide the total building surface by their volume. The higher the ratio is the higher the potential for heat gain during the hot period and heat loss during the cold period. On the other hand, high ratio increases ventilation and daylight (Raydan et al, cited in Edwards et al. 2006, p.141).

In hot climate, in the case of Bahrain, the building thermal mass cools down through heat radiation during night hours. Thermal mass is slow in cooling and heating air temperatures as they increase or decrease. High thermal mass presumes an increase in temperature time lag between interior and exterior temperatures. In a courtyard dwelling, by increasing the thermal mass of East-West facing walls, heat gain reduces and temperature variations balance.

Materials have thermal properties that affect the space thermal comfort. Material thermal properties characterizes as absorbance, reflectance, and emissivity. A high reflective material reduces heat gain and high emissive material increases heat loss during night hours.

Aldawoud (2008) have analyzed the thermal performance of courtyard buildings. The assessment considered several factors that are climate, height ranging from 1 to 10 floors and various glazing types. The analysis performed on the courtyard and its adjacent zones, Figure 2.34.

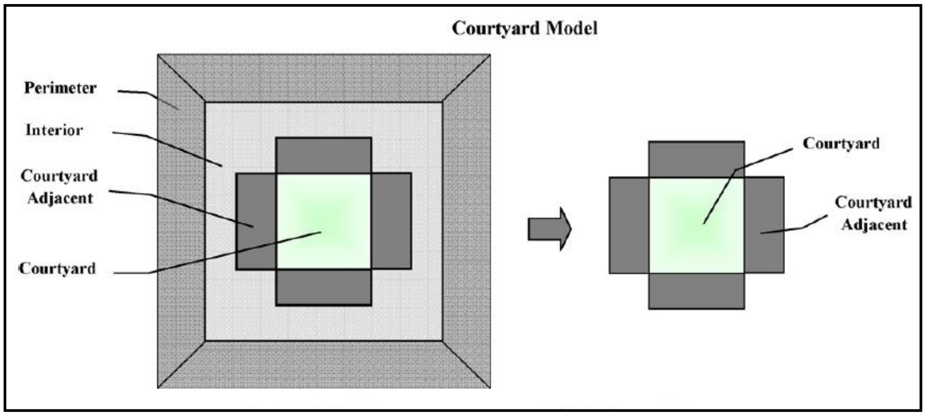

Fig.2.34. Excluded common components for both models (Source: Aldawoud 2008).

The study findings were that integrating the courtyard within a building in various climates is thermally comfortable and energy efficient. Hot arid climate presented an increase in energy reduction, hence, proving the courtyard efficiency of being thermally comfortable by reducing the use of mechanical and lighting systems. Moreover, as materials do affect thermal comfort, glazing type and percentage proved to affect the thermal performance and comfort of the courtyard. As Table 2.3 views reduction in energy consumption in terms of mechanical and electrical systems to mitigate the thermal comfort. Moreover, courtyard is found to be in its optimum efficiency in low and midrise building levels.

Table 2.3. Courtyard thermal performance compared with thermal performance of courtyard having single clear glass with 67% glazing at 10 floors in hot-humid climate (Source: Aldawoud 2008)

Courtyard type	Energy consumption	Reduction in energy consumption (%)
Courtyard/single clear glass	1367.271	
Courtyard/double clear glass	1086.624	−21
Courtyard/double low-e	1018.27	−26
Courtyard/triple glass	971.298	−29

Sadafi N. et al. (2008) have studied the thermal effect on the adjoining zones of having a courtyard in a tropical climate of Malaysia. The house consists of a ground and first level. The study is through computer simulation by the use of Ecotect Analysis. The material input for the house is from Ecotect library. The thermal performance investigation was conducted for March, June, and December. The first mode A was the house without a courtyard. The second mode B was the house integrated with a rectangular courtyard with 2.2x2.5m dimension. Figure 2.35 and 2.36 demonstrates the temperature difference between mode A and mode B in June and December.

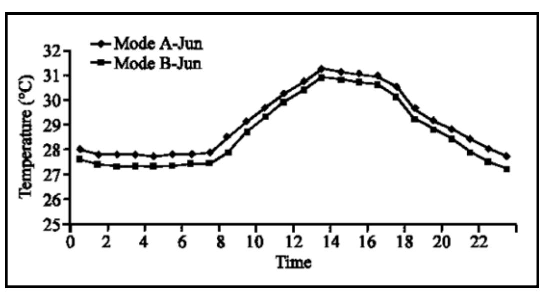

Fig.2.35. Temperature difference between mode A and B for living are in June (Source: Sadafi N. et al. 2008).

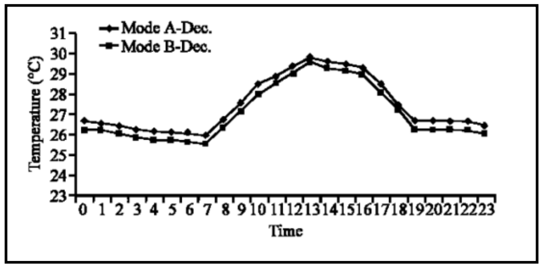

Fig.2.36. Temperature difference between mode A and B for living are in June (Source: Sadafi N. et al. 2008).

The thermal performance of the living room demonstrates a decrease in temperature in both months. However, solar gain will increase, increasing the solar heat in the dining area since it does not have enough openings to release, hence increasing inter-zonal heat gain of the living area. Results illustrate that integrating a courtyard will enhance the thermal conditions by increasing natural ventilation and internal heat release through window openings. Therefore, by having openings both to the internal courtyard and outdoor will experience a better thermal condition, than having an opening only toward the courtyard.

2.8.Contemporary Dimensions

Vernacular architecture are hybrids of indigenous and foreign typography that change and adapt, establishing a national identity of their own that should adapt with the interchange of the present world (Curtis 2001, p.74, cited in Edwards et al. 2006). Conversely, the urban and architectural design of modern cities does not present the application of Curtis statement, as well as considering vernacular architecture as old disregarding their passive design strategies, valued principles and guidelines that present the courtyards environmental and social legacy. Essential factors that sculpt the built form such as climate are overlooked, as evidenced by Bahrain's contemporary typology of westernized freestanding units in the centre of exposed plot with the extensive use of glazing, and having internal halls replace the multifunctional courtyard context.

On the contrary, the built environment requires designers to benefit from vernacular studies and their offering solutions in providing comfort. Courtyards have not been developed into contemporary formats, as they are neglected due their representation of heritage and to globalization standards. Courtyard typology must reposition beyond the superficial distinction of traditional and modern. It is essential to develop environmentally efficient courtyard housing compatible with modern developments.

There are few examples of attempts in revitalizing the courtyard concept. Such examples are the Al-Nakheel district in Riyadh, and a Dean's residence in the campus of the American University of Sharjah, in the United Arab Emirates (Edwards et al. 2006). Those two projects demonstrate successful interpretations of courtyard integrations in a modern built form in a hot arid climate such as Bahrain.

The Al-Nakheel project developed a residential community with approximate 500 residential units, Figure 2.37. The unit plots vary between 179sqm to 1475sqm. They consist of a ground and first floor. There are three types of units differing in their privacy scale. In the first type, the designer adopted the conventional courtyard centrality within the built form with internal spaces surrounding the courtyard. The second type, the designer employed three connecting courtyards and each represents a different scale of privacy. The first courtyard is the entrance courtyard, the second articulates the men reception area, and the third articulates the women's area that is set at the back of the residence. The third type of courtyard is similar to the second type, yet it has a higher scale of privacy, where the third female courtyard is enclosed on three sides.

Fig.2.37. Al-Nakheel contemporary courtyard housing (Source: Abdelsalam 2006, cited in Edwards et al 2006).

The Dean's unit in the American University of Sharjah reconsidered the attributes of the courtyard in terms of courtyard thermal comfort, transition spaces between the courtyard and the interiors, public and private space treatment, facade treatment, and view arrangement throughout the house, Figure 2.38. The courtyard is oriented toward North-East, and placing the entrance at the South-West facade. The facade opposing the street does not attempt of direct viewing or entry into the house. The visitors have to turn 90^{o} to enter the reception area and another 90^{o} to access private areas. Corresponding to the traditional house and entrance form, visitors have a narrow view of the courtyard as they progress to the reception area. Figure 2.39 demonstrates the house plan showing the transition space arrangements.

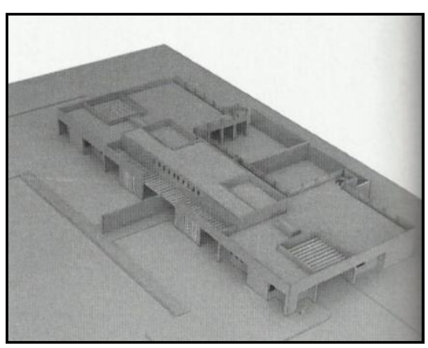

Fig.2.38. Dean's contemporary courtyard housing, American University of Sharjah (Source: Mitchell, cited in Edwards et al 2006).

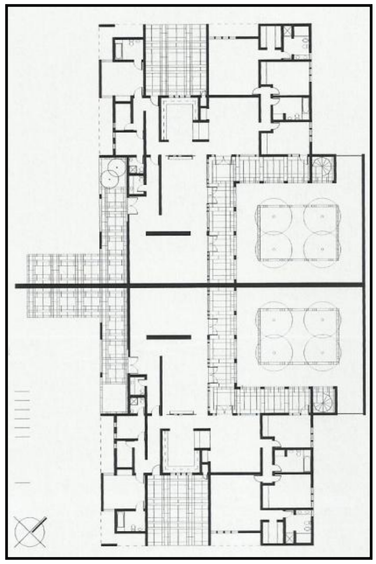

Fig.2.39. Contemporary courtyard house plan (Source: Mitchell, cited in Edwards et al 2006).

The facade treatment also reinterprets the traditional courtyard system by its volumetric expression, massive walls, and integration of deep openings and niches. It has three integrated elements, which are an outermost blank wall that surrounds the house and open for light to access, a recessed stone-faced wall that defines the private spaces, and a stone face volume that represents the public functions. The space between the outermost blank wall and the public volume provides a shaded transition that mediates between the harsh glare of the exterior and interior natural light, hence reinterpreting the entry sequence of conventional courtyard.

Moreover, the unit relies on staggered wall surfaces on the South-East and South-West facade to reduce their exposure to solar radiation, as an alternative of relying on thermal mass to mediate the microclimate. Facade openings are small and recessed, and the facade is surrounded by arcade (loggia) having the inner facade glazed to allow adequate daylight, Figure 2.40. Glazing is operable to be open for ventilation and circulation. Non-reflective materials are in use for the floor to reduce heat gain and glare.

Fig.2.40. Internal courtyard facade showing arcade and internal arrangement of openings (Source: Mitchell, cited in Edwards et al 2006).

2.9.Summary of Literature Review Findings

Bahrain modular housing units have been analyzed in terms of plot area, openings, height, and material specifications. Previous studies on courtyard house typology presented the courtyards role, characteristic, and functionality in addressing its historical, social, and cultural, design parameters, and environmental aspects. Environmental performance studies are represented expansively, in terms of solar radiation, daylight, shading, ventilation, and thermal parameters. Additionally, studying the courtyard's environmental performance in relation to the courtyard's design principles; geometry, form, configuration, orientation, and openings.

The courtyards main role and functions are:

- An environmental moderator enhances the interior climate through mitigating excess solar radiation, and have adequate source of light and natural ventilation. Also, protects the space from dust and sand.
- A secluded safe external space that creates a private shelter zone for recreation and management needs.

The major findings of the revised studies are:

- The climatic issue of Bahrain of having high humidity can be mediated by the hot arid and humid climatic context, as evidentially through the studies the finding strategies were very similar in attributes, such as utilizing cross ventilation design.
- Regarding the effect of height on courtyards environmental performance, the ideal height must not exceed 10 storey levels (Aldawoud 2007). In addition, the integration of a courtyard within a dwelling is optimum for low-rise structures within a hot arid climate context.
- In terms of solar radiation, daylight, and shading, the findings are as follows:
    - Form and geometry effects the courtyard solar radiation penetration and shading levels. Therefore, the recommended form for Bahrain's climate is a low aspect ratio form, which is a narrow and deep courtyard (Muhaisen 2006, and Muhaisen and Gadi 2005).
    - Compact and dense built form to provide maximum shading.
    - In terms of semi-enclosed courtyard, providing a central courtyard that is enclosed from three sides will provide adequate light and ventilation (Hakmi 2006, cited in Edwards et al 2006).
    - Orientation affects the courtyard exposure to solar radiation. Muhaisen concluded that large exposed surfaces should be towards the North-South, having the long axis between North-South and Northeast-Southwest that is effective all year long (2006).
    - Openings should be small with low daylight factor in the hot arid climate.
- The percentage of courtyard area in relation to the structural built plot is between 25%-30%.
- In terms of airflow patterns and ventilation, the findings are as follow:
    - By increasing the courtyard height, and distance between high and low ventilation openings, the stack effect of the courtyard will increase.

  - Cross ventilation increases interior thermal comfort. It can be increased by having large openings on the leeward surface and small on the windward surface.
  - Cross ventilation and wind speed can increase by orienting the courtyard at a 45^o angle from the wind.
  - By increasing the length of the courtyard forming the structure into a narrow form, the wind percentage within the courtyard would increase creating wind shelter.
- The thermal performance is obviously affected by the building principles in terms of airflow patterns, heat gain, daylight accessibility, and shading levels. By increasing the thermal mass of the East-West facing walls, heat gain will decrease.

With thorough review of previous scientific papers and books in the field of courtyard archetypal form, several restrictions and limitation were identified. Studies lacked sufficient investigations and findings regarding the environmental performance of semi-enclosed courtyard typology proposals. Many of the investigations were studying the traditional fully enclosed courtyard lacking some investigating of different shapes and configurations of the courtyard built form. The previous findings will present as guidelines and principle indicator to be in application for this study and develop a baseline model. Bahrain building regulation and specification on their modular housing units will be in application within the study.

Chapter 3

Methodology

Introduction

Passive systems and designs lost their recognition to active systems due to their relation of being a non-modernistic approach. The present architectural development does not provide comfort within the hot climate. This study is set on the basis of previous study findings and recommendations in terms of environmental performance analysis of courtyards. This chapter will define the parameters and the effect of various variables that the study investigation establishes on, and various methodologies employed to similar research topics in order to determine the best effective methodology to be in conduct in this study.

3.1.Study Proposal

This study will examine the performance of low-rise semi-enclosed courtyard housing within Bahrain's hot arid climate with respect to the assessment criteria and variable parameters. The assessment criteria measuring the parameters are natural daylight, shading, solar radiation, thermal comfort, and ventilation. The parameters are the courtyard shape, opening orientation, and active system, Table 3.1. Any other effecting variable are fixed on both courtyard forms in terms of height and materials, with respect to Bahrain's housing floor levels (2 storey's) and Bahrain's material specification. The courtyard size is fixed by adopting the traditional common courtyard size according to the literature review; the courtyard area percentage in relation to the built area is 25% to 30% of the plot. Fixed variables allow investigating the effect of the independent variables only to observe the outcome of the simulation; that are the dependent variables. Active system relation to the two assessment criteria: thermal comfort and airflow is due to the effect it has on cooling and heating on the two measures only. Active system does not affect daylight, solar radiation, or shading measures. The study methodology compares the fully enclosed introverted courtyard housing form to the introverted semi-enclosed courtyard housing form, Figure 3.1. The traditional courtyard form will be referred to as *Courtyard-T*, and the semi-enclosed courtyard will be referred to as *Courtyard-S*.

Table 3.1. The parameters in relation to the assessment criteria

Independent Variable/Parameter / **Assessment Criteria**	**Courtyard Shape**	**Opening Orientation**	**Active System**
Natural Daylight	x	x	
Shading	x	x	
Thermal	x	x	x
Solar Radiation	x	x	
Airflow	x	x	x

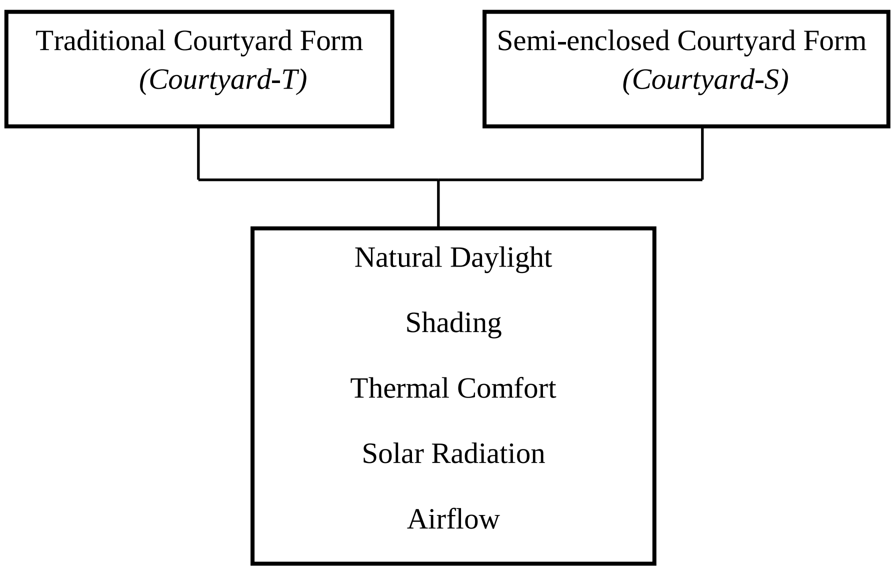

Fig.3.1. Comparison between the traditional courtyard form and semi-enclosed courtyard form

The selected variables will be assessing in both courtyard forms: *Courtyard-T* and *Courtyard-S*. The assessment will occur on an indoor space: the living room, and an outdoor space: the courtyard. To study the effect of the independent variables of the courtyard housing form on the indoor space, natural daylight, and thermal comfort will be assessed. However, to study the effect of the variables on the courtyard form environmental performance, solar radiation, shading, and airflow will be assessed. The assessment will occur on different timing and season for each orientation. The hours of assessment are at 9 O'clock in the morning, 12 O'clock noon, and 3 O'clock in the afternoon. The days of assessment are on the summer solstice June 21st, and winter solstice December 21st.

The study steps are as follows:

- At first, convert the extroverted Bahrain modular housing form into a traditional introverted fully enclosed courtyard-housing form. The given model is oriented North. The converted form is referred as *Courtyard-T*. *Courtyard-T* form will have the same built-up dimensions as the modular housing, including the courtyard area. Therefore, the courtyard area percentage will deduct from the built area. The options between 25% and 30% will be studied to decide the ultimate courtyard area. *Courtyard-T* form will adopt the exterior openings of the given model and will add additional windows on the walls facing the courtyard. Moreover, the additional windows will have the common window size of the given model of the modular housing, which is 1.2mx1.6m. The living room will be in place in the same position in the given model of the modular housing. The courtyard house form will be modeled without the boundary walls; however, the boundary wall will exist as a recess between housing to follow Bahrain building regulations.
- Secondly, test the fixed variables on the traditional fully enclosed courtyard form to compare *Courtyard-T* and *Courtyard-S* optimum environmental performance and investigate the appropriateness of having a semi-enclosed courtyard form within the hot arid climate context, Table 3.2.
- Thirdly, develop a semi-enclosed courtyard form through the application of the varying parameters and testing their effect on the living room and

courtyard performance, Table 3.3. *Courtyard-S* will have equal built-up area as *Courtyard-T*.

- Lastly, after achieving the optimum semi-enclosed courtyard performance, compare both form performances.

Table 3.2. Matrix of variables of Courtyard-T model

Parameter/Variable **Space**	**Courtyard Shape**	**Opening Orientation**	**Active System**
Living Room	Fully Enclosed	N/A	A/C on in summer
			A/C off in winter
Courtyard	Fully Enclosed	N/A	Natural Ventilation

Table 3.3. Matrix of variables of Courtyard-S model

Parameter/Variable **Space**	**Courtyard Shape**	**Opening Orientation**	**Active System**
Living Room	2 shapes	North, South, West for each courtyard shape	A/C on in summer
			A/C off in winter
Courtyard	2 shapes	North, South, West for each courtyard shape	Natural Ventilation

Variable 1: The courtyard shape

The model is assessing into two different courtyard shapes to demonstrate the effect of different openings of a semi-enclosed courtyard. The first shape is a U-shape, and the second is a C-shape. Each shape will be assessing for every orientation and active system mode. Hence, one shape will be fixed to test its effect on all other variables for both seasons and all timings. The size of the courtyard will be fixed for both courtyard shapes. Nonetheless, the courtyard shape will maintain the recommended shape for hot-arid climate by having a longitudinal-narrow shape. The options will be looked up between 25% and 30% to decide the ultimate courtyard area.

Variable 2: Opening orientation

The courtyard model opening of the different shapes will be assessing on different orientations. The opening orientation vary from North, South, and West to evaluate the impact of orientation with respect to sun and wind on the shape of the courtyard into delivering best natural lighting levels, thermal comfort, and effective ventilation. The East orientation will not be studied due to several reasoning. First, due to the similar measurement results between the East and West orientation. Second, since the operational hours of the living room is mostly within the afternoon hours, which is in relation to the social life of the people where most women in Bahrain are workers.

Variable 3: Active system mode

As in, a hot arid country as Bahrain, active systems in summer are always in function to modify thermal comfort. Therefore, for the study the air conditioning system will be on during the summer season for all examining hours.

3.2.Study Methadology

In order to investigate and test courtyard environmental performance, many research methodologies have been in application. All methodologies have their positive and negative attributes. However, their functional application depends on the research aim, objectives, parameters, variables, and the study resources in terms of period, equipment, and labor. Present technology assesses findings of high accurate results. Such research methods are numerical, computer simulation, and field experimental methodology. Each methodology will be explored with respect to their advantages and disadvantages to determine the most suitable research method applied for this study.

3.2.1.Numerical Method

The numerical method employs empirical equations to analyze the courtyard environmental performance; solar radiation, shading percentage, daylight penetration, airflow, and thermal effect in any climatic condition and site location. Data and measurements of the courtyard have to be collected to formulate the numerical equation and input data for analysis. In the equations the variables are defined and in control. The numerical methodology is at the risk of human error within any stage of collecting, formulating, or processing the data. It is a time consuming methodology and the results have to be validated. Through this methodology, some difficulties might encounter such as the difficulty of taking measurements for a specific time of the year or all year long, and result accuracy.

Safarzadeh & Bagadori (2005) investigates the passive cooling outcomes of courtyards by the application of the numerical method. The analysis focuses on the thermal aspects in terms of airflow, solar radiation, solar absorption climatic conditions, heat transfer, water vapor, soil evaporation. The equations are formulated by collecting and inputting data of the location latitude, sun altitude, solar hour and angle, and hourly ambient air and sky conditions. Then the equations developed through calculating the wind flow and pressure. On the other hand, the process required computer analysis in order to compare energy and cooling measures, and validate and finalize the findings.

3.2.2.Computer Simulation

Computer simulation is an extensive tool utilized for research and analysis within the design and construction field. It replaces mathematical equations and field investigation. Computer simulation replicates and represents the real world conditions in terms of climatic conditions, site location, orientation, and materials. Using software tools it allows to study various parameters, variables either classified as physical or environmental, various built form either conceptual or realistic models in a short frame of time. Moreover, computer simulation eases and allows the study in differing scenarios in terms of location, orientation, climate, and form. Additionally, at the present time, different environmental, architectural, rendering software are compatible and user friendly such as AutoCAD Architecture, 3D Max, Revit, Ecotect Analysis, Integrated Environmental Solutions (IES), RADIANCE, and Google Sketch up.

Muhaisen (2006) have used IES computer simulation extensively in his courtyard studies of thermal performance, solar radiation, and shading performance within different climatic and physical conditions such as Rome, Cairo, Kuala Lumpur, and Stockholm. Through his studies, different parameters and variables were looked at such as form, proportion, materials, energy consumption, and efficiency. All analysis were performed in ease. However, in order to use IES, the requires a period of time to learn the software, which in the case of this study time is limited.

3.2.3.Field Experimental

The field experimental methodology analyzes the courtyard environmental conditions in direct relation to the real world. Therefore, there is the risk of facing environmental conditions that maybe are conscious or unconscious of. This methodology holds on some restrictions such as repeating the process of the collecting and analyzing data, restriction to a climatic condition, results are not applicable to any other situation in terms of courtyard form or region. This process requires a long period of time that consumes energy and resources. Furthermore, some shortages may affect the method such as availability of the technology and equipments. At the end of the experiment there is a need to validate the results through an additional method such as computer simulation.

Tsianka (2006) performs an experimental study in Athens by the usage of high technological instruments. The study is to analyze the courtyard performance in terms of reducing the cooling load and its cross ventilation performance. The field experiment is undertaken on each site by analyzing solar radiation and absorption, and the indoor and outdoor temperatures. The study requires a long period to conduct and evaluate the results. Through the process of the experiment, validating the weather profile and re-checking the results was required. Thus, the study is restricted and cannot repeat the process and results due to the external changing factors.

3.3.Selected Methadology

Based on the comparison on the differing methodologies with respect to their advantages, disadvantages, and the study's parameter and variable, available resources and timeframe in order to conduct the study, computer simulation methodology will be in use. The computer simulation method will be in use to test and compare the traditional courtyard form and the semi-enclosed courtyard form in terms of their environmental performance at all stages; modeling the courtyard models, testing the range of parameters and variables, and comparing and analyzing the test findings.

This methodology will be applicable due to its advantageous offerings listed as the following:

- It is flexible in developing any form of model that a study requires for conducting the research.
- The software validity that can produce efficient and feasible results to be translated into the real world.
- Testing and inputting various parameters and variables to be tested at any climatic condition.
- The benefit to simulate any scale of project.

- Various range of affordable software.
- Compatibility between diverse software applications.
- It has a comprehensive simulation process that can calculate various factors.
- Prompt and saves time in producing the research results.

Hence, indicating that computer simulation is a compelling and efficient method. However, for any study to achieve positive and accurate results, the software selection has to be carefully done.

3.4.Selected Software and Validity

Software selection is sensitive where every software has different limitations, restrictions, capabilities, and functionality that have to be looked at to meet with the testing of the study parameters in order to visualize and simulate the courtyard performance within the context of its environment. The requirement for this research is software that is capable to measure and simulate micro-climatic condition of an outdoor courtyard space, and an indoor context. Software capable of simulating outdoor and indoor is Integrated Environmental Solution (IES), and Ecotect Analysis. For this study the following simulation software and plug-in will be in use: Ecotect by Autodesk, RADIANCE plug-in, and WinAIR4 plug-in. Secondary software used is AutoCAD Architecture for simple building design configuration and layout.

Autodesk® Ecotect® is sustainable design analysis software. Ecotect analysis performs a vast range of simulation analysis that can improve and provide designers competent in designing a sustainable built environment. It is a comprehensive detailed sustainable tool. The software capabilities are as the following:

- It can draw models that replicate real world models or new conceptual models.
- It can integrate data model from different software such as Auto CAD, Google SketchUp, and 3D MAX.
- It can analyze models of any climatic region at any location.

- It can display the sun path and position relative to the model at any location, time, and date.
- It can calculate and visualize solar radiation on the model surfaces.
- It can analyze the thermal performance of the model by calculating the cooling and heating load and analyze the effect of occupancy.
- It can calculate the illuminance level and daylight factors.
- It can estimate the water consumption.
- It can analyze the building energy consumption and carbon emissions.
- Inputting and extracting data is an easy process.
- It has the compatibility of integrating plug-ins to perform other studies such as WinAIR4 for airflow computer fluid dynamics, and RADIANCE for lighting.

Researchers that have similar research topics have selected Ecotect Analysis as the simulation tool such as Sadafi N. et al. (2008) that utilized the software to simulate the thermal and shading performance of the courtyard in a terrace house in Malaysia. They stated that Ecotect is a compelling tool that simulates the environmental performance of the built form. Moreover, it is a tool with accurate, simple, and visually responsive analysis performance (Sadafi N. et al. 2008). A wide range of data tables can be exported to AutoCAD, EnergyPlus, RADIANCE, WinAir4, POV Ray, VRML, and more. Marsh 2003 states that Ecotect is an inclusive building environmental and design tool, which conveys a broad range of simulation and analysis, functions to depict the way that a building would perform (Sadafi N. et al. 2008).

Other researchers have also chosen Ecotect Analysis simulation tool for their studies such as Khaled Al-Sallal (2007) that also used RADIANCE to study daylighting levels and glare in a new university architectural department building in the Al-Ain University. Kharrufa and Adil (2008) used it to study the thermal performance of a room. Kruger and Dorigo (2008) used Ecotect to investigate daylighting for various building orientations in order to improve the public school room's daylighting level and thermal performance. Alexandria and Jones (2008) studied the shading pattern of the canyon geometry at different climatic regions.

RADIANCE is a lighting simulation engine that calculates daylight factors and illuminance lighting levels. It uses ray tracing to perform the calculations. RADIANCE pioneered high dynamic range imaging. It uses the Monte Carlo method to sample the light falling on an exact point. It can work as an underlying simulation engine for other software package such as Ecotect Analysis.

Calcagni and Paronicini (2004) have used RADIANCE tool to study the daylight conditions on the atrium and its adjoining spaces. They stated that RADIANCE is widely used due to its scientific validity and study measures. Moreover, according to Hviid et al (2008), in his research paper he stated that of all lighting simulation tools, RADIANCE is extensively validated competitive program in its functionality that serves accuracy.

WinAir4 is a Computational Fluid Dynamics method developed internally by the Cardiff University. It carries out detailed simulations of airflow patterns of the environment with respect to the design. Additionally, it produces accurate results that support the model in terms of air pressure and cell temperature. However, concerning the generated output of WinAir velocity flow vector is not precisely accurate and fully reliable. Therefore, the generated output information is to be overlaid with other accurate velocity and frequency data as reference such as the wind rose of the country that is generated from Ecotect weather tool. Yet, it is a simple plug-in and user friendly. Other options are very much complex. Alexandria and Jones (2008) used WinAir4 to study the air velocity in the canyon.

3.5.Summary of Study Methadology

In conclusion, to analyze and approach the best courtyard form that serves the hot arid climate context, a process of comparison simulation between *Courtyard-T* and

Courtyard-S will be taken, with respect to the selected variables. However, before processing this comparison, the optimum *Courtyard-S* is to be selected by simulating the varying variables. The selected methodology to perform the investigation is computer simulation, due to its advantageous measures that serve the study's time, resources, and manpower. Likewise, the computer simulation software selected is Ecotect Analysis, with the integration of RADIANCE due to its substantial validation and WinAir due its simplicity. In the following chapter, a detailed methodology process and simulation of the study aim and objective is in construction within the software allowing the study of the effect of the parameters.

Chapter 4

Simulation Methodology

Introduction

This chapter will explain the simulation process right through results of the analysis were extracted in order to understand the parameters effect on the proposed built forms. An analysis of Bahrain's weather data will be investigated thoroughly to comprehend the performance of the building within Bahrain's climatic context. Further on, the models of the simulated buildings are going to be developed in order to perform the simulation assessments on them. The simulation process will encounter all assessments with respect to the parameters; fixed and variable.

4.1 .Bahrain's Weather Data for Simulations

Within this section, to analyze and understand Bahrain climate, the weather data of Bahrain are extracted from the computer simulation software Ecotect Analysis using the weather tool. The weather data is set to Bahrain International Airport.

Figure 4.1 and 4.2 shows the weekly average temperature and humidity levels. The highest temperatures range from 9 in the morning to 4 in the afternoon with temperatures ranging between 30^{o}C to 45^{o}C. While between those hours, the humidity levels decreases.

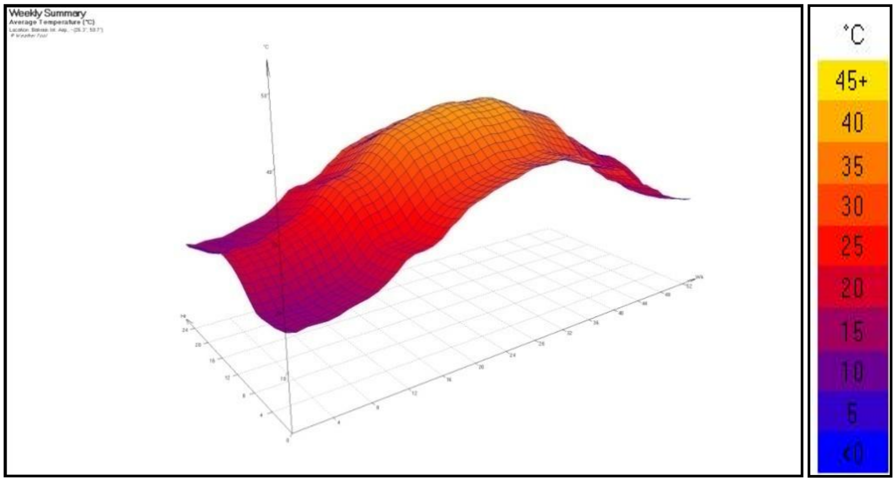

Fig.4.1. The weekly average temperature of Bahrain (ECOTECT).

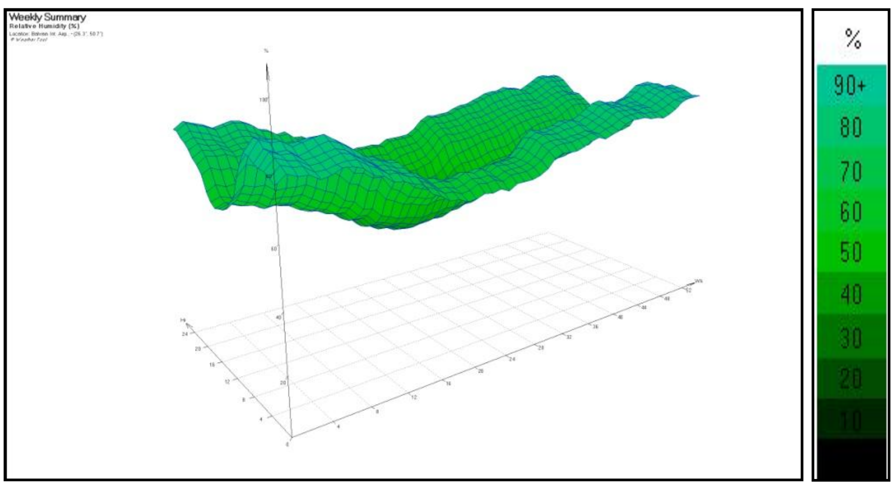

Fig.4.2. The weekly average humidity of Bahrain (ECOTECT).

The hourly dry bulb temperature starts to increase around the month of April, reaching its peak in June-July-August, and decreases in October, as shown in Figure 4.3. The dry bulb temperature gets in the thermal comfort zone from November to December and March to May. The rest of the months, temperatures are above the comfort level.

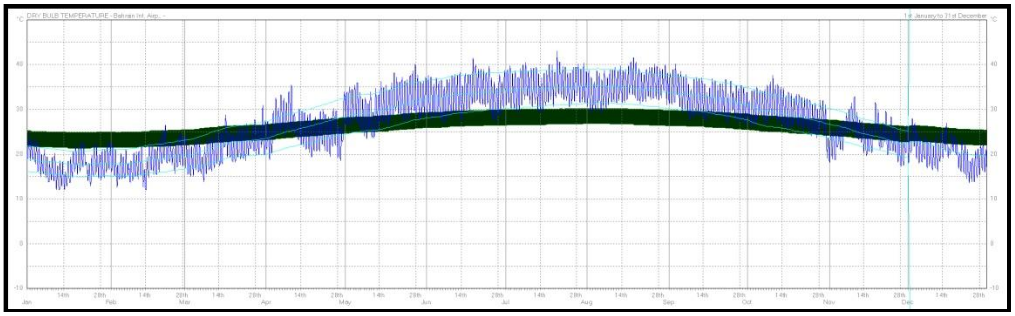

Fig.4.3. Hourly Dry Bulb Temperature of Bahrain (ECOTECT).

The most frequent prevailing wind is from North, North-West, and North-East, Figure 4.4. Figure 4.5 illusrtates the highest temperatures of the prevailing wind are blown from South-East and South-West. During the summer season, a dry hot South-West wind blows sand clouds known as qaws, while in winter prevailing South-East wind brings damp air known as the shamal. The highest frequency temperatures coming from the north-west are at 25^{o}C with a percentage of 2.8%. The overall wind temperatures range from 20^{o}C to 30^{o}C. Precipitation is very low with an average of 72mm per year.

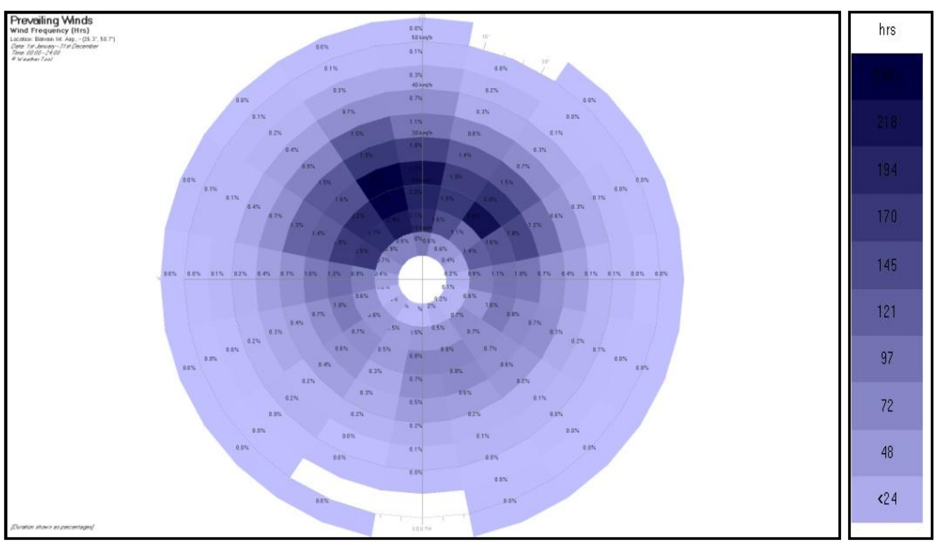

Fig.4.4. Bahrain wind rose showing the frequent prevailing wind from North, North-West, and North-East of Bahrain (ECOTECT).

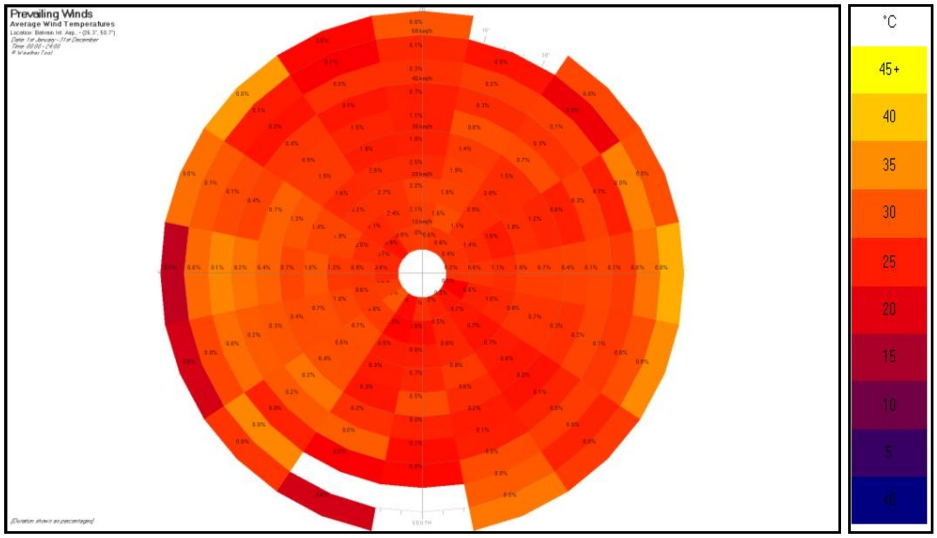

Fig.4.5. Bahrain wind rose showing the temperature of the prevailing wind of Bahrain (ECOTECT).

The duration of the average annual sunshine is 9.5 hours per day. Figure 4.6 shows Bahrain's annual incident solar radiation. The peak months with most annual solar radiation are from May to August, and then decreases from November to February. The average annual solar radiation measurement on a horizontal surface is 461.23kWh/m^2. The underheated period solar collection reads 72.74kWh/ m^2. While, the overheated period solar collection reads 161.62kWh/ m^2.

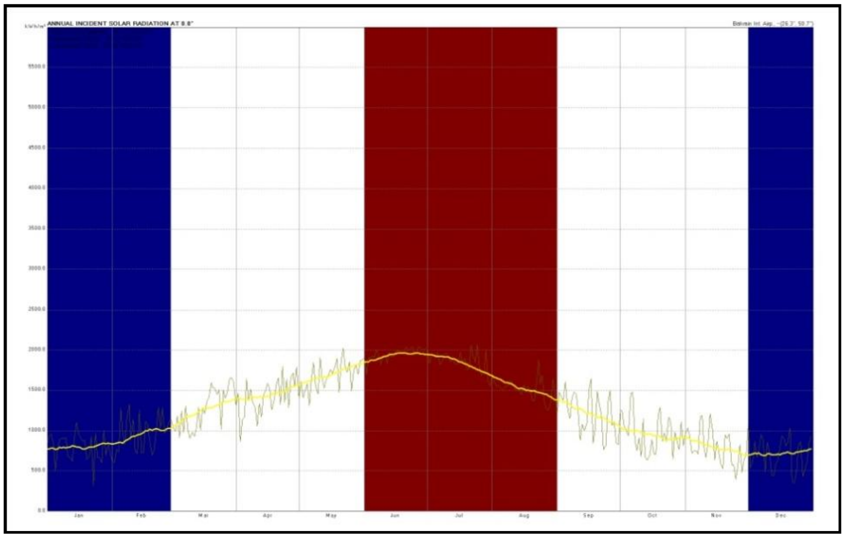

Fig.4.6. Bahrain annual incident solar radiation of Bahrain (ECOTECT).

Orientation assess in the performance of the building. In Bahrain, the following figures represent a stereographic diagram of the solar position. Figure 4.7 demonstrates the sun position in 21st of June at 9 O'clock in the morning, at 85.8^{o}, 54.1^{o}. Figure 4.8 demonstrates the sun position in 21st of June at 12 O'clock at noon, at -119.0^{o}, 84.3^{o}. Figure 4.9 demonstrates the sun position in 21st of June at 3 O'clock at the afternoon, at -82.1^{o}, 44.4^{o}. Figure 4.10 demonstrates the sun position in 21st of December at 9 O'clock in the morning, at 139.7^{o}, 27.8^{o}. Figure 4.11 demonstrates the sun position in 21st of December at 12 O'clock at noon, at -172.4^{o}, 39.8^{o}. Figure 4.12 demonstrates the sun position for 21st of December at 3 O'clock in the afternoon, at -172.6^{o}, 39.9^{o}.

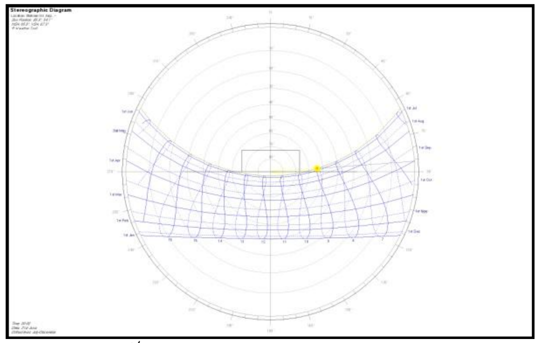

Fig.4.7. Solar Position in 21st of June at 9 O'clock in the morning (ECOTECT).

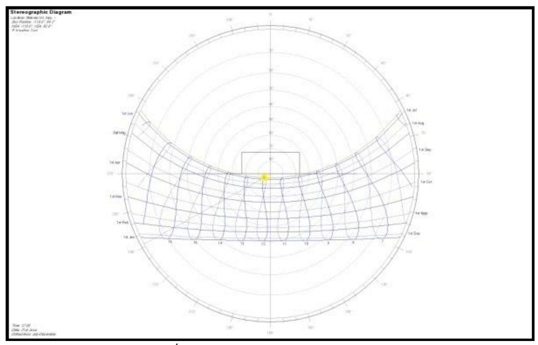

Fig.4.8. Solar Position in 21st of June at 12 O'clock at noon (ECOTECT).

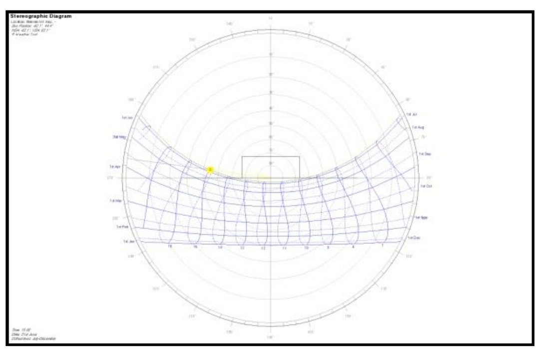

Fig.4.9. Solar Position in 21st of June at 3 O'clock at the afternoon *(ECOTECT).*

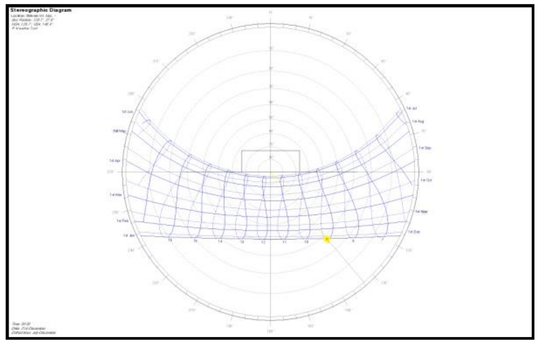

Fig.4.10. Solar Position in 21st of December at 9 O'clock in the morning (ECOTECT).

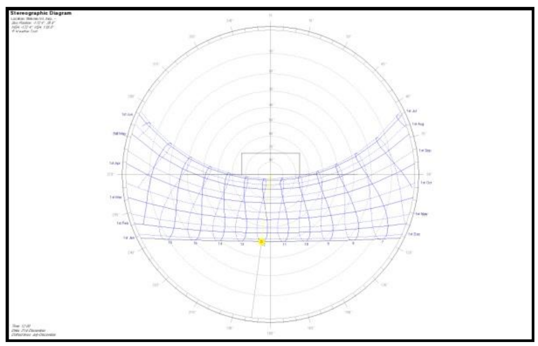

Fig.4.11. Solar Position in 21st of December at 12 O'clock at noon (ECOTECT).

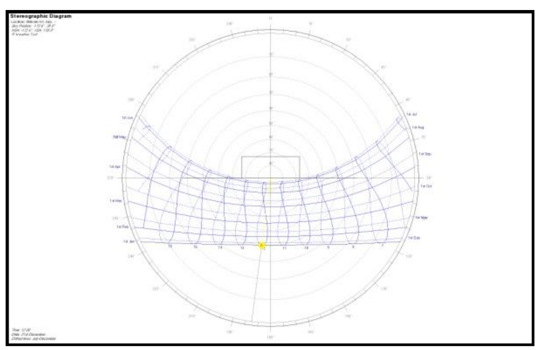

Fig.4.12. Solar Position in 21st of December at 3 O'clock at the afternoon *(ECOTECT).*

Psychrometric chart represents the condition of air at a specific location. It describes the relation between Dew Point, Air Volume, Enthlapy, relative Humidity, Vapor Pressure, Wet Bulb Temperature, and Dry Bulb Temperature. The human thermal comfort zone is defined within the chart without the need for additional cooling ventilation system. When the built environment implements simple considerations, comfort levels increase, such as natural ventilation. Bahrain's psychrometric chart shows the lack of outdoor comfort zones in summer unless natural ventilation is incorporated within the design that extends the comfort level. Figure 4.13 and 1.14 represents the extended comfort levels achievable when natural ventilation is implemented in summer and winter.

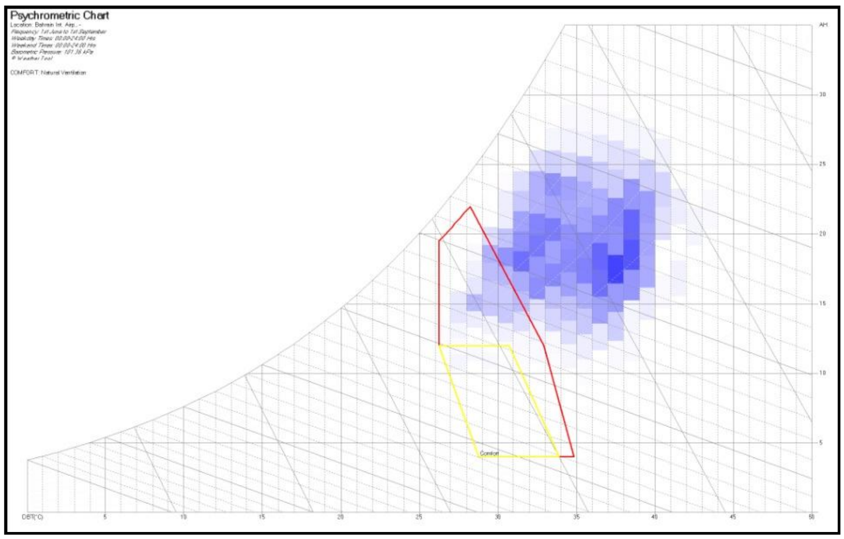

Fig.4.13. Psychrometric chart of Bahrain in summer (ECOTECT).

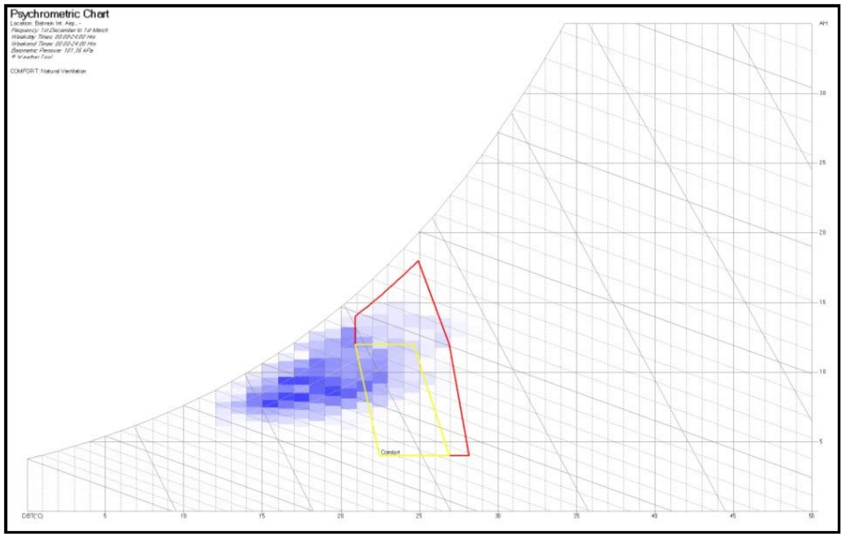

Fig.4.14. Psychrometric chart of Bahrain in winter (ECOTECT).

4.2.Building Models Study

Two different courtyard configurations are simulated. The first form is the fully enclosed courtyard representing the traditional courtyard form. The second form is the semi-enclosed courtyard representing a developed form from the old courtyard form. Consecutively, to perform the study, first the extroverted Bahrain modular housing as a three-dimensional model is modeled. All structures are modeled through the Ecotect Analysis software. Sequentially, to compare both forms *Courtyard-T* and *Courtyard-S,* first the percentage of the courtyard is to be determined, with regards to the literature review findings. The courtyard ground area is fixed in both courtyard forms. Following that is, modelling the building structures: the converted courtyard form *Courtyard-T,* and the two semi-enclosed courtyard form *Courtyard-S*. Many of variables interconnect and affect the built form performance; therefore, some variables are assigned as constant. All models have the same building materials applied from the Bahrain building regulation. *Courtyard-T* and *Courtyard-S* will have the same exterior window openings that the extroverted modular house; however, they will have additional window openings looking upon the courtyard internal walls.

This is to ensure that only the courtyard form and orientation affects the environmental performance. Bahrain weather file is loaded into Ecotect software to analyze close to realistic results.

4.2.1.Bahrain Modular House

The common modular housing form in Bahrain is in representation to be converted into a courtyard form. As the housing characteristics been discussed earlier, it is a low-rise building consisting of a ground and first level each are 3.17m in height. The dimensions are 8mx12.8m with a ground floor built up plot area of 102.4m^2, with a 6.34m in height without the roof and roof staircase. The total height with the roof staircase is 10.56m. The house has two different roof levels, along the East side of the house its 1.65m and the West side its 2.05m. The living room floor area is 17.27m^2. Table 4.1 lists down the window opening sizes for the spaces. There are a total of 11 window openings. Figure 4.15 and 4.16 demonstrates the modular house floor plan and building elevations.

Table 4.1. Window Opening Dimensions

Internal Space	Window Opening Size
Rooms	1.2mx1.3m
Kitchen	1.1mx1m
Bathrooms	0.6mx0.8m

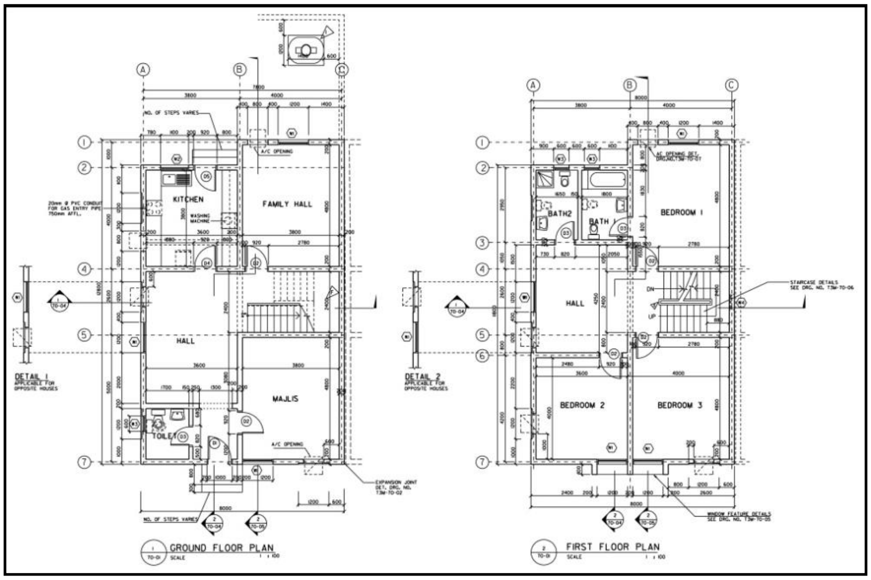

Fig.4.15. Bahrain modular housing floor plan (courtesy to Housing projects Planning & Design Directorate, Kingdom of Bahrain).

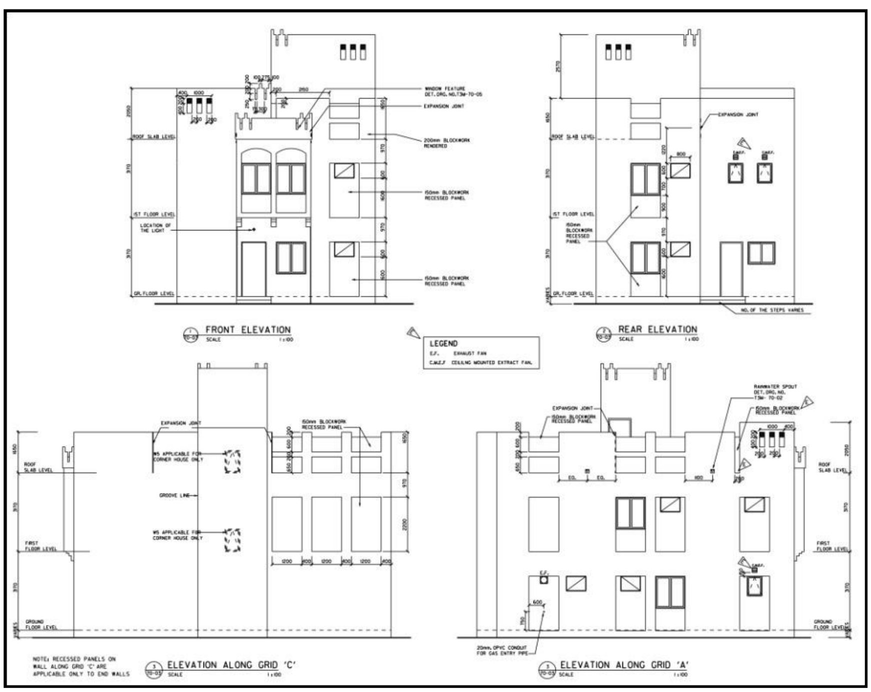

Fig.4.16. Bahrain modular housing elevation (courtesy to Housing projects Planning & Design Directorate, Kingdom of Bahrain).

A three-dimensional model of the house is modelled in Ecotect Analysis software l with the application of the Bahrain regulation specified materials. The house is modelled without the boundary walls; however, there is a recess between each housing unit to maintain the building regulations. The building architecture model is simplified to control the simulation calculation time, and facilitates the conversion from the extroverted form into the courtyard form. Figure 4.17 and 4.18 shows the South-West and North-East view of the house modelled.

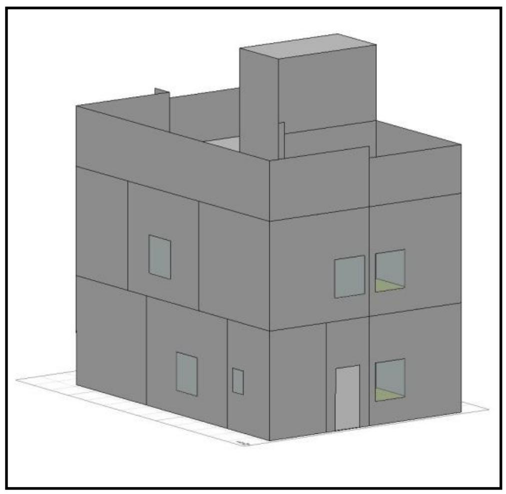

Fig.4.17. South-West view of the Bahrain modular house-front view (ECOTECT).

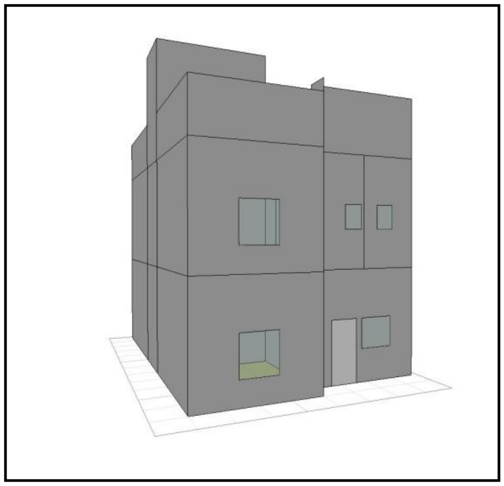

Fig.4.18. North-East view of the Bahrain modular house-rear view (ECOTECT).

The material specification input in the Ecotect software is tabulated below, Table 4.2. The window properties are listed in a separate table due to its different parameters, Table 4.3. Those material specified are applied for all models and specification as it is a constant parameter.

Table 4.2. Building Material Specification input in Ecotect Analysis software

Element	Material Description	U-Value (W-m2.k)	Admittance (W-m2.k)	Solar Absorption (0-1)	Thermal Decrement (0-1)	Time Lag (hrs)
Wall	200mm concrete block with 10mm plaster either side.	1.800	3.360	0.506	0.78	5
Floor	100mm thick concrete slab on ground plus ceramic tiles.	0.880	6.100	0.475208	0.31	4.6
Ceiling	10mm suspended plaster board ceiling, plus 50mm insulation, with remainder (150mm) joists as air gap.	0.500	0.900	0.368	0.32	0.7
Door	40mm thick solid core pine timber door.	2.310	3.540	0.404	0.98	0.4

Table 4.3. Window Material Specification input in Ecotect Analysis software

Element	Material Description	U-Value (W-m2.k)	Admittance (W-m2.k)	Solar Heat Gain Coeff.(0-1)	Visible Transmittance (0-1)	Refractive Index of Glass
Window	Double glazed with aluminum frame (no thermal break).	2.700	2.700	0.81	0.639	1.74

4.2.1.1.Courtyard-T

The second model is the fully enclosed courtyard form *Courtyard-T*, a courtyard integrated into the modular housing, representing the base-line model. *Courtyard-T* is the first configuration to be in comparison for the study. At first, the percentage of the courtyard is in evaluation with the assist of AutoCAD Architecture software. Two percentages are being investigated to determine which is best incorporated within the modular house. The percentages are 25% and 30%. The courtyard area deducts from the extroverted modular house form. Figure 4.19 previews the various applicable options for the 25% of the courtyard in relation to the housing structure. Figure 4.20 previews the various applicable options for the 30% of the courtyard in relation to the housing structure. Table 4.4 illustrates the dimensions of the various proportions for both percentages.

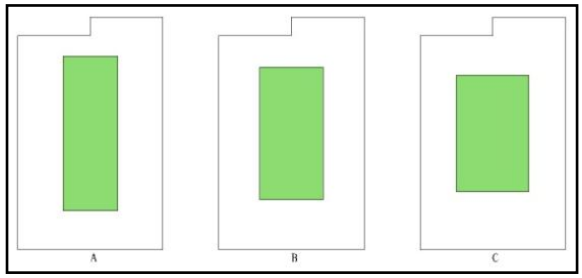

Fig.4.19. Various proportions for 25% courtyard in relation to the built form (AutoCAD Architecture).

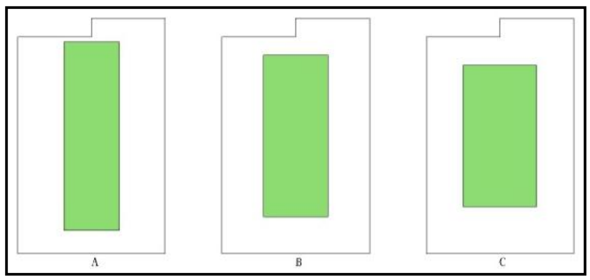

Fig.4.20. Various proportions for 30% courtyard in relation to the built form (AutoCAD Architecture).

Table 4.4. Dimensions for 25% and 30% courtyard proportions

Courtyard percentage		Built-up Length		Built-up Width		Courtyard Dimension	Built-up Area	Courtyard Area
		X Axis	Y Axis	X Axis	Y Axis			
25%	**A**	8m	12.8m	2.5m	2.135m	3mx8.53m	76.8 m^2	25.6 m^2
	B			2.25m	2.743m	3.5mx7.314m		
	C			2m	3.2m	4mx6.4m		
30%	**A**	8m	12.8m	2.5m	1.28m	3mx10.24m	71.68 m^2	30.72 m^2
	B			2.25m	2.0115m	3.5mx8.777m		
	C			2m	2.56m	4mx7.68m		

The optimum courtyard percentage and proportion to be applied in the study is 30% option **B**, with a total area of 30.719m^2. The courtyard aspect ratio; degree of openness to the sky is **0.3047**. Referring back to the literature review courtyard geometry section, option B represents the best form because of its longitudinal form elongated in the North-South direction and the internal space must not exceed 2.5 times the height of the opening to maintain adequate daylight penetration without the constant need of artificial lighting.

As the study will assess the living room as an internal space and the courtyard, only the living room space is determined within *Courtyard-T* form. The living room unit preserves its location in the North-East of the structure represented in blue. Figure 4.21 demonstrates the relation of the living room to the courtyard and the structure. In addition, it maintains the same total area of a 17.27m^2 as the extroverted modular house. Table 4.5 exhibits the living room dimension referring back to the figure. The living room is assigned in the North-East location similar to the modular house with those specific dimensions to maintain the exterior facade and not alter with the window openings. As at the rear facade there is the living room window opening and kitchen door and window opening, therefore, the living room space is extended to 5m to maintain the total area but not go beyond and alter the kitchen door and window. On the East facade, there are no window opening restrictions; hence, the living room space extends up to 5.2208m to maintain the total area.

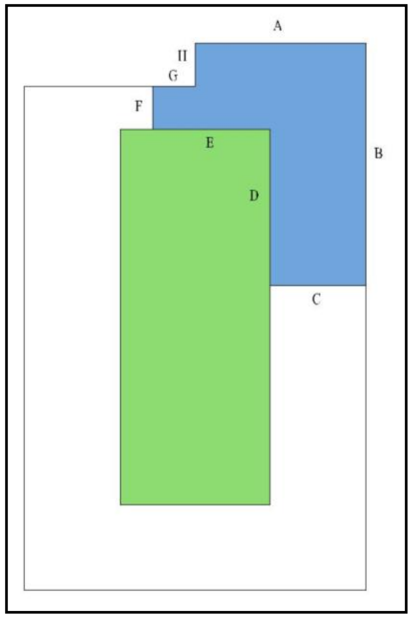

Fig.4.21. The living room relation to the courtyard and the built structure (AutoCAD Architecture).

Table 4.5. Dimensions of the living room

Letter	Dimension
A	5m
B	5.2208m
C	2.25m
D	3.6533m
E	2.75m
F	1.0115m
G	1m
H	1m

Courtyard-T housing form maintains the Northern extroverted modular house orientation, as the overall structure orientation is fixed. Nonetheless, as the height is fixed, *Courtyard-T* will maintain the same height consisting of two floor levels with similar height differential positions on the East and West sections. The courtyard exposed floor material is specified as sand, referring back to the extroverted Bahrain modular house courtyard.

The exterior window-opening configurations are kept the same as the modular house. The exterior facades of the extroverted housing module are maintained in *Courtyard-T* housing form. Figures 4.22 and 4.23 and 4.24 illustrate the Courtyard-T model, representing the exterior facade and the alteration of the form from an extroverted into an introverted building form. Moreover, regarding the walls facing the courtyard, the internal spaces are assigned with additional window and door opening. The window and door opening maintains the same dimensions of the extroverted housing module. The window-opening dimension is 1.2mx1.3m, and the door dimension is 0.92mx2.1m. The living room wall facing the courtyard are assigned with two windows; one on the Northern wall, and another on the Eastern wall, and a door on the Eastern wall. Figure 4.25 shows the living room windows and door openings facing the courtyard excluded from the rest of the building model. The window material characteristics are fixed, therefore maintaining similar properties of the extroverted modular house.

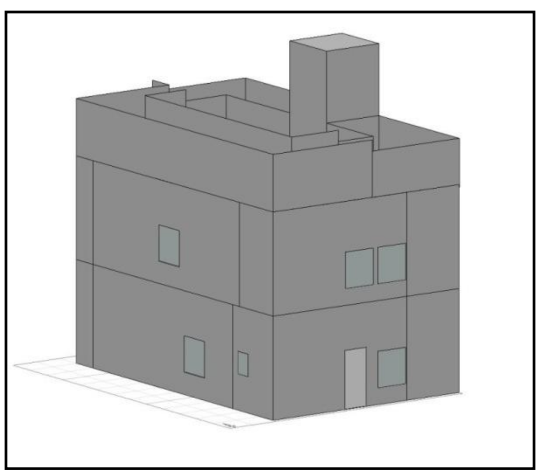

Fig.4.22. Courtyard-T South-West exterior facade (ECOTECT).

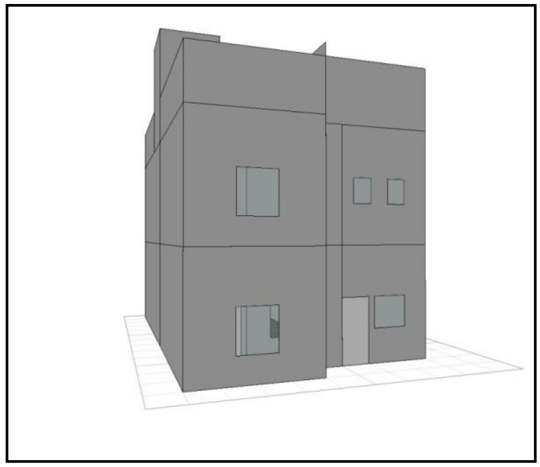

Fig.4.23. Courtyard-T North-East exterior facade (ECOTECT).

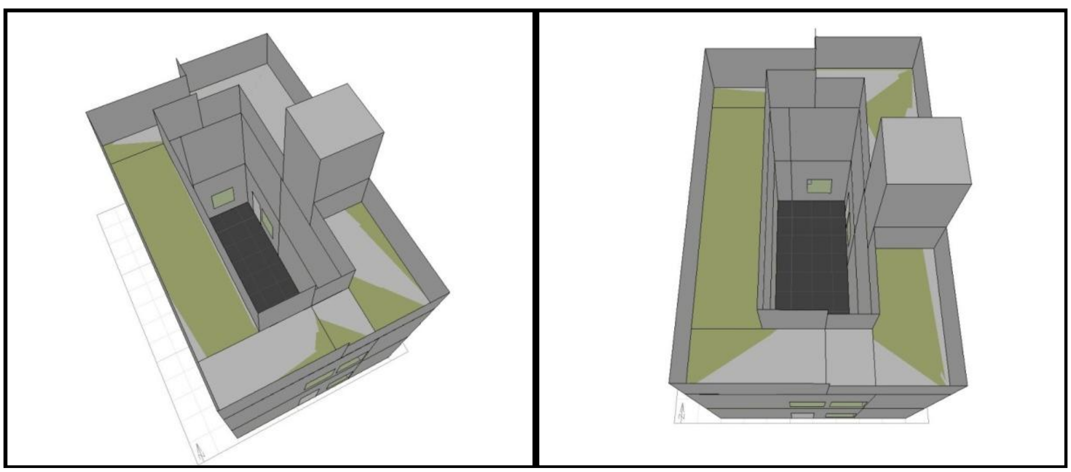

Fig.4.24. Courtyard-T bird's eye view (ECOTECT).

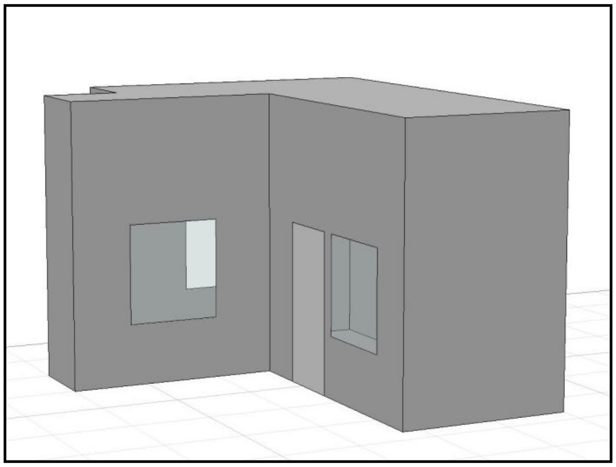

Fig.4.25. Excluded Living Room facing the courtyard (ECOTECT).

4.2.1.2.Courtyard-S

The third model is the semi-enclosed courtyard form *Courtyard-S*, it's the conversion of *Courtyard-T* from a fully enclosed courtyard configuration into a semi-enclosed courtyard configuration. *Courtyard-S* is the second configuration of the study in which the variables are going to be in assessment.

As discussed earlier, the varying parameters that *Courtyard-S* will be tested on are the courtyard shape, courtyard-opening orientation, and the active systems mode. Consequently, *Courtyard-S* configuration will study a U-shape courtyard typology, and a C-shape courtyard typology directed to three orientations: North, South, and West.

Courtyard-S configuration will maintain the original overall structure Northern orientation, the overall building height with similar height differential positions on the East and West sections, and the building material specification where the courtyard is specified as sand. The courtyard percentage is constant with a total area of 30.7195m^2. The living room area is constant with a total area of 17.27m^2. The overall plot area is constant with a total of 102.4m^2 of the ground floor only. In the *Courtyard-S* building models configurations, only the living room will have window and door openings, for the specific means of differentiating the living room from other internal spaces, and focusing on the living room internal space with its relation to the courtyard.

The study of the variables develops a cycle tuning the building structure. As the configuration alters in shape and orientation, the built up area shape follows and adapts, which consequently modifies the living room configuration in terms of dimension shape and location, effecting and altering the exterior and internal facade, hence affecting the amount and position of the window and door openings. Amid testing each shape with regards to orientation, all the affects representing the cycle are going to be explained thoroughly. Each configuration of each shape is designated with its own code. Figure 4.26 presents a legend to explain each configuration code.

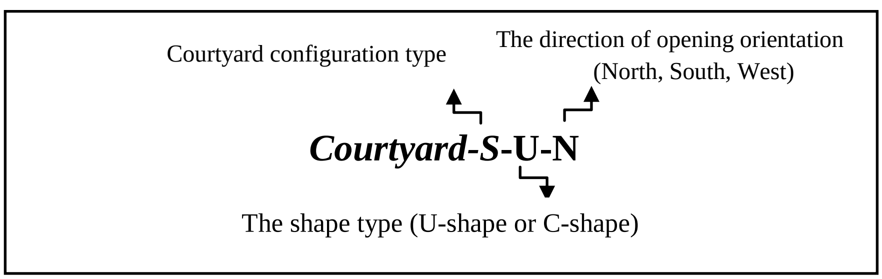

Fig.4.26. Configurations proposed legend

U-Shape Configurations:

The first shape is the U-shape, developing three various configurations resulting from the varying orientation. The first of the configuration is developing the U-shape with the opening oriented towards the North. This configuration code is *Courtyard-S*-U-N. Figure 4.27 illustrates *Courtyard-S*-U-N opening subtraction and the final configuration with the living room highlighted in blue. Figure 4.28 shows the final configuration modeled in Ecotect.

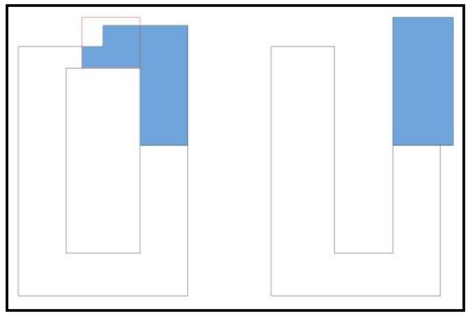

Fig.4.27. Courtyard-S-U-N opening subtraction and final configuration (AutoCAD Architecture).

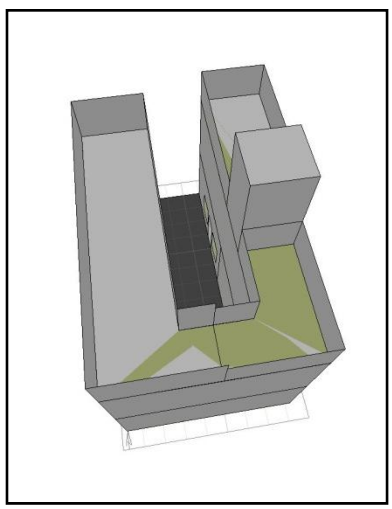

Fig.4.28. Courtyard-S-U-N final configuration model (ECOTECT).

The following steps produce the *Courtyard-S*-U-N configuration layout:

- At first, the courtyard internal West wall is shifted East, in order to maintain and not alter the kitchen width, hence decreasing the courtyard area by a 6.58275m^2.

- To maintain the total courtyard area and orient the courtyard into the North direction, the Northern section of the built form specifically the living room area is subtracted replacing it with the same amount of the deducted courtyard area 6.58275m^2. Therefore, forming a U-shape courtyard configuration. However, by forming the U-shape and maintain the kitchen width, the living room area is deducted.
- In order to preserve the original living room area of 17.27m^2, the deducted living room area of 4.531625m^{2}will be added to the living room. From the North side, 0.85995m^2 is added, while from the East side 605.9616m^2 is added. Therefore, the living room shape has been modified having it extruded from the Eastern side towards the exterior changing the external Eastern and Northern facades.
- Furthermore, the external and internal windows and door opening are modified in terms of location and quantity, but upholding the opening dimensions. The Northern external window is shifted along the living room Northern wall, yet it maintains the same location. The courtyard internal window and door openings are also shifted along the courtyard internal Eastern wall, however, adding another window opening facing the courtyard. Hence, the living room wall facing the courtyard has a total of two windows on the same wall.

The second of the configuration is developing the U-shape with the opening oriented towards the South. This configuration code is *Courtyard-S*-U-S. Figure 4.29 illustrates *Courtyard-S*-U-S opening subtraction and the final configuration. Figure 2.30 shows the final configuration modeled in Ecotect.

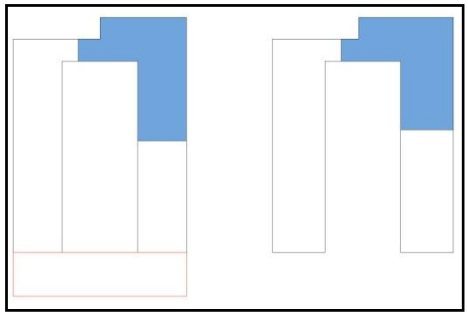

Fig.4.29. Courtyard-S-U-S opening subtraction and final configuration (AutoCAD Architecture).

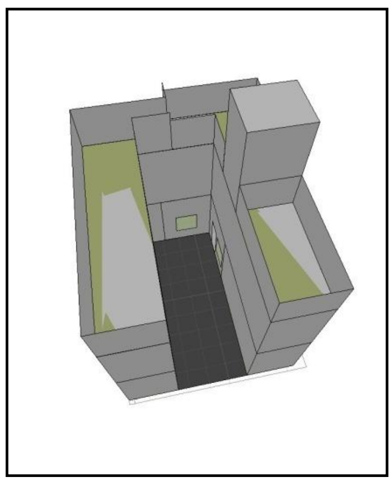

Fig.4.30. Courtyard-S-U-S final configuration model (ECOTECT).

The following steps produce the *Courtyard-S*-U-S configuration layout:

- At first, subtracting the full Southern built up area, to form a U-shape courtyard opening oriented from the South. The subtracted built up area is 16.092 m^2.
- Sequentially, the deducted built up area is added on the Eastern and Western built form sides, increasing the built form width and the living room total area. Each side is increased by a 185.4mm. However, the living room increases from both the East and West sides.

- The additional living room area of 1.2384357m^2 will be deducted from the Southern side of the living room to maintain the external and internal facade opening and living room configuration. Therefore, the living room Southern side will reduce 508.514mm.
- The external and internal openings are the same as the base-line model *Courtyard-T*.

The third of the configuration is developing the U-shape with the opening oriented towards the West. This configuration code is *Courtyard-S*-U-W. Figure 4.31 illustrates *Courtyard-S*-U-W opening subtraction and the final configuration. Figure 4.32 shows the final configuration modeled in Ecotect.

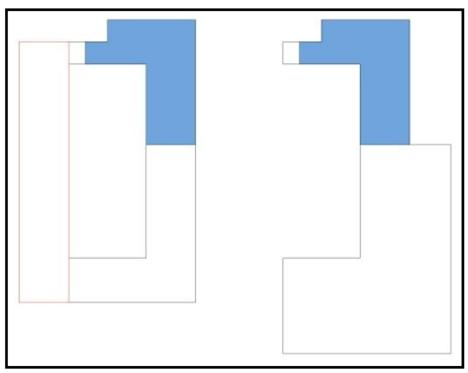

Fig.4.31. Courtyard-S-U-W opening subtraction and final configuration (AutoCAD Architecture).

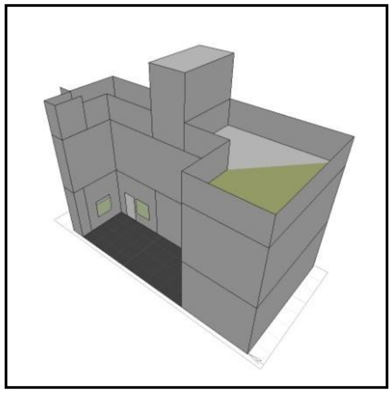

Fig.4.32. Courtyard-S-U-W final configuration model (ECOTECT)

The following steps produce the *Courtyard-S*-U-W configuration layout:

- Firstly, subtracting the full Western built up area, to form a U-shape courtyard opening oriented from the West. The subtracted built up area is 26.55m^2.
- In order to maintain the living room area, external and internal facades, subtracted built up area is added on the Southern and Eastern sides of the built form. However, the added area on the East side is restricted towards the living room parameters, thus not adding any additional space in the living room. On the South side, the walls offset 2.308695m, and on the East side, the walls offset 1.86049m.
- The living room internal and external openings are maintained in the same position as the base-line model *Courtyard-T*.

C-Shape Configurations:

The second shape is the C-shape, developing three various configurations resulting from the varying orientation. In order to develop the C-shape, all configurations deduct an area of 2.25m^2. The first of the configuration is developing the C-shape with the opening oriented towards the North. This configuration code is *Courtyard-S-*

C-N. Figure 4.33 illustrates *Courtyard-S*-C-N opening subtraction and the final configuration. Figure 4.34 shows the final configuration modeled in Ecotect.

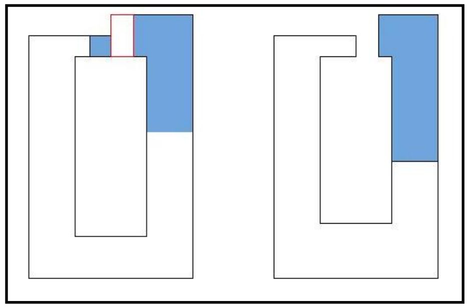

Fig.4.33. Courtyard-S-C-N opening subtraction and final configuration (AutoCAD Architecture).

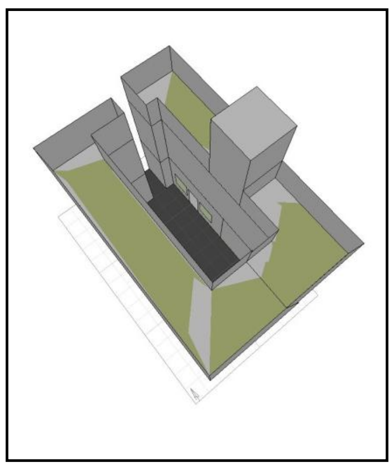

Fig.4.34. Courtyard-S-C-N final configuration model (ECOTECT)

The following steps produce the *Courtyard-S*-C-N configuration layout:

- The opening in the North orientation is positioned in the y-axis longitudinal section of the living room to preserve the overall shape of the opening itself. The opening dimension in the North wall is 1.1186mx2.0115m. However, as the opening is positioned subtracting from the living room area, hence detaching the living room space, therefore, subtracting a bigger portion of the living room. The detached living room area is 1.0115m^2. The subtracted living room area is 2.0115m^2. As a result, a total of 3.2615m^2 is to be added to the living room space.

- The additional living room space is added in the South part of the living room. Hence, extending 1.44955m of the living room Southern side.
- However, by adding an opening in the Northern orientation, the courtyard area increases, thus to maintain its area it has to be decreased by 2.2501m^2. The courtyard decreases in the internal South side of the courtyard with 642.885mm.
- By the opening position, the external window opening position did not alter, but the living room wall facing the courtyard is assigned with a different door and window position. The window and door opening shift toward the Southern side by 1.0449m allowing enough space to integrate an additional window along them.

The second of the configuration is developing the C-shape with the opening oriented towards the South. This configuration code is *Courtyard-S*-C-S. Figure 4.35 illustrates *Courtyard-S*-C-S opening subtraction and the final configuration. Figure 4.36 shows the final configuration modeled in Ecotect.

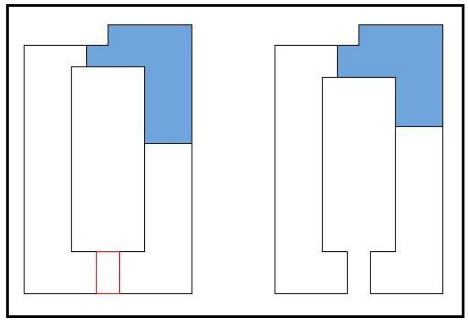

Fig.4.35. Courtyard-S-C-S opening subtraction and final configuration (AutoCAD Architecture).

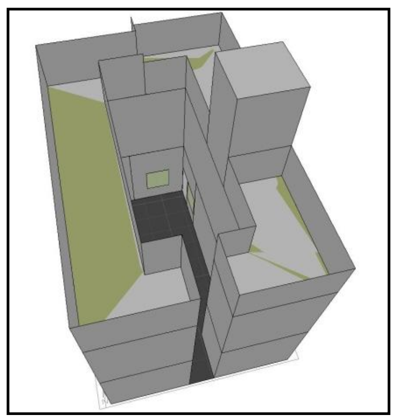

Fig.4.36. Courtyard-S-C-S final configuration model (ECOTECT)

The following steps produce the *Courtyard-S*-C-S configuration layout:

- The opening in South orientation is centralized with the same area and dimensions of the North opening 1.1186mx2.0115m. By integrating an opening, the courtyard area is enlarged reducing the built up area. Therefore, to maintain the built up area, the courtyard on the Northern side decreases by offsetting the internal North wall by 641.5mm.
- As the internal Northern wall enlarges, the living room area increases by 1.68819m^2. This additional space is reduced from the living room Southern side not to alter the external built form facade.

- The external window opening is maintained in its same position, but the internal openings are re-positioned to fit into the living room space. The window opening located on the Northern side of the internal courtyard is shifted with the increase of the living room space. The door opening and window opening located on the Eastern side of the internal courtyard the shifts North by 166mm.

The third of the configuration is developing the C-shape with the opening oriented towards the West. This configuration code is *Courtyard-S*-C-W. Figure 4.37 illustrates *Courtyard-S*-C-W opening subtraction and the final configuration. Figure 4.38 shows the final configuration modeled in Ecotect.

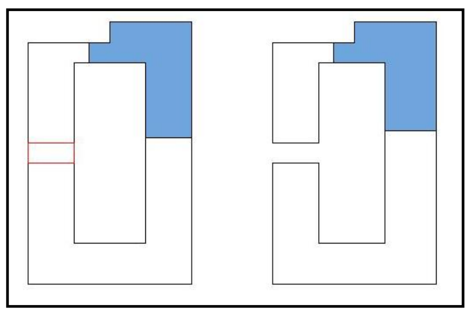

Fig.4.37. Courtyard-S-C-W opening subtraction and final configuration (AutoCAD Architecture).

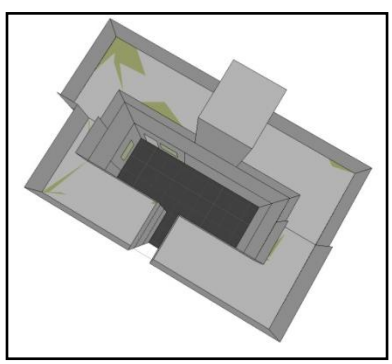

Fig.4.38. Courtyard-S-C-W final configuration model (ECOTECT)

The following steps produce the *Courtyard-S*-C-W configuration layout:

- The opening in West orientation is centralized with the same area. Yet, the dimensions of the opening differ. It has an opening of 1mx2.25m. By integrating an opening, the courtyard area is enlarged reducing the built up area. The courtyard on the East courtyard side decreases by offsetting the internal East wall by 257.495mm.
- As the Eastern walls increase in width, the living room area increases. Therefore, to maintain the living room area, the South side of the living room is reduced by 376.75mm.
- By the internal courtyard walls and living room area modifications, the window and door opening on the Eastern side of the internal courtyard shifts North by 200mm.

4.3.The Simulation Process

The following assessment criteria for **natural daylight**, **shading, thermal**, **solar radiation**, and **airflow** will study the effect of parameters within both **courtyard forms; courtyard shape, opening orientation,** and the **active system**. The first process will test the effect of the parameters on the selected indoor space; the living room. The assessments that are going to be simulated for the effect on the living room are natural daylight through RADIANCE plug-in in Ecotect, and thermal performance of the living room by calculating the Thermal analysis. The second process will test the effect of the parameters on the courtyard itself. The assessments that will simulated for the effect on the courtyard are **Solar Radiation** by calculating **Solar Access analysis**, **Shading** to analyze the shadows, and **Airflow** through WinAir4 plug-in in Ecotect.

All building models are to be in simulation in the selected hours of the day: **9a.m.** in the morning**, 12** at noon, and **3p.m.** in the afternoon, within the 2 solstice of **summer** June 21 and **winter** December 21. Some simulations will only record the specific month disregarding the day and time.

The following simulation assessments are in application congruously for all building models of *Courtyard-T* and *Courtyard-S*.

4.3.1. Thermal Analysis

The living room zone is clearly identified by being the only activated interior space thermally. All other interior zones are thermally deactivated. The living room zone management is setup. Figure 4.39 and 4.40 views the zone management setup of the living room.

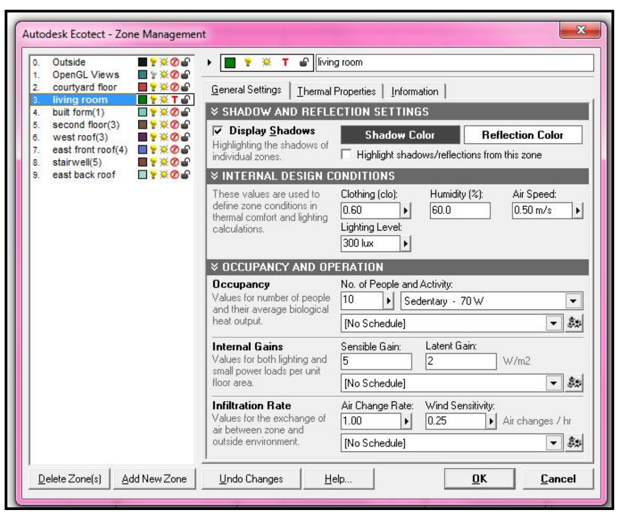

Fig.4.39. Living room zone management general settings (ECOTECT).

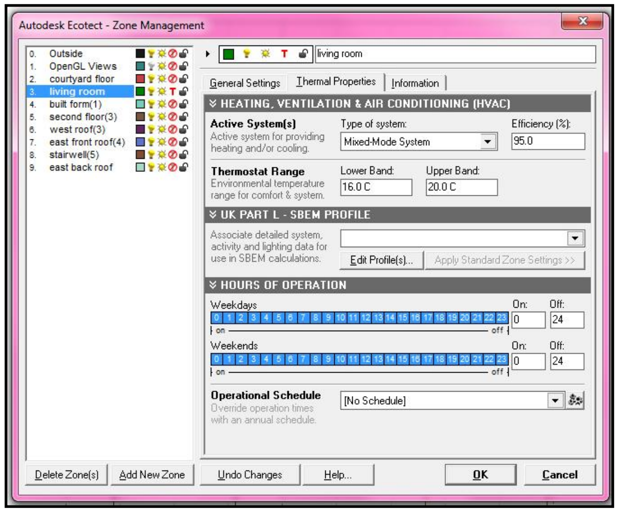

Fig.4.40. Living room zone management thermal properties (ECOTECT).

The internal design condition in term of clothing is chosen to be 0.6 clo casual trouser and shirt. In terms of lighting level, 300lux is set which is between the waiting area Lux level of 200 (ECOTECT).

Regarding occupancy and operation, 10 people are determined to occupy the living room space as $3m^2$ per person. The activity level is set as sedentary 70W to understand the people heat output. The infiltration rate of air exchange between the zone and the outdoor environment is set as average 1.00 since there are window openings and frequent opening doors.

Regarding the thermal properties of the living room zone, the active system is set as a mix mode system with a thermostat range of a lower band 16^oC and an upper band of 20^oC. The hours of operation is fixed to operate throughout the 24 hours, as it is a residential space. This setting will test the active system mode parameter.

In order, the thermal calculation calculates accurately materials and any leakages effect. The calculation is checked by using each object alternate materials for the coincide elements of wall, floor, and ceiling. Alternate materials are specified as the same. The inter-zonal adjacencies are calculated with high precision to check any leakages between zones. All surfaces are to be calculated to ensure the exposed surfaces are facing outwards. Then, set a performing a detailed shading calculation for exposed surfaces with a high surface sampling 10x10 grid.

The thermal analysis calculates only monthly without specifying any timing. Therefore, the simulation timings assessment will be disregarded. The thermal calculates various calculations for each zone by taking into consideration the inter-zonal gain and solar radiation. Those calculations are hourly temperature profile, hourly heat/gain losses, temperature distributions, indirect and direct solar gain, and passive gain breakdown. Each calculation is looked upon separately.

The hourly temperature profile calculates the internal living room and external hourly temperatures stating the temperature difference and the average temperature. Additionally, it represents the wind speed, beam, and diffuse solar radiation derived from the climate data loaded. The hourly temperature is calculated for the 21st of June and December.

The hourly heat/gain loss is calculated for the summer solstice 21st of June and winter solstice 21st of December specifically for the living room zone. This calculation illustrates seven sectors that are HVAC load, conduction, Sol-Air, direct solar, ventilation, internal, and inter-zonal. To understand and fully interpret the results of each calculation, the sectors have to be empathized. The HVAC load is the amount of energy required to maintain the zone at a comfortable internal temperature. Conduction is the gain and loss through the building fabric, as the selected building materials affect due to conduction. Sol-Air temperature is the heat gain through indirect solar exposure by opaque surface materials exposed to solar radiation. Direct solar heat gain occurs through transparent surfaces such as windows. Ventilation represents the heat gain and loss through ventilation via opening and closing window openings and rate of infiltration that is set earlier to an average. Internal gain is due to occupancy, and artificial lighting that is set in the zone management. Inter-zonal gain and loss occurs between adjacent zones. As in this study, the aim is to interpret the microclimatic condition of the space, energy requirements and load such as HVAC is disregarded. Nonetheless, as the building materials are set as fixed variables, the conduction calculation will be overlooked. Moreover, as in this study, the only activated thermal zone is the living room, the inter-zonal gains and losses are going to be overlooked. From this calculation, only Sol-Air temperature analysis will be taken into consideration as it's the most relevant to the assessment representing indirect solar radiation.

The temperature distribution calculates annually the hours throughout the year that the living room zone is within the comfort band without the need of a HVAC system.

The direct solar gain calculates an annual analysis that is set as monthly average that illustrates as admittance factors.

4.3.2. Daylight Levels: RADIANCE

All models will be exported to Radiance to test and study the Lux levels, daylight measures to identify the optimum lighting level provided from mainly the courtyard configuration which is the focus of this study in addition to other facade, into the indoor space developed from the opening size and opening orientation. An analysis grid is placed to calculate the lighting levels. It is positioned on the floor plane with an axial offset set to 600mm to calculate and simulate Lux levels at human level. The x-axis number of cells is 25, while the y-axis and z-axis are 20. The RADIANCE analysis set up is shown below in Figure 4.41.

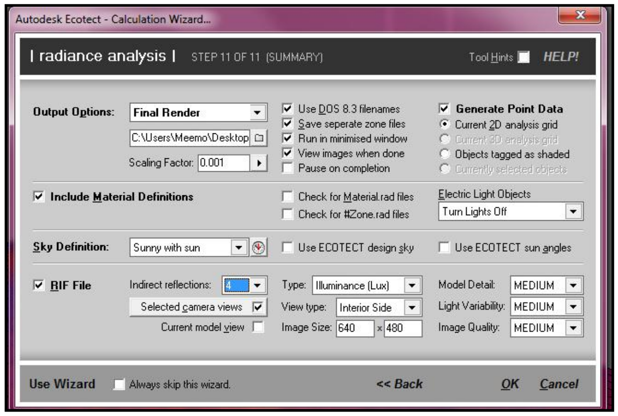

Fig.4.41. Radiance Analysis calculation Wizard (ECOTECT).

The lighting analysis will calculate illuminance image Lux of the living room interior. No artificial lighting will be included in the calculation. In the summer season of June, the sky definition is set to sunny, while in December, its set to overcast sky. In the RIF file, four incident reflections are chosen to base the calculations. The model detail, image quality, and light variability are all set as medium level to control the calculation time.

The RADIANCE automatically opens the calculation window to generate and display all information. The Radiance interface opens to display the three-dimensional perspective image of the interior, which can display the contour lines, contour bands, and daylight factors on the same output image. However, the RADIANCE image can be viewed in Ecotect by importing the image back in Ecotect. The import is done through the grid management in the analysis grid. After importing the data, a visual of the Lux levels are displayed on the grid analysis. The average, minimum, and maximum Lux levels are identified in Ecotect from the visual after importing the calculation output.

4.3.3. Simple Airflow Simulation: WinAir4

A simplified CFD analysis via WinAir4 analyzes the courtyard thermal comfort and identifies the optimum airflow developed from the opening size and opening orientation in terms of airflow rate, flow vector, and air temperature. A 3-D airflow analysis grid is selected, which is a plane that calculates the CFD cell blockages. The analysis grid is positioned on the full floor plane of the building model covering the exterior and interior spaces. The grid axial offset is set to 600mm. The x-axis and y-axis number of cells are 54 while the z-axis number of cell is set to 30. The slice position of the analysis grid plane is set to 600mm from the floor level to calculate and simulate the airflow at the human level.

All Ecotect building model file are exported to WinAir4 after selecting the calculation and setting the setup as shown below in Figure 4.42.

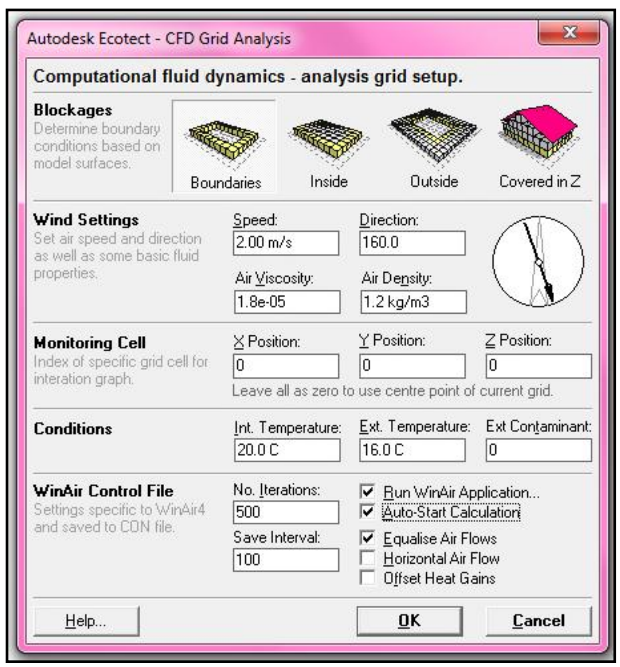

Fig.4.42. CFD analysis grid setup (ECOTECT).

The CFD analysis grid set up includes blockages, wind setting, monitoring cell, conditions, and WinAir control file. Boundary blockage is selected to determine the boundary condition on the model surface. The wind setting is set by the loaded climatic data of Bahrain by specifying the minimum wind speed of 2.00 m/s, and North-West wind direction of 160^o. Air viscosity and air density is default by Ecotect. The air viscosity calculated is 1.8e-05μ. The air density is 1.2kg/m3. In order to calculate the effect of June and December weather conditions on the built form, the external temperature conditions are set according the average temperatures loaded from the weather file. The external temperature condition of December is set to 16^{o}C and in June is set to 35^{o}C. The internal temperature conditions are fixed to 20^{o}C. The WinAir control file are setting specific to WinAir. The following aspects are marked: to run the WinAir application, Auto start the calculations, and equalize the air flow.

WinAir4 calculation window opens to run the CFD calculation of the model. As the calculation completes, by viewing the domain data, the results of the CFD calculation can be viewed within WinAir4 application plug-in by selecting the IJ section plane and choosing the specific analysis to be viewed. However, the CFD results can be viewed in Ecotect. Hence, the WinAir CFD calculation data is exported back to Ecotect by loading the CFD data in the analysis grid calculation section. The Output file is loaded into the model to display the WinAir CFD calculation results into Ecotect. From the analysis grid, the type of data is chosen for viewing and analysis, such as the cell temperature, flow vector, and airflow rate. However, the flow vector output by WinAir is not fully reliable, as it has to be overlay with other generated data such as the speed from the wind rose.

4.3.4. Shading Analysis:

The shading analysis displays the shadow assembly to study the effect of the courtyard built form in terms of daily sun path, solar radiation, and shadow range. Each model shadow is evaluated for the two extreme days per year which are the 21st of June and 21st of December. Each day is simulated three times to represent various positions of the sun at different times of the day. The different timings are 9a.m. in the morning, 12p.m. representing midday afternoon, and 3p.m. representing late afternoon.

4.3.5. Solar Access Analysis

This form of analysis will simulate a visual of the incident solar radiation on the courtyard surface to understand the effect of the building configuration on the solar exposure. To perform the calculation, at first an analysis grid should be placed over the courtyard area. The analysis grid cell numbers are decreased in size, having x-axis as 25, y-axis as 20, and z-axis as 20. The grid is placed on the courtyard surface to analyze the courtyard material surface. Then, the chosen calculation is incident solar radiation, which would demonstrate the total, direct, diffuse, solar radiation that falls on the courtyard surface. The simulation will run for a specific period of time. June 21st is selected to represent summer, between the timing of 5 a.m. to 5 p.m. December 21st is selected to represent winter, between the timing of 7 a.m. to 3 p.m. The average hourly value is selected to give in the overall average by calculating the sum of all values in each metric and then divide the amount by the number of hourly values added. A detailed shading calculation will be performed. In order to select the shading accuracy, the surface sampling is set as full with a 25x25 grid, and the sky subdivision is set as medium with 5x5. Figure 4.43 will demonstrate the Solar Access Analysis calculation wizard summary.

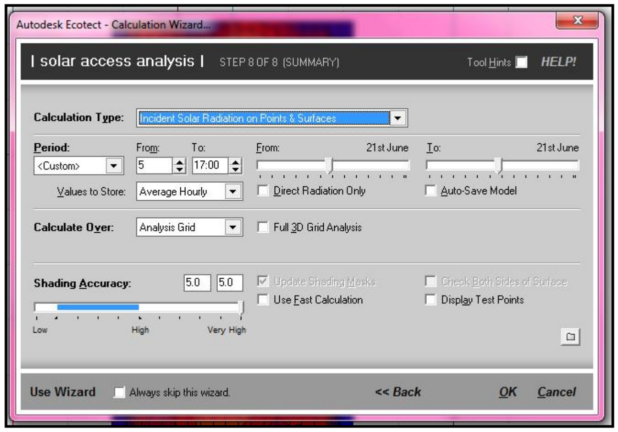

Fig.4.43. Solar Access Analysis calculation wizard summary *(ECOTECT).*

4.4. Conclusion

The two types of courtyards undergo several environmental assessments to evaluate the best performing courtyard type in terms of microclimatic conditions. The building types, with regards to the varying parameters, are modelled and simulated in Ecotect Analysis computer software. Several calculations are performed to analyze the courtyards. In terms of assessing the living room performance, thermal and RADIANCE analysis are calculated. In terms of assessing the courtyard performance, WinAir, shading, solar access, solar exposure analysis, and simulations are calculated.

Each type of analysis calculated the two courtyard types and each opening orientation. All building models undergo similar steps for each analysis setup and calculation. The total number of thermal analysis calculations for all courtyard case studies are 105. The hourly temperature profile analysis for each month of June and December are 21 tests. The heat gain/loss analysis for each month of June and December are 21 tests. The annual temperature distributions are 7 tests. The direct and indirect solar gains are 7 calculations for each type.

The total number of RADIANCE analysis calculations for all courtyard case studies are 42 sets for each month of June and December, at the three chosen hours of 9 a.m., 12 p.m., and 3 p.m.

The total number of WinAir analysis calculations for all courtyard case studies are 42 sets of tests for each month of June and December.

The total number of shading simulation for all courtyard case studies are 42 sets of tests for each month of June and December, at the three chosen hours of 9 a.m., 12 p.m., and 3 p.m.

The total number of solar exposure analysis calculation for single day hourly exposure is 14, for each of 21^{st} June and December.

The total number of Solar Access analysis calculation for single day hourly exposure is 14, for each of 21^{st} of June and December.

Chapter 5

Results and Discussion

Introduction

By running the simulations, all results are in process within this chapter. The simulation results are visualized, extracting numerical data of each simulation detail. The extracted details are wind flow vector and temperature gradient, shading percentage, Lux levels, direct and indirect solar heat gain, and Watt per hour solar exposure. The extracted numerical data using Excel are summarized, graphically represented, and tabulated. In order to comprehend the behaviour of the different courtyard configurations, it is important to verify the factors that affect the simulations. As discussed earlier, the independent factors, or the varying parameters that are the courtyard shape and configuration, and the opening orientation, influence the dependant factors performances; which are natural daylight and thermal comfort within the living room, airflow, solar exposure, and shading within the courtyard.

5.1. Results

5.1.1. Thermal Analysis Results

The thermal analysis performs several calculations, which are annual temperature distribution, hourly temperature profile, direct solar gain, and hourly heat gain. Each calculation is analyzed separately, and then the relation between all analysis and courtyards are expressed (Appendix A).

The total hourly heat gain analysis calculates Sol-Air, which is the indirect solar radiation absorbed on the internal surfaces and materials. The indirect solar radiation unit is measured by Watt per hour. Figure 5.1 illustrates a chart presenting a summary of the total indirect solar heat gain for all courtyard configurations between *Courtyard-T* and *Courtyard-S*.

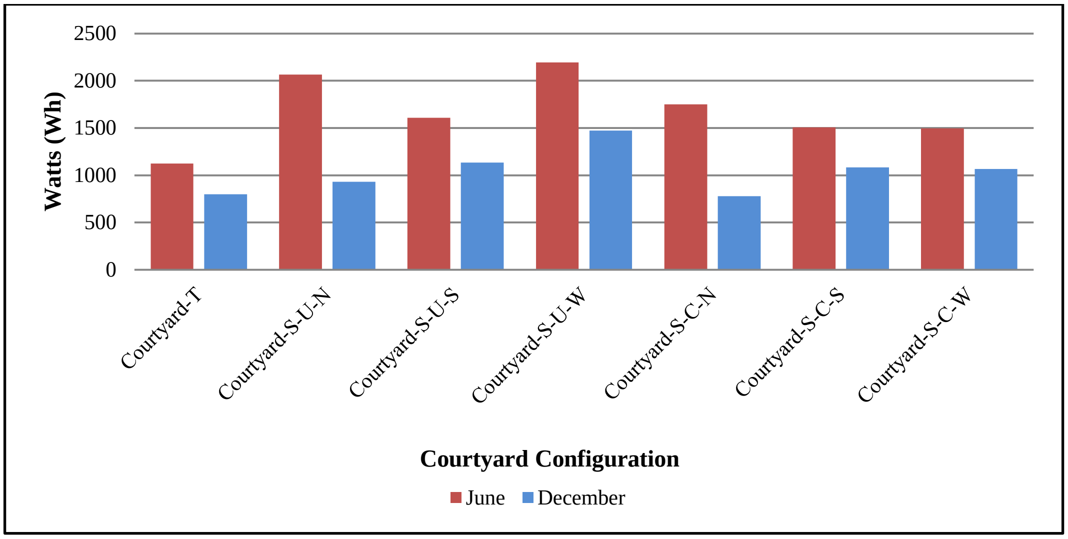

Fig.5.1. Sol-Air total hourly indirect solar heat gain analysis for Courtyard-T and Courtyard-S

Solar heat gain is directly related to the building shape, the configuration exposure to solar radiation, and sun's position. Comparing the U-shape to the C-shape and *Courtyard-T*, it presents the highest figures of indirect solar heat gain exposure in both seasons presented by June and December, as it has a larger courtyard due to the large opening exposed to solar radiation. Within the U-shape, *Courtyard-S*-U-W has the highest indirect solar heat gain in both months of June receiving 2195Wh and December receiving 1472Wh. This is justified, as *Courtyard-S*-U-W has the largest courtyard opening comparing it to *Courtyard-S*-U-N and *Courtyard-S*-U-S, which admits a higher rate of solar exposure and least shading.

Within the C-shape, the season change effects solar heat gain values. As in June, *Courtyard-S*-C-W has the least solar heat gain receiving 1497Wh, while in December; *Courtyard-S*-C-N has the least solar exposure receiving 779Wh. However, in June *Courtyard-S*-C-N has the highest solar heat gain receiving 1751Wh. This is justified that in December, *Courtyard-S*-C-N has the least solar heat gain is due to the low sun position in winter season, in comparison to June's high sun's position. As the sun is high, the living room area is exposed to extreme solar radiation. Moreover, *Courtyard-S*-C-W receives the least indirect solar heat gain, due to the West opening orientation that as the sun rotates towards East its low, allowing the courtyard and living room to be exposed to shade more than solar radiation.

Courtyard-T presents the lowest indirect solar heat gain value in June by comparing it to *Courtyard-S*. In December, *Courtyard-T* receives 800Wh, which is a higher value of indirect solar heat gain than Courtyard-S-C-N that receives 779Wh, but a less value than Courtyard-S-U-N that receives 931Wh; as the North orientation receive the least solar heat gain in December. The analysis reading shows a 374Wh difference in indirect solar heat gain between *Courtyard-T* and the least configuration of *Courtyard-S* receiving solar heat gain *Courtyard-S*-C-W. Hence, the fully enclosure of *Courtyard-T* presents an advantage of the least heat gain.

The Direct solar gain analysis calculates the monthly average. Therefore, the whole month of June and December are calculated to present the sum. The calculations presents that in the month of June direct solar gain occurs between 5 a.m. to 5 p.m., while in December it occurs between 7 a.m. to 3.p.m due to the late sunset in June, and late in sunrise in December. Moreover, the sun's angle and position affects the direct solar gain in both months.

Courtyard-T in the month of June receives 560Wh of direct solar heat gain. In the month of December, it receives 830Wh, which is a higher value of direct solar heat gain than June. Figure 5.2 illustrates a chart of the direct solar heat gain of *Courtyard-T* in both seasons.

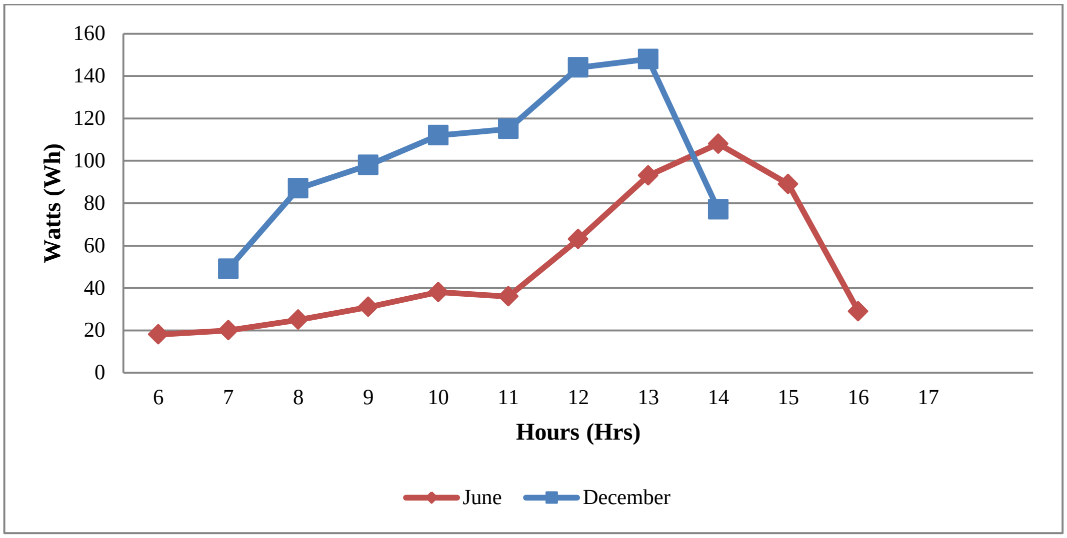

Fig.5.2. Hourly direct solar heat gain for Courtyard-T in both months of June and December

The U-shape in general presents higher solar gain due to its large opening that allows a higher exposure to the solar radiation. Within the U-shape, in June, *Courtyard-S*-U-W receives the highest direct solar gain of 2167Wh in comparison to *Courtyard-S*-U-S, which receives the lowest direct solar heat gain of 788Wh. While in December, *Courtyard-S*-U-W also receives the highest direct solar heat gain of 2094Wh. Hence, the opening orientation and the size of the opening increases direct solar heat gain. Figure 5.3 illustrates a chart of the direct solar heat gain of the U-shape in June.

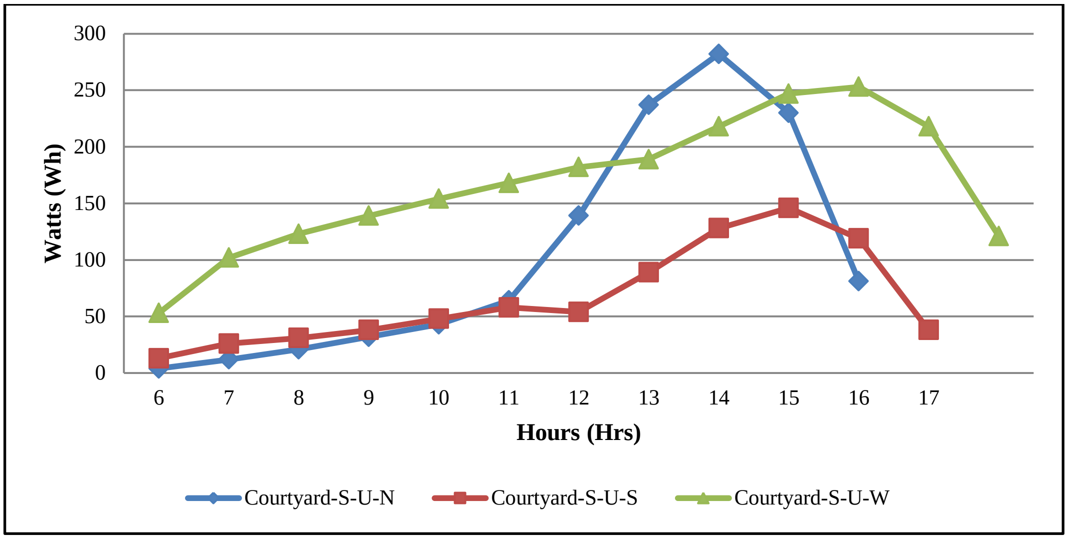

Fig.5.3. Hourly direct solar heat gain for Courtyard-S-U in June

The C-shape, in the month of June, *Courtyard-S*-C-W receives the least solar heat gain of 745Wh due to the opening size, opening orientation, as the West sun position is lower. Nonetheless, in December, *Courtyard-S*-C-N receives the least solar heat gain of 581Wh due to the opening orientation, and the low solar position in the winter season. Figure 5.4 illustrates a chart of the direct solar heat gain of the C-shape in June.

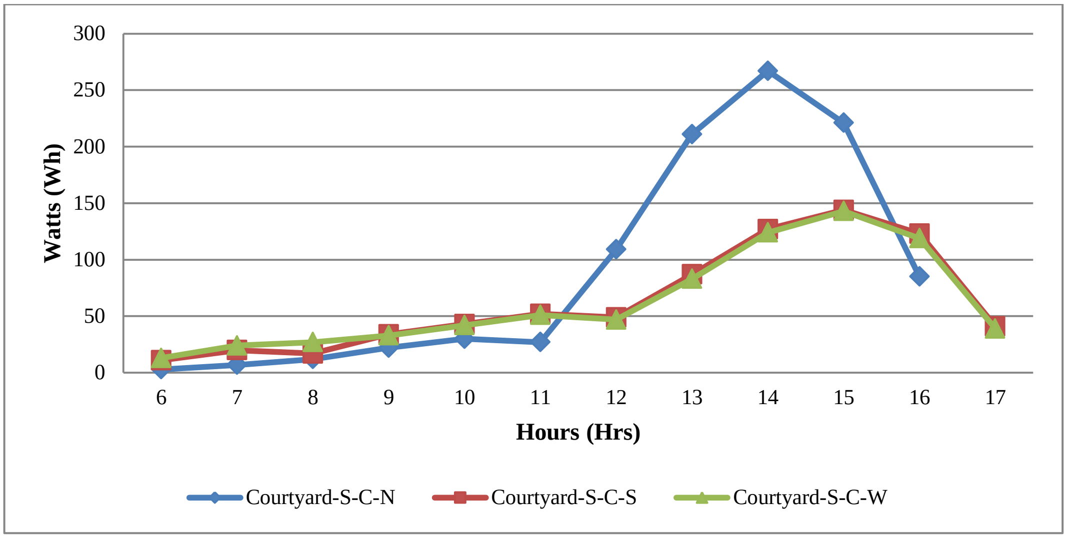

Fig.5.4. Hourly direct solar heat gain for Courtyard-S-C in June

Comparing *Courtyard-T* and *Courtyard-S*, *Courtyard-T* demonstrates the least direct solar heat gain in June due to the least solar radiation absorption, as an affect of its fully enclosed configuration. *Courtyard-S*-C-W also presents a low direct solar heat gain, which may provide thermal comfort within the crucial hot summer season of June. The direct solar heat gain difference between *Courtyard-T* and *Courtyard-S*-C-W in June is 185Wh, and in December is 270Wh. However, in the winter season adequate heat gain is needed to mitigate the cold weather and reduce the heating load in winter. Therefore, by having a medium or an average value of heat gain within the winter season is thermally comfortable. Table 5.1 tabulates a summary of the direct solar heat gain of *Courtyard-T* and *Courtyard-S* in both seasons.

Table 5.1. Summary of daily direct solar heat gain analysis for Courtyard-T and Courtyard-S configurations

Configuration, Shape, Orientation			Solar Gain in June (Wh)	Solar Gain in December (Wh)
Courtyard-T			560	830
Courtyard-S	**U-Shape**	*Courtyard-S*-U-N	1145	653
		Courtyard-S-U-S	788	1133
		Courtyard-S-U-W	2167	2094
	C-Shape	*Courtyard-S*-C-N	994	581
		Courtyard-S-C-S	748	1125
		Courtyard-S-C-W	745	1106

The hourly temperature profile calculates the direct and diffuse solar radiation for the internal living room space, and the external weather conditions presenting the difference of temperature and the average indoor temperature. Table 5.2 presents a summary of the average hourly temperature profile calculation for both *Courtyard-T* and *Courtyard-S* in both seasons.

Table 5.2. Summary average of the hourly temperature profile analysis for Courtyard-T and Courtyard-S configurations

Configuration, Shape, Orientation			Living Room Average Temperature (°C)		Average Temperature Difference (°C)	
			June	December	June	December
Courtyard-T			38.46	22.7	3.087	4.379
Courtyard-S	**U-Shape**	*Courtyard-S*-U-N	37.4	21.49	2.11	3.17
		Courtyard-S-U-S	37.35	21.45	1.97	3.12
		Courtyard-S-U-W	37.39	21.45	2.01	3.13
	C-Shape	*Courtyard-S*-C-N	37.45	21.4	2.08	3.07
		Courtyard-S-C-S	37.35	21.47	1.97	3.14
		Courtyard-S-C-W	37.32	21.42	1.95	3.1

Courtyard-S-U configuration presents *Courtyard-S*-U-N in having the highest average temperature differential in both seasons. On the other hand, *Courtyard-S*-U-S has the lowest average temperature differential in both seasons. However, *Courtyard-S*-U-N maintains the highest average temperature due to the high solar heat gain in both seasons. Figure 5.5 and 5.6 shows the hourly temperature profile for *Courtyard-S*-U-N and *Courtyard-S*-U-S in June. The opening position as its windward assists in increasing the temperature differential of the Northern opening, as it has the most frequent prevailing wind.

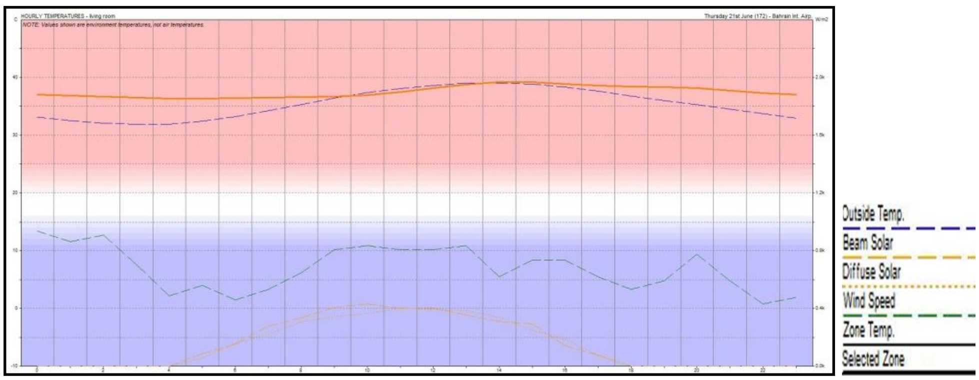

Fig.5.5. Hourly temperature profile for Courtyard-S-U-N in June (ECOTECT)

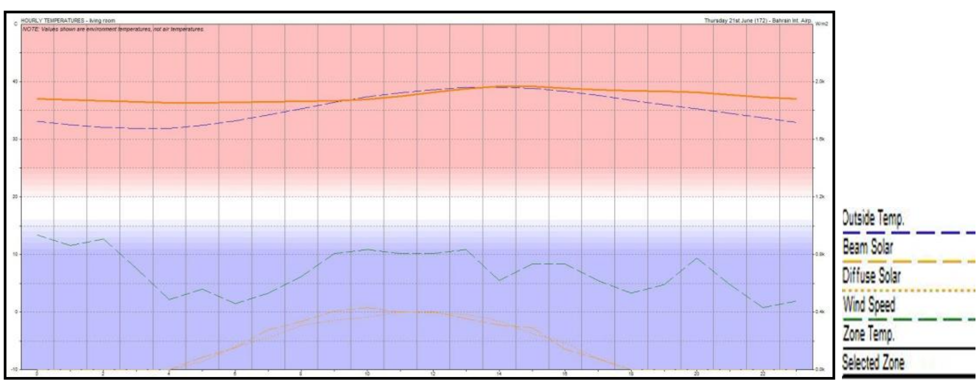

Fig.5.6. Hourly temperature profile for Courtyard-S-U-S in June (ECOTECT)

Courtyard-S-C configuration presents *Courtyard-S*-C-N in having the highest average temperature differential in June, due to the assistance of wind pressure and frequency. *Courtyard-S*-C-S has the highest average temperature differential in December due to low solar position in winter that increases shade. Although, both opening orientation have high solar heat gain. *Courtyard-S*-C-W has the lowest average temperature due to the opening orientation and solar position. Figure 5.7, 5.8, and 5.9 shows the hourly temperature profile for *Courtyard-S*-C-N, *Courtyard-S*-C-S, *Courtyard-S*-C-W and in June.

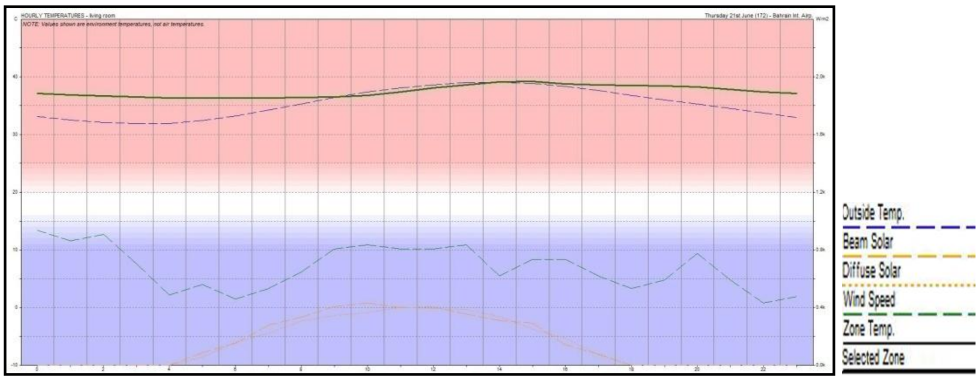

Fig.5.7. Hourly temperature profile for Courtyard-S-C-N in June (ECOTECT)

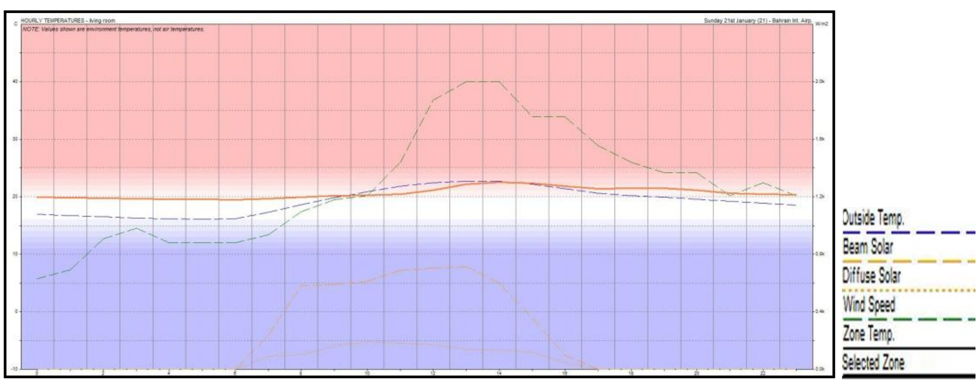

Fig.5.8. Hourly temperature profile for Courtyard-S-C-S in June (ECOTECT)

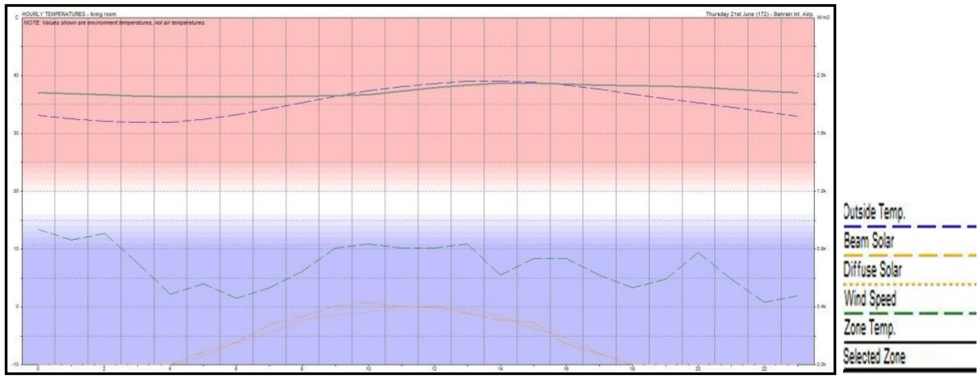

Fig.5.9. Hourly temperature profile for Courtyard-S-C-W in June (ECOTECT)

In terms of average temperature difference, *Courtyard-S*-U provides a higher temperature difference than *Courtyard-S*-C in both seasons. However, *Courtyard-S*-C provides a lower average temperature than *Courtyard-S*-U. This is justified due to the large opening size that increases temperature difference. However, due to the low solar heat gain, *Courtyard-S*-C maintains to achieve a lower range of average temperature within the living room. Specifically in June, this then assists in reducing the cooling load and providing thermal comfort, although the average temperature is still above the thermal comfort zone with reference to the psychrometric chart.

Courtyard-T has the highest living room average temperature compared to *Courtyard-S* configurations within both seasons. However, due to its fully enclosed configuration and receives the least solar heat gain; it has the highest average temperature difference between the courtyard and the living room in both seasons. Therefore, *Courtyard-T* performs as the best temperature modifier in presenting thermal comfort within the courtyard. Figure 5.10 and 5.11 demonstrates the hourly temperature profile of *Courtyard-T* living room in June and December.

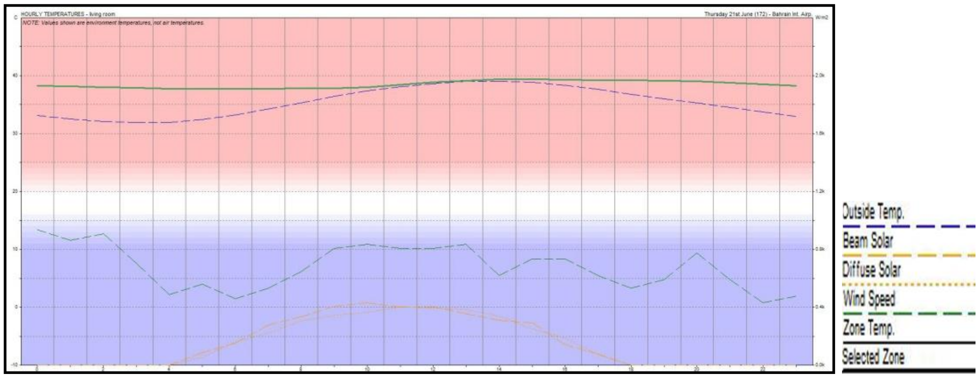

Fig.5.10. Hourly temperature profile for Courtyard-T in June (ECOTECT)

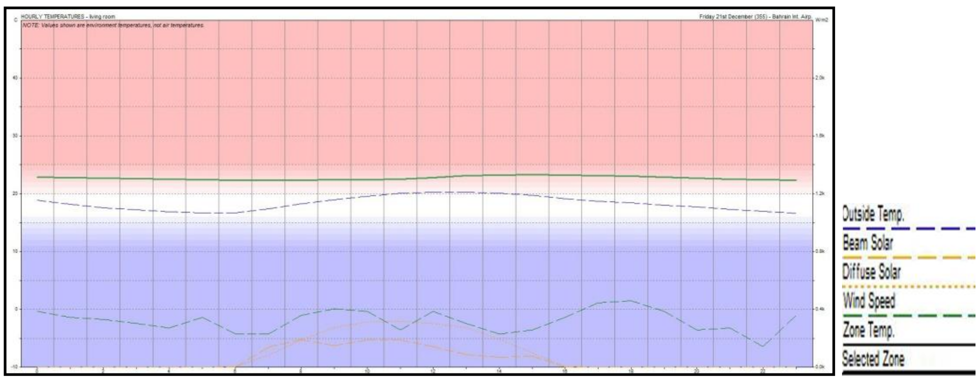

Fig.5.11. Hourly temperature profile for Courtyard-T in December (ECOTECT)

The annual temperature distribution calculates the total amount of hours and percentage that the configuration is within the comfort zone in relation to the psychrometric chart without the use of HVAC as the comfort band is within 16^{o}C - 20^{o}C. Table 5.3 provides a total summary of the annual temperature distribution in terms of hours and percentage of the living in all the courtyard configurations.

Table 5.3. Summary of annual temperature distribution for Courtyard-T and Courtyard-S configurations

Configuration, Shape, Orientation			Total Hours in Comfort (Hrs)	Total Percentage in Comfort (%)
Courtyard-T			1397 Hrs	15.9%
Courtyard-S	**U-Shape**	*Courtyard-S*-U-N	1834 Hrs	20.9%
		Courtyard-S-U-S	1854 Hrs	21.2%
		Courtyard-S-U-W	1838 Hrs	21%
	C-Shape	*Courtyard-S*-C-N	1844 Hrs	21.1%
		Courtyard-S-C-S	1854 Hrs	21.1%
		Courtyard-S-C-W	1863 Hrs	21.3%

Courtyard-T living room presents the least hours and percentage in providing thermal comfort within the psychrometric chart. As the psychrometric chart includes humidity levels, while in the study humidity is not part of the analysis, it reflects a direct connection in reducing *Courtyard-T* living room thermal comfort.

Courtyard-S divides into two shapes; U and C shape. The first shape is the U-shape. Looking into *Courtyard-S*-U-S living room, it has the highest hours in comfort, while *Courtyard-S*-U-N living room has the least hours. Looking into the second shape, C-shape, *Courtyard-S*-C-N has the least hours in comfort, while *Courtyard-S*-C-W has the highest hours in comfort.

Comparing the U-shape and C-shape, *Courtyard-S*-C-W provides longer hours in comfort than *Courtyard-S*-U-S within the living room. This is due to the least solar heat gain it receives, the small opening size, the high ratio of enclosure, and the solar exposure that the West orientation receives less than the South. Moreover, comparing *Courtyard-S* and *Courtyard-T*, *Courtyard-S*-C-W provides longer hours in comfort.

Courtyard-T demonstrates the least hours in comfort from both *Courtyard-S*-U and *Courtyard-S*-C.

Drawn from all the thermal analysis calculations, *Courtyard-T* configuration sums up to achieve the highest thermal comfort. It receives the least direct and indirect solar heat gain in the summer month. While in December, it receives higher direct solar heat gain than *Courtyard-S*-C-N and *Courtyard-S*-U-N, and higher indirect solar heat gain than *Courtyard-S*-C-N. Yet, the North opening orientation for all thermal analysis calculation presented to have low thermal comfort in comparison to *Courtyard-T*. Furthermore, *Courtyard-T* provides a higher average temperature differential in both seasons, due to the low solar heat gain. Hence, modifies the indoor temperature to achieve thermal comfort levels more efficiently than *Courtyard-S*. On the other hand, it has been analyzed that it provides the lowest comfort hours, which is due to the lack of humidity studies.

The second configuration that achieves thermal comfort best is Courtyard-S-C-W. Comparing it to the other *Courtyard-S* configurations, it has the lowest indirect and direct solar heat gain in June. Moreover, it has the lowest average temperature in June, and the highest hour and percentage of comfort. Although both configurations are not within the comfort zone provided by the psychrometric chart, yet if provided with natural ventilation, the comfort zone extends to encompass both configuration results in providing thermal comfort. Those analysis calculations support that the fully enclosed courtyard performs better in modifying and providing thermal comfort more than the semi-enclosed courtyard.

5.1.2. RADIANCE Results

A natural daylight level is a key measurement in providing occupants comfort within an indoor space. A view to the outdoor environment provides psychological and physiological comfort. Adequate daylight penetration reduces the need of artificial lighting. Daylight is the penetration of direct and indirect solar radiation through openings. It is affected by the opening size, indoor space geometry, glazing transmittance and reflectance. However, daylight should take in control to control the quantity of light, distribution of light, and heat gain. The occupant activity level within the living room is identified as sedentary. IESNA recommends the living room an illuminance level of 200-300 Lux of well-distributed daylight for various ranges of activities (Rea M.S., 2002). RADIANCE calculated the illuminance levels within the living for each courtyard configuration in June and December in the morning, midday, and late noon hours. RADIANCE illuminance simulations are imported into Ecotect. Refer to Appendix B for all results.

Courtyard-T results viewed that is has the highest average Lux levels at 12 p.m. due to the high solar angle. In the month of June, all average values are beyond the recommended standards, the highest value at 12 p.m. with 857.89 Lux. In the month of December, at 12 p.m. average value is within the recommended standards with 270.18 Lux, and however, 9 a.m. reaches the approximate of the recommended standards with 199.74 Lux. At 3 p.m. in both seasons, daylight level is the least due to the low solar angle and position, and the effect of having a fully enclosed narrow courtyard with the given height. Figure 5.12 shows the illuminance level and distribution of *Courtyard-T* in June at 12 p.m. in Ecotect, as the month of June receives higher solar radiation. The light intensity of the hot spots by the window during this hour is at its peak. The Northern window receives more light however less intense due to the exterior window. The east window of the courtyard has the most excessive intensity level reaching up to5460 Lux, while the Northern window of the courtyard reaches up to 2520 Lux. The hot spots by the window are forms of strips parallel to the window; however, the intensity reduces by going further away creating a smooth flow of light intensity.

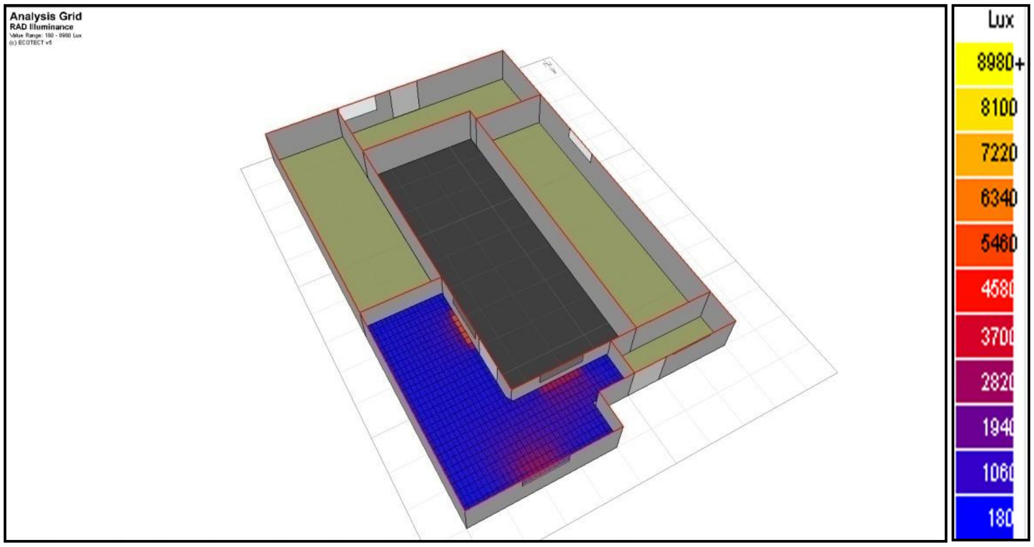

Fig.5.12. Courtyard-T RAD illuminance simulation in June at 12 p.m. (ECOTECT)

Regarding light distribution, between 9 a.m. and 3 p.m., the living room is exposed to three spots of excessive light, which decrease in size, yet the intensity of the glare spots increase in intensity, as it reaches its peak at 12 p.m. and decrease by 3 p.m. As the excessive intensive light decreases, the overall distribution of light is well maintained. The intensive light areas are by the window openings. Light is well distributed at a smooth intensity level between 12 p.m. and 3 p.m. The best well-distributed light is at 3 p.m. as it has the least and smallest glare spots.

Courtyard-S-U is calculated for its three orientations; North, South, and West. Within the peak hours, with the highest heat gain, *Courtyard-S*-U-W exposes excessive illuminance levels within the living room at both hours of 12 p.m. and 3 p.m., and during both seasons. In June, at 12 p.m. the average value of illuminance level is 1278.43 Lux, while at 3 p.m. its 3885.58 Lux. This extreme illuminance levels within the living room is due to its Western opening orientation as the sun exposure is high and its opening orientation within those hours exposes the living room to excessive solar radiation. Nonetheless, *Courtyard-S*-U-W has the largest courtyard opening, hence higher exposure to solar radiation and higher accessibility of lighting within the living room that equals to occupants discomfort.

Courtyard-S-U-S is exposed to less solar radiation that receives the least daylighting level within the peak hours of the month of June, as all illuminance levels are higher than the recommended levels. At 12 p.m., it receives 928.89 Lux. In December at 12 p.m., it also provides the most adequate lighting of 315.27 Lux. Figure 5.13, 5.14, 5.15 shows the illuminance level and distribution of *Courtyard-S*-U-N, *Courtyard-S*-U-S, and *Courtyard-S*-U-W in June at 12 p.m. in Ecotect, as the month of June receives higher solar radiation.

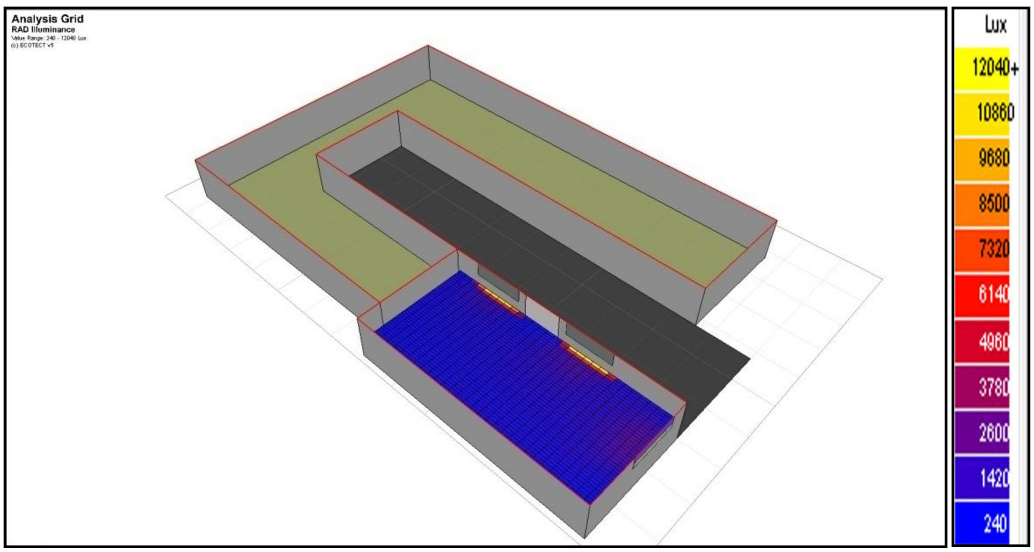

Fig.5.13. Courtyard-S-U-N *RAD illuminance simulation in June at 12 p.m. (ECOTECT)*

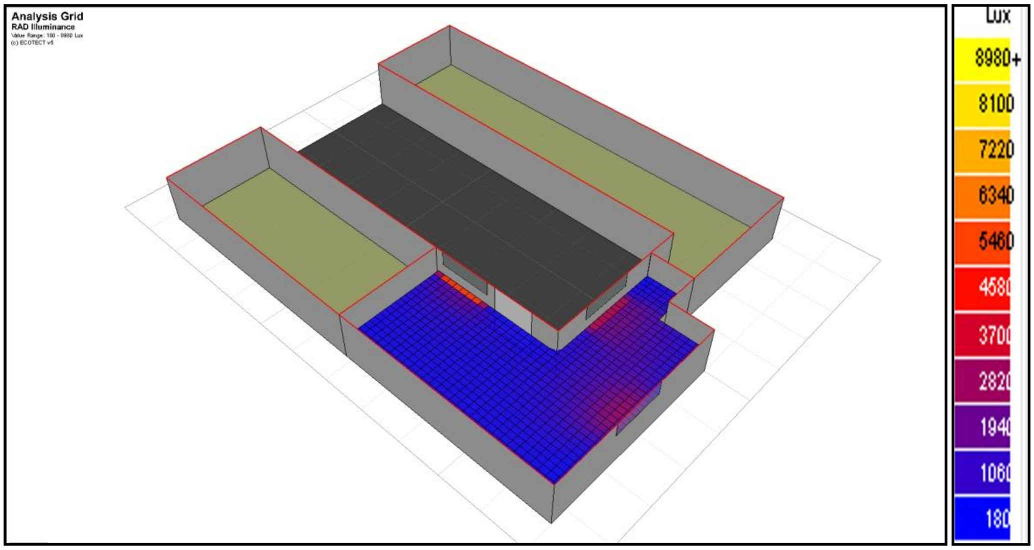

*Fig.5.14. Courtyard-S-*U-S *RAD illuminance simulation in June at 12 p.m. (ECOTECT)*

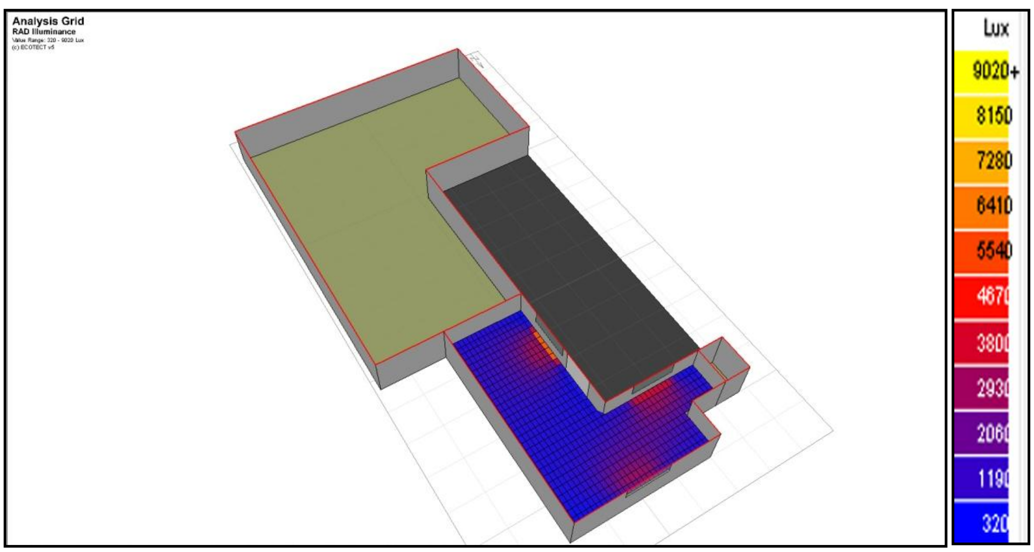

*Fig.5.15. Courtyard-S-*U-W *RAD illuminance simulation in June at 12 p.m. (ECOTECT)*

However, in terms of lighting distribution, *Courtyard-S*-U-S is the most adequate and comfortable with the least intensive glare spots. All at 9 a.m. produce three intensive glare spots that decrease in size yet increase in intensity by noon. However, as the sun changes in position and gets higher, the intensive light by the window reduces and increases the smooth distribution of light within the living room. The North and West orientation have the highest levels of intensive illuminance light that reaches the middle areas of the living room causing extreme discomfort. This is due to the solar position, opening orientation that allows high solar exposure, and the courtyard opening size that affected the courtyard configuration.

Courtyard-S-C is calculated for its three orientations; North, South, and West. Within the peak hours, *Courtyard-S*-C-N exposes excessive illuminance levels within the living room at both hours of 12 p.m. and 3 p.m., during the month of June. At 12 p.m. its average value of illuminance level is 932.81 Lux, while at 3 p.m. its 491.78 Lux. In June, all illuminance levels are beyond IESNA recommended standards. In June, *Courtyard-S*-C-N and *Courtyard-S*-C-S are equivalent to each other in illuminance levels. Yet *Courtyard-S*-C-S is still lower. This is justified to the small opening orientation, and significantly the window opening position differential between the North and South orientation within the courtyard that with high solar position allows excessive solar radiation.

Courtyard-S-C-W receives the least and most appropriate illuminance levels within the living room, although all orientations receive beyond the comfortable recommendation levels. In June, at the peak hour of noon it receives 813.62 Lux. During December, *Courtyard-S*-C-S is the most appropriate and reaches the comfortable levels. In December, *Courtyard-S*-C-W and *Courtyard-S*-C-N are equivalent in illuminance levels although the North orientation receives less, and both receive less than the South orientation. This is justified to the opening orientation and solar position that exposes *Courtyard-S*-C-S living room to receive more illuminance levels. Figure 5.16, 5.17, 5.18 shows the illuminance level and distribution of

Courtyard-S-C-N, *Courtyard-S*-C-S, and *Courtyard-S*-C-W in June at 12 p.m. in Ecotect, as the month of June receives higher solar radiation.

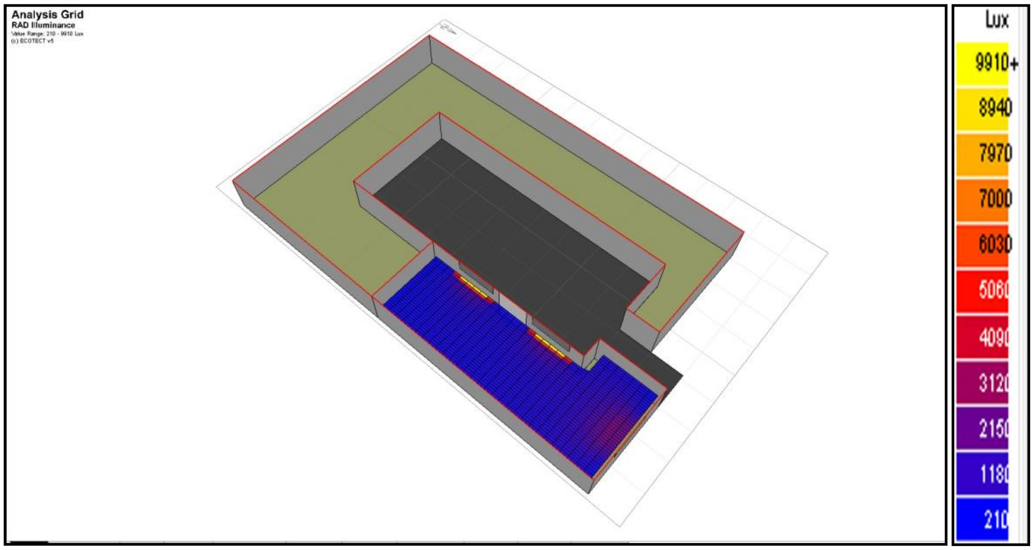

Fig.5.16. Courtyard-S-C-N *RAD illuminance simulation in June at 12 p.m. (ECOTECT)*

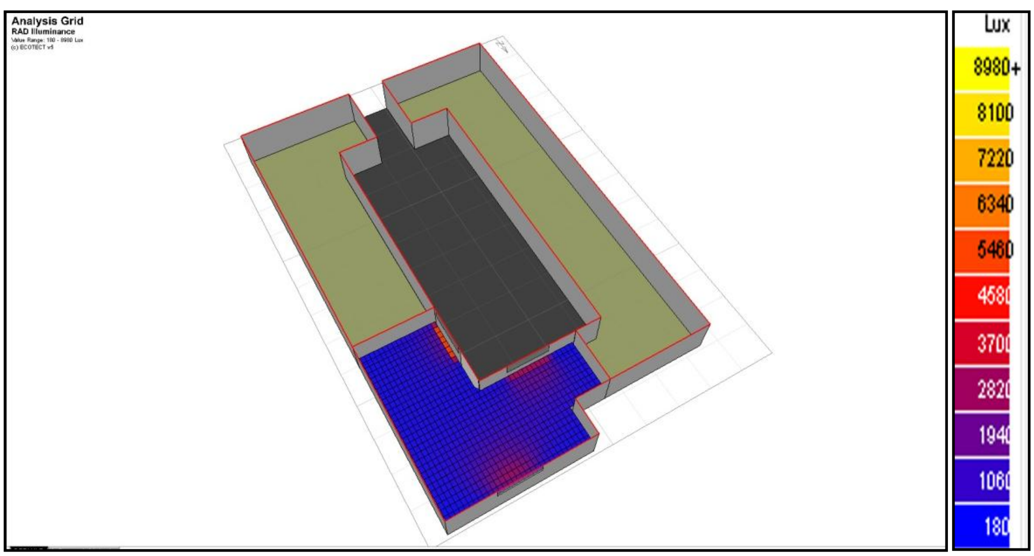

Fig.5.17. Courtyard-S-C-S *RAD illuminance simulation in June at 12 p.m. (ECOTECT)*

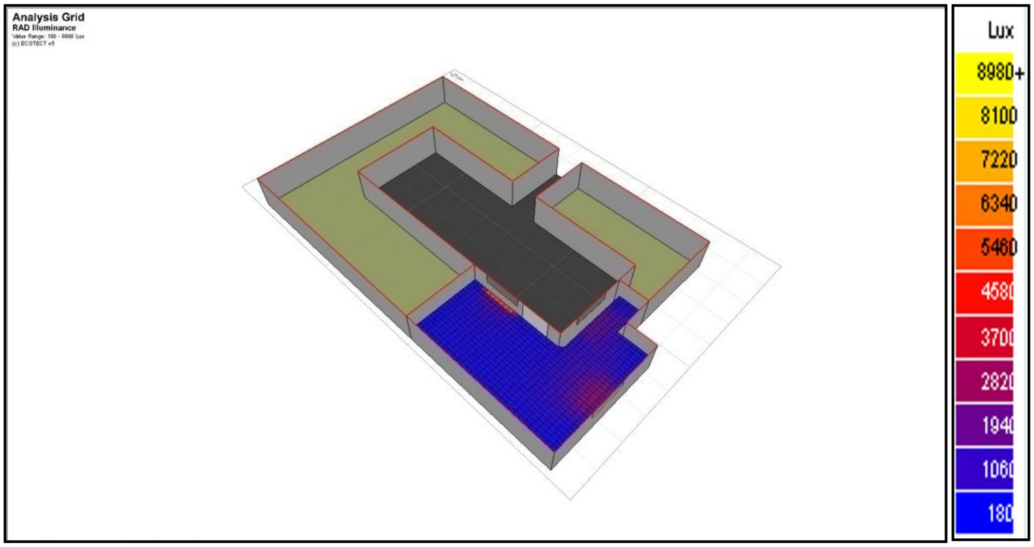

*Fig.5.18. Courtyard-S-*C-W *RAD illuminance simulation in June at 12 p.m. (ECOTECT)*

In terms of light distribution, in June, all at 9 a.m. produce three intensive glare spots that decrease in size yet increase in intensity by noon. However, as the sun changes in position and gets higher, the intensive light by the window reduces and increases the smooth distribution of light within the living room. *Courtyard-S-*C-W is the most adequate and comfortable with the least intensive glare spots. Although at 9a.m. the average level of illuminance is not well distributed creating various values, however, the intensity is the least. At 12 p.m. the average illuminance level and high intensive glare spots are similar in distribution between *Courtyard-S-*C-W and *Courtyard-S-*C-S, however, the intensity levels of *Courtyard-S-*C-W are less providing more comfort. The window opening distribution affects daylight penetration and the size of the intensive light spots. Although *Courtyard-S-*C-W and *Courtyard-S-*C-S have larger intensive light spots within the living room than *Courtyard-S-*C-N, yet the illuminance level of the intensive light spot of *Courtyard-S-*C-N is higher. This is due to the window placement, as *Courtyard-S-*C-N has both windows on the East side of the courtyard (the west wall of the living room). Therefore, the sun position and courtyard opening affects light penetration.

In general, *Courtyard-S*-C receives better daylight levels within the living room than *Courtyard-S*-U, although both shapes are not within the comfort or IESNA recommended illuminance levels. Table 5.4 summarizes the average value of illuminance Lux level for all courtyard configurations at each orientation in both months at all calculated hours. In June, all exceed the 200-300 Lux levels. In June, *Courtyard-S*-C-W receives the best daylight illuminance levels at 9 a.m. and 12 p.m., yet *Courtyard-S*-C-S receives the best at 3 p.m. In December, *Courtyard-S*-C receive adequate light within the recommended range, while *Courtyard-S*-U exceeds the recommended range. Therefore, the opening size of the semi-enclosed courtyard demonstrates a great difference of daylight within the living room, as the opening decreases in size it promotes comfortable illuminance level to satisfy the living room activity.

Table 5.4. Summary of the average illuminance Lux level for all courtyard configurations at the studied period

Configuration, Shape, Orientation			**June Lux Levels**			**December Lux Levels**		
			9	**12**	**3**	**9**	**12**	**3**
Courtyard-T			477.76	857.76	438.61	199.74	270.18	146.02
Courtyard-S	**U-Shape**	*Courtyard-S*-U-N	472.52	1012.92	768.58	252.38	342.88	184.27
		Courtyard-S-U-S	472.91	928.89	469.04	225.02	315.27	164.24
		Courtyard-S-U-W	442.77	1278.43	3885.58	356.21	486.44	260.33
	C-Shape	*Courtyard-S*-C-N	527.79	932.81	491.78	199.78	271.64	145.96
		Courtyard-S-C-S	514.73	895.22	448.2	212.25	287.9	155.01
		Courtyard-S-C-W	430.46	813.62	472.1	200.47	272.55	146.23

Courtyard-T receives higher illuminance levels than *Courtyard-S*-C-W in June, while in December it receives less at 9 a.m. and 12 p.m. However, in June, at 3.p.m it receives less illuminance levels than *Courtyard-S*-C-W. In December, although *Courtyard-T* receives less illuminance levels, yet *Courtyard-S*-C-W is very much similar in values. Both, *Courtyard-T* and *Courtyard-S*-C-W are similar in light distribution within the living room, due to the window opening position. Both provide adequate light distribution. However, the only difference is the illuminance level. This is justified by the courtyard opening and the opening orientation. The west opening affected the living room geometry its width, and decreasing the courtyard width. Therefore, *Courtyard-S*-C-W receives better illuminance levels. *Courtyard-S*-C-W provides the most comfortable illuminance level within the living room in both seasons.

5.1.3. Airlfow Results Through WinAir

The CFD simulation output by WinAir is exported back to Ecotect. The CFD simulated and recorded each configuration cell temperature, cell pressure and flow vector. Celsius Centigrade represents the cell temperature. Cell pressure is represented by the Pascal unit (Pa). Wind is represented by flow vectors to indicate the wind speed and direction. WinAir calculates the pressure of wind surrounding the courtyard. The wind speed is represented by miles per second. However, the generated output of WinAir velocity vector will not be considered in terms of figures, yet it will be backed up with the generated prevailing wind frequency from the weather tool wind rose of Bahrain. Therefore, the wind speed will be represented by Km/h. The values were extracted from a horizontal and vertical analysis grid. The horizontal slice position of the analysis grid is close to the ground surface at around 600mm. The initial wind speed input is 0.2m/s. The initial wind temperature input obtained from the temperature wind rose for June is 35^{o}C, and for December is 16^{o}C.

The obtained simulation result focuses on the courtyard only, to scrutinize the effect of the configuration on the courtyard performance. Refer to all results in Appendix C.

Courtyard-T CFD simulation analysis in June in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 21^{o}C. In terms of Flow Vector, the wind speed within the courtyard is at its slowest speed. The wind vector direction is from North-North-West to South, with reference to the frequent prevailing wind rose of June, the prevailing wind coming from this direction is less frequent at a 20 Km/h from North. The Northern part of the courtyard where the living room is located lacked airflow. This is justified by the fully enclosed courtyard shape, that causes the wind flow coming from the North to reach the human level low ground of the courtyard at the midpoint of the courtyard moving South, hence, creating lack of air flow on the horizontal Northern part of the court yard. Although the airflow is not equally circulated due to the wind in June within the courtyard, yet the temperature behavior is decreased. Figure 5.19 and 5.20 shows a visual simulation of WinAir CFD simulation loaded in Ecotect representing the cell temperature and airflow in June.

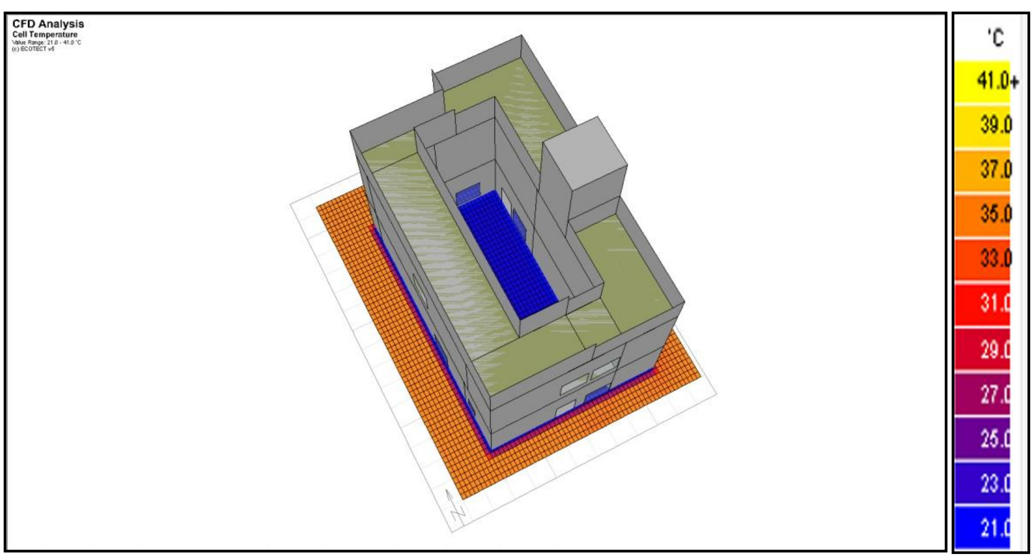

Fig.5.19. CFD Analysis of cell temperature for Courtyard-T in June (ECOTECT)

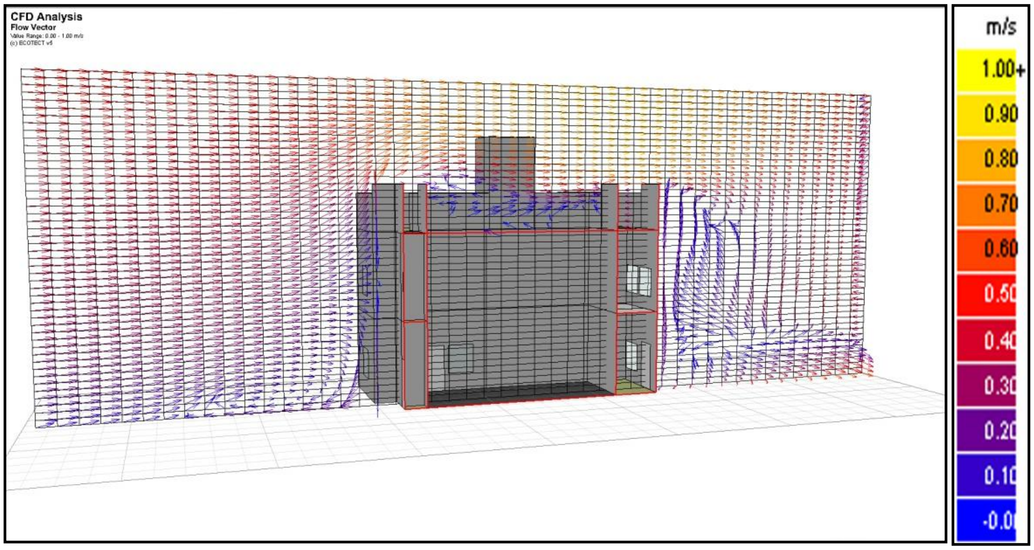

Fig.5.20. CFD Analysis of flow vector for Courtyard-T in June (ECOTECT)

The CFD simulation analysis in December, in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 18.5^{o}C. The courtyard contour has a temperature variation between 19^{o}C -20^{o}C. In terms of Flow Vector, the wind speed within the courtyard is between slow to medium speed. This is due to the frequency of the prevailing wind, as in December, the North and North-North-West has higher frequent prevailing wind at 20-30 Km/h than June. The wind vector direction is from North to South, as the wind enters from the North-North-West side of the courtyard, it circulates downward towards the South moving towards the horizontal Northern part of the courtyard to escalate and exit from the courtyard, creating a vertical calm eddy. Therefore, at the human level, wind flow is directed from the South with an escalating wind speed. This form of wind circulation is due to the effect of the fully enclosed courtyard configuration and the building height. Hence creating a stack effect, as Kwok stated that stack effect is effective when the outside temperatures are cooler than the inner courtyard with a minimum difference of 1.7^{o}C, however in this case the temperature difference is 2.5^{o}C (Kwok and Grondzik 2007, p. 145). Increase of wind speed occurs around the Northern part of the courtyard. The effect of having a higher wind speed and full airflow circulation affects the temperature differentials between June and December. Therefore, the direction of the wind flow at a high frequency assists in mitigating the temperature and providing adequate wind flow entering the courtyard throughout the year. Figure 5.21 shows a visual simulation of WinAir CFD simulation loaded in Ecotect representing the airflow in December.

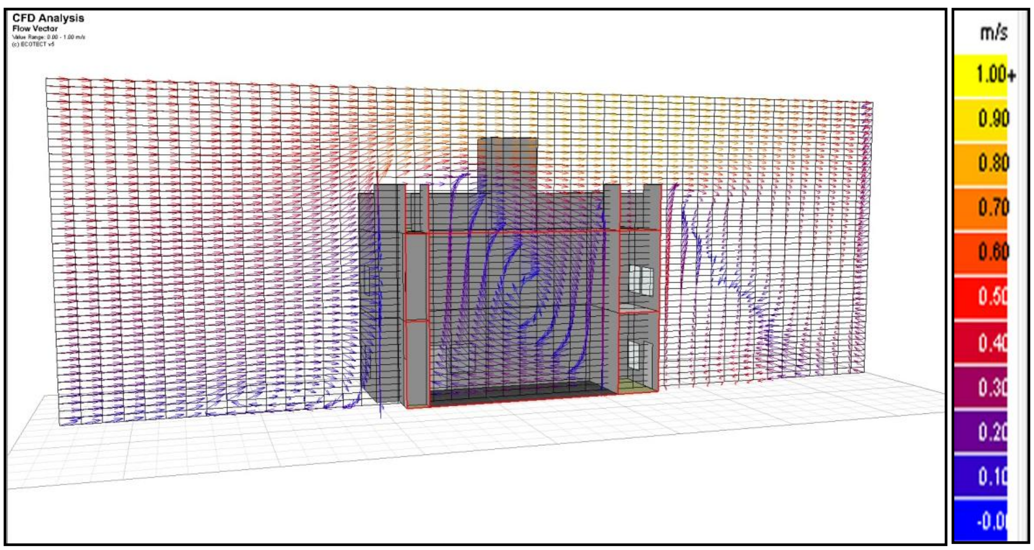

Fig.5.21. CFD Analysis of flow vector for Courtyard-T in December (ECOTECT)

Courtyard-T in June has a low-pressure differential between the North and the South, yet it has a high pressure within the courtyard that mitigates the temperature, Figure 5.22. Low-pressure differential justifies the form of airflow entering the courtyard and its unequal distribution within the month of June.

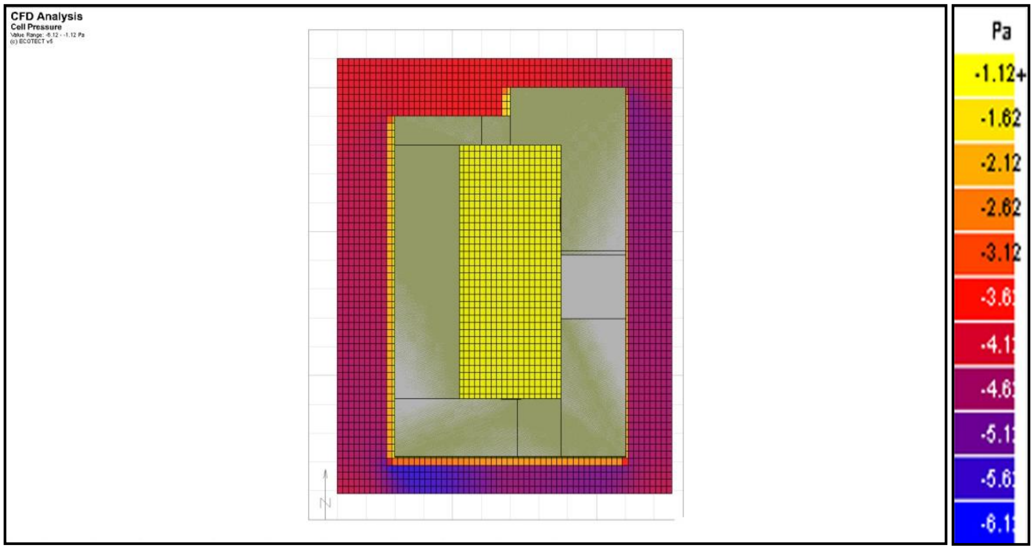

Fig.5.22. CFD Analysis of cell pressure for Courtyard-T in June (ECOTECT)

Courtyard-S configuration simulated two types of shapes; each has three types of configuration according to their opening orientation. The first shape is the U-shape. The first configuration is *Courtyard-S*-U-N. *Courtyard-S*-U-N CFD simulation analysis in June, in terms of Cell temperature illustrated to maintain a temperature value of 27°C. In terms of Flow Vector, the wind speed within the courtyard is high. The wind vector direction is from North-North-West to South, as it is directed towards the South the wind escalates higher to exit from the courtyard top opening. With reference to the frequent prevailing wind rose, the prevailing wind is coming at a less frequency of 20 Km/h. However, the wind that is 3.7m high hits the South wall to circulate back downward at the slowest speed to direct its way to the Northern opening exit. Therefore, the configuration creates a downdraft perpendicular to the wind at the Southern wall of the courtyard, due to the less frequent wind speed that reduces in wind-generated pressure in June creating the downdraft as cross ventilation. By the living room area, the wind speed is higher than the South, due to the cause of having the courtyard opening windward. The wind speed and frequency affects the temperature by the courtyard opening, where it decreases the initial temperature of 35°C to 31°C.

The CFD simulation analysis in December, in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 18.5°C. In terms of Flow Vector, the wind speed within the courtyard is high. The wind vector direction is from North-North-West to South, as it is directed South, the wind escalates to exit from the top Southern side of the courtyard opening. However, wind flow that is relatively close to the ground level, circulates, and rotates back to exit from the Northern opening. With similar circulation to the month of June, yet, the wind flow is calmer in December, escalating at a slower rate to the courtyard top opening creating adequate wind flow circulation throughout the courtyard. This is due to the relation between the direction of the wind entering the courtyard and the opening of the courtyard, which is more frequent and smoother in December.

The second configuration is *Courtyard-S*-U-S. *Courtyard-S*-U-S CFD simulation analysis in June, in terms of Cell temperature illustrated to maintain a temperature value of 27°C. In terms of Flow Vector, the wind speed is medium. North-North-West wind in June has a low frequency of 20 Km/h. Due to the building height and enclosure on the Northern section, the wind vector is directed from North and does not move downward to the lower level of the courtyard, however, it exit from the Southern opening. Wind that is coming from the building sides enters the courtyard and is directed from South to North to exit from the North top courtyard opening. However, wind that enters from the South is less frequent at 10-20 Km/h. This configuration creates a vertical wind movement by the living room area, in order for the wind to exit. The wind speed affects the temperature by the courtyard opening, where it decreases the initial temperature of 35°C to 33°C. Therefore, the wind behavior in terms of temperature, direction, and speed is due to the large opening position being leeward.

The CFD simulation analysis in December, in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 18.5°C. In terms of Flow Vector, the wind speed is medium. The wind vector is directed from North-North-West and has a high frequency of 20-30 Km/h. Therefore, to the opposite of June wind flow, it does move downwards to the lower level of the courtyard especially by the living room area. Therefore, in this configuration wind is directed from the top opening of the courtyard, and from the Southern opening. As the Southern wind is very much less frequent, this explains the wind flow circulation of the wind entering from the North and less air movement in the South.

The third configuration is *Courtyard-S*-U-W. *Courtyard-S*-U-S CFD simulation analysis in June, in terms of Cell temperature illustrated to maintain a temperature value of 27^{o}C. In terms of Flow Vector, the wind speed is between slow to fast. The wide courtyard opening increases wind speed. This configuration, affects the wind speed, where the highest wind speed is at the human level. The opening configuration on the West side affects the wind speed entering and exiting the courtyard. As wind enters, the speed is at its highest, referring to the wind rose in June as it has a medium frequency of 10-20 Km/h directed from North-North-West and West. As it exists, the wind speed is at its lowest, due to the low frequency of prevailing wind in the West opening. Moreover, the opening orientation affects the temperature level at the opening, in which it reduces from 35^{o}C to 31^{o}C. The wind vector direction enters from the West opening and creates a vertical and horizontal calm eddy. The wind enters from the West directed towards the South and circulates East going North. The Northern part of the courtyard has an upward draft of wind, while the Southern part of the courtyard has a downdraft due to the horizontal movement of wind entering the courtyard.

The CFD simulation analysis in December, in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 18.5^{o}C. In terms of Flow Vector, the wind speed is between slow to fast. Wind flow is similar to June, not affected by the initial wind temperature. However, only the speed is affected, by change of season, where by the living room area, in the Northern part of the courtyard, the wind speed is higher than the Southern part due to the high frequent wind entering the courtyard from the North-North-West and West side in December.

The second shape is the C-shape. The first configuration is *Courtyard-S*-C-N. *Courtyard-S*-C-N CFD simulation analysis in June, in terms of Cell temperature illustrated to maintain a temperature value of 27^{o}C. In terms of Flow Vector, the wind speed is slow. The opening orientation and size affects the wind speed and temperature by the courtyard opening, where speed increases from slow to very fast, and temperature decreases from the initial temperature of 35^{o}C to 31^{o}C. The wind vector direction is from the North-North-West, as it is enters it escalates to a higher level to exit from the courtyard top opening. However, the wind that hits the Southern wall, which is at a level higher than 4m, circulates West to move back North and exits from the Northern opening. This configuration and opening, creates a wind pattern that is adequate at the Northern part of the courtyard, however, the Southern part of the courtyard lacks airflow. Therefore, the configuration creates a downdraft perpendicular to the wind at the Southern wall of the courtyard. By the living room area, the wind speed is higher than the South, due to the cause of having the courtyard opening windward.

The CFD simulation analysis in December, in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 18^{o}C. In terms of Flow Vector, the wind speed is between slow to very fast. The wind vector direction is from North-North-West to South, and it enters at a higher speed than in June. Wind flow circulation is adequate throughout the courtyard, being directed from North to South, however, as it moves toward South, the wind speed decreases till its slow. On the Western side, the wind is circulated, as the wind hits the Southern courtyard wall, it rotates West and directs towards the North to circulate again. The speed and wind flow does not affect the temperature at the opening, where it is maintained at an 18^{o}C.

The second configuration is *Courtyard-S*-C-S. *Courtyard-S*-C-S CFD simulation analysis in June, in terms of Cell temperature illustrated to maintain a temperature value of 27^{o}C. In terms of Flow Vector, the wind speed is medium. The opening orientation and size affects the wind speed and temperature by the courtyard opening, where speed increases to very fast, and temperature decreases from the initial temperature of 35°C to 27°C. The wind vector is directed from North of the top courtyard opening, and downdrafts to the lower ground and Southern part of the courtyard. Due to the wind entrance to the courtyard from the top opening, the North-North-East section of the courtyard does not receive airflow. As the opening is leeward, the wind flow is sucked out from the courtyard. The wind flow meets from the West and East side of the courtyard, directed to exit from the South oriented opening, which then their adjoining increases in their speed. Although the opening orientation is at the South, however, the narrow courtyard size, and the small size of the opening wind pattern it creates causes the increase of speed at the opening.

The CFD simulation analysis in December, in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 18°C. In terms of Flow Vector, the wind speed is between slow to fast. The speed and wind flow did not affect the temperature at the opening, where it is maintained at an 18°C. The wind vector direction is from North to South. Wind flow circulation is adequate throughout the courtyard, creates a vertical circulation or eddy. As the wind is directed from the top courtyard opening at the North orientation, it downdrafts South and to the lower ground, which then rotates North and is directed upward to circulate again. Therefore, this configuration affects the lower ground wind direction, as it is directed from South to North. Nonetheless, the Southern part of the courtyard has a downdraft, while the Northern part of the courtyard is directed upward. Cross ventilation in December is better than June, as air distribution is efficient all over the courtyard.

The third configuration is *Courtyard-S*-C-W. *Courtyard-S*-C-W CFD simulation analysis in June, in terms of Cell temperature illustrated to maintain a temperature value of 25°C. In terms of Flow Vector, the wind speed is slow. The opening orientation and size affects the wind speed and temperature by the courtyard opening, where speed increases to very fast in the opening, and temperature decreases from the initial temperature of 35°C to 25°C. The West opening orientation creates a suction mechanism, in which the air that is within the courtyard is sucked outside from the opening to exit. In this configuration, as the wind enters from the top Northern courtyard opening, it is directed downward, which creates a gap at the North courtyard area that lacks airflow. Hence, this is due to the low to medium frequency of wind entering the courtyard. Moreover, wind flow coming from the South part of the courtyard joins with the wind flow coming from the North.

The CFD simulation analysis in December, in terms of Cell temperature illustrated that the courtyard maintained a temperature value of 19^{o}C. In terms of Flow Vector, the wind speed is between slow to fast. The speed and wind flow did not affect the temperature at the opening, where it is maintained at 19^{o}C. The wind vector direction is from North-North-West to South. Wind circulation is adequate throughout the courtyard, creates a vertical circulation or eddy due to the high frequency of wind entering from the opening and the North top opening of the courtyard. At the human level, wind is directed South to North. The Northern part of the courtyard is directed upward, while the Southern part has a downdraft creating a stack effect. The wind speed entering from the West opening is fast. At the horizontal plane, the wind entering from the West opening is divided forming two calm eddies North and South at slow speed.

Each set of shape configuration is compared, in order to compare the two various shapes with the traditional courtyard form. The data for each shape configuration is summarized. The results are observed in terms of the relation temperature and speed relative to the configuration.

The U-shape temperature and wind speed is summarized in the graphs shown in Figure 5.23 and Table 5.5 illustrating the effect of the courtyard shape and opening orientation effect on the wind speed and flow, and courtyard temperature.

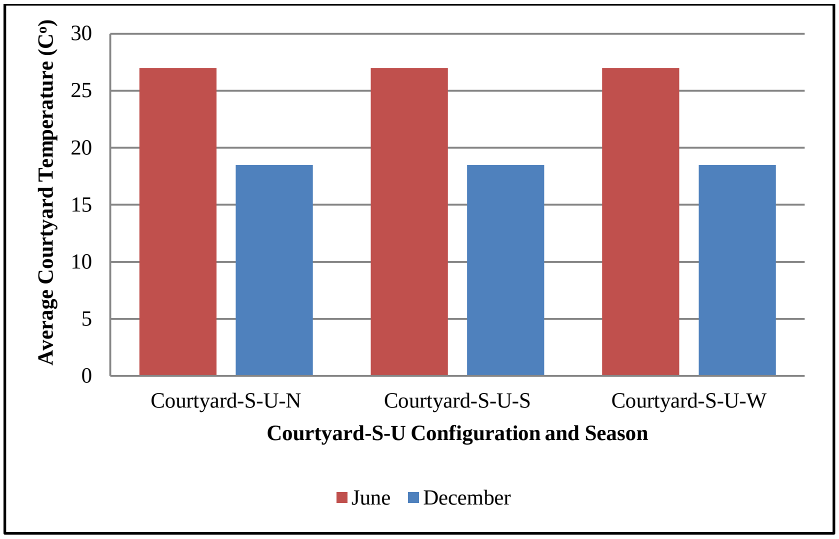

Fig.5.23. Average courtyard temperature for Courtyard-S-U configurations calculated in the specified hours in the two seasons.

Table 5.5. Summary of Courtyard-S-U configurations effect on temperature

Courtyard Configuration	Initial Temperature		Courtyard Temperature		Temperature Difference	
	June	**December**	**June**	**December**	**June**	**December**
***Courtyard-S*-U-N**	35°C	16°C	27°C	18.5°C	-8°C	+2.5°C
***Courtyard-S*-U-S**	35°C	16°C	27°C	18.5°C	-8°C	+2.5°C
***Courtyard-S*-U-W**	35°C	16°C	27°C	18.5°C	-8°C	+2.5°C

Comparing the U-shape courtyard configurations, all configurations resulted similar courtyard temperatures within both months of June of 27°C and December 18.5°C, disregarding the opening orientation. Hence, the opening orientation did not create a significant effect to differentiate between each configuration. Table 5.6 presents *Courtyard-S*-U configuration effect on wind speed. The following graph, Figure 5.24 will represent the wind speed on a scale 0.1-0.4, as 0.1 is slow and 0.4 is fast.

Table 5.6. Courtyard-S-U configurations effect on wind speed

Courtyard Configuration	**Courtyard Wind Speed**	
	June	**December**
***Courtyard-S*-U-N**	Fast 0.36m/s	Fast 0.36m/s
***Courtyard-S*-U-S**	Medium 0.21m/s	Medium 0.21m/s
***Courtyard-S*-U-W**	Fast 0.3m/s	Fast 0.3m/s

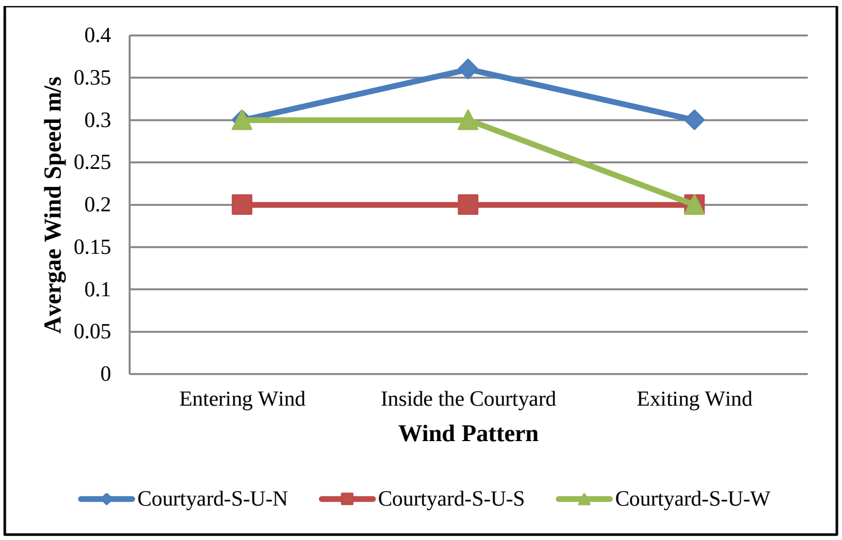

Fig.5.24. Average wind speed for Courtyard-S-U configurations of both seasons.

Moreover, as each configuration affected differently on the wind flow and speed, yet the wind flow and speed of each configuration did not affect the courtyard temperature to result differently between each. All three configurations have different size of openings, yet all are large. As the openings increase in size, the wind speed and fluctuation does not affect temperature. However, the opening size and orientation affects the wind speed and fluctuation. Change in season did not affect significantly the wind speed in any configuration. The North and West openings are similar at speed entering the courtyard due to overall site orientation as the prevailing wind with highest speed is from North, North-West. In June, the wind speed for *Courtyard-S*-U-S is relatively slower than *Courtyard-S*-U-N, due to the perpendicular opening position is leeward, and less frequent prevailing wind coming from the South. *Courtyard-S*-U-N resulted the highest wind speed due to the opening being windward, and the most fluctuating wind speed. *Courtyard-S*-U-S maintained a steady wind speed. It has the lowest wind speed due to the effect of its orientation, wind direction, and that the opening is leeward. *Courtyard-S*-U-W maintained a steady wind speed when entering and throughout the courtyard, but as it exits it reduces dramatically. This is justified by the courtyard having the largest opening.

In terms of cross ventilation, the U-shape demonstrated that *Courtyard-S*-U-N has the highest-pressure differential between the North and South side, which relates to the courtyard's wind speed and flow distribution. *Courtyard-S*-U-W has the lowest-pressure differential between North and South. Yet *Courtyard-S*-U-W has the highest courtyard pressure within the courtyard. Figures 5.25 and 5.26 illustrates the CFD simulation of cell pressure comparing *Courtyard-S*-U-N and *Courtyard-S*-U-W in the month of June.

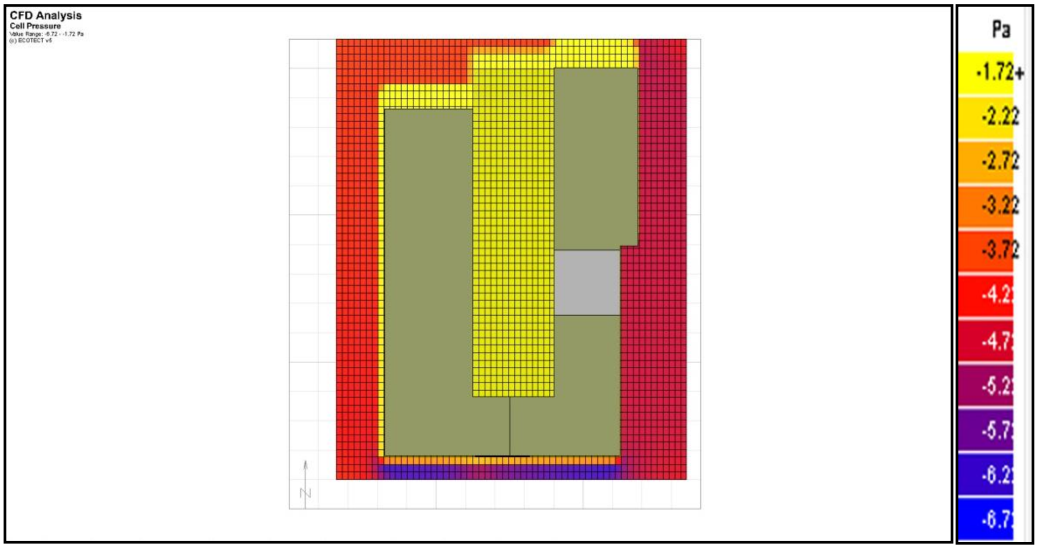

Fig.5.25. CFD Analysis of cell pressure for Courtyard-S-U-N *in June (ECOTECT)*

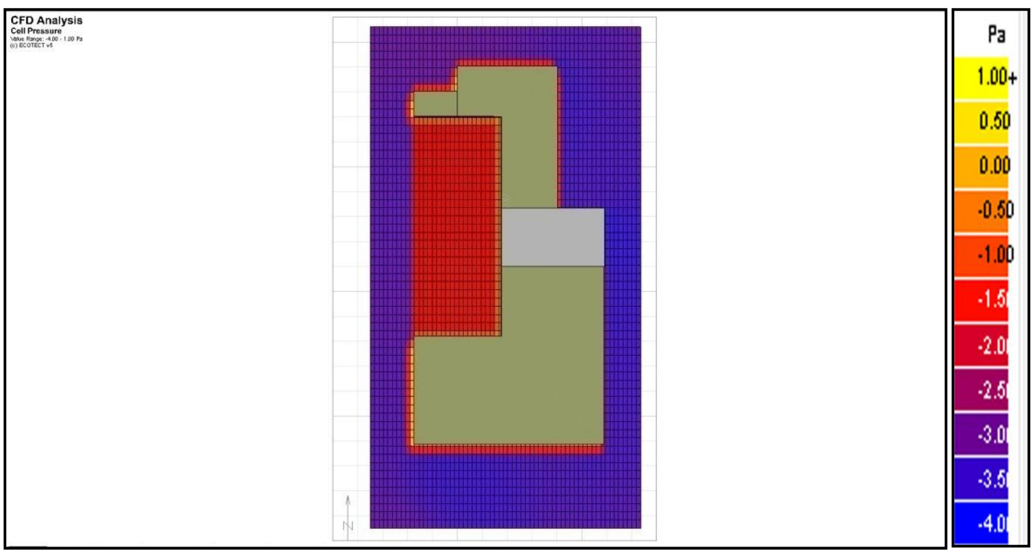

Fig.5.26. CFD Analysis of cell pressure for Courtyard-S-U-W *in June (ECOTECT)*

The C-shape temperature and wind speed is summarized in the graphs shown in Figure 5.27 and Table 5.7 illustrating the effect of the courtyard shape and opening orientation effect on the wind speed and flow, and courtyard temperature.

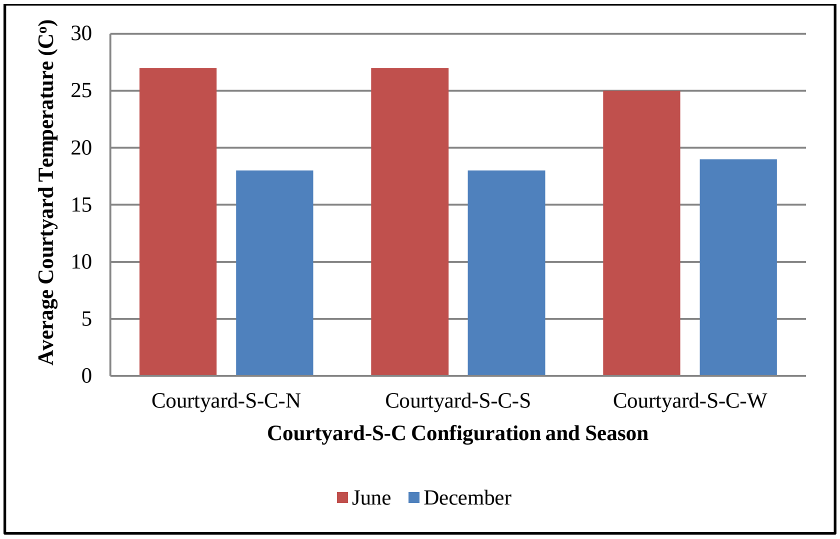

Fig.5.27. Average courtyard temperature for Courtyard-S-C configurations in the two seasons.

Table 5.7. Summary of Courtyard-S-C configurations effect on temperature

Courtyard Configuration	Initial Temperature		Courtyard Temperature		Temperature Difference	
	June	December	June	December	June	December
***Courtyard-S*-C-N**	35^{o}C	16^{o}C	27^{o}C	18^{o}C	-8^{o}C	+2^{o}C
***Courtyard-S*-C-S**	35^{o}C	16^{o}C	27^{o}C	18^{o}C	-8^{o}C	+2^{o}C
***Courtyard-S*-C-W**	35^{o}C	16^{o}C	25^{o}C	19^{o}C	-10^{o}C	+3^{o}C

Comparing the C-shape courtyard configurations, the openings reduced the temperature in June, and increased the temperature in December, hence modifying the courtyard temperature in relation to the exterior. *Courtyard-S*-C-W had the best effect from the courtyard opening, as the courtyard temperature reduced 10 degrees from the initial temperature surrounding the building. In addition, in December it demonstrated the best increase in temperature by 3 degrees. The combination of having the highest fluctuating wind speed, small opening size, and opening orientation situated in the middle of the Western side in relation to the direction of the prevailing wind, affected the temperature difference in having the highest decrease in

June, and increase in December. Table 5.8 tabulates Courtyard-S-C configurations effect on wind speed. The following graph, Figure 5.28 will represent the wind speed on a scale 0.1-0.4, as 0.1 is slow and 0.4 is fast.

Table 5.8. Courtyard-S-C configurations effect on wind speed

Courtyard Configuration	**Courtyard Wind Speed**	
	June	**December**
***Courtyard-S*-C-N**	Slow 0.14m/s	Slow 0.14m/s
***Courtyard-S*-C-S**	Medium 0.21m/s	Medium 0.21m/s
***Courtyard-S*-C-W**	Slow 0.14m/s	Slow 0.14m/s

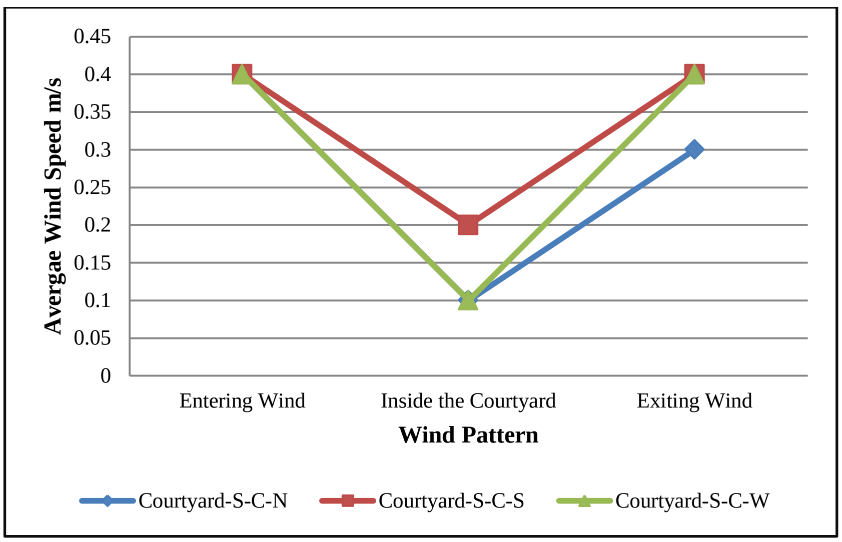

Fig.5.28. Average wind speed for Courtyard-S-C configurations of both seasons.

Comparing the C-shape courtyard configurations, all configurations resulted similar wind speed entering the courtyard, disregarding the opening orientation. This justifies the effect of the opening size in both shapes. As the smaller the opening size, the higher the wind speed, in comparison to the U-shape.

Courtyard-S-C-S had the highest overall wind speed within the courtyard. Following it is *Courtyard-S*-C-W. As stated earlier, the Northern and Western opening are similar in speed due to the building orientation as the prevailing wind with highest speed is from North, North-West. This is similar to the U-shape.

The C-shape demonstrated that *Courtyard-S*-C-W has the highest-pressure differential between the North and South side, which relates to the courtyard's wind speed and flow distribution. *Courtyard-S*-C-N has the lowest-pressure differential between North and South. Yet *Courtyard-S*-C-N has the highest courtyard pressure within the courtyard. Figure 5.29 and 5.30 illustrates the CFD simulation of cell pressure comparing *Courtyard-S*-C-N and *Courtyard-S*-C-W in the month of June.

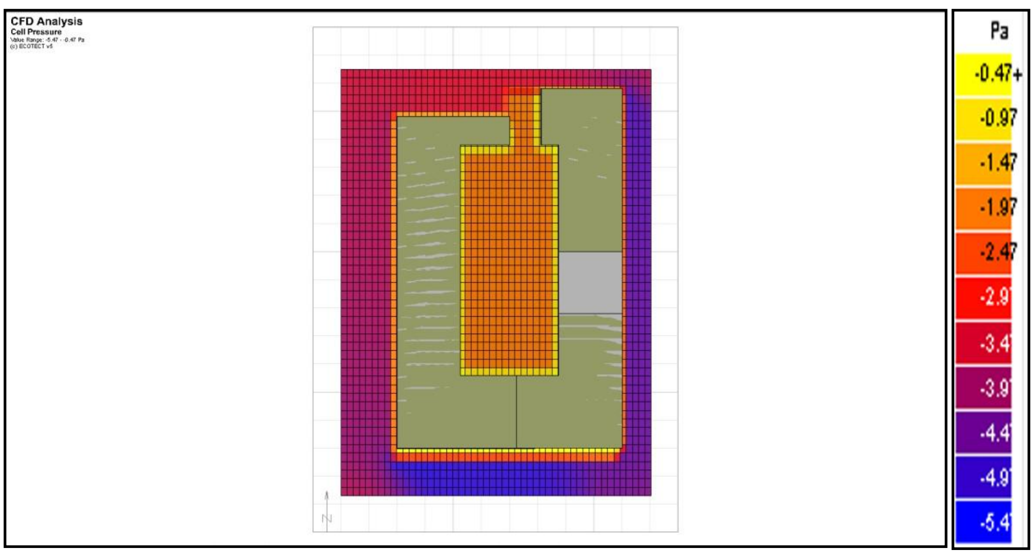

Fig.5.29. CFD Analysis of cell pressure for Courtyard-S-C-N *in June (ECOTECT)*

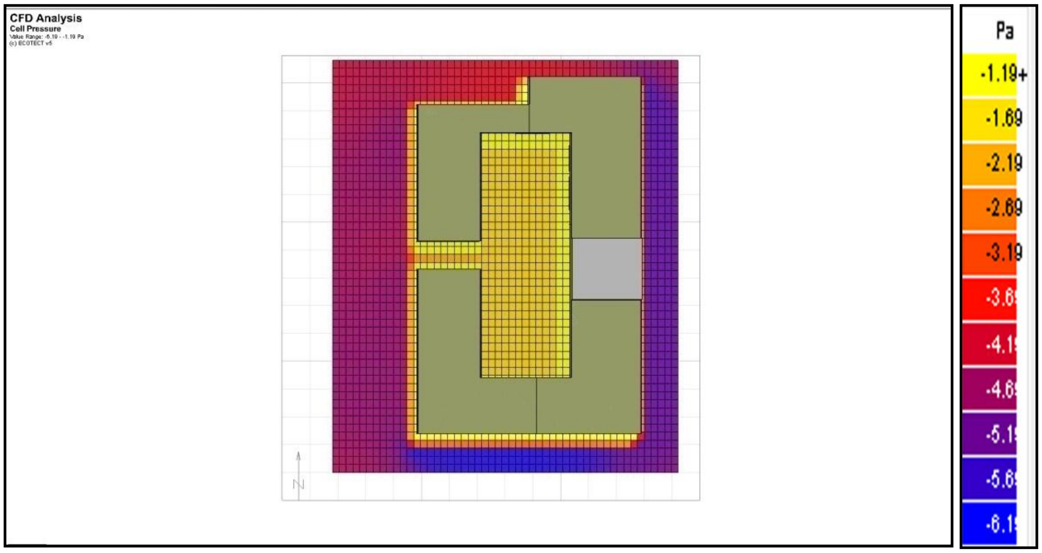

*Fig.5.30. CFD Analysis of cell pressure for Courtyard-S-*C-W *in June (ECOTECT)*

Each configuration in terms of opening size and opening orientation affected differently on the wind flow and speed within the courtyard, and speed fluctuation, hence affecting the courtyard temperature. *Courtyard-S-*C-N and *Courtyard-S-*C-S courtyard opening have the same temperature difference. This is justified by having less speed fluctuation and less frequent prevailing wind affecting the air distribution within, as *Courtyard-S-*C-W illustrates dramatic wind speed fluctuation with a very fast speed entering the courtyard, a slow speed within the courtyard, and an increase in speed to fast exiting the courtyard. Temperature at the opening and *Courtyard-S-*C-S is less than *Courtyard-S-*C-N because wind exits at a parallel movement of the wind, not perpendicular to the wind, and because of the frequent prevailing wind direction as South is less frequent. Change in season did not affect significantly the wind speed within the courtyard in any configuration.

Comparing the U-shape to the C-shape, the effect of the opening is significantly highlighted in both shapes. As the courtyard opening is smaller in size, the higher the wind speed regardless of the opening orientation. Furthermore, as the opening increases in size, such as the U-shape, the wind speed and fluctuations does not affect temperature. As the U-shape has a high wind speed within the courtyard, and the C-shape has a low speed within the courtyard. Therefore, the opening size manipulates and affects wind speed and fluctuation. Each shape has a different reason that results into similar temperature. The U-shape delivered 8^{o}C of temperature difference, because of its opening size, while the C-shape delivered 8^{o}C of temperature difference, because of the wind speed and fluctuation. The U-shape large opening size cancels out the high wind speed within the courtyard, which affects the courtyard temperature. As the North and South C-shape has low wind speed within the courtyard cancels out the effect of the entrance speed, which results into the same temperature difference of the U-shape. If the U-shape reduces opening size, then the wind speed will affect the temperature to modify the courtyard temperature. Hence, the situation will be the same as the C-shape.

Both shapes are similar in two ways, both demonstrated that orientation does not affect temperature significantly, and that the opening orientation and size affected the wind flow, speed, and fluctuation.

From all configurations of both shapes, *Courtyard-S*-C-W stands out due to the highest fluctuating wind speed from entrance to within the courtyard, having a calm average wind within the courtyard similar to *Courtyard-T*. Comparing *Courtyard-S*-U-W and *Courtyard-S*-C-W, *Courtyard-S*-C-W air flow performs better in modifying the courtyard temperature due to the opening size which helps to maintain a higher temperature differential. Although within the courtyard the wind speed of the *Courtyard-S*-U-W is higher, but it is eliminated by the large opening size. *Courtyard-S*-C-W has calm average wind within the courtyard resulting in the highest decrease of temperature in June.

Courtyard-T temperature is summarized in the graphs shown in Figure 5.31 and Table 5.9 illustrating the effect of the courtyard shape and opening orientation effect on the courtyard temperature.

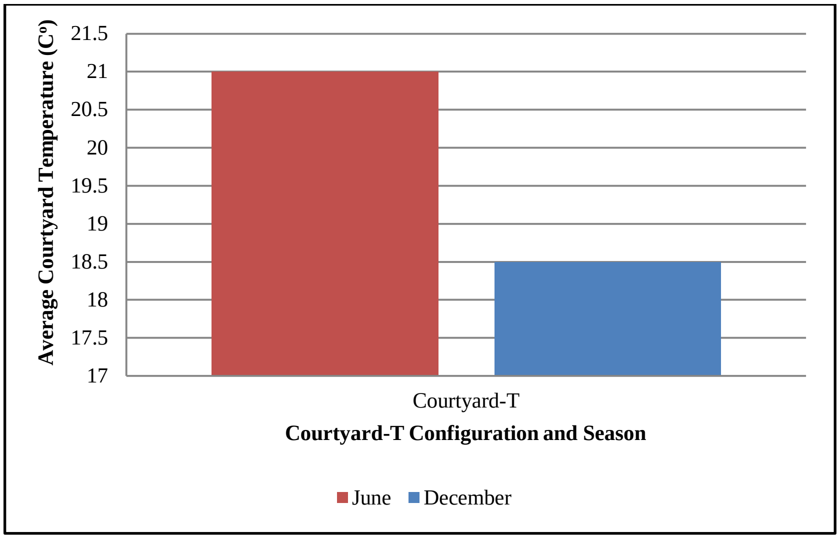

Fig.5.31. Average courtyard temperature for Courtyard-T configuration in the two seasons.

Table 5.9. Summary of Courtyard-T configuration effect on temperature

Courtyard Configuration	Initial Temperature		Courtyard Temperature		Temperature Difference	
	June	December	June	December	June	December
Courtyard-T	35°C	16°C	21°C	18°C	-14°C	+2°C

Comparing the semi-enclosed courtyard "*Courtyard-S*" with the traditional courtyard "*Courtyard-T*" performance, *Courtyard-T* demonstrates the highest courtyard temperature difference between the exterior and the courtyard by 14°C in June, as modifying the heat of the summer month is crucial. Nonetheless, modifying the temperature in December is as significant as June, due to the ability of achieving thermal comfort in the courtyard to perform outdoor activities. *Courtyard-T* average speed in both seasons is slow, presenting a calm wind. Nonetheless, of its medium pressure differential, the courtyard developed a very high-pressure zone. As air movement and distribution are equally important in mitigating the courtyard temperatures, the cross ventilation circulation in the airflow pattern interpreted to occur across the building as being driven by wind pressure, and wind speed frequency. In the case of a fully enclosed courtyard, having a low airflow and a non-fluctuating speed results into a higher temperature differential. This is in relation to having a less frequent hot wind entering the courtyard in June. *Courtyard-S*-C shape is similar to *Courtyard-T* in wind speed within the courtyard, due to the high ratio of enclosure.

Although the building is not oriented at any degrees, yet, as the prevailing wind comes from North-North-West at high frequency in December and medium in June, it is considered to flow at a 45^{o} from the building. Hence, referring to the Koch-Nielsen that cross ventilation and air movement increase by having the building oriented 45^{o} to the wind (2002, p.126).

5.1.4. Solar Access Analysis Results

The insolation analysis simulates the average hourly total, direct, and diffuse solar radiation on the courtyard surface (ECOTECT). The simulation is carried out between 5 a.m. to 5p.m. in June, and 7a.m. to 3p.m. in December. The timing is set as stated is based on the Direct Solar Gain analysis calculation as it calculates the month for June till 5p.m. and in the month of December till 3p.m. due to the early sunrise and late sunset in June and late sunrise and early sunset in December. *Courtyard-T* average hourly radiation value in June is 123.35Wh, and in December is 70.70Wh. The solar radiation distribution within the courtyard in June, presents the East side of the courtyard receiving higher solar radiation than the West side, and the South section of the courtyard receives the lowest solar radiation. In December, the distribution is different, as the middle of the courtyard receives the highest solar radiation in comparison to all the other sides. Figure 5.32 and 5.33 demonstrates the hourly average solar radiation for *Courtyard-T* in June and December. Refer to all results in Appendix D.

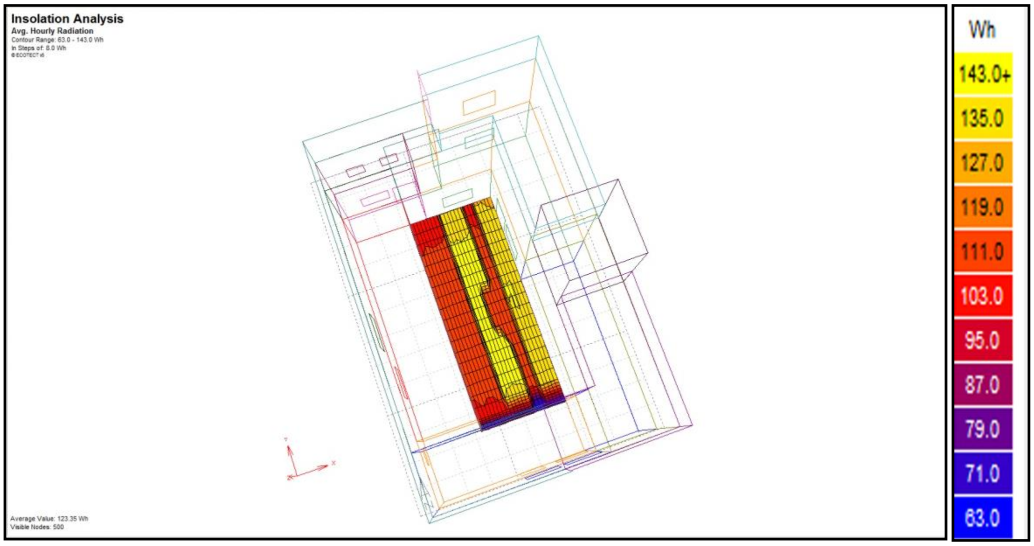

Fig.5.32. The Average Hourly Radiation analysis for Courtyard-T in June(ECOTECT)

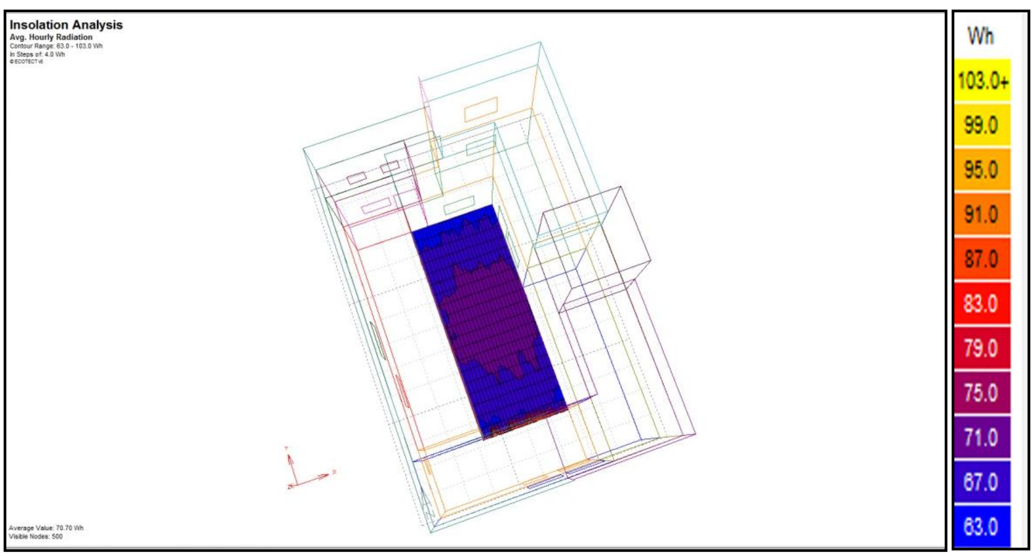

Fig.5.33. The Average Hourly Radiation analysis for Courtyard-T in December(ECOTECT)

Each orientation for *Courtyard-S*-U is simulated. *Courtyard-S*-U-W exposes the courtyard to the highest levels of radiation within both June and December. In June, it receives an average of 264.75Wh, and in December, it receives an average of

144.15Wh. However, in June, *Courtyard-S*-U-S receives lower solar radiation of 158.50Wh, Figure 5.34. In December, *Courtyard-S*-U-N receives the lowest solar exposure of 96.66, Figure 5.35. This is due to the courtyard configuration, as the West courtyard orientation presents a larger courtyard opening.

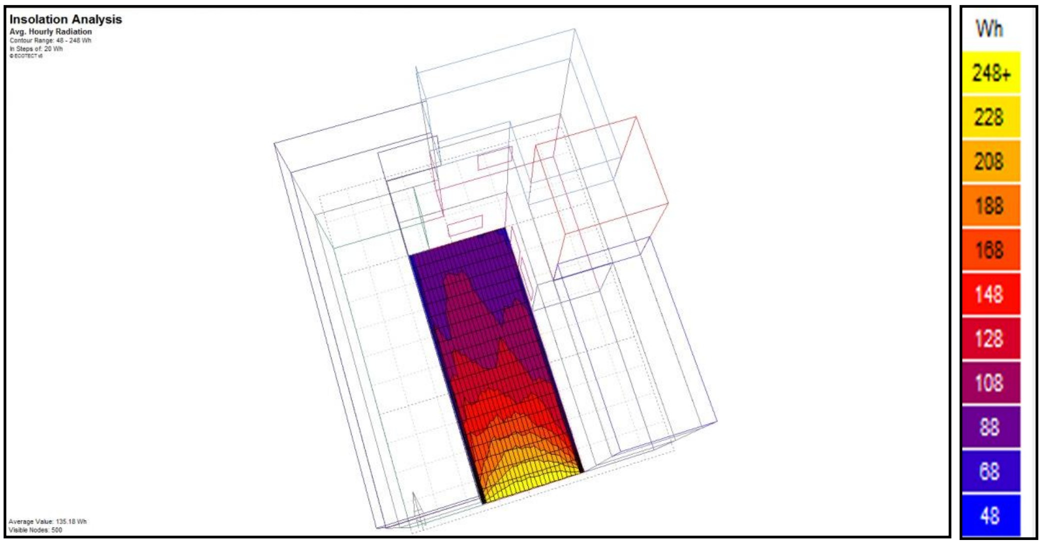

Fig.5.34. The Average Hourly Radiation analysis for Courtyard-S-U-S in June(ECOTECT)

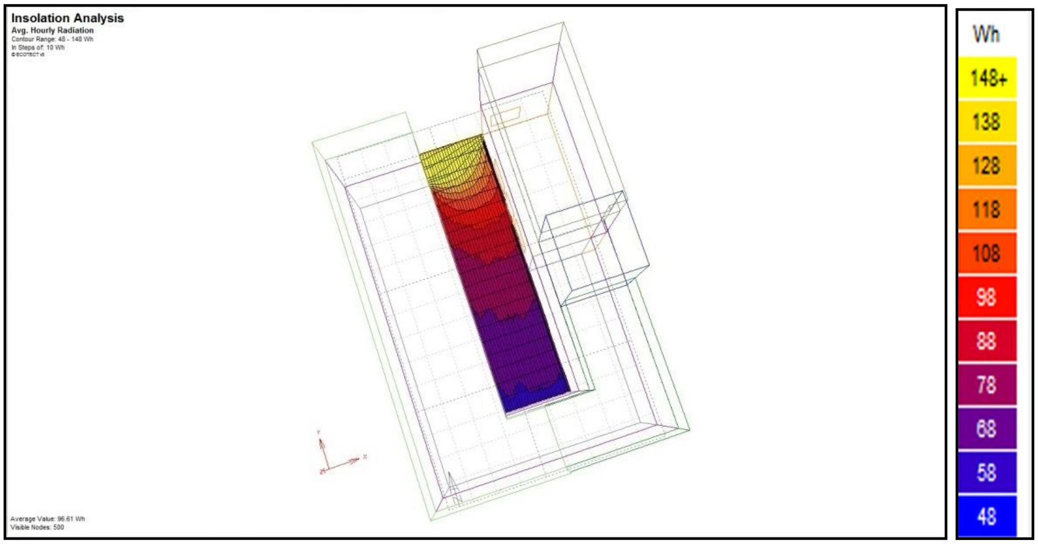

Fig.5.35. The Average Hourly Radiation analysis for Courtyard-S-U-N in December(ECOTECT)

In terms of solar radiation distribution within the courtyard, in June and December, *Courtyard-S*-U-W is the best well distributed, as the solar radiation intensity reduces in a smooth form from the opening towards the East wall of the courtyard, Figure 5.36. The other two opening orientation presents dramatic change along the depth of the courtyard between solar radiations levels in terms of distribution.

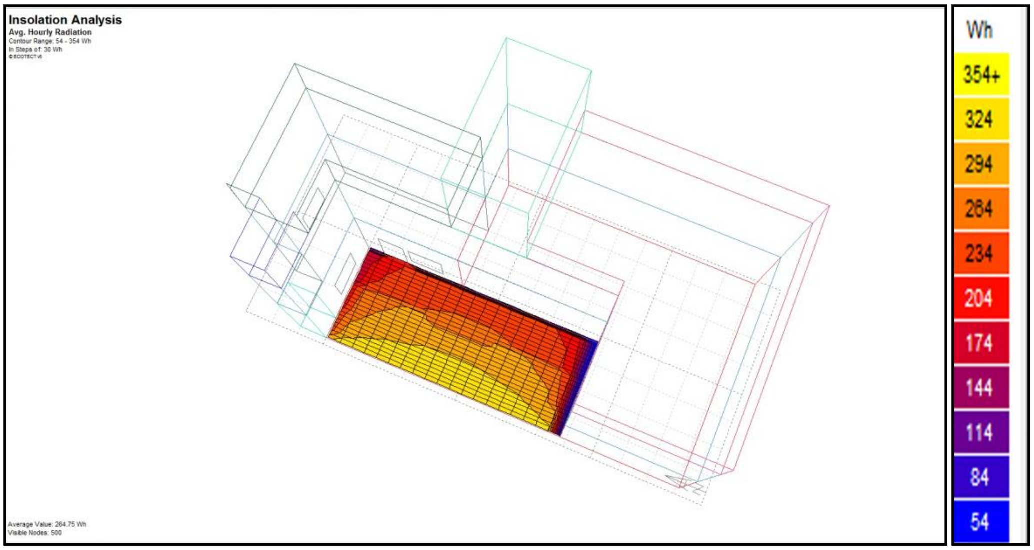

Fig.5.36. The Average Hourly Radiation analysis for Courtyard-S-U-W in June(ECOTECT)

Within *Courtyard-S*-C opening orientation, *Courtyard-S*-C-W receives the lowest exposure levels within both months of June and December, Figure 5.37 and 5.38. In June, it receives 127.8Wh, and in December, it receives 70.47Wh. However, the highest levels oppose each other as season changes. In June *Courtyard-S*-C-S receives the highest solar radiation of 138.55Wh, while in December, *Courtyard-S*-C-N receives the highest solar radiation of 83.5Wh. In December, between *Courtyard-S*-C-N and *Courtyard-S*-C-S, radiation levels do not have a great difference. This exposure levels are due to the courtyard configuration and the affect of the openings orientation in relation to the sun position allowing solar exposure.

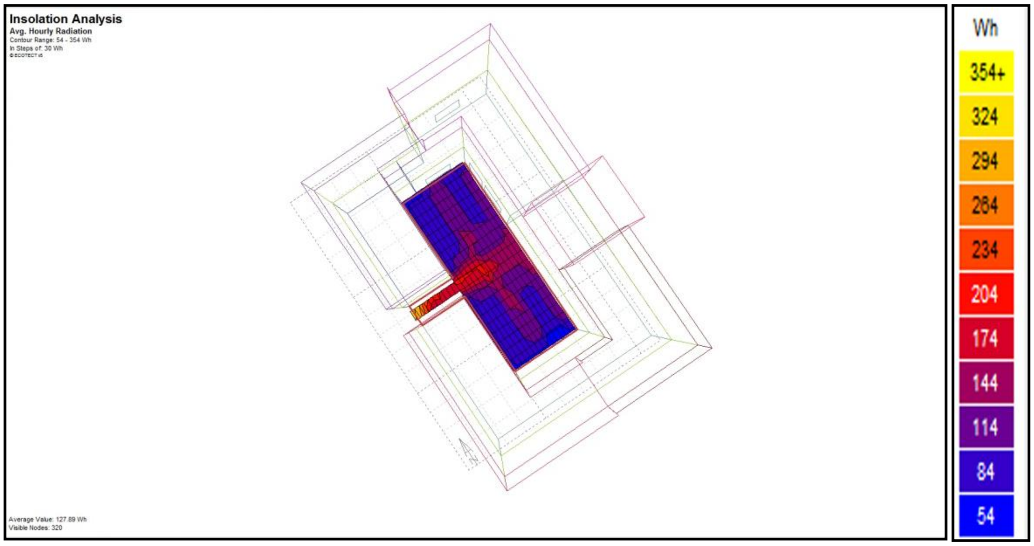

Fig.5.37. The Average Hourly Radiation analysis for Courtyard-S-C-W in June(ECOTECT)

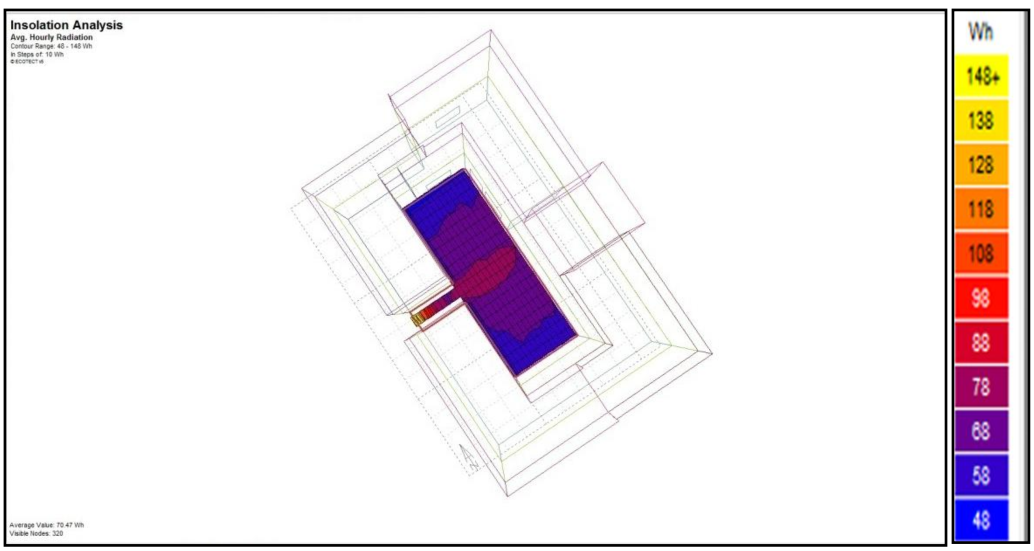

Fig.5.38. The Average Hourly Radiation analysis for Courtyard-S-C-W in December (ECOTECT)

In terms of solar radiation distribution on the courtyard surface, in June, *Courtyard-S-*C-W presents the best light distribution. *Courtyard-S-*C-W divides the radiation distribution from the middle section of the courtyard towards North and South. The

North and South sections of the courtyard have equal amount and distribution of solar radiation, as the opening has the highest solar radiation. The average radiation level is well distributed within the courtyard. *Courtyard-S*-C-S and *Courtyard-S*-C-N divides the radiation distribution between East and West. However, the light is not distributed equally in both sections for both courtyards.

In December, *Courtyard-S*-C-W has the best well distributed solar radiation, as light is distributed North and South equally. On the other hand, *Courtyard-S*-C-S and *Courtyard-S*-C-N create spaces within the courtyard along the opening section with excessive light that causes discomfort, and spaces by the walls that receive low exposure.

Comparing *Courtyard-S*-U and *Courtyard-S*-C, *Courtyard-S*-U has the highest solar exposure levels during both season's summer and winter. *Courtyard-S*-C-W receives the least solar radiation. This is directly relevant to the courtyard shape and large opening size that increases the courtyard surface in receiving radiation.

Comparing *Courtyard-T* and *Courtyard-S*, *Courtyard-T* receives the least solar exposure than *Courtyard-S*-C-W during the month of June. This is due to the fully enclosed structure that provides more shade. Yet, in December, it receives higher solar radiation than *Courtyard-S*-C-W with few degrees. Figure 5.39 illustrates both courtyards in June and December. The difference between them in December is 0.23Wh. However, in December, a higher solar exposure level is needed to modify the courtyard by increasing the warmth levels to provide a more comfortable outdoor space. Therefore, *Courtyard-T* provides more comfort levels than *Courtyard-S*-C-W in both months of June and December.

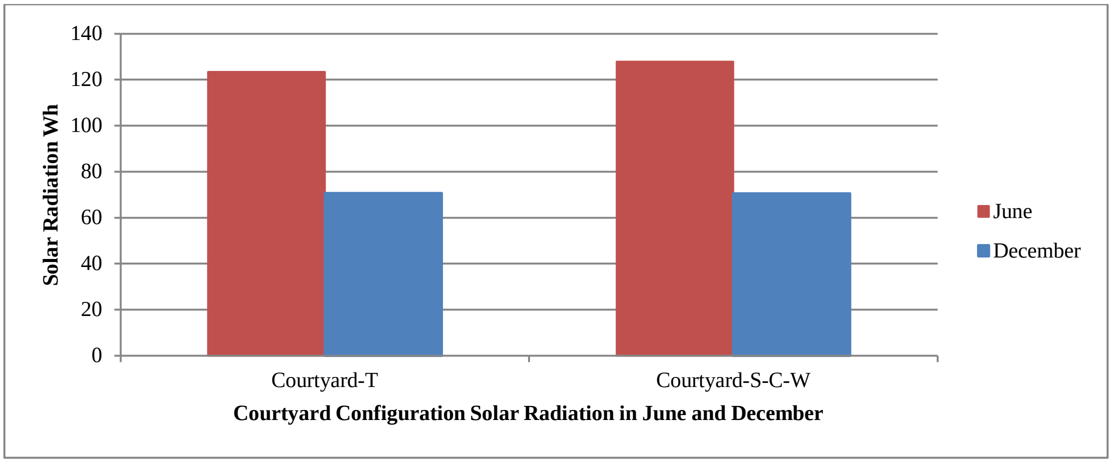

Fig.5.39. A comparison of solar radiation between Courtyard-T and Courtyard-S-C-W in June and December

5.1.5. Shading Results

Solar shading is directly linked to solar exposure and providing thermal comfort. Solar exposure and shading impacts on the cooling load and heating load. Shading range is viewed for the 21st of June and December at 9 in the morning, 12 noon, and 3 in the afternoon. Highest solar radiation is received between 11 a.m. to 1p.m. *Courtyard-T* shadow distribution in June is fully shaded. The intensity of the shade and the shadow distribution decreases at noon due to the increase of solar exposure. At 12 p.m., the South and West courtyard walls enjoy a small strip of intense shade, while the other walls receive less shade. Therefore, the living room receives less shade being exposed to more solar radiation as the sun is at highest position. In December, the courtyard is fully shaded between 9a.m. and 3p.m. However, at 12 p.m. the living room walls are exposed to solar radiation. Figure 5.40 shows the shadow casting range for *Courtyard-T* in June and December at all studied hours. Refer to all results in Appendix E.

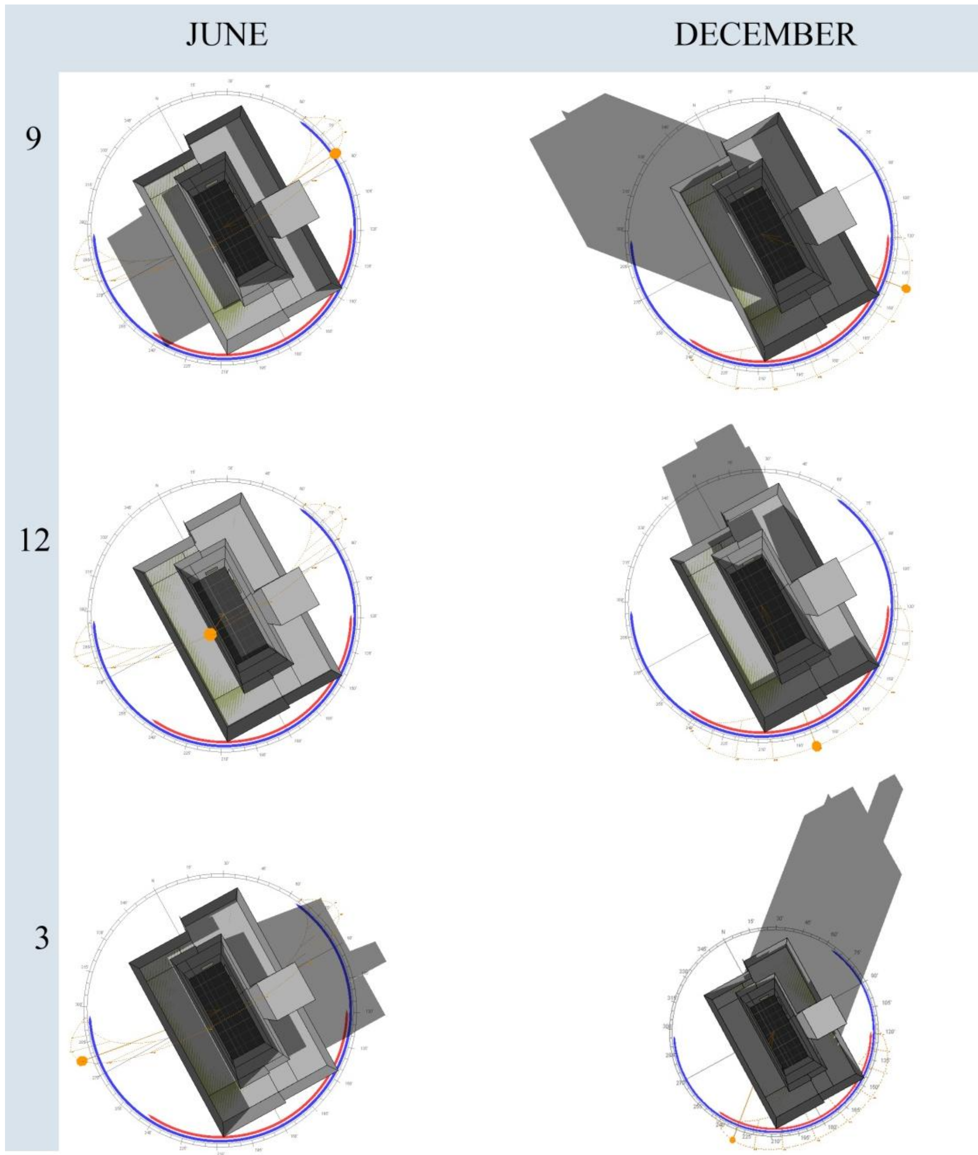

Fig.5.40. Courtyard-T shading analysis for June and December (ECOTECT)

Courtyard-S-U demonstrates the effect of the opening orientation on shadow range. In June, *Courtyard-S*-U-S demonstrates the highest percentage of shade, where at 12 p.m. the courtyard receives 60% of shadow, Figure 5.41. *Courtyard-S*-U-W receives the least amount of shade, specifically at the peak hour of solar heat gain at 12 p.m. as it receives 56% of shadow, Figure 5.42. The large courtyard opening as the configuration lacks a West wall penetrates a higher level of solar exposure in *Courtyard-S*-U-W. The South opening orientation receives the most amount of shadow and is least exposed to solar radiation demonstrates the effect of the opening orientation which provides more shade. The living room is exposed to solar radiation and less shade in *Courtyard-S*-U-N due to the North opening which allows the living room walls to receive solar exposure at noon and afternoon. Nonetheless, at 9a.m. *Courtyard-S*-U-N opening is exposed to solar radiation.

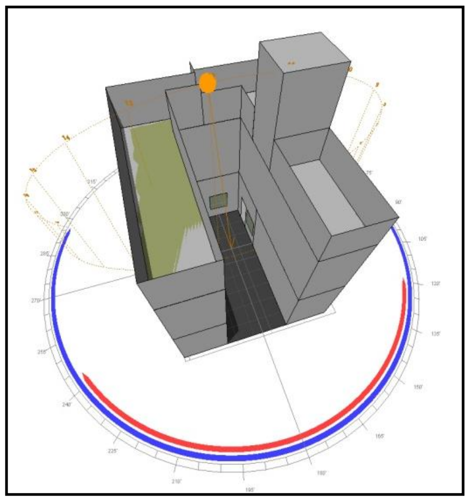

Fig.5.41. Courtyard-S-U-S shading analysis for June at 12 p.m. (ECOTECT)

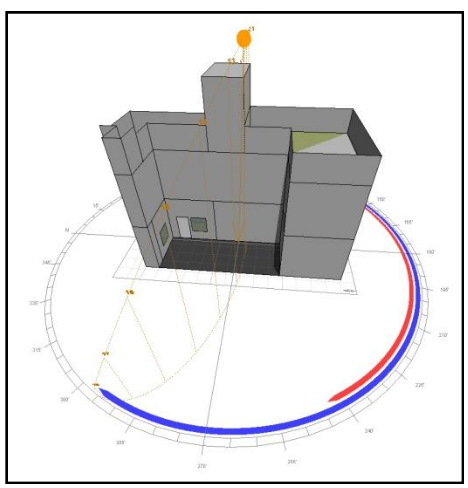

Fig.5.42. Courtyard-S-U-W shading analysis for June at 12 p.m. (ECOTECT)

In December, *Courtyard-S*-U-S receives the least amount of shade and is exposed to highest amount of solar radiation, Figure 5.43. At noon, it receives 60% of shade, while *Courtyard-S*-U-N receives 83%. *Courtyard-S*-U-W receives the highest amount of shade, specifically at noon with 85% of shade, Figure 5.44.

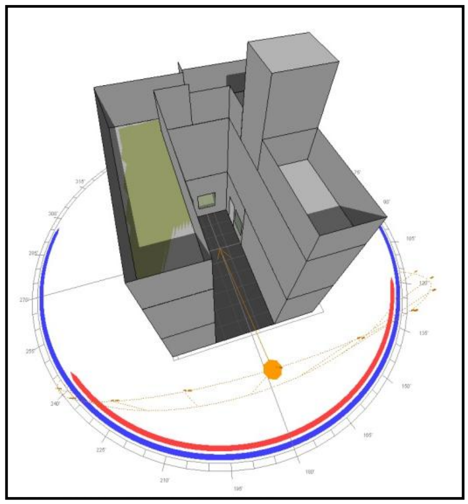

Fig.5.43. Courtyard-S-U-S shading analysis for December at 12 p.m. (ECOTECT)

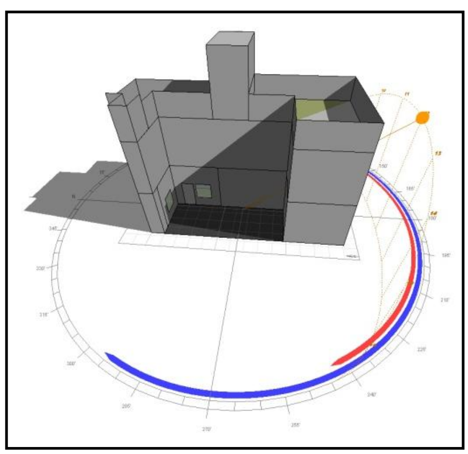

Fig.5.44. Courtyard-S-U-S shading analysis for December at 12 p.m. (ECOTECT)

Courtyard-S-C, In June, *Courtyard-S*-C-S receives the highest percentage of shade at 12 p.m. of 64%, Figure 5.45, 5.46, 5.47. *Courtyard-S*-C-N and *Courtyard-S*-C-W receive an equivalent percentage of shade of 59%. All three courtyards, at 9a.m. and 3p.m. are fully shaded, however, at 12p.m. the courtyard and the living room walls are exposed which increases solar heat gain. The similar behavior is due to the small opening size.

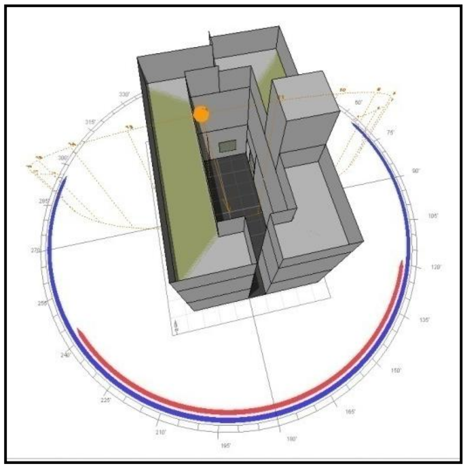

Fig.5.45. Courtyard-S-C-S shading analysis for June at 12 p.m. (ECOTECT)

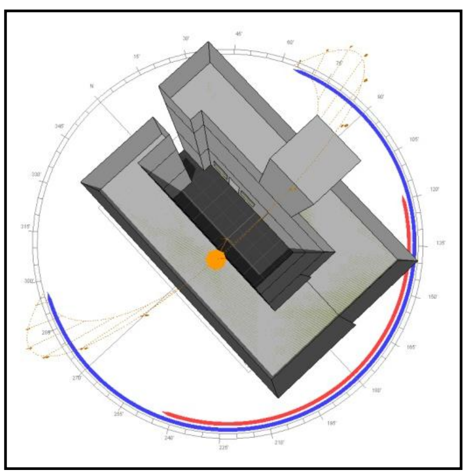

Fig.5.46. Courtyard-S-C-N shading analysis for June at 12 p.m. (ECOTECT)

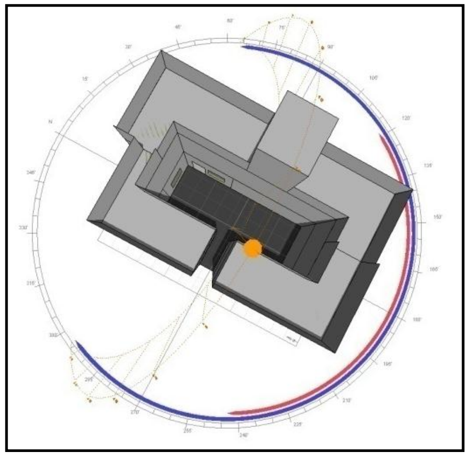

Fig.5.47. Courtyard-S-C-W shading analysis for June at 12 p.m. (ECOTECT)

In December, *Courtyard-S*-C-S receives the least percentage of shade of 86%, and *Courtyard-S*-C-N receives the highest percentage of shade of 96%. *Courtyard-S*-C-W is relatively close to *Courtyard-S*-C-N, as it receives 93% of shade during the peak hour.

Comparing *Courtyard-S*-U and *Courtyard-S*-C in terms of openings orientation, the Northern opening orientation at noon allows a large portion of the courtyard surface and living room walls to be highly exposed to solar radiation, hence the North and East courtyard walls are fully exposed during June and December. At 3p.m. a portion of the living room wall is exposed.

The South opening orientation, in June, at peak hours, both the courtyard and living room are fully exposed. However, in December, at noon, *Courtyard-S*-C provides more shade, hence is less exposed to solar radiation than *Courtyard-S*-U.

The West opening orientation, in June and December, *Courtyard-S*-C is less exposed to solar radiation and receives more shade, due to *Courtyard-S*-U-W large courtyard opening. At 12p.m. and 3 p.m., *Courtyard-S*-U-W exposes the courtyard and living room fully.

Courtyard-T shadow range is similar to *Courtyard-S*-C due to high percentage of courtyard enclosure, as *Courtyard-S*-C has small size openings. *Courtyard-T* receives higher amount of shade due to it's fully enclosure.

5.2.Discussion

The calculations results complement each other. From all simulations *Courtyard-T* and *Courtyard-S*-C-W resulted in providing the most efficient and comfortable microclimatic condition in comparison to other courtyard configurations. As *Courtyard-S*-C-W semi-enclosed courtyard configuration is similarly relevant to the fully enclosed courtyard.

Relating the simulations to one another, solar exposure analysis results complements the shading simulations. *Courtyard-T*'s courtyard is exposed to low solar radiation, hence, the courtyard surface and the internal courtyard walls are mostly shaded. Therefore, it receives low solar heat gain. However, it receives a higher illuminance level within the living room than *Courtyard-S*-C-W which the most comfortable adequate illuminance level and distribution. This is justified to the courtyard geometry, as *Courtyard-S*-C-W is narrower by having a smaller width than *Courtyard-T* due to the opening that decreases the courtyard width, which effects the living room configuration. Although, in December, *Courtyard-T* provides adequate illuminance levels and distribution that provides occupants comfort. All courtyard configurations receive higher illuminance levels within the hot month of June, yet *Courtyard-T* and *Courtyard-S*-C-W are the most comfortable in receiving adequate illuminance level and distribution.

Moreover, the CFD analysis backs up the positive performance of *Courtyard-T* and *Courtyard-S*-C-W in modifying the courtyard and living room microclimatic condition. CFD results presents that *Courtyard-T* and *Courtyard-S*-C-W achieve the best temperature difference within the courtyard comparing to the exterior temperatures. Nonetheless, the courtyard configuration and shape demonstrates the effect on the adequate air distribution within the courtyard. *Courtyard-T* provides the highest temperature difference between the external surrounding and the courtyard. Hence, this demonstrates the complementary effect of high shading percentage within the courtyard, in comparison to the exterior surrounding that assists in mitigating the courtyard temperatures.

Relating all simulations to the living room thermal comfort, results provide that *Courtyard-T* and *Courtyard-S*-C-W are thermally comfortable. However, *Courtyard-S*-C-W living room presents the highest hours of comfort without the need of HVAC. This is clearly related to the high percentage of courtyard enclosure that relates to low solar exposure, adequate daylight penetration, which achieves low solar heat gain. However, *Courtyard-T* performs best by achieving the lowest solar heat gain and the highest temperature differential.

The hourly temperature of *Courtyard-S*-U demonstrates that the average levels are higher than *Courtyard-S*-C. This is justified to its relation to the wind distribution and flow, as *Courtyard-S*-U has higher wind speed within the courtyard than *Courtyard-S*-C. From the study, prevailing wind speed and pressure assists in increasing the average wind temperature for *Courtyard-S*-U, however, the configuration and the opening size of *Courtyard-S*-C assists in receiving less solar heat gain that results in receiving lower average temperature.

Courtyard-S-U receives higher solar exposure due to the low shadow range. This is justified to the courtyard shape and the large opening size. Specifically *Courtyard-S*-U-W that has the highest solar heat gain due its large courtyard opening, hence, exposing it to high solar radiation.

The courtyard shape, opening orientation, and opening size reflected on each of the studied models performance. As the opening size of the courtyard increases as in *Courtyard-S*-U case, the built form is exposed to higher solar radiation, simultaneously increasing solar heat gain, which then reduces indoor and outdoor thermal comfort. Hence, the microclimatic conditions are poor and it increases the cooling load. However, the increase of courtyard opening size has one benefit, in which it airflow within the courtyard are at high speed that assists in mitigating the courtyard temperatures. The opening orientation demonstrates an effect, however, by comparing each orientation, *Courtyard-S*-U-W presents the worst case, and that is relevantly related to the bigger courtyard opening area, which increases the courtyard exposure.

In the case of *Courtyard-S*-C shape, due to its high enclosure in relation to the small size openings, the courtyard and the indoor spaces receive a higher percentage of shade, hence decreasing solar exposure and solar heat gain. Simultaneously, with the decrease of solar exposure, the shape affects on decreasing and controlling the natural lighting illuminance levels penetrating the living room. With less solar radiation, the living room receives less solar radiation that increases its thermal comfort and reduces the need of HVAC. Contrary to *Courtyard-S*-U, airflow within the courtyard is slow and that is due to the opening size and building shape in relation to the prevailing winds. However, both courtyard shapes mitigate the courtyard wind temperature, but to different reasons. *Courtyard-S*-U is mitigated due to the high wind speed, while *Courtyard-S*-C is mitigated to its lower solar exposure. However, overall *Courtyard-S*-C provides a better modified microclimatic condition in terms of daylight and airflow distribution within the courtyard and living room. The opening orientation demonstrated its affect in relation to the solar altitude and the frequent prevailing wind direction, which mitigates and provides thermal comfort. The North opening had the advantage of more frequent prevailing wind, however, due to the high sun altitude and the living room is positioned in the North, it decreased the comfort levels. The South opening orientation, in December, was exposed to higher percentage of solar radiation due to the sun altitude and angle within the winter month. Moreover, the South orientation receives the least frequent prevailing wind that affects the airflow performance within the courtyard in providing comfort. The West orientation enjoys several benefits. First, it has high frequent prevailing wind entering the courtyard to maintain an adequate airflow. Second, The opening orientation in relation to the airflow entering, it allows a better air distribution by having an equal air distribution on the North and South sections of the courtyard. Third, due to the solar altitude movement during the day in relation to the full enclosure of the courtyard on the North and South, the courtyard, and the living room is less exposed to excessive solar radiation. Fourth, daylight penetration within the living room is controlled with the most adequate intensity, and well distribution.

Furthermore, the window opening position within the courtyard walls in relation to the courtyard openings affect the light distribution and comfort within the living room. As the North openings orientation positions both windows on the Eastern wall of the courtyard, it positions the courtyard in a situation of higher and not a well distributed illuminance. However, as in the case of the South and West orientation, the living room is well protected from intensive solar radiation.

The month of December is equally important to the crucial month of June in modifying the courtyard microclimatic condition and providing thermal comfort within the living room. By modifying the cold month, heating load is reduced. Therefore, the results of *Courtyard-T* and *Courtyard-S*-C-W demonstrate an equal efficient performance in December.

Chapter 6

Conclusion and Recommendations

6.1 Conclusion

In this study the aim and objectives has been successfully achieved, as various semi-enclosed courtyard configurations has been analyzed and compared the fully enclosed courtyard in terms of performance and modifying the microclimatic condition.

This study demonstrated that the courtyard enclosure and configuration affects the courtyard microclimatic condition. Previous research have substantiated that the traditional fully enclosed courtyard as an introverted building structure modifies the microclimatic conditions in comparison to the contemporary extroverted building structure. This study showed that ratio of the courtyard enclosure and opening orientations affects the microclimatic conditions in different behaviors. Beyond the relation of the courtyard configuration, shape and geometry, opening and orientation, the living room configuration, geometry, and opening position affects the microclimatic behavior. The courtyards and living room for the various configurations are equivalent in area, yet their geometry, configuration, and shape differs which demonstrates an effect on their performance.

The most efficient courtyard configuration in modifying the courtyard and living room microclimatic condition is the fully enclosed courtyard referred to *Courtyard-T*. It has recorded from all simulations to perform best. It receives the lowest solar radiation in June of 123.35Wh, and adequate solar radiation in December of 70.7Wh. Simultaneously, solar exposure affects the building solar heat gain, as *Courtyard-T* receives the lowest direct and indirect solar heat gain. Despite its highest hourly average temperature within the living room, it recorded to have the highest temperature difference between the exterior and the interior living room of 3.1^{o}C in June and 4.4^{o}C in December.

A fully enclosed courtyard configuration represented as *Courtyard-T* performs best. From the semi-enclosed configuration, *Courtyard*-S-C-W performs best. Furthermore, despite the low solar radiation, *Courtyard-T* recorded to receive the adequate illuminance level within the living room in both months of June and December. Although *Courtyard-S*-C-W receives lower illuminance levels in June, yet both courtyard configurations have high illuminance levels above the standards. Yet, solar heat gain, temperature difference, and solar radiation exposure results records that *Courtyard-T* performs effectively.

In addition, although *Courtyard-T* has low wind speed within the courtyard, yet it records the highest mitigating air temperature within the courtyard. In June, it decreased the courtyard temperature to 21^{o}C and in December increased it to 18.5^{o}C.

In December, the courtyard temperatures did not vary significantly, *Courtyard-S*-C-W, had the highest increase. *Courtyard-S*-U demonstrated the worst courtyard shape due to the high solar exposure.

The courtyard shape influences the opening size. By decreasing the opening size, solar heat gain reduces dramatically. As this is viewed in the comparison between *Courtyard-S*-C and *Courtyard-S*-U performance. In terms of average temperatures within the living room, all configurations received approximate similar temperature. This is due to the correlation and contribution between opening orientation, prevailing wind frequency and direction, and sun altitude and movement. As the opening size increases, wind speed within the courtyard increases. As the opening size decreases, the wind speed within the courtyard decreases. However, as *Courtyard-S*-U has higher wind speed, *Courtyard-S*-C has lower solar exposure.

In this research, it is safe to conclude that the courtyard configuration, courtyard shape, percentage of enclosure, opening orientation, and courtyard geometry plays a role in modifying the courtyard and living room comfort levels in terms of temperature, illuminance levels, illuminance distribution, airflow, and wind temperatures. They have an effect on modifying temperature and adequately distribute light and airflow, which reduces solar heat gain and cooling and heating loads. The temperature difference between interior and exterior due to low heat gain reduces the cooling load. In addition by receiving adequate solar radiation it reduces the artificial lighting consumption. Hence, reducing electricity consumption, that simultaneously reduces the impact of the building development industry are generating in terms of energy usage and greenhouse gas emissions.

The configuration shape and opening size performance were influenced by exterior measures such as the sun altitude and frequent prevailing wind. Each factor affects the other like a cycle. The configurations manipulates the wind and solar exposure within the courtyard that provides various airflow and light distribution behavior. Therefore, they are the resultant of the courtyard enclosure level and courtyard geometry.

Orientation is significant in terms of its alignment to the sun and wind. However, aligning to both the sun and wind is not achievable as each behave differently. *Courtyard-S*-U and *Courtyard-S*-C behavior demonstrated different results due to the treatment of enclosure to the two factors; sun and wind, although the orientations are the same. Therefore, justifying that the courtyard shape and opening size matters.

The fully enclosed courtyard *Courtyard-T* is selected as the recommended courtyard configuration. It responds efficiently to Bahrain's climatic conditions, and reflects the society's culture. It is highly efficient and environmentally appropriate.

6.2. Recommendations for Future Works

As this research is specifically carried out for the country of Bahrain, the orientations and configurations are oriented accordingly to Bahrain modular housing. There are future works that can be carried out from this study.

Any future work to be carried out must involve in repeating the simulations for configurations that are not oriented North, and that have different courtyard and building geometry and shape.

Suggestions for future work include:

- It is recommended that designers capitalize on the minor differences to achieve a climatic responsive approach. In terms of design, windows on the courtyard internal wall could have shaded structures, window blinds, light shelves, or overhangs to reduce the living room illuminance levels in order to achieve a well distributed natural lighting without the uncomfortable high intensive light. In winter, such structures can be removed to increase solar access and promote temperature increase.
- Study the effect of integrating vegetation and water features within the courtyard over the courtyard microclimatic performance in terms of wind and solar radiation, and living room thermal and natural lighting penetration.
- Explore different semi-enclosed courtyard configurations with different opening dimensions to explore the effect of different courtyard shapes and geometry to compare it with the results obtained in this research.
- Investigate the effect of increasing and decreasing the building height.
- Investigate the effect of changing the building and courtyard materials and colors as an impact.
- Study the performance of semi-enclosed courtyard in terms of achieving privacy.
- Study the configurations simulations for various latitudes, to further understand the configuration behavior in different climatic conditions.

- Further intensive studies regarding wind and solar altitude effects in relation to the courtyard opening and enclosure in modifying the courtyard temperature.
- Study the effect of semi-enclosed courtyards on urban heat island as a bigger scale.
- Revise the current regulations in promoting efficient planning by encouraging built form studies that have a lower impact on the microclimate and environment.

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Appendices

Appendix A

Thermal Analysis

Courtyard-T

Hourly Temperatures: for 21st June

Zone: living room
Avg. Temperature: 35.7 C (Ground 27.0 C)
Total Surface Area: 146.808 m2 (290.9% flr area).
Total Exposed Area: 67.138 m2 (133.0% flr area).
Total South Window: 1.560 m2 (3.1% flr area).
Total Window Area: 4.680 m2 (9.3% flr area).
Total Conductance (AU): 126 W/°K
Total Admittance (AY): 544 W/°K
Response Factor: 4.06

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	38.3	33.1	5.2
1	38.1	32.5	5.6
2	38	32.1	5.9
3	37.9	31.9	6
4	37.7	31.9	5.8
5	37.7	32.4	5.3
6	37.7	33.2	4.5
7	37.7	34.2	3.5
8	37.8	35.3	2.5
9	37.8	36.4	1.4
10	38	37.4	0.6
11	38.4	38.1	0.3
12	38.8	38.6	0.2
13	39.1	39	0.1
14	39.4	39	0.4
15	39.4	38.8	0.6
16	39.3	38.3	1
17	39.2	37.6	1.6
18	39.2	36.8	2.4
19	39.1	36	3.1
20	39	35.3	3.7
21	38.7	34.5	4.2
22	38.5	33.7	4.8
23	38.3	32.9	5.4
	38.4625		3.0875

Courtyard-T

Hourly Temperatures: for 21st December

Zone: living room

Avg. Temperature: 20.6 C (Ground 27.0 C)

Total Surface Area: 146.808 m2 (290.9% flr area).

Total Exposed Area: 67.138 m2 (133.0% flr area).

Total South Window: 1.560 m2 (3.1% flr area).

Total Window Area: 4.680 m2 (9.3% flr area).

Total Conductance (AU): 126 W/°K

Total Admittance (AY): 544 W/°K

Response Factor: 4.06

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	22.9	18.9	4
1	22.8	18.2	4.6
2	22.7	17.6	5.1
3	22.6	17.2	5.4
4	22.5	16.9	5.6
5	22.4	16.7	5.7
6	22.3	16.7	5.6
7	22.3	17.4	4.9
8	22.4	18.3	4.1
9	22.4	19	3.4
10	22.4	19.6	2.8
11	22.5	20.1	2.4
12	22.8	20.3	2.5
13	23.1	20.3	2.8
14	23.2	20.1	3.1
15	23.3	19.7	3.6
16	23.2	19.1	4.1
17	23.1	18.7	4.4
18	23.1	18.4	4.7
19	22.9	18	4.9
20	22.7	17.7	5
21	22.5	17.3	5.2
22	22.4	17	5.4
23	22.4	16.6	5.8
	22.704167		4.37916667

Courtyard-T

Annual Temperature Distribution

Living Room

Operation: Weekdays 00-24, Weekends 00-24.

Comfort Band: 16.0 - 20.0 C

In Comfort: 1397 Hrs (15.9%)

TEMP.	HOURS	PERCENT
0	0	0.00%
2	0	0.00%
4	0	0.00%
6	0	0.00%
8	0	0.00%
10	0	0.00%
12	0	0.00%
14	0	0.00%
16	82	0.90%
18	500	5.70%
20	815	9.30%
22	872	10.00%
24	759	8.70%
26	718	8.20%
28	434	5.00%
30	496	5.70%
32	730	8.30%
34	1144	13.10%
36	1305	14.90%
38	848	9.70%
40	57	0.70%
42	0	0.00%
44	0	0.00%
46	0	0.00%
COMFORT	**1397**	**15.90%**

Courtyard-T

Direct Solar Gain

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
1	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
2	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
3	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
4	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
5	-55	-56	-52	-43	-24	-17	-33	-44	-49	-59	-58	-56
6	-55	-53	-39	-14	4	10	2	-10	-26	-34	-45	-54
7	-11	-12	-11	-4	9	18	16	1	-9	2	9	0
8	42	28	23	13	11	20	23	12	22	38	56	49
9	73	67	56	36	22	25	30	32	51	69	85	87
10	97	94	79	62	33	31	38	47	74	91	106	98
11	104	106	89	73	44	38	46	57	82	101	117	112
12	103	105	90	70	38	36	42	56	82	108	122	115
13	130	124	111	93	80	63	63	87	114	140	146	144
14	145	128	124	107	99	93	92	104	125	146	147	148
15	101	102	104	99	110	108	97	103	105	106	71	77
16	-8	32	46	50	91	89	81	74	34	2	-55	-52
17	-55	-55	-49	-31	26	29	27	-1	-49	-59	-58	-56
18	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
19	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
20	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
21	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
22	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56
23	-55	-56	-52	-46	-49	-49	-48	-47	-51	-59	-58	-56

Courtyard-T

Hourly Gain: for 21st June

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	1650	0	482	252	-85
1	0	1575	0	453	252	-84
2	0	1508	0	443	252	-83
3	0	1435	0	413	252	-82
4	0	1367	0	386	252	-81
5	0	1322	26	413	252	-81
6	0	1284	53	424	252	-81
7	0	1267	69	468	252	-81
8	0	1270	83	523	252	-81
9	0	1289	87	586	252	-82
10	0	1501	92	626	252	-83
11	0	1743	101	646	252	-86
12	0	1996	99	664	252	-89
13	0	2163	120	683	252	-91
14	0	2283	131	644	252	-93
15	0	2308	128	659	252	-93
16	0	2299	88	641	252	-93
17	0	2304	46	597	252	-92
18	0	2343	0	554	252	-92
19	0	2310	0	538	252	-91
20	0	2240	0	542	252	-90
21	0	2069	0	487	252	-88
22	0	1858	0	436	252	-86
23	0	1651	0	417	252	-85
TOTAL	**0**	**43037**	**1123**	**12726**	**6056**	**-2072**

Courtyard-T

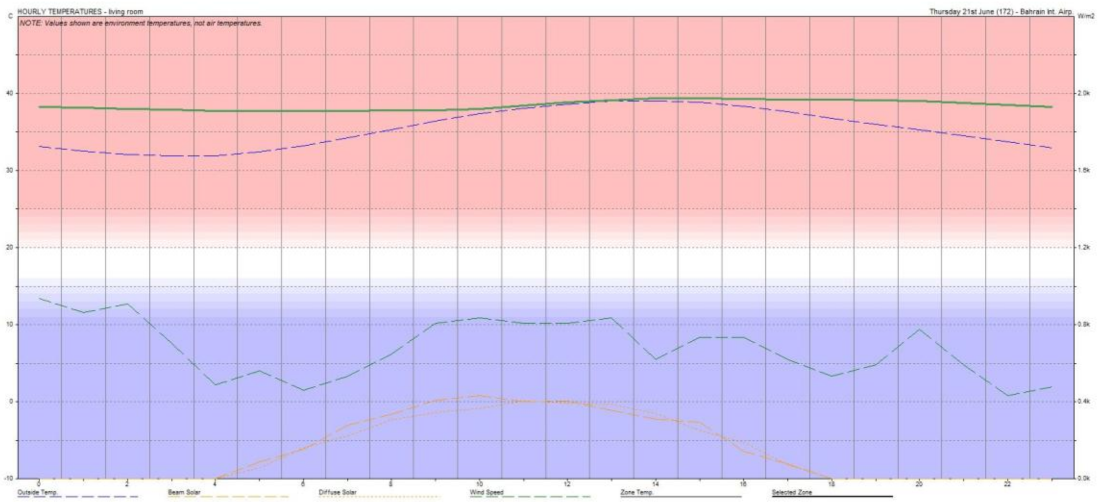
Hourly Gain: for 21st December

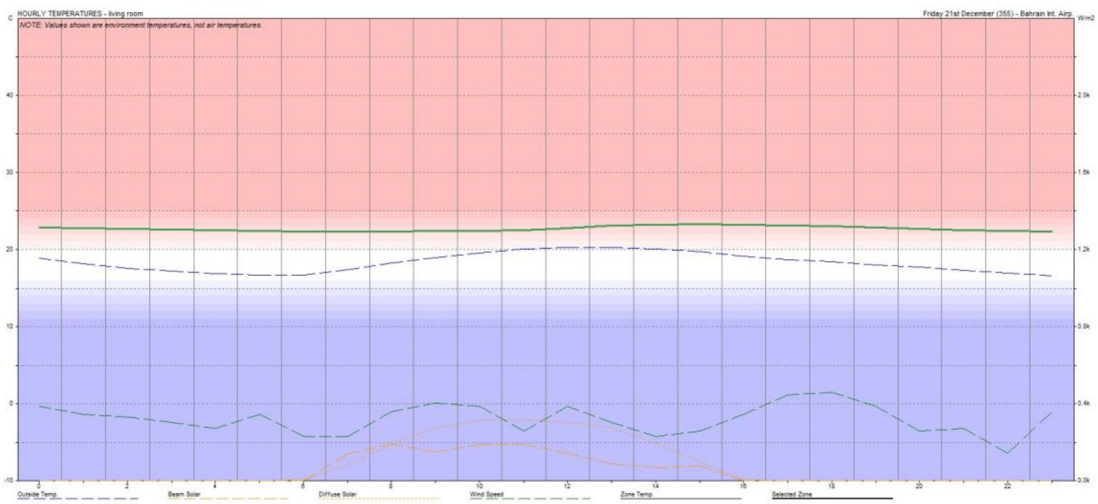
ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	85	0	0	252	31
1	0	51	0	0	252	32
2	0	17	0	0	252	33
3	0	0	0	0	252	33
4	0	0	0	0	252	34
5	0	0	0	0	252	35
6	0	0	2	0	252	35
7	0	0	42	0	252	35
8	0	1	79	0	252	35
9	0	2	98	0	252	35
10	0	4	118	0	252	34
11	0	11	123	3	252	34
12	0	219	110	9	252	32
13	0	356	95	9	252	29
14	0	384	75	3	252	29
15	0	410	56	0	252	28
16	0	395	1	0	252	29
17	0	358	0	0	252	29
18	0	323	0	0	252	30
19	0	232	0	0	252	31
20	0	143	0	0	252	33
21	0	4	0	0	252	34
22	0	0	0	0	252	35
23	0	0	0	0	252	35
TOTAL	**0**	**2996**	**800**	**24**	**6056**	**780**

Courtyard-T

Hourly Temperatures: for 21st June and December





***Courtyard-S*-U-N**

Hourly Temperatures: for 21st June

Zone: living room

Avg. Temperature: 35.7 C (Ground 27.0 C)

Total Surface Area: 100.624 m2 (582.4% flr area).

Total Exposed Area: 57.677 m2 (333.8% flr area).

Total South Window: 0.000 m2 (0.0% flr area).

Total Window Area: 4.680 m2 (27.1% flr area).

Total Conductance (AU): 109 W/°K

Total Admittance (AY): 339 W/°K
Response Factor: 2.92

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	37	33.1	3.9
1	36.8	32.5	4.3
2	36.7	32.1	4.6
3	36.5	31.9	4.6
4	36.3	31.9	4.4
5	36.3	32.4	3.9
6	36.4	33.2	3.2
7	36.5	34.2	2.3
8	36.6	35.3	1.3
9	36.7	36.4	0.3
10	36.9	37.4	-0.5
11	37.5	38.1	-0.6
12	38.2	38.6	-0.4
13	38.7	39	-0.3
14	39.2	39	0.2
15	39.2	38.8	0.4
16	38.8	38.3	0.5
17	38.6	37.6	1
18	38.4	36.8	1.6
19	38.3	36	2.3
20	38.2	35.3	2.9
21	37.7	34.5	3.2
22	37.3	33.7	3.6
23	37	32.9	4.1

***Courtyard-S*-U-N**

Hourly Temperatures: for 21st December

Zone: living room
Avg. Temperature: 20.6 C (Ground 27.0 C)
Total Surface Area: 100.624 m2 (582.4% flr area).
Total Exposed Area: 57.677 m2 (333.8% flr area).
Total South Window: 0.000 m2 (0.0% flr area).
Total Window Area: 4.680 m2 (27.1% flr area).
Total Conductance (AU): 109 W/°K
Total Admittance (AY): 339 W/°K
Response Factor: 2.92

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	21.7	18.9	2.8
1	21.5	18.2	3.3
2	21.4	17.6	3.8
3	21.3	17.2	4.1
4	21.2	16.9	4.3
5	21.1	16.7	4.4
6	20.9	16.7	4.2
7	20.9	17.4	3.5
8	21.1	18.3	2.8
9	21.2	19	2.2
10	21.2	19.6	1.6
11	21.3	20.1	1.2
12	21.7	20.3	1.4
13	22.2	20.3	1.9
14	22.3	20.1	2.2
15	22.4	19.7	2.7
16	22.2	19.1	3.1
17	22	18.7	3.3
18	21.9	18.4	3.5
19	21.7	18	3.7
20	21.4	17.7	3.7
21	21.2	17.3	3.9
22	21.1	17	4.1
23	21	16.6	4.4
	21.495833		3.17083333

***Courtyard-S*-U-N**

Annual Temperature Distribution

living room

Operation: Weekdays 00-24, Weekends 00-24.

Comfort Band: 16.0 - 20.0 C

In Comfort: 1834 Hrs (20.9%)

TEMP.	HOURS	PERCENT
0	0	0.00%
2	0	0.00%
2	0	0.00%
6	0	0.00%
8	0	0.00%
10	0	0.00%
12	0	0.00%
14	28	0.30%
16	296	3.40%
18	715	8.20%
20	823	9.40%
22	806	9.20%
24	752	8.60%
26	526	6.00%
28	488	5.60%
30	580	6.60%
32	974	11.10%
34	1110	12.70%
36	1167	13.30%
38	463	5.30%
40	32	0.40%
42	0	0.00%
44	0	0.00%
46	0	0.00%
COMFORT	**1834**	**20.90%**

Courtyard-S-U-N

Direct Solar Gain

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
1	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
2	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
3	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
4	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
5	-48	-57	-70	-73	-62	-52	-70	-81	-71	-66	-50	-44
6	-48	-52	-49	-28	-18	-10	-17	-29	-34	-39	-37	-41
7	-14	-13	-13	-10	-8	4	6	-9	-14	-16	-7	-5
8	4	6	15	12	-1	12	20	10	12	3	9	10
9	25	28	43	36	18	21	33	34	33	25	24	27
10	39	43	63	57	32	32	46	44	51	38	40	36
11	48	52	71	73	42	43	58	55	59	42	45	42
12	48	53	70	72	44	64	52	50	67	75	73	37
13	120	128	143	157	173	139	138	157	174	186	167	140
14	196	194	212	224	249	237	227	231	243	257	229	209
15	181	198	218	242	294	282	248	261	246	234	155	152
16	31	101	132	147	246	230	211	207	113	59	-45	-38
17	-48	-56	-65	-46	79	81	76	20	-71	-66	-50	-44
18	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
19	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
20	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
21	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
22	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44
23	-48	-57	-70	-78	-99	-98	-94	-86	-73	-66	-50	-44

***Courtyard-S*-U-N**

Hourly Gain: for 21st June

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	1427	0	482	86	-46
1	0	1362	0	452	86	-45
2	0	1305	0	442	86	-44
3	0	1243	0	413	86	-43
4	0	1185	0	386	86	-42
5	0	1148	39	412	86	-43
6	0	1118	83	424	86	-43
7	0	1108	109	468	86	-43
8	0	1113	133	523	86	-44
9	0	1134	141	585	86	-44
10	0	1324	149	625	86	-45
11	0	1549	164	646	86	-48
12	0	1785	180	664	86	-51
13	0	1936	231	683	86	-54
14	0	2053	272	644	86	-56
15	0	2058	282	658	86	-56
16	0	2031	183	641	86	-54
17	0	2021	97	596	86	-53
18	0	2070	0	553	86	-52
19	0	2052	0	537	86	-52
20	0	1993	0	542	86	-51
21	0	1823	0	487	86	-49
22	0	1624	0	435	86	-47
23	0	1427	0	417	86	-46
TOTAL	**0**	**37888**	**2065**	**12716**	**2073**	**-1148**

Courtyard-S-U-N

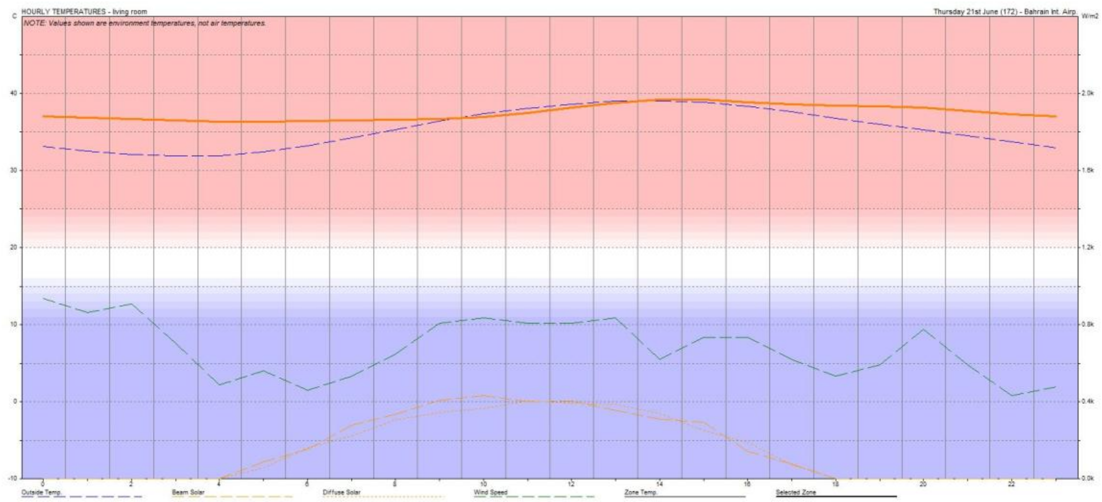
Hourly Gain: for 21st December

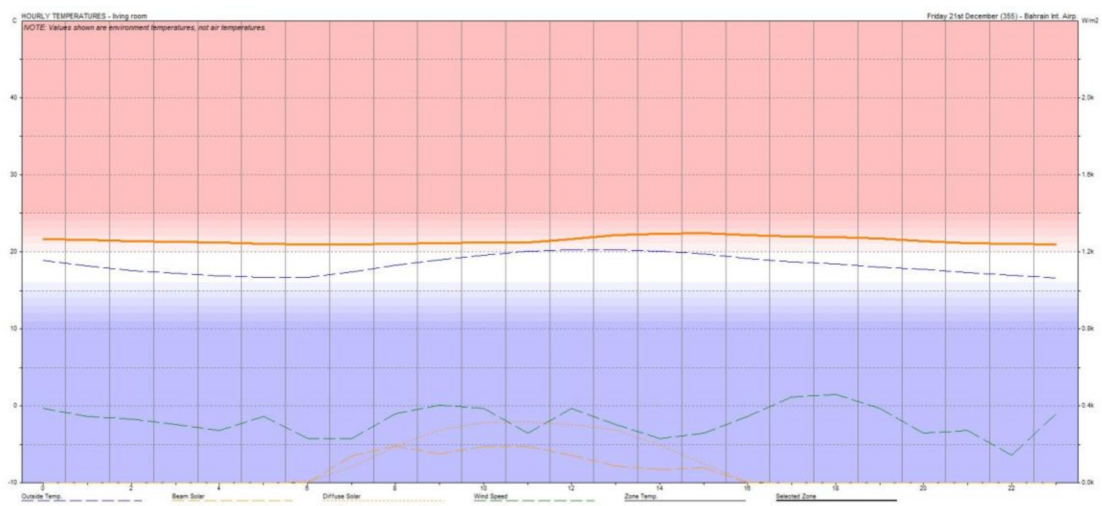
ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	72	0	0	86	24
1	0	43	0	0	86	25
2	0	14	0	0	86	26
3	0	0	0	0	86	26
4	0	0	0	0	86	27
5	0	0	0	0	86	27
6	0	0	2	0	86	28
7	0	0	35	0	86	28
8	0	2	77	0	86	27
9	0	4	112	0	86	27
10	0	6	127	0	86	26
11	0	13	130	3	86	26
12	0	205	124	9	86	24
13	0	327	129	9	86	22
14	0	346	109	3	86	21
15	0	360	84	0	86	21
16	0	338	2	0	86	22
17	0	302	0	0	86	23
18	0	284	0	0	86	23
19	0	208	0	0	86	24
20	0	129	0	0	86	25
21	0	3	0	0	86	27
22	0	0	0	0	86	27
23	0	0	0	0	86	28
TOTAL	**0**	**2655**	**931**	**24**	**2073**	**605**

***Courtyard-S*-U-N**

Hourly Temperatures: for 21st June and December





***Courtyard-S*-U-S**

Hourly Temperatures: for 21st June

Zone: living room
Avg. Temperature: 35.7 C (Ground 27.0 C)
Total Surface Area: 111.275 m2 (644.3% flr area).
Total Exposed Area: 63.275 m2 (366.4% flr area).
Total South Window: 1.560 m2 (9.0% flr area).
Total Window Area: 4.680 m2 (27.1% flr area).
Total Conductance (AU): 119 W/°K
Total Admittance (AY): 376 W/°K
Response Factor: 2.99

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	37	33.1	3.9
1	36.8	32.5	4.3
2	36.6	32.1	4.5
3	36.5	31.9	4.6
4	36.3	31.9	4.4
5	36.3	32.4	3.9
6	36.3	33.2	3.1
7	36.4	34.2	2.2
8	36.5	35.3	1.2
9	36.6	36.4	0.2
10	36.7	37.4	-0.7
11	37.3	38.1	-0.8
12	37.9	38.6	-0.7
13	38.4	39	-0.6
14	38.7	39	-0.3
15	38.7	38.8	-0.1
16	38.6	38.3	0.3
17	38.4	37.6	0.8
18	38.3	36.8	1.5
19	38.2	36	2.2
20	38	35.3	2.7
21	37.6	34.5	3.1
22	37.3	33.7	3.6
23	37	32.9	4.1
	37.35		1.975

***Courtyard-S*-U-S**

Hourly Temperatures: for 21st December

Zone: living room
Avg. Temperature: 20.6 C (Ground 27.0 C)
Total Surface Area: 111.275 m2 (644.3% flr area).
Total Exposed Area: 63.275 m2 (366.4% flr area).
Total South Window: 1.560 m2 (9.0% flr area).
Total Window Area: 4.680 m2 (27.1% flr area).
Total Conductance (AU): 119 W/°K
Total Admittance (AY): 376 W/°K
Response Factor: 2.99

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	21.6	18.9	2.7
1	21.5	18.2	3.3
2	21.4	17.6	3.8
3	21.3	17.2	4.1
4	21.2	16.9	4.3
5	21	16.7	4.3
6	20.9	16.7	4.2
7	21	17.4	3.6
8	21.1	18.3	2.8
9	21.1	19	2.1
10	21.2	19.6	1.6
11	21.3	20.1	1.2
12	21.6	20.3	1.3
13	22.1	20.3	1.8
14	22.2	20.1	2.1
15	22.3	19.7	2.6
16	22.1	19.1	3
17	22	18.7	3.3
18	21.9	18.4	3.5
19	21.6	18	3.6
20	21.4	17.7	3.7
21	21.1	17.3	3.8
22	21	17	4
23	20.9	16.6	4.3
	21.45		3.125

***Courtyard-S*-U-S**

Annual Temperature Distribution

living room

Operation: Weekdays 00-24, Weekends 00-24.

Comfort Band: 16.0 - 20.0 C

In Comfort: 1854 Hrs (21.2%)

TEMP.	HOURS	PERCENT
0	0	0.00%
2	0	0.00%
4	0	0.00%
6	0	0.00%
8	0	0.00%
10	0	0.00%
12	0	0.00%
14	31	0.40%
16	301	3.40%
18	726	8.30%
20	827	9.40%
22	817	9.30%
24	752	8.60%
26	536	6.10%
28	476	5.40%
30	612	7.00%
32	1003	11.40%
34	1153	13.20%
36	1145	13.10%
38	370	4.20%
40	11	0.10%
42	0	0.00%
44	0	0.00%
46	0	0.00%
COMFORT	**1854**	**21.20%**

***Courtyard-S*-U-S**

Direct Solar Gain

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
1	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
2	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
3	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
4	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
5	-76	-77	-72	-61	-34	-25	-46	-61	-69	-82	-80	-76
6	-75	-72	-54	-19	6	13	3	-13	-35	-45	-61	-73
7	-13	-15	-14	-4	14	26	24	3	-11	4	13	1
8	58	40	33	20	19	31	35	20	33	54	77	68
9	101	93	81	53	35	38	46	48	73	97	117	119
10	133	130	112	90	51	48	58	69	105	128	147	135
11	144	147	127	105	66	58	69	84	116	141	162	154
12	143	147	128	102	57	54	64	82	117	150	168	158
13	178	171	154	130	112	89	91	122	157	191	198	195
14	197	175	169	147	136	128	128	143	171	197	198	199
15	136	138	141	135	148	146	133	141	142	143	96	104
16	-12	42	62	67	122	119	108	99	45	1	-75	-71
17	-76	-76	-68	-44	33	38	34	-4	-68	-82	-80	-76
18	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
19	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
20	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
21	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
22	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76
23	-76	-77	-72	-65	-69	-69	-68	-66	-71	-82	-80	-76

***Courtyard-S*-U-S**

Hourly Gain: for 21st June

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	1559	0	479	86	-47
1	0	1488	0	449	86	-46
2	0	1425	0	440	86	-45
3	0	1357	0	411	86	-44
4	0	1292	0	384	86	-44
5	0	1251	37	410	86	-44
6	0	1216	76	421	86	-44
7	0	1202	100	465	86	-44
8	0	1205	120	520	86	-44
9	0	1225	127	582	86	-45
10	0	1429	134	621	86	-46
11	0	1660	148	642	86	-48
12	0	1899	144	660	86	-51
13	0	2057	172	679	86	-54
14	0	2169	186	640	86	-55
15	0	2195	178	654	86	-55
16	0	2191	123	637	86	-54
17	0	2186	63	593	86	-54
18	0	2218	0	550	86	-53
19	0	2181	0	534	86	-53
20	0	2113	0	538	86	-52
21	0	1956	0	484	86	-50
22	0	1756	0	433	86	-48
23	0	1559	0	414	86	-47
TOTAL	**0**	**40790**	**1608**	**12638**	**2072**	**-1168**

***Courtyard-S*-U-S**

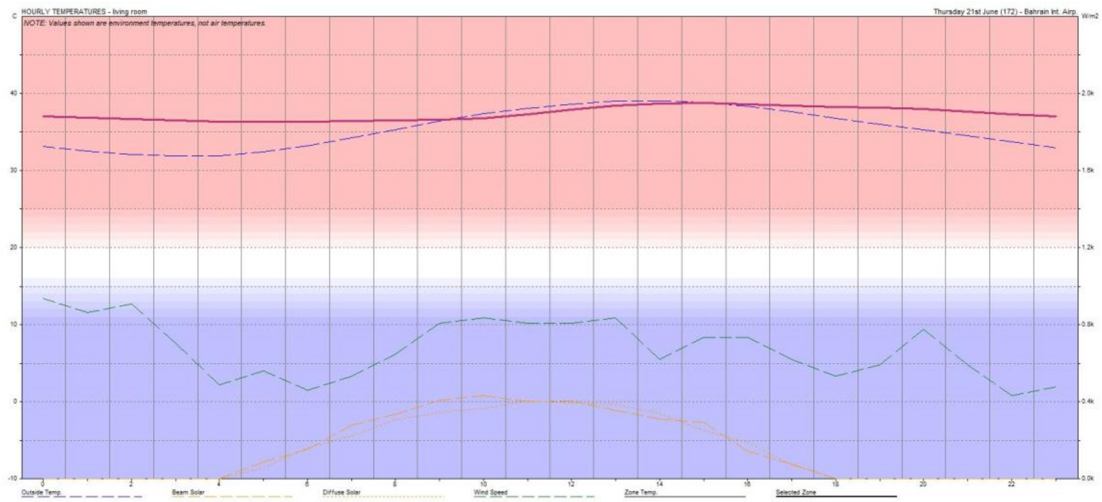
Hourly Gain: for 21st December

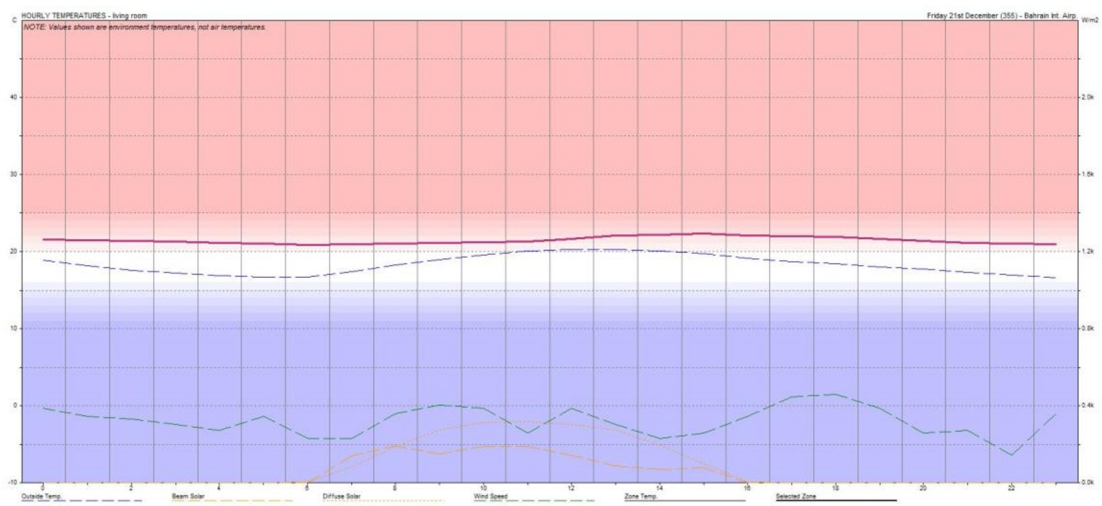
ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	80	0	0	86	25
1	0	48	0	0	86	26
2	0	16	0	0	86	27
3	0	0	0	0	86	27
4	0	0	0	0	86	28
5	0	0	0	0	86	28
6	0	0	2	0	86	29
7	0	0	59	0	86	29
8	0	1	112	0	86	28
9	0	3	139	0	86	28
10	0	4	167	0	86	27
11	0	11	175	3	86	27
12	0	206	157	9	86	25
13	0	338	136	9	86	23
14	0	369	106	3	86	23
15	0	395	78	0	86	22
16	0	382	1	0	86	23
17	0	347	0	0	86	24
18	0	313	0	0	86	24
19	0	223	0	0	86	25
20	0	136	0	0	86	27
21	0	4	0	0	86	28
22	0	0	0	0	86	28
23	0	0	0	0	86	29
TOTAL	**0**	**2874**	**1133**	**24**	**2072**	**630**

***Courtyard-S*-U-S**

Hourly Temperatures: for 21st June and December





***Courtyard-S*-U-W**

Hourly Temperatures: for 21st June

Zone: living room

Avg. Temperature: 35.7 C (Ground 27.0 C)

Total Surface Area: 113.688 m2 (658.0% flr area).

Total Exposed Area: 67.156 m2 (388.7% flr area).

Total South Window: 1.560 m2 (9.0% flr area).

Total Window Area: 4.680 m2 (27.1% flr area).

Total Conductance (AU): 126 W/°K

Total Admittance (AY): 385 W/°K

Response Factor: 2.89

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	37	33.1	3.9
1	36.8	32.5	4.3
2	36.6	32.1	4.5
3	36.4	31.9	4.5
4	36.2	31.9	4.3
5	36.3	32.4	3.9
6	36.3	33.2	3.1
7	36.4	34.2	2.2
8	36.5	35.3	1.2
9	36.6	36.4	0.2
10	36.8	37.4	-0.6
11	37.4	38.1	-0.7
12	38	38.6	-0.6
13	38.5	39	-0.5
14	38.9	39	-0.1
15	38.9	38.8	0.1
16	38.7	38.3	0.4
17	38.5	37.6	0.9
18	38.4	36.8	1.6
19	38.3	36	2.3
20	38.1	35.3	2.8
21	37.6	34.5	3.1
22	37.2	33.7	3.5
23	37	32.9	4.1
	37.391667		2.01666667

***Courtyard-S*-U-W**

Hourly Temperatures: for 21st December

Zone: living room

Avg. Temperature: 20.6 C (Ground 27.0 C)

Total Surface Area: 113.688 m2 (658.0% flr area).

Total Exposed Area: 67.156 m2 (388.7% flr area).

Total South Window: 1.560 m2 (9.0% flr area).

Total Window Area: 4.680 m2 (27.1% flr area).

Total Conductance (AU): 126 W/°K

Total Admittance (AY): 385 W/°K

Response Factor: 2.89

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	21.6	18.9	2.7
1	21.5	18.2	3.3
2	21.3	17.6	3.7
3	21.2	17.2	4
4	21.1	16.9	4.2
5	21	16.7	4.3
6	20.9	16.7	4.2
7	20.9	17.4	3.5
8	21.1	18.3	2.8
9	21.2	19	2.2
10	21.3	19.6	1.7
11	21.3	20.1	1.2
12	21.7	20.3	1.4
13	22.2	20.3	1.9
14	22.3	20.1	2.2
15	22.4	19.7	2.7
16	22.2	19.1	3.1
17	22	18.7	3.3
18	21.9	18.4	3.5
19	21.6	18	3.6
20	21.3	17.7	3.6
21	21.1	17.3	3.8
22	21	17	4
23	20.9	16.6	4.3
	21.458333		3.13333333

***Courtyard-S*-U-W**

Annual Temperature Distribution

living room
Operation: Weekdays 00-24, Weekends 00-24.
Comfort Band: 16.0 - 20.0 C
In Comfort: 1838 Hrs (21.0%)

TEMP.	HOURS	PERCENT
0	0	0.00%
2	0	0.00%
4	0	0.00%
6	0	0.00%
8	0	0.00%
10	0	0.00%
12	0	0.00%
14	32	0.40%
16	296	3.40%
18	720	8.20%
20	822	9.40%
22	821	9.40%
24	748	8.50%
26	532	6.10%
28	486	5.50%
30	606	6.90%
32	988	11.30%
34	1169	13.30%
36	1122	12.80%
38	401	4.60%
40	17	0.20%
42	0	0.00%
44	0	0.00%
46	0	0.00%
COMFORT	**1838**	**21.00%**

***Courtyard-S*-U-W**

Direct Solar Gain

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	6	43	53	28	7	2	0	0	0
6	1	6	27	63	95	102	91	70	51	47	25	4
7	77	79	81	88	111	123	122	98	84	107	110	92
8	156	143	140	121	125	139	144	124	139	166	182	167
9	209	206	200	169	150	154	164	163	189	219	230	228
10	250	251	242	212	172	168	180	189	230	257	268	247
11	263	274	260	237	195	182	198	214	247	273	286	270
12	263	274	263	234	188	189	194	211	247	284	292	272
13	293	296	284	255	240	218	220	253	284	319	316	305
14	304	291	289	263	252	247	247	259	286	315	307	304
15	233	243	247	236	252	253	241	245	244	248	194	198
16	70	134	154	154	214	218	205	189	133	91	7	7
17	0	1	6	27	113	121	117	72	3	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0

***Courtyard-S*-U-W**

Hourly Gain: for 21st June

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	1651	0	484	86	-47
1	0	1575	0	454	86	-46
2	0	1508	0	444	86	-45
3	0	1436	0	415	86	-44
4	0	1367	0	388	86	-43
5	0	1322	46	414	86	-44
6	0	1286	102	425	86	-44
7	0	1271	135	470	86	-44
8	0	1275	169	525	86	-45
9	0	1296	182	587	86	-45
10	0	1514	192	628	86	-46
11	0	1768	212	648	86	-49
12	0	2024	216	666	86	-52
13	0	2200	240	685	86	-54
14	0	2324	245	646	86	-56
15	0	2354	222	661	86	-56
16	0	2349	156	643	86	-55
17	0	2354	76	598	86	-54
18	0	2388	0	555	86	-54
19	0	2351	0	539	86	-53
20	0	2274	0	543	86	-52
21	0	2096	0	489	86	-50
22	0	1870	0	437	86	-48
23	0	1651	0	418	86	-47
TOTAL	**0**	**43505**	**2195**	**12763**	**2073**	**-1174**

***Courtyard-S*-U-W**

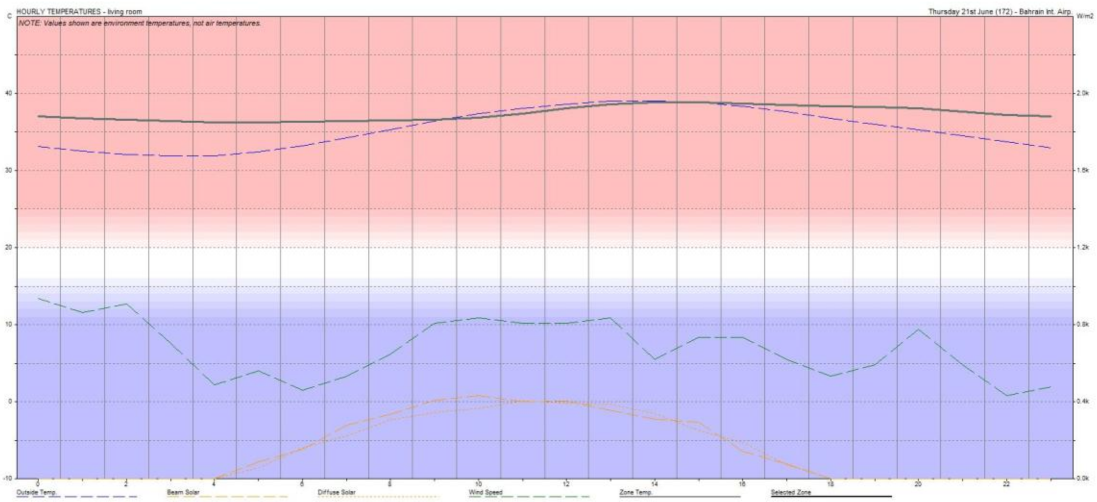
Hourly Gain: for 21st December

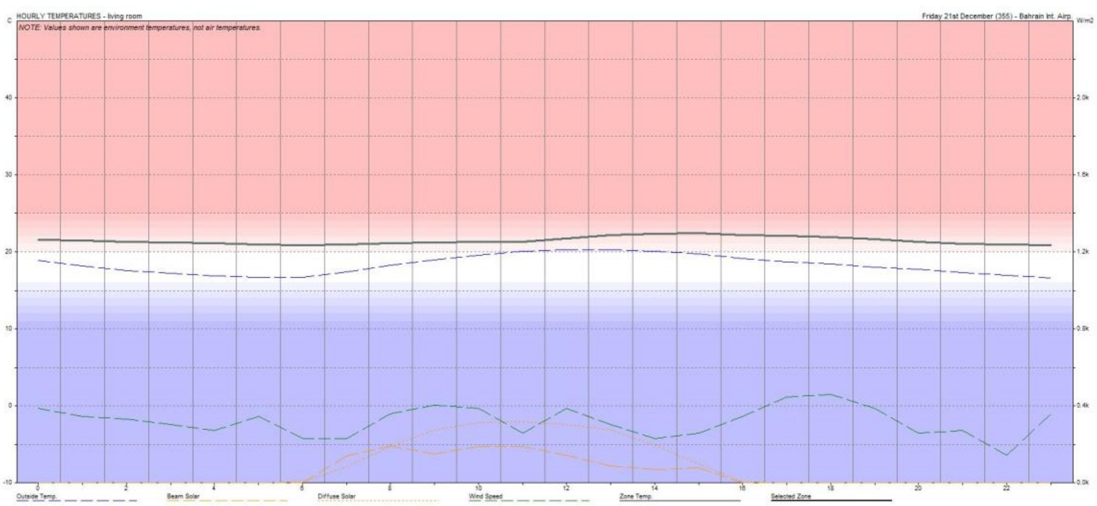
ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	85	0	0	86	26
1	0	51	0	0	86	26
2	0	17	0	0	86	27
3	0	0	0	0	86	27
4	0	0	0	0	86	28
5	0	0	0	0	86	28
6	0	0	3	0	86	29
7	0	0	73	0	86	29
8	0	3	142	0	86	28
9	0	7	184	0	86	27
10	0	10	219	0	86	27
11	0	19	228	3	86	27
12	0	234	207	9	86	25
13	0	382	181	9	86	23
14	0	419	139	3	86	22
15	0	449	95	0	86	22
16	0	433	2	0	86	23
17	0	394	0	0	86	23
18	0	355	0	0	86	24
19	0	255	0	0	86	25
20	0	155	0	0	86	27
21	0	4	0	0	86	28
22	0	0	0	0	86	28
23	0	0	0	0	86	29
TOTAL	**0**	**3271**	**1472**	**24**	**2073**	**628**

Courtyard-S-U-W

Hourly Temperatures: for 21st June and December





***Courtyard-S*-C-N**

Hourly Temperatures: for 21st June

Zone: living room
Avg. Temperature: 35.7 C (Ground 27.0 C)
Total Surface Area: 108.724 m2 (629.3% flr area).
Total Exposed Area: 65.821 m2 (381.0% flr area).
Total South Window: 0.000 m2 (0.0% flr area).
Total Window Area: 4.680 m2 (27.1% flr area).
Total Conductance (AU): 124 W/°K
Total Admittance (AY): 368 W/°K
Response Factor: 2.82

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	37.1	33.1	4
1	36.9	32.5	4.4
2	36.7	32.1	4.6
3	36.5	31.9	4.6
4	36.3	31.9	4.4
5	36.3	32.4	3.9
6	36.3	33.2	3.1
7	36.4	34.2	2.2
8	36.4	35.3	1.1
9	36.5	36.4	0.1
10	36.7	37.4	-0.7
11	37.3	38.1	-0.8
12	38	38.6	-0.6
13	38.6	39	-0.4
14	39.1	39	0.1
15	39.1	38.8	0.3
16	38.8	38.3	0.5
17	38.6	37.6	1
18	38.5	36.8	1.7
19	38.4	36	2.4
20	38.2	35.3	2.9
21	37.8	34.5	3.3
22	37.4	33.7	3.7
23	37.1	32.9	4.2

***Courtyard-S*-C-N**

Hourly Temperatures: for 21st December

Zone: living room

Avg. Temperature: 20.6 C (Ground 27.0 C)

Total Surface Area: 108.724 m2 (629.3% flr area).

Total Exposed Area: 65.821 m2 (381.0% flr area).

Total South Window: 0.000 m2 (0.0% flr area).

Total Window Area: 4.680 m2 (27.1% flr area).

Total Conductance (AU): 124 W/°K

Total Admittance (AY): 368 W/°K

Response Factor: 2.82

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	21.6	18.9	2.7
1	21.5	18.2	3.3
2	21.4	17.6	3.8
3	21.3	17.2	4.1
4	21.1	16.9	4.2
5	21	16.7	4.3
6	20.9	16.7	4.2
7	20.8	17.4	3.4
8	20.9	18.3	2.6
9	21	19	2
10	21	19.6	1.4
11	21	20.1	0.9
12	21.5	20.3	1.2
13	22	20.3	1.7
14	22.2	20.1	2.1
15	22.3	19.7	2.6
16	22.1	19.1	3
17	22	18.7	3.3
18	21.9	18.4	3.5
19	21.7	18	3.7
20	21.4	17.7	3.7
21	21.1	17.3	3.8
22	21	17	4
23	20.9	16.6	4.3

***Courtyard-S*-C-N**

Annual Temperature Distribution

living room
Operation: Weekdays 00-24, Weekends 00-24.
Comfort Band: 16.0 - 20.0 C
In Comfort: 1844 Hrs (21.1%)

TEMP.	HOURS	PERCENT
0	0	0.00%
2	0	0.00%
4	0	0.00%
6	0	0.00%
8	0	0.00%
10	0	0.00%
12	0	0.00%
14	33	0.40%
16	310	3.50%
18	716	8.20%
20	818	9.30%
22	815	9.30%
24	740	8.40%
26	523	6.00%
28	486	5.50%
30	591	6.70%
32	955	10.90%
34	1107	12.60%
36	1149	13.10%
38	484	5.50%
40	33	0.40%
42	0	0.00%
44	0	0.00%
46	0	0.00%
COMFORT	**1844**	**21.10%**

***Courtyard-S*-C-N**

Direct Solar Gain

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
1	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
2	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
3	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
4	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
5	-43	-50	-61	-64	-53	-43	-61	-71	-63	-59	-45	-39
6	-42	-46	-44	-25	-16	-7	-15	-26	-32	-37	-34	-36
7	-14	-14	-15	-12	-10	3	4	-12	-15	-17	-9	-7
8	0	1	9	6	-7	7	13	3	6	-3	4	5
9	17	19	31	26	8	12	23	23	23	16	16	19
10	28	32	48	44	20	22	33	31	38	26	30	27
11	36	39	54	56	28	30	43	41	44	30	33	31
12	36	41	54	52	21	27	38	37	51	59	60	28
13	106	112	122	131	143	109	107	129	150	166	152	128
14	185	179	194	202	224	211	201	208	224	241	218	196
15	174	188	205	229	279	267	232	246	234	227	151	147
16	33	100	130	144	242	221	203	202	112	62	-40	-34
17	-43	-50	-57	-38	83	85	79	25	-62	-59	-45	-39
18	-43	-50	-61	-68	-87		-82	-76	-64	-59	-45	-39
19	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
20	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
21	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
22	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39
23	-43	-50	-61	-68	-87	-86	-82	-76	-64	-59	-45	-39

***Courtyard-S*-C-N**

Hourly Gain: for 21st June

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	1619	0	484	86	-47
1	0	1545	0	454	86	-46
2	0	1479	0	444	86	-46
3	0	1409	0	415	86	-45
4	0	1341	0	388	86	-44
5	0	1298	35	414	86	-44
6	0	1261	71	426	86	-44
7	0	1245	93	470	86	-44
8	0	1248	111	525	86	-44
9	0	1268	116	588	86	-45
10	0	1483	123	628	86	-46
11	0	1739	135	649	86	-49
12	0	2011	131	667	86	-52
13	0	2186	190	686	86	-55
14	0	2320	236	647	86	-57
15	0	2331	256	661	86	-57
16	0	2291	165	644	86	-56
17	0	2282	90	599	86	-54
18	0	2344	0	556	86	-54
19	0	2332	0	540	86	-54
20	0	2272	0	544	86	-53
21	0	2070	0	489	86	-51
22	0	1844	0	437	86	-49
23	0	1620	0	419	86	-47
TOTAL	**0**	**42836**	**1751**	**12774**	**2073**	**-1182**

Courtyard-S-C-N

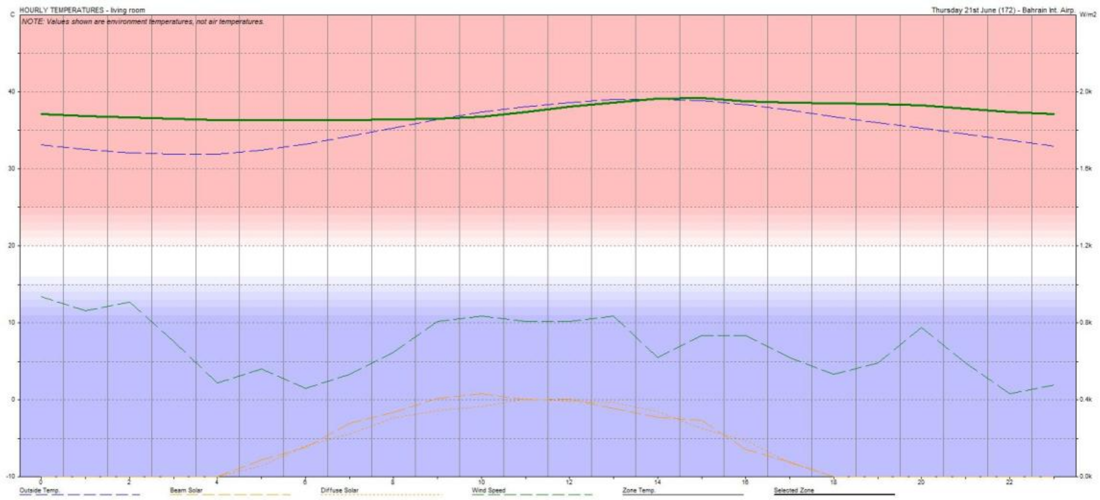
Hourly Gain: for 21st December

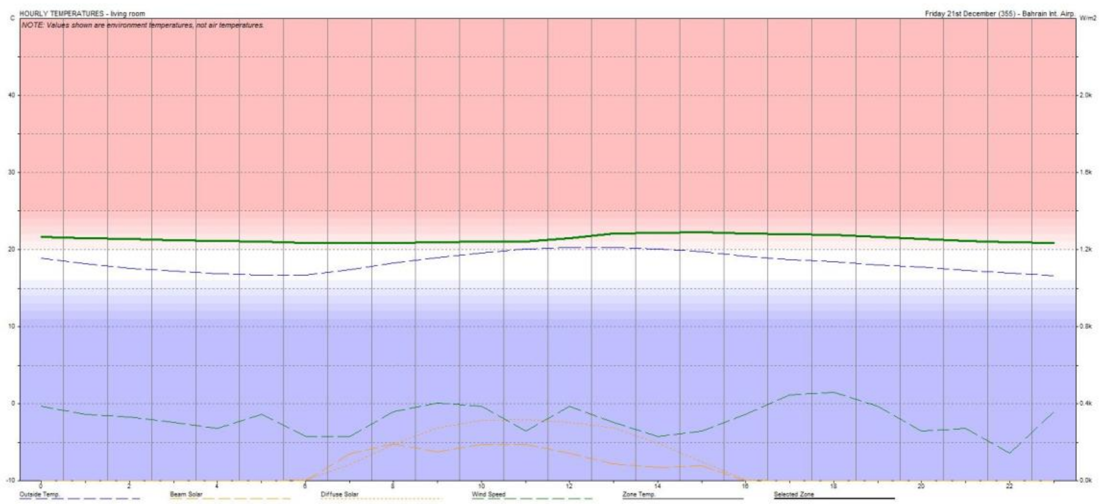
ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	83	0	0	86	25
1	0	50	0	0	86	26
2	0	17	0	0	86	27
3	0	0	0	0	86	27
4	0	0	0	0	86	28
5	0	0	0	0	86	28
6	0	0	2	0	86	29
7	0	0	29	0	86	29
8	0	1	63	0	86	29
9	0	3	92	0	86	29
10	0	4	105	0	86	28
11	0	11	107	3	86	28
12	0	225	102	9	86	26
13	0	360	108	9	86	23
14	0	378	94	3	86	23
15	0	392	76	0	86	22
16	0	363	1	0	86	23
17	0	335	0	0	86	24
18	0	316	0	0	86	24
19	0	233	0	0	86	25
20	0	148	0	0	86	27
21	0	4	0	0	86	28
22	0	0	0	0	86	28
23	0	0	0	0	86	29
TOTAL	**0**	**2923**	**779**	**24**	**2073**	**636**

Courtyard-S-C-N

Hourly Temperatures: for 21st June and December





***Courtyard-S*-C-S**

Hourly Temperatures: for 21st June

Zone: living room
Avg. Temperature: 35.7 C (Ground 27.0 C)
Total Surface Area: 106.819 m2 (634.1% flr area).
Total Exposed Area: 58.342 m2 (346.3% flr area).
Total South Window: 1.560 m2 (9.3% flr area).
Total Window Area: 4.680 m2 (27.8% flr area).
Total Conductance (AU): 110 W/°K
Total Admittance (AY): 361 W/°K
Response Factor: 3.09

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	37	33.1	3.9
1	36.8	32.5	4.3
2	36.7	32.1	4.6
3	36.5	31.9	4.6
4	36.3	31.9	4.4
5	36.3	32.4	3.9
6	36.4	33.2	3.2
7	36.4	34.2	2.2
8	36.5	35.3	1.2
9	36.6	36.4	0.2
10	36.8	37.4	-0.6
11	37.3	38.1	-0.8
12	37.9	38.6	-0.7
13	38.4	39	-0.6
14	38.7	39	-0.3
15	38.8	38.8	0
16	38.6	38.3	0.3
17	38.4	37.6	0.8
18	38.2	36.8	1.4
19	38.1	36	2.1
20	37.9	35.3	2.6
21	37.6	34.5	3.1
22	37.3	33.7	3.6
23	37	32.9	4.1

***Courtyard-S*-C-S**

Hourly Temperatures: for 21st December

Zone: living room
Avg. Temperature: 20.6 C (Ground 27.0 C)
Total Surface Area: 106.819 m2 (634.1% flr area).
Total Exposed Area: 58.342 m2 (346.3% flr area).
Total South Window: 1.560 m2 (9.3% flr area).
Total Window Area: 4.680 m2 (27.8% flr area).
Total Conductance (AU): 110 W/°K
Total Admittance (AY): 361 W/°K
Response Factor: 3.09

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	21.6	18.9	2.7
1	21.5	18.2	3.3
2	21.4	17.6	3.8
3	21.3	17.2	4.1
4	21.2	16.9	4.3
5	21.1	16.7	4.4
6	20.9	16.7	4.2
7	21	17.4	3.6
8	21.1	18.3	2.8
9	21.2	19	2.2
10	21.3	19.6	1.7
11	21.3	20.1	1.2
12	21.7	20.3	1.4
13	22.1	20.3	1.8
14	22.2	20.1	2.1
15	22.3	19.7	2.6
16	22.1	19.1	3
17	22	18.7	3.3
18	21.9	18.4	3.5
19	21.6	18	3.6
20	21.4	17.7	3.7
21	21.1	17.3	3.8
22	21	17	4
23	21	16.6	4.4
	21.470833	18.325	

***Courtyard-S*-C-S**

Annual Temperature Distribution

living room
Operation: Weekdays 00-24, Weekends 00-24.
Comfort Band: 16.0 - 20.0 C
In Comfort: 1851 Hrs (21.1%)

TEMP.	HOURS	PERCENT
0	0	0.00%
2	0	0.00%
4	0	0.00%
6	0	0.00%
8	0	0.00%
10	0	0.00%
12	0	0.00%
14	30	0.30%
16	295	3.40%
18	730	8.30%
20	826	9.40%
22	817	9.30%
24	756	8.60%
26	536	6.10%
28	475	5.40%
30	606	6.90%
32	1001	11.40%
34	1149	13.10%
36	1167	13.30%
38	361	4.10%
40	11	0.10%
42	0	0.00%
44	0	0.00%
46	0	0.00%
COMFORT	**1851**	**21.10%**

***Courtyard-S*-C-S**

Direct Solar Gain

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
1	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
2	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
3	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
4	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
5	-75	-75	-71	-59	-33	-24	-44	-59	-67	-81	-79	-75
6	-74	-71	-53	-21	3	11	2	-16	-35	-44	-60	-73
7	-13	-15	-12	-6	9	20	19	0	-8	5	13	1
8	58	41	33	18	11	17	23	16	33	55	76	67
9	101	92	78	55	31	34	42	45	71	96	116	119
10	133	128	109	86	45	43	52	65	101	125	144	133
11	140	144	121	100	61	52	63	80	112	137	159	151
12	139	143	122	96	54	49	57	77	113	150	165	155
13	177	168	151	127	110	87	89	119	155	190	199	196
14	195	173	166	144	134	127	126	140	168	196	197	201
15	134	136	139	129	148	144	132	136	139	140	93	102
16	-12	41	60	67	122	123	110	98	44	0	-74	-71
17	-75	-75	-67	-42	36	41	37	-1	-67	-81	-79	-75
18	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
19	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
20	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
21	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
22	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75
23	-75	-75	-71	-63	-67	-66	-64	-64	-69	-81	-79	-75

***Courtyard-S*-C-S**

Hourly Gain: for 21st June

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	1443	0	466	84	-46
1	0	1377	0	437	84	-45
2	0	1319	0	427	84	-44
3	0	1256	0	399	84	-44
4	0	1197	0	373	84	-43
5	0	1160	35	398	84	-43
6	0	1130	71	410	84	-43
7	0	1118	91	452	84	-43
8	0	1123	105	505	84	-44
9	0	1142	118	566	84	-44
10	0	1332	124	604	84	-45
11	0	1547	137	624	84	-47
12	0	1768	133	641	84	-50
13	0	1917	163	660	84	-52
14	0	2027	178	622	84	-54
15	0	2053	171	636	84	-54
16	0	2045	119	619	84	-53
17	0	2026	62	576	84	-52
18	0	2050	0	535	84	-52
19	0	2013	0	519	84	-51
20	0	1944	0	523	84	-50
21	0	1805	0	471	84	-49
22	0	1621	0	421	84	-47
23	0	1443	0	403	84	-46
TOTAL	**0**	**37857**	**1507**	**12289**	**2022**	**-1142**

***Courtyard-S*-C-S**

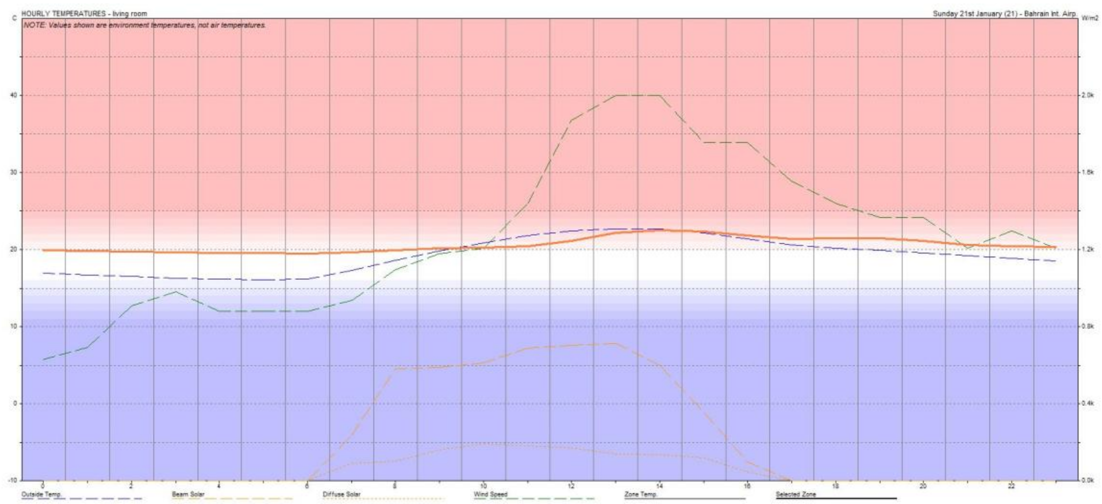
Hourly Gain: for 21st December

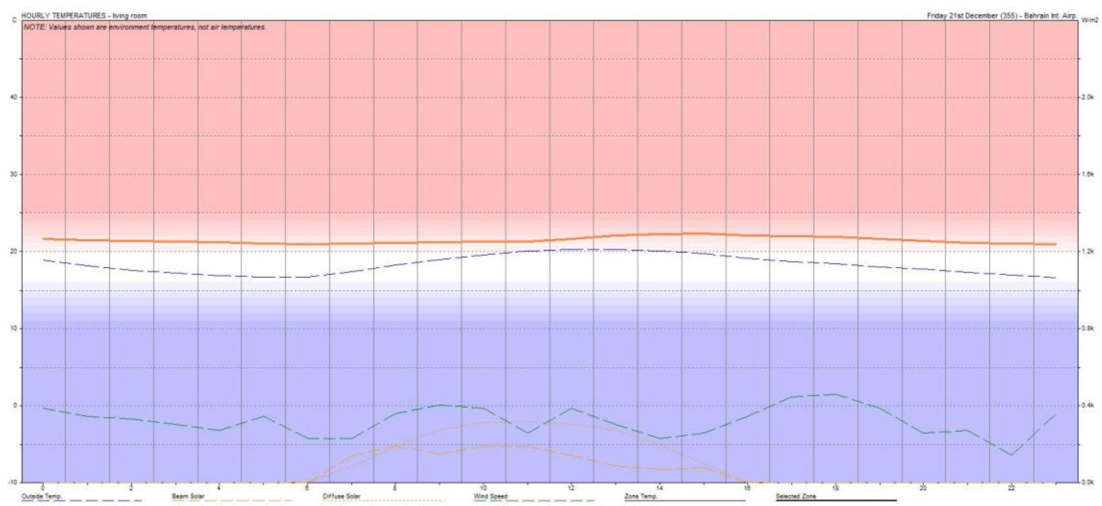
ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	73	0	0	84	25
1	0	44	0	0	84	25
2	0	15	0	0	84	26
3	0	0	0	0	84	26
4	0	0	0	0	84	27
5	0	0	0	0	84	27
6	0	0	2	0	84	28
7	0	0	58	0	84	28
8	0	1	107	0	84	27
9	0	2	133	0	84	27
10	0	4	160	0	84	26
11	0	10	167	3	84	26
12	0	192	149	9	84	25
13	0	314	129	9	84	23
14	0	341	102	3	84	22
15	0	365	76	0	84	22
16	0	351	1	0	84	22
17	0	320	0	0	84	23
18	0	287	0	0	84	23
19	0	204	0	0	84	25
20	0	122	0	0	84	26
21	0	3	0	0	84	27
22	0	0	0	0	84	27
23	0	0	0	0	84	28
TOTAL	**0**	**2648**	**1084**	**23**	**2022**	**611**

***Courtyard-S*-C-S**

Hourly Temperatures: for 21st June and December





Courtyard-S-C-W

Hourly Temperatures: for 21st June

Zone: living room
Avg. Temperature: 35.7 C (Ground 27.0 C)
Total Surface Area: 110.884 m2 (641.9% flr area).
Total Exposed Area: 63.405 m2 (367.1% flr area).
Total South Window: 1.560 m2 (9.0% flr area).
Total Window Area: 4.680 m2 (27.1% flr area).
Total Conductance (AU): 119 W/°K
Total Admittance (AY): 375 W/°K
Response Factor: 2.97

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	37	33.1	3.9
1	36.8	32.5	4.3
2	36.6	32.1	4.5
3	36.5	31.9	4.6
4	36.3	31.9	4.4
5	36.3	32.4	3.9
6	36.3	33.2	3.1
7	36.3	34.2	2.1
8	36.4	35.3	1.1
9	36.5	36.4	0.1
10	36.7	37.4	-0.7
11	37.3	38.1	-0.8
12	37.9	38.6	-0.7
13	38.3	39	-0.7
14	38.7	39	-0.3
15	38.7	38.8	-0.1
16	38.5	38.3	0.2
17	38.3	37.6	0.7
18	38.3	36.8	1.5
19	38.2	36	2.2
20	38	35.3	2.7
21	37.6	34.5	3.1
22	37.3	33.7	3.6
23	37	32.9	4.1

***Courtyard-S*-C-W**

Hourly Temperatures: for 21st December

Zone: living room
Avg. Temperature: 20.6 C (Ground 27.0 C)
Total Surface Area: 110.884 m2 (641.9% flr area).
Total Exposed Area: 63.405 m2 (367.1% flr area).
Total South Window: 1.560 m2 (9.0% flr area).
Total Window Area: 4.680 m2 (27.1% flr area).
Total Conductance (AU): 119 W/°K
Total Admittance (AY): 375 W/°K
Response Factor: 2.97

HOUR	INSIDE	OUTSIDE	TEMP.DIF
	(C)	(C)	(C)
0	21.6	18.9	2.7
1	21.5	18.2	3.3
2	21.3	17.6	3.7
3	21.3	17.2	4.1
4	21.2	16.9	4.3
5	21	16.7	4.3
6	20.9	16.7	4.2
7	20.9	17.4	3.5
8	21	18.3	2.7
9	21.1	19	2.1
10	21.2	19.6	1.6
11	21.2	20.1	1.1
12	21.6	20.3	1.3
13	22	20.3	1.7
14	22.2	20.1	2.1
15	22.3	19.7	2.6
16	22.1	19.1	3
17	22	18.7	3.3
18	21.9	18.4	3.5
19	21.6	18	3.6
20	21.3	17.7	3.6
21	21.1	17.3	3.8
22	21	17	4
23	20.9	16.6	4.3

Courtyard-S-C-W

Annual Temperature Distribution

living room

Operation: Weekdays 00-24, Weekends 00-24.

Comfort Band: 16.0 - 20.0 C

In Comfort: 1863 Hrs (21.3%)

TEMP.	HOURS	PERCENT
0	0	0.00%
2	0	0.00%
4	0	0.00%
6	0	0.00%
8	0	0.00%
10	0	0.00%
12	0	0.00%
14	32	0.40%
16	306	3.50%
18	726	8.30%
20	831	9.50%
22	811	9.30%
24	759	8.70%
26	532	6.10%
28	469	5.40%
30	618	7.10%
32	1006	11.50%
34	1154	13.20%
36	1143	13.00%
38	362	4.10%
40	11	0.10%
42	0	0.00%
44	0	0.00%
46	0	0.00%
COMFORT	**1863**	**21.30%**

***Courtyard-S*-C-W**

Direct Solar Gain

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
1	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
2	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
3	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
4	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
5	-74	-74	-69	-58	-32	-23	-43	-58	-66	-79	-78	-74
6	-73	-70	-52	-19	6	13	3	-13	-35	-45	-59	-72
7	-14	-16	-15	-6	12	24	22	1	-12	3	12	0
8	56	38	30	17	15	27	31	16	30	51	74	65
9	97	89	75	48	30	33	41	42	68	92	114	116
10	129	125	105	83	44	42	51	63	98	122	142	131
11	138	142	119	97	58	51	61	77	109	135	156	149
12	138	141	120	94	51	47	56	75	110	144	163	154
13	174	165	148	124	106	83	85	116	152	187	195	192
14	194	171	165	142	132	124	123	138	167	195	195	197
15	135	136	138	132	146	143	130	138	141	142	95	102
16	-11	42	62	67	122	119	108	98	45	2	-73	-69
17	-74	-74	-65	-41	35	39	36	-2	-65	-79	-78	-74
18	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
19	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
20	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
21	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
22	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74
23	-74	-74	-69	-62	-66	-66	-64	-63	-67	-79	-78	-74

***Courtyard-S*-C-W**

Hourly Gain: for 21st June

ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	1562	0	485	86	-47
1	0	1491	0	455	86	-46
2	0	1428	0	445	86	-45
3	0	1359	0	416	86	-44
4	0	1295	0	389	86	-44
5	0	1253	35	415	86	-44
6	0	1218	71	427	86	-44
7	0	1204	93	471	86	-44
8	0	1207	111	526	86	-44
9	0	1227	116	589	86	-45
10	0	1429	123	629	86	-46
11	0	1659	135	650	86	-48
12	0	1898	131	668	86	-51
13	0	2055	160	687	86	-53
14	0	2168	175	648	86	-55
15	0	2190	170	663	86	-55
16	0	2182	117	645	86	-54
17	0	2177	61	600	86	-53
18	0	2214	0	557	86	-53
19	0	2179	0	541	86	-53
20	0	2114	0	545	86	-52
21	0	1957	0	490	86	-50
22	0	1759	0	438	86	-48
23	0	1563	0	420	86	-47
TOTAL	**0**	**40785**	**1497**	**12800**	**2073**	**-1166**

***Courtyard-S*-C-W**

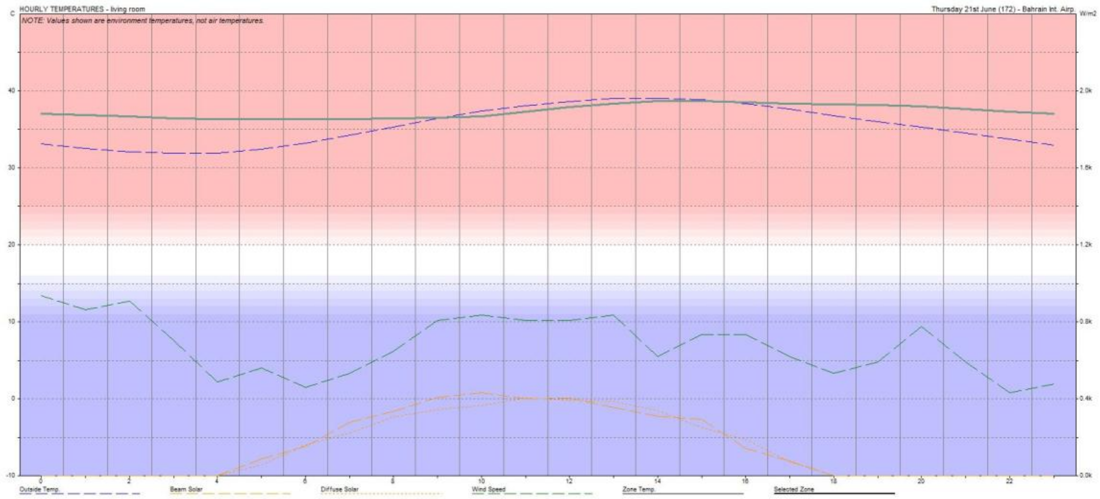
Hourly Gain: for 21st December

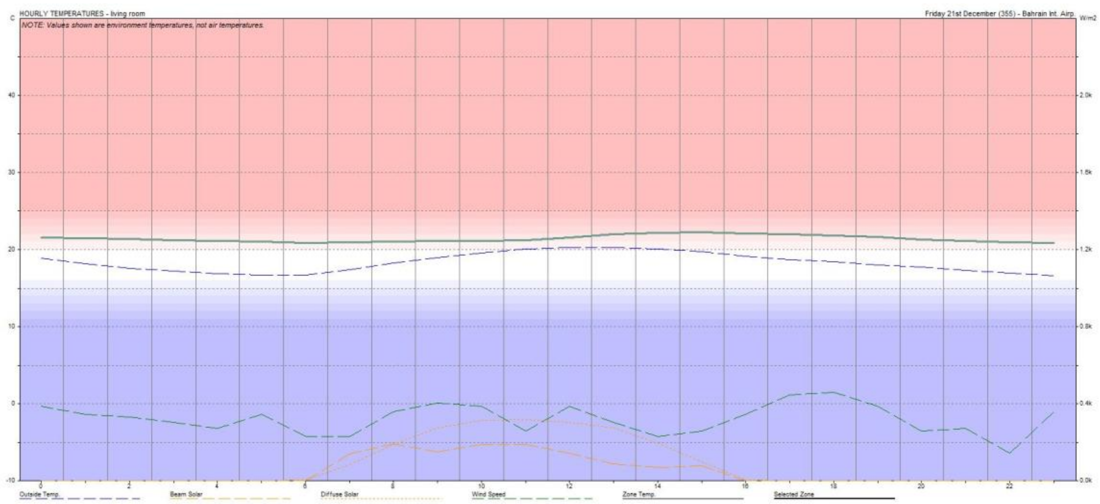
ADMITTANCE FACTOR TABLE
Direct Solar Gains - Qg
living room - Monthly Averages

HOUR	HVAC	FABRIC	SOLAR	VENT.	INTERN	ZONAL
	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)	(Wh)
0	0	80	0	0	86	26
1	0	48	0	0	86	26
2	0	16	0	0	86	27
3	0	0	0	0	86	27
4	0	0	0	0	86	28
5	0	0	0	0	86	28
6	0	0	2	0	86	29
7	0	0	56	0	86	29
8	0	1	106	0	86	28
9	0	2	131	0	86	28
10	0	3	157	0	86	28
11	0	10	165	3	86	27
12	0	204	147	9	86	26
13	0	333	127	9	86	23
14	0	361	100	3	86	23
15	0	385	75	0	86	22
16	0	372	1	0	86	23
17	0	336	0	0	86	24
18	0	304	0	0	86	24
19	0	218	0	0	86	25
20	0	133	0	0	86	27
21	0	4	0	0	86	28
22	0	0	0	0	86	28
23	0	0	0	0	86	29
TOTAL	**0**	**2811**	**1067**	**24**	**2073**	**632**

***Courtyard-S*-C-S**

Hourly Temperatures: for 21st June and December





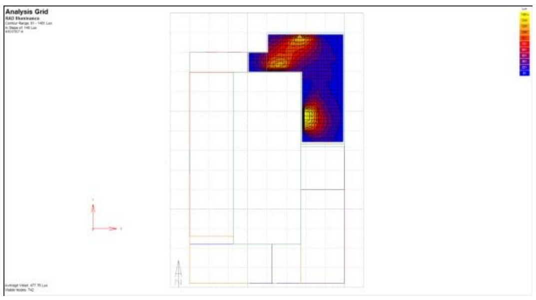
Appendix B

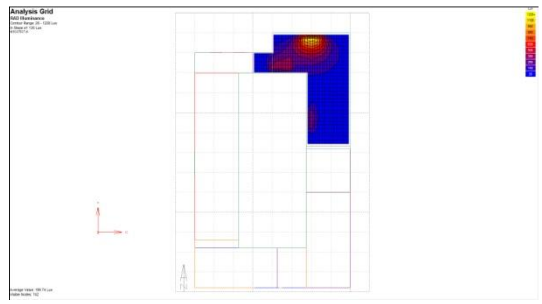
RADIANCE Simulation

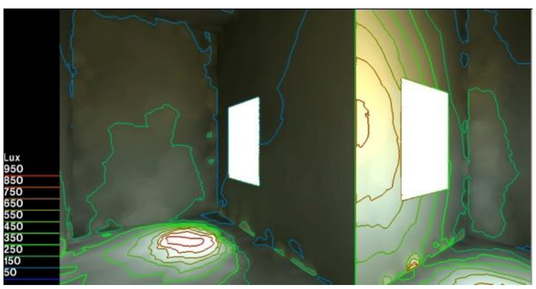
Courtyard-T

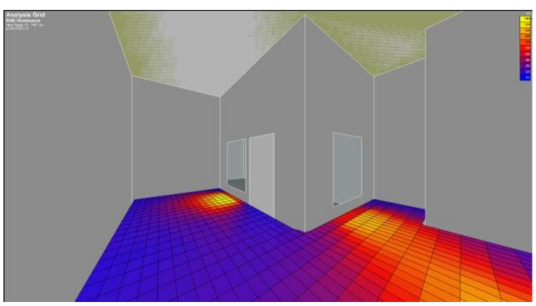
Radiance Simulation from Ecotect and Radiance: 9 a.m. in June and December

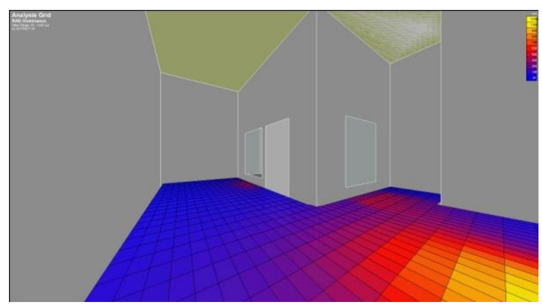
JUNE	DECEMBER

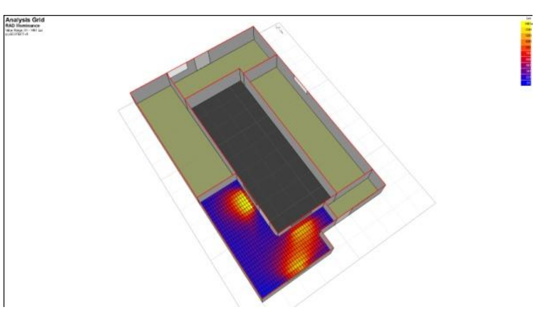


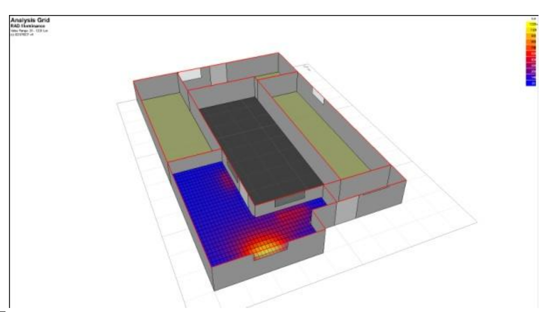








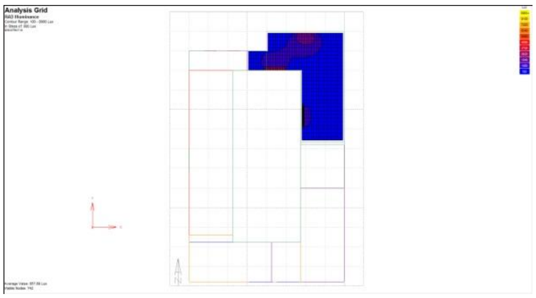


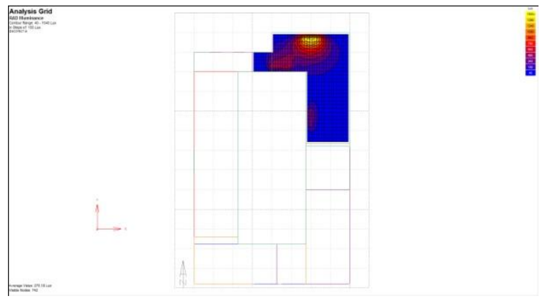


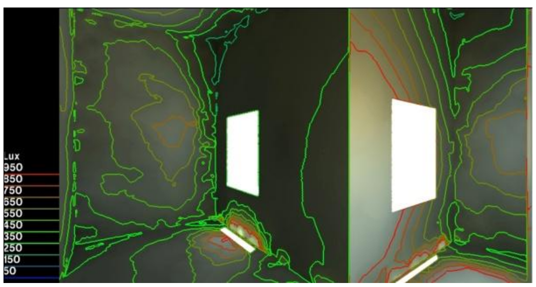
Courtyard-T

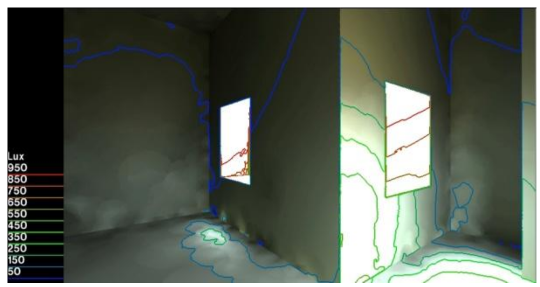
Radiance Simulation from Ecotect and Radiance: 12 p.m. in June and December

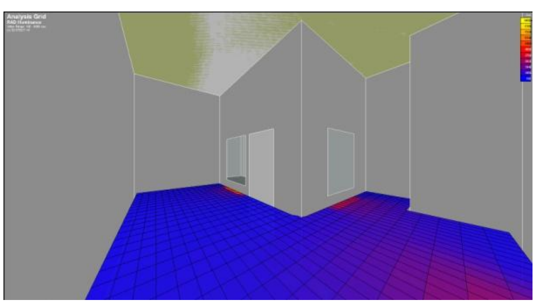
JUNE DECEMBER

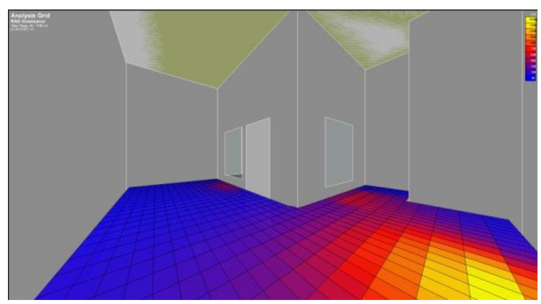


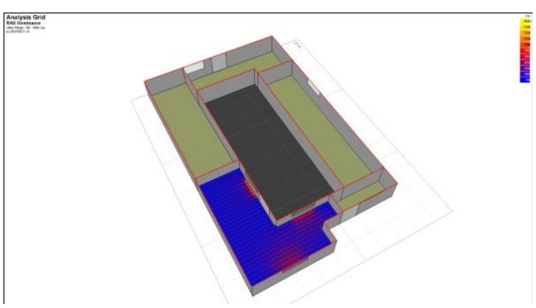


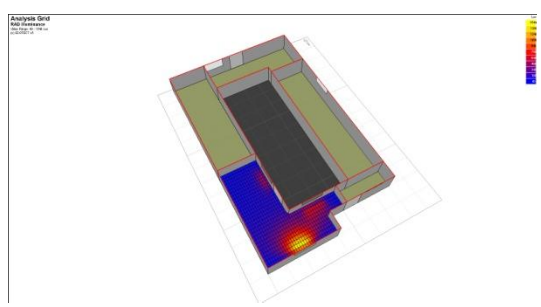








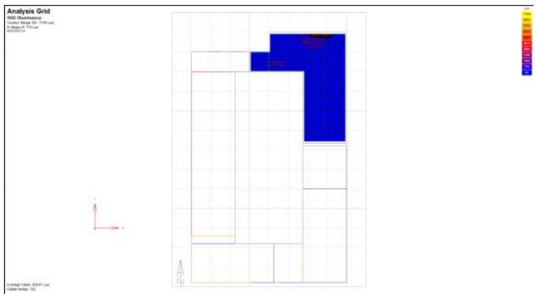


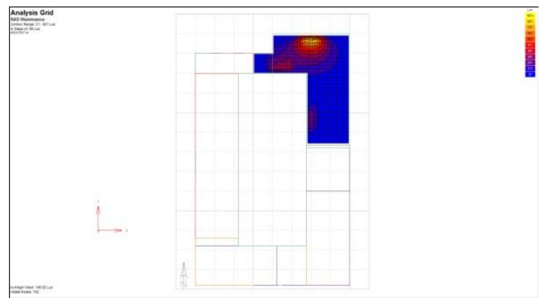


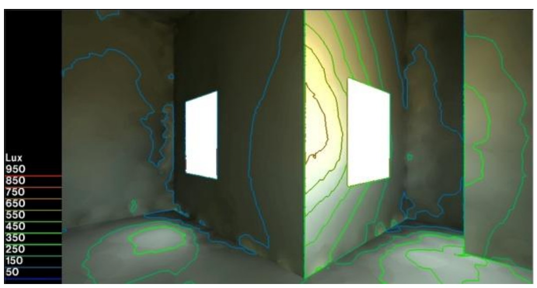
Courtyard-T

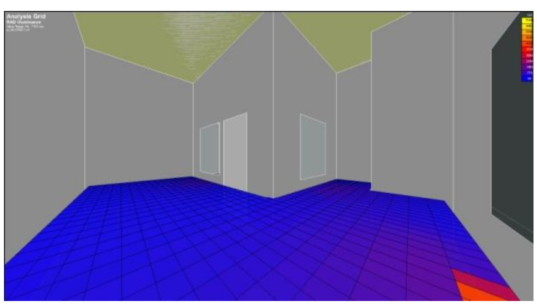
Radiance Simulation from Ecotect and Radiance: 3 p.m. in June and December

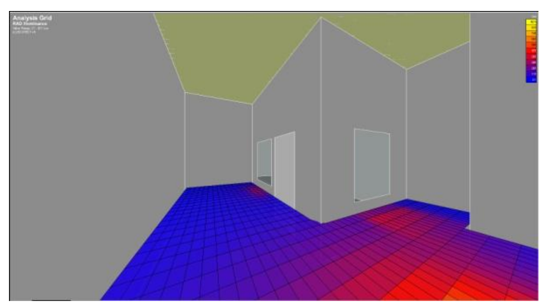
JUNE | DECEMBER

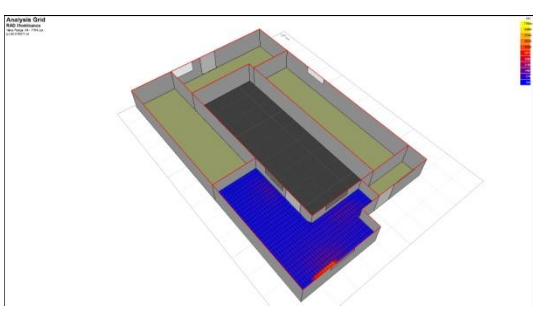


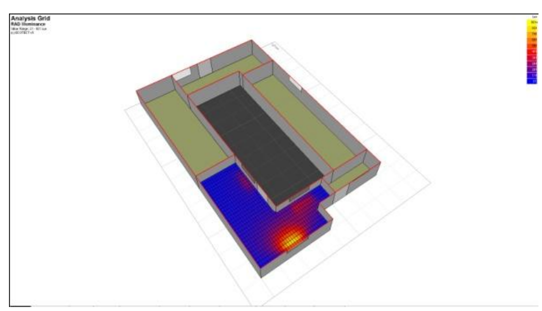








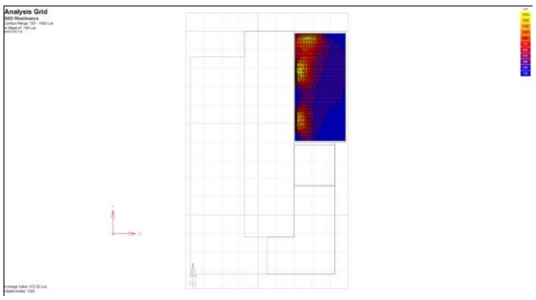


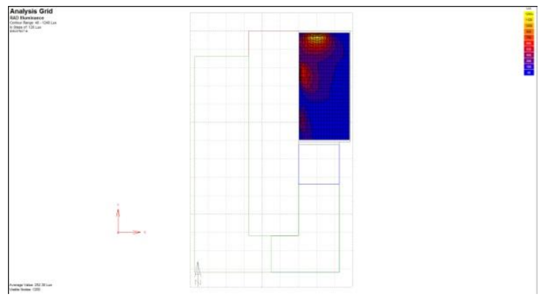


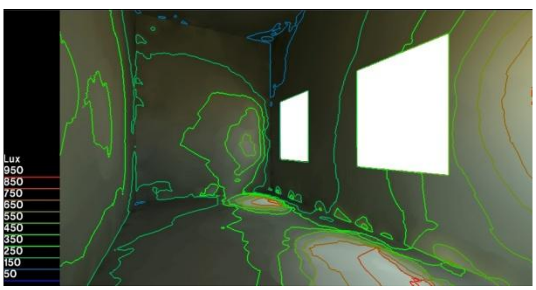
***Courtyard-S*-U-N**

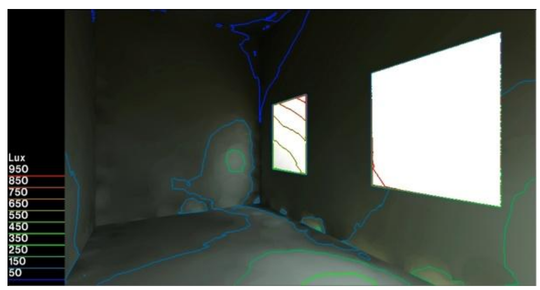
Radiance Simulation from Ecotect and Radiance: 9 a.m. in June and December

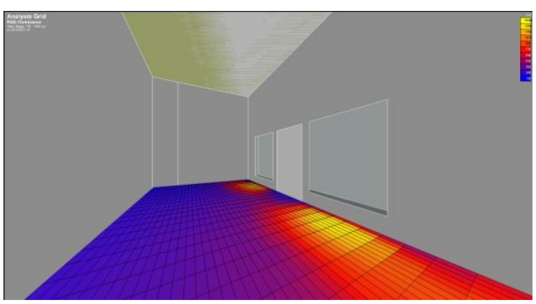
JUNE DECEMBER

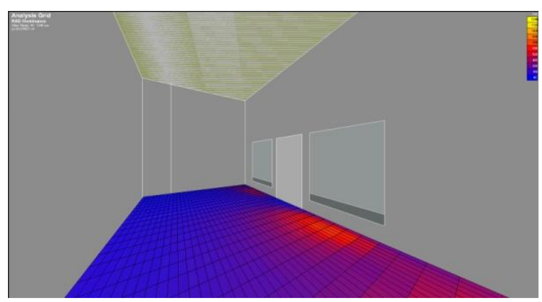


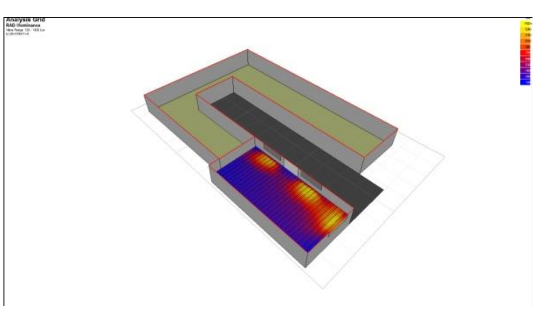


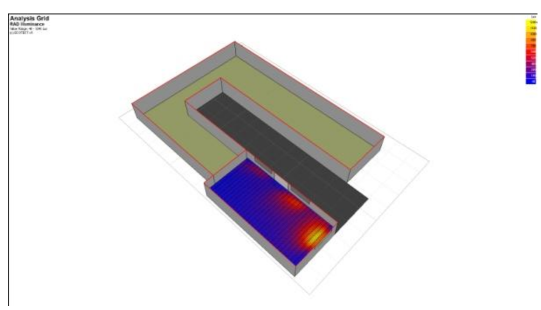








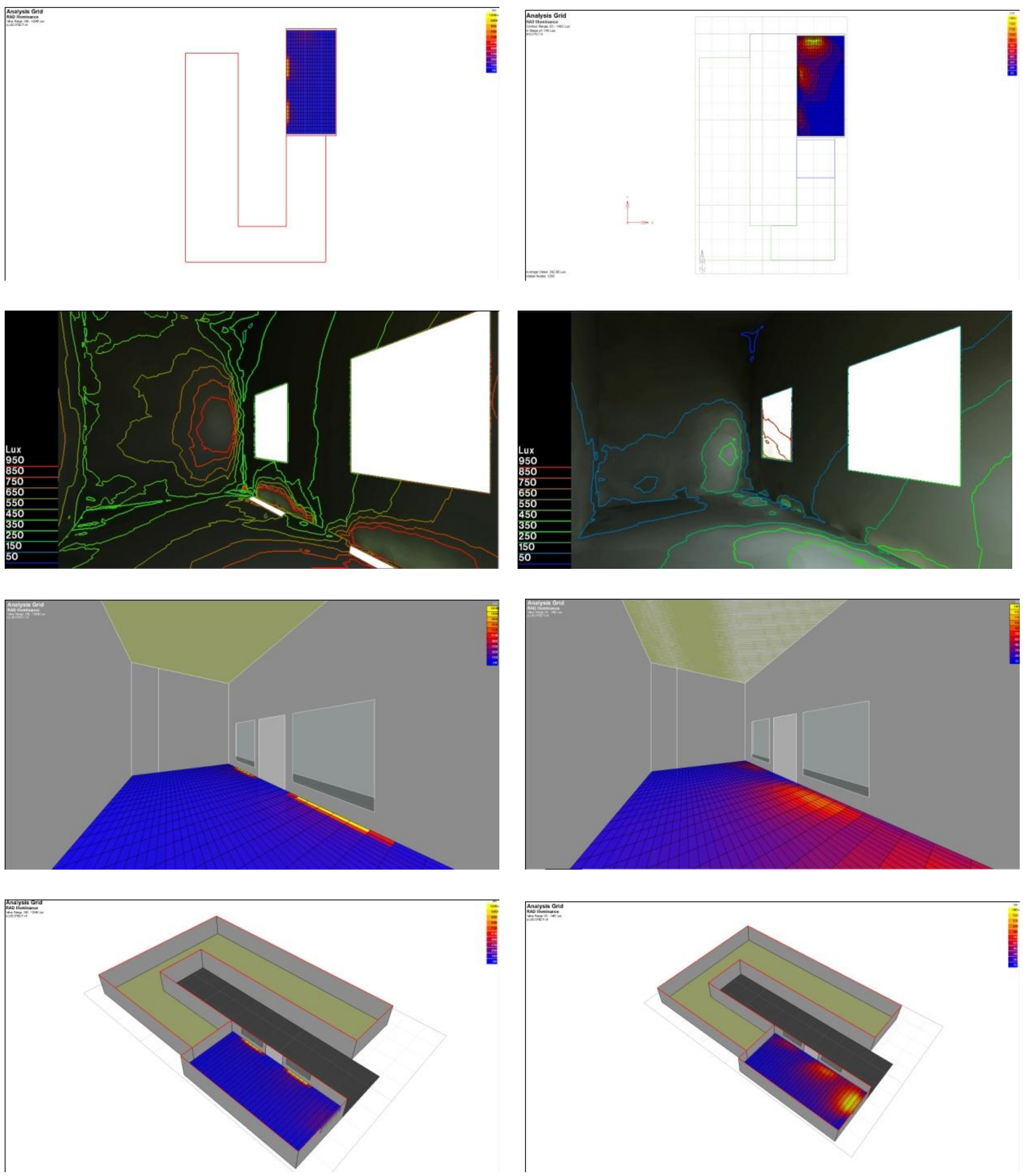




***Courtyard-S*-U-N**

Radiance Simulation from Ecotect and Radiance: 12 p.m. in June and December

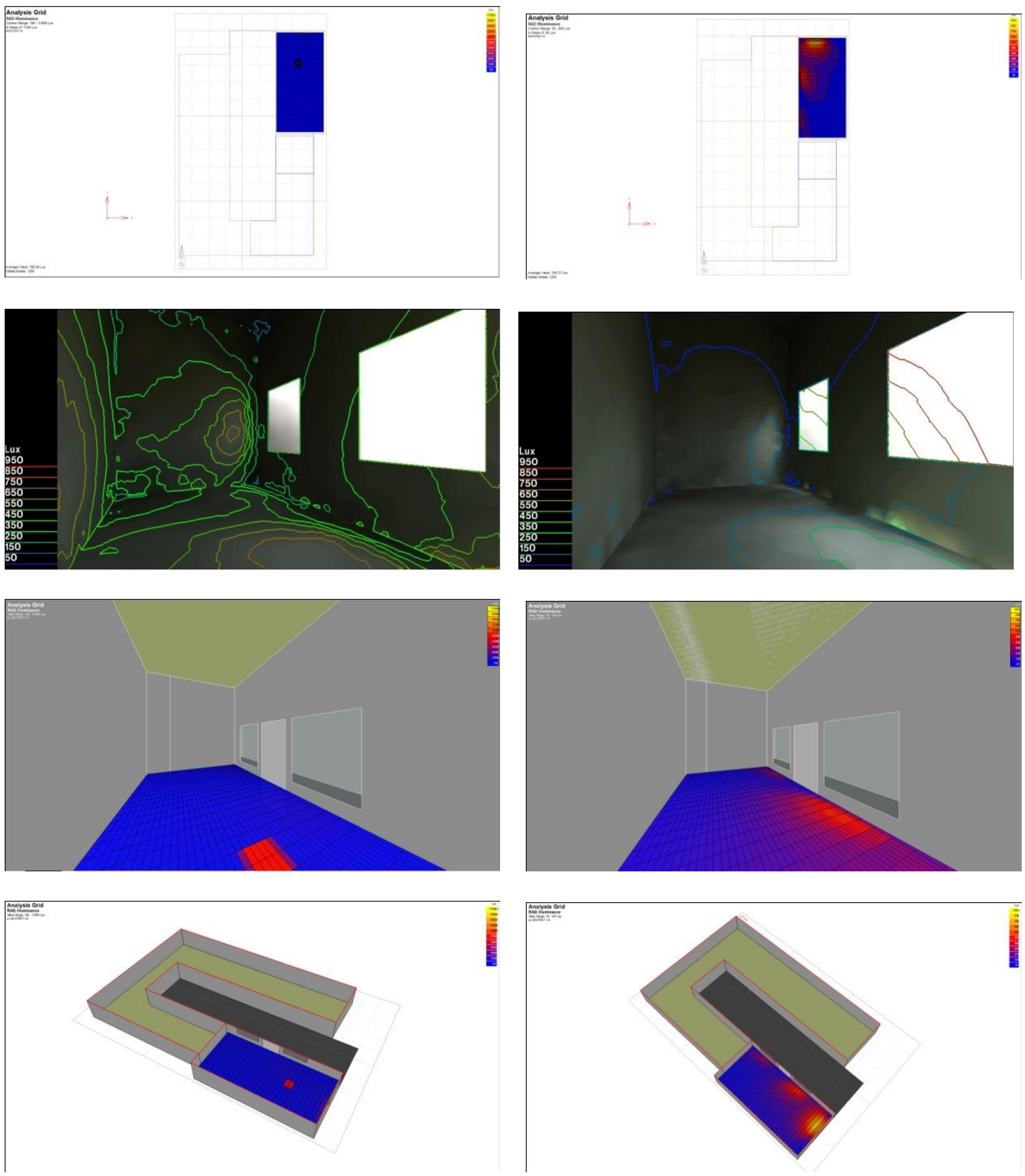
JUNE DECEMBER



***Courtyard-S*-U-N**

Radiance Simulation from Ecotect and Radiance: 3 p.m. in June and December

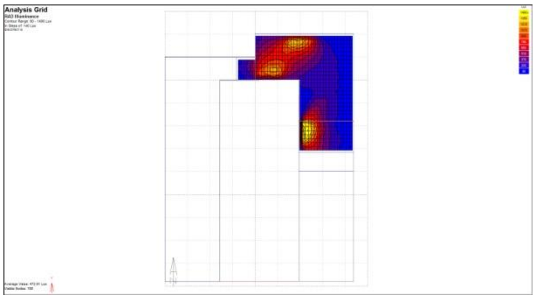
JUNE DECEMBER

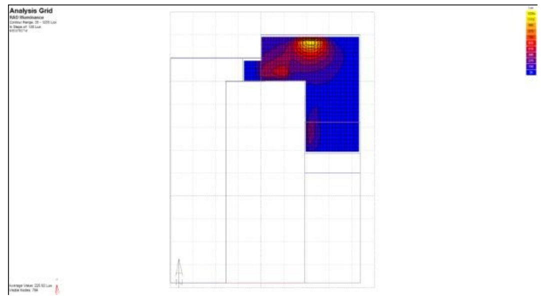


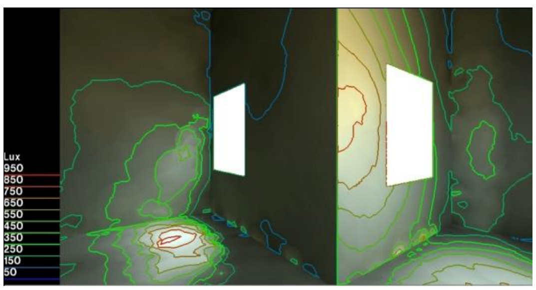
***Courtyard-S*-U-S**

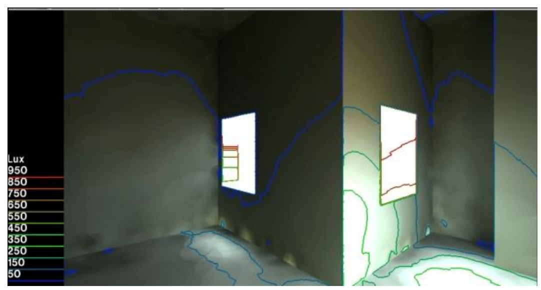
Radiance Simulation from Ecotect and Radiance: 9 a.m. in June and December

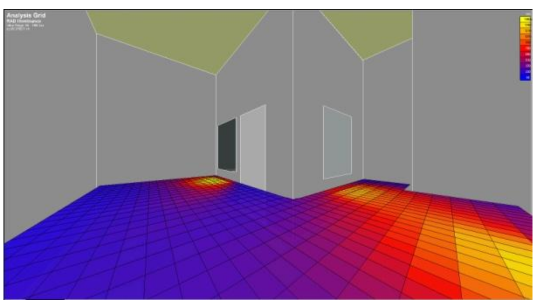
JUNE | DECEMBER

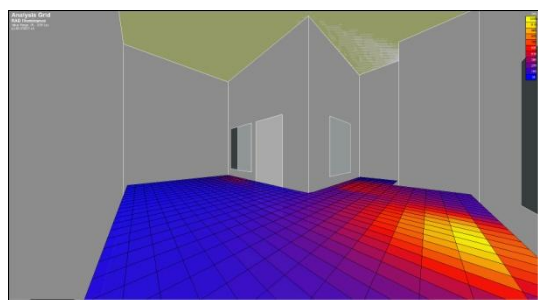


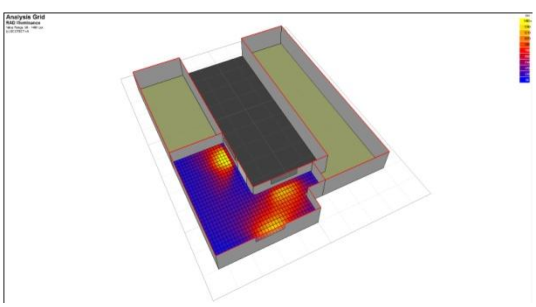


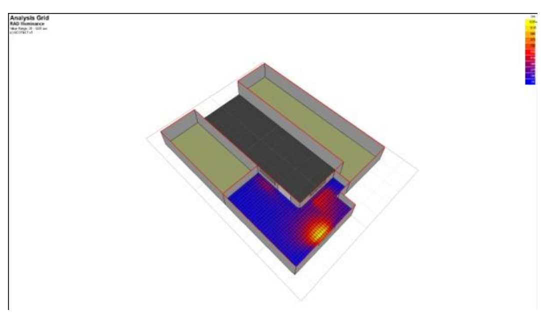








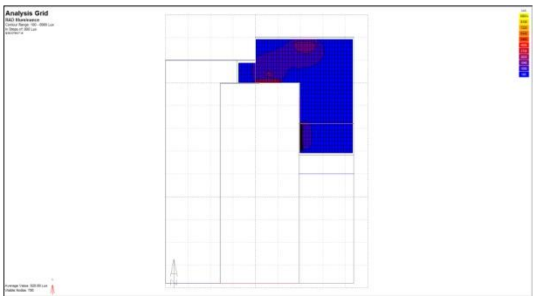


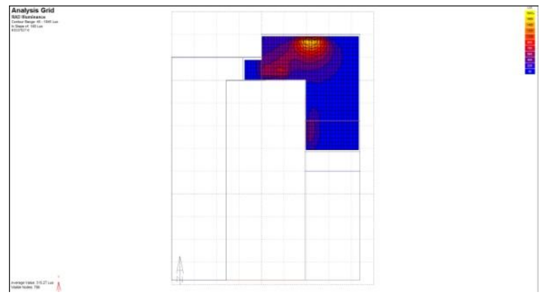


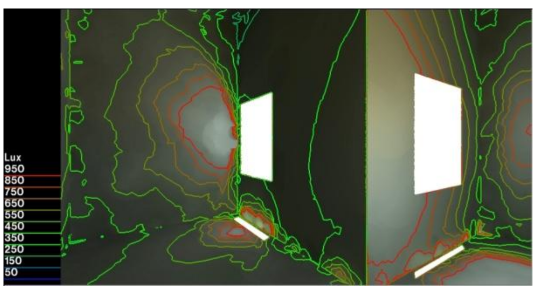
Courtyard-S-U-S

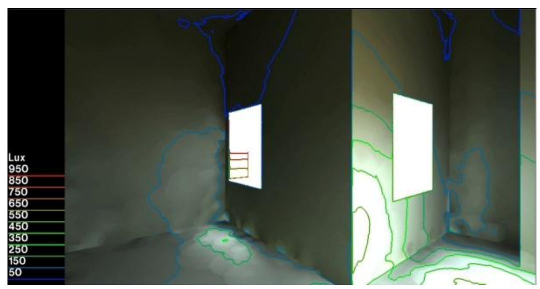
Radiance Simulation from Ecotect and Radiance: 12 p.m. in June and December

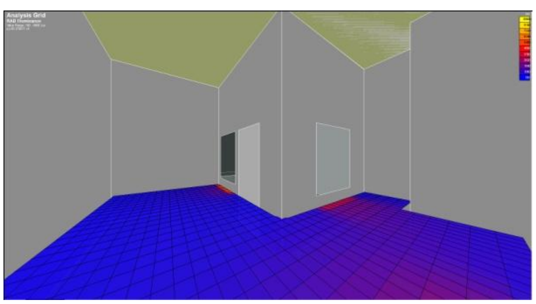
JUNE DECEMBER

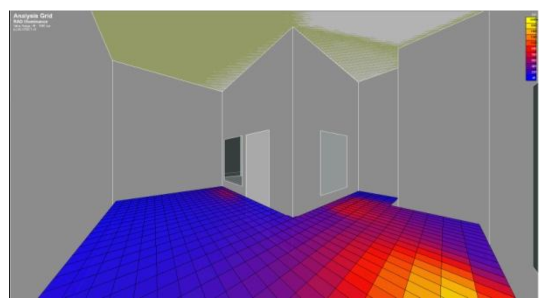


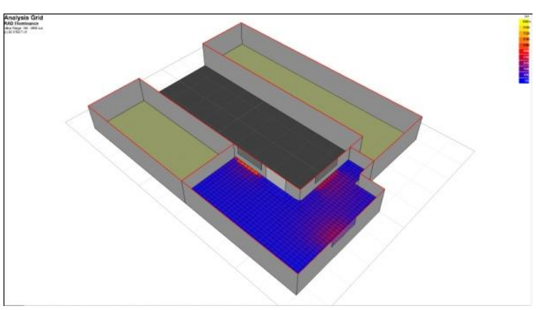


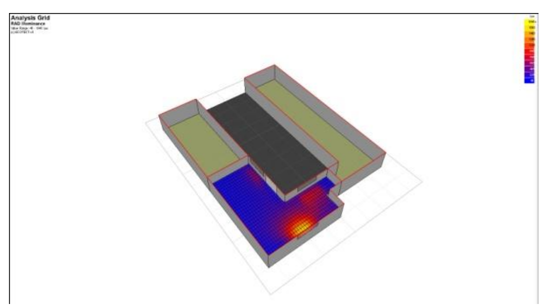








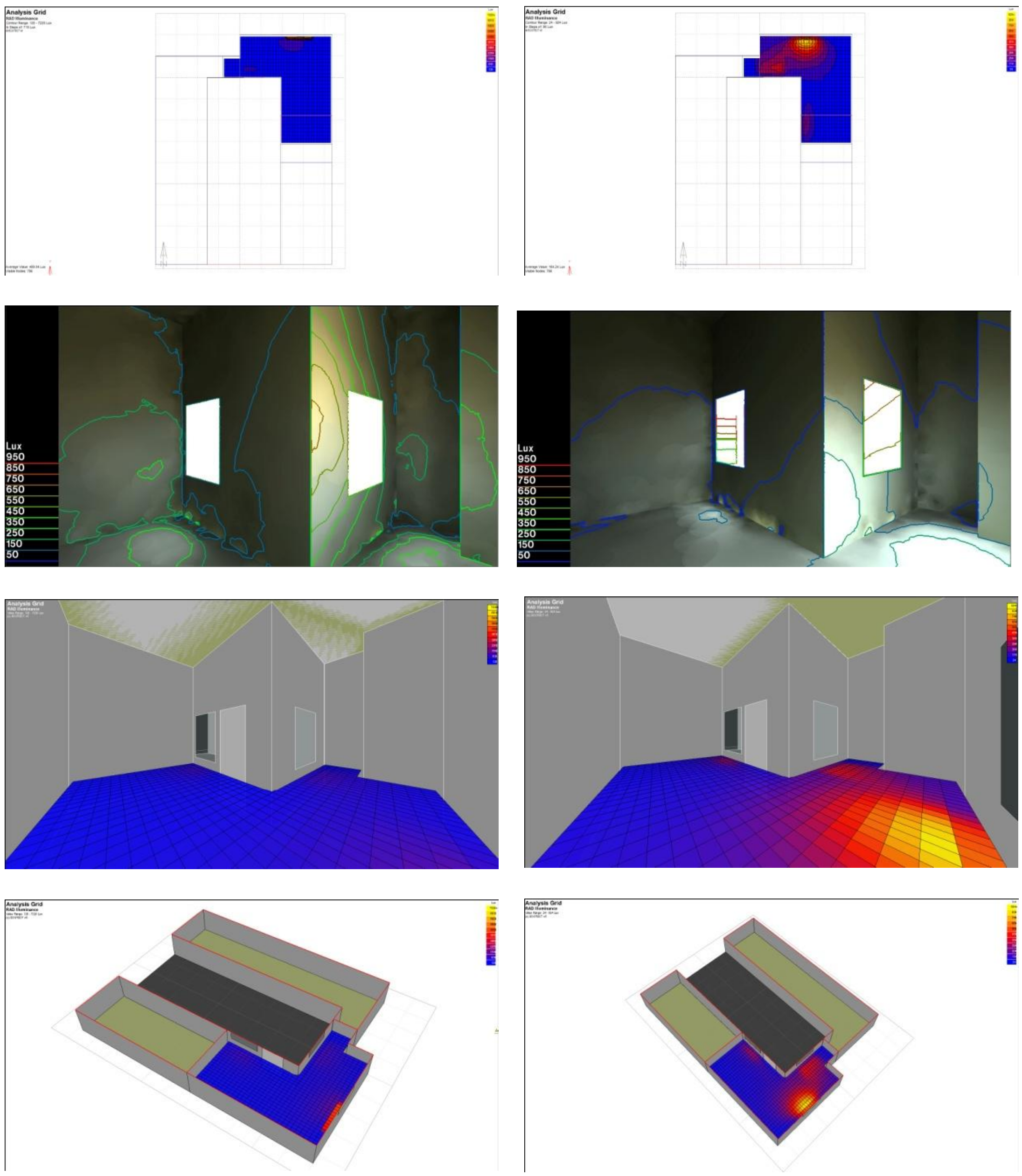




***Courtyard-S*-U-S**

Radiance Simulation from Ecotect and Radiance: 3 p.m. in June and December

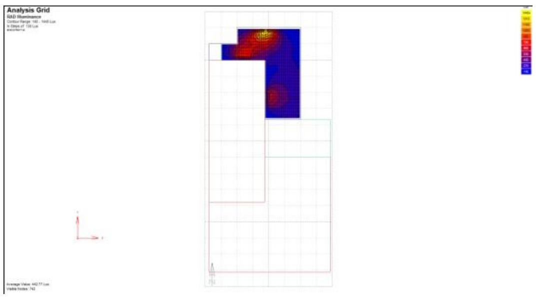
JUNE DECEMBER

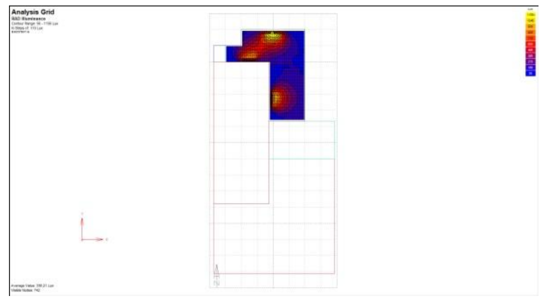


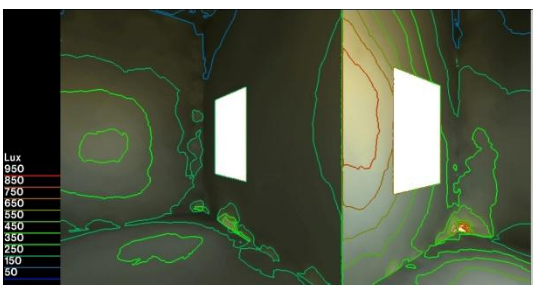
***Courtyard-S*-U-W**

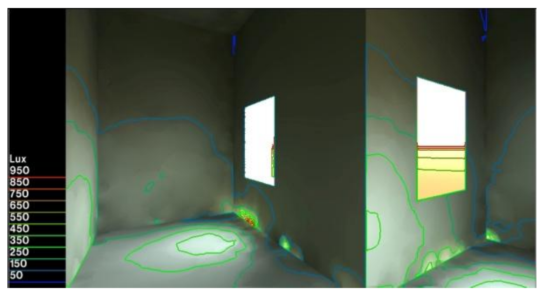
Radiance Simulation from Ecotect and Radiance: 9 a.m. in June and December

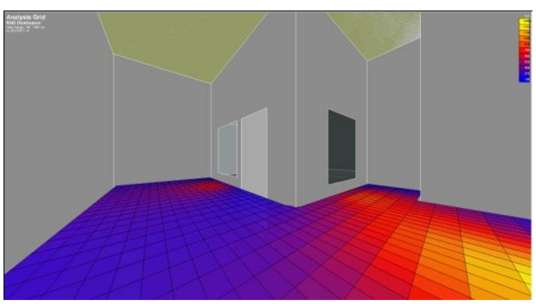
JUNE | DECEMBER

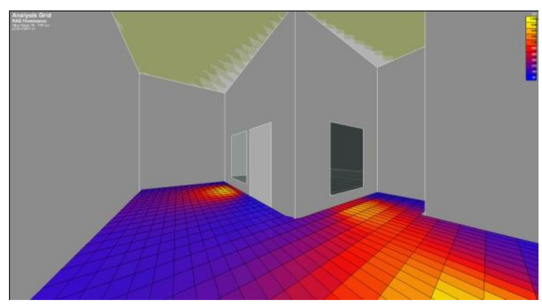


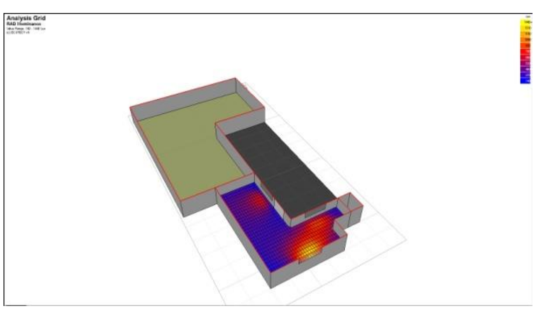


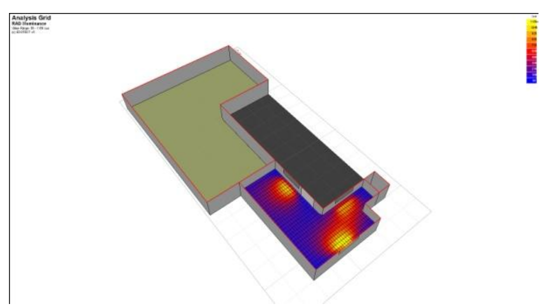








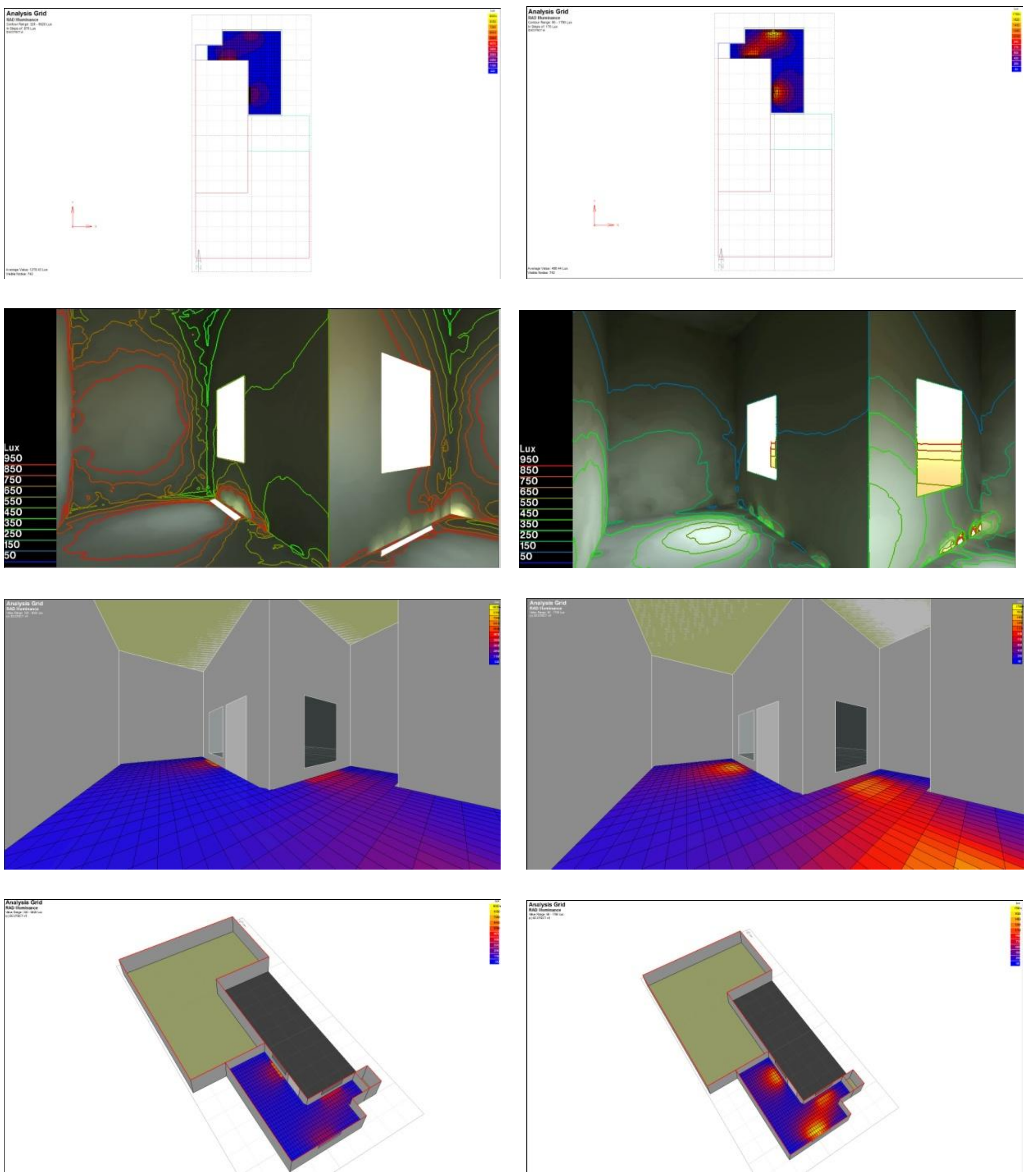




***Courtyard-S*-U-W**

Radiance Simulation from Ecotect and Radiance: 12 p.m. in June and December

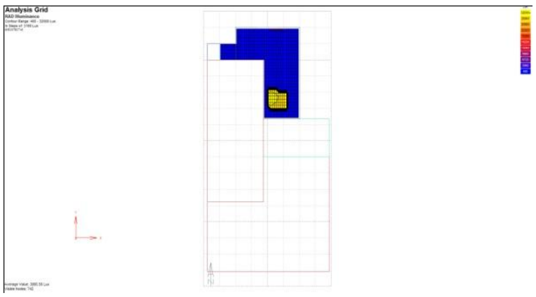
JUNE DECEMBER

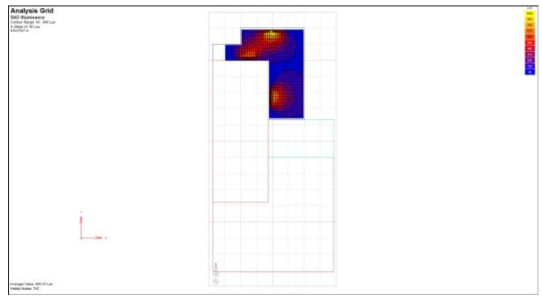


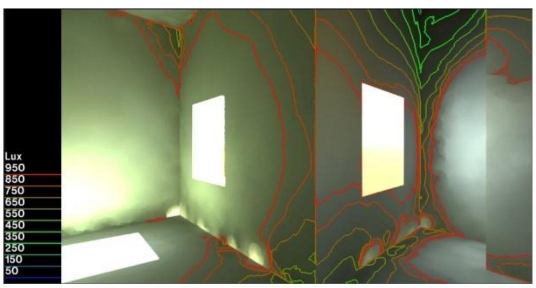
***Courtyard-S*-U-W**

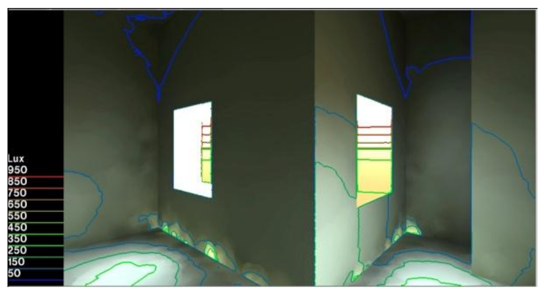
Radiance Simulation from Ecotect and Radiance: 3 p.m. in June and December

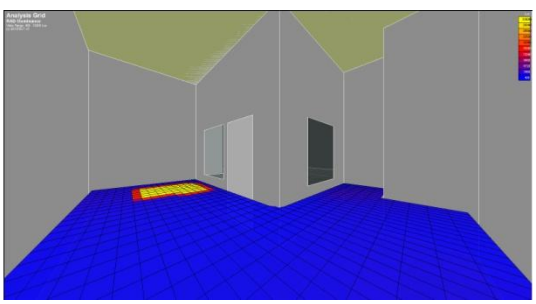
JUNE DECEMBER

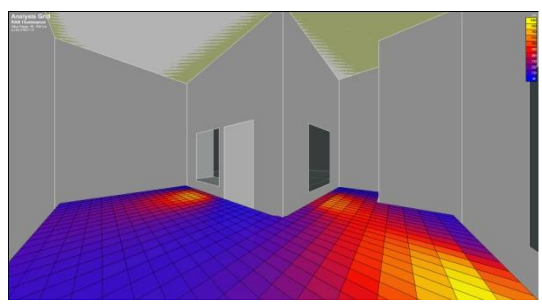


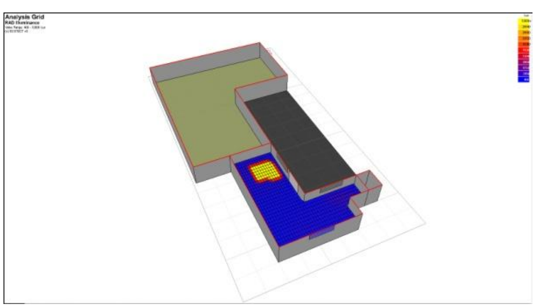


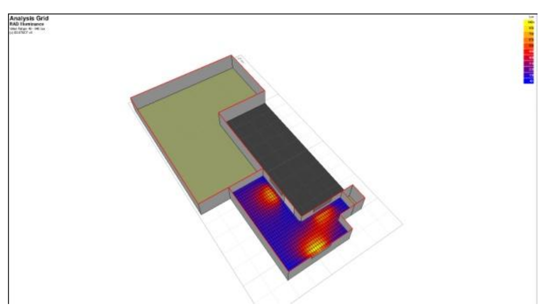








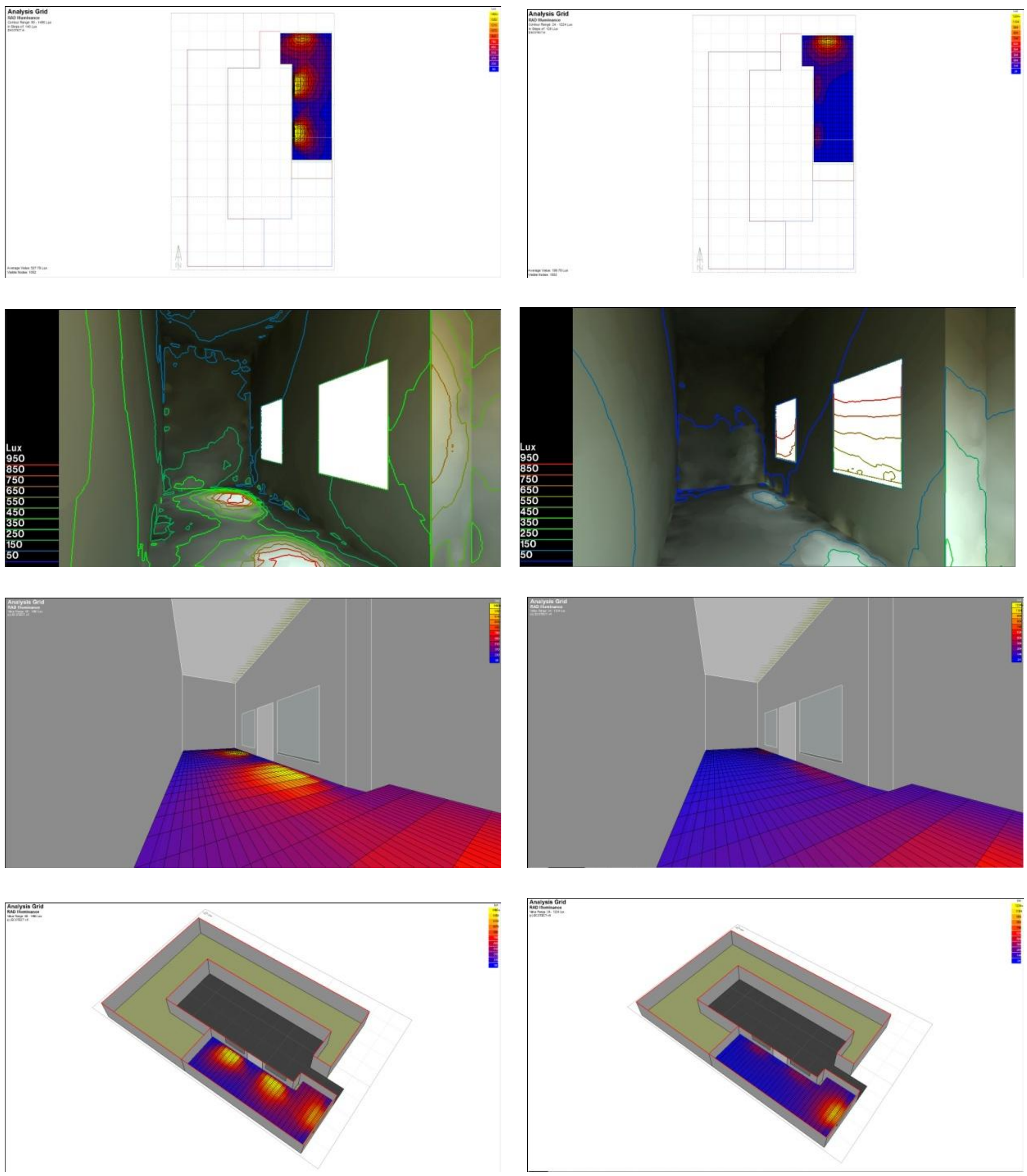




***Courtyard-S*-C-N**

Radiance Simulation from Ecotect and Radiance: 9 a.m. in June and December

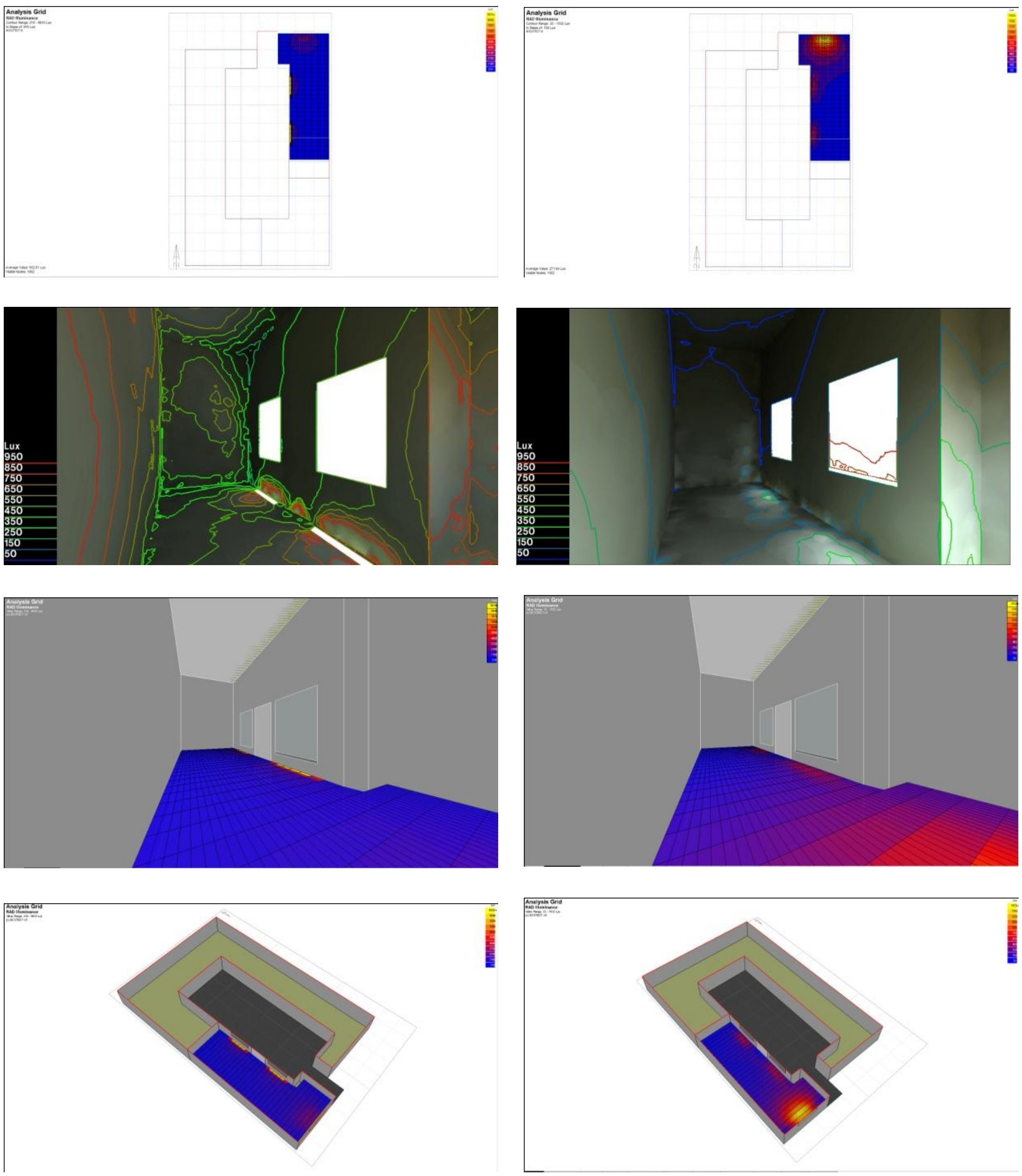
JUNE DECEMBER



***Courtyard-S*-C-N**

Radiance Simulation from Ecotect and Radiance: 12 p.m. in June and December

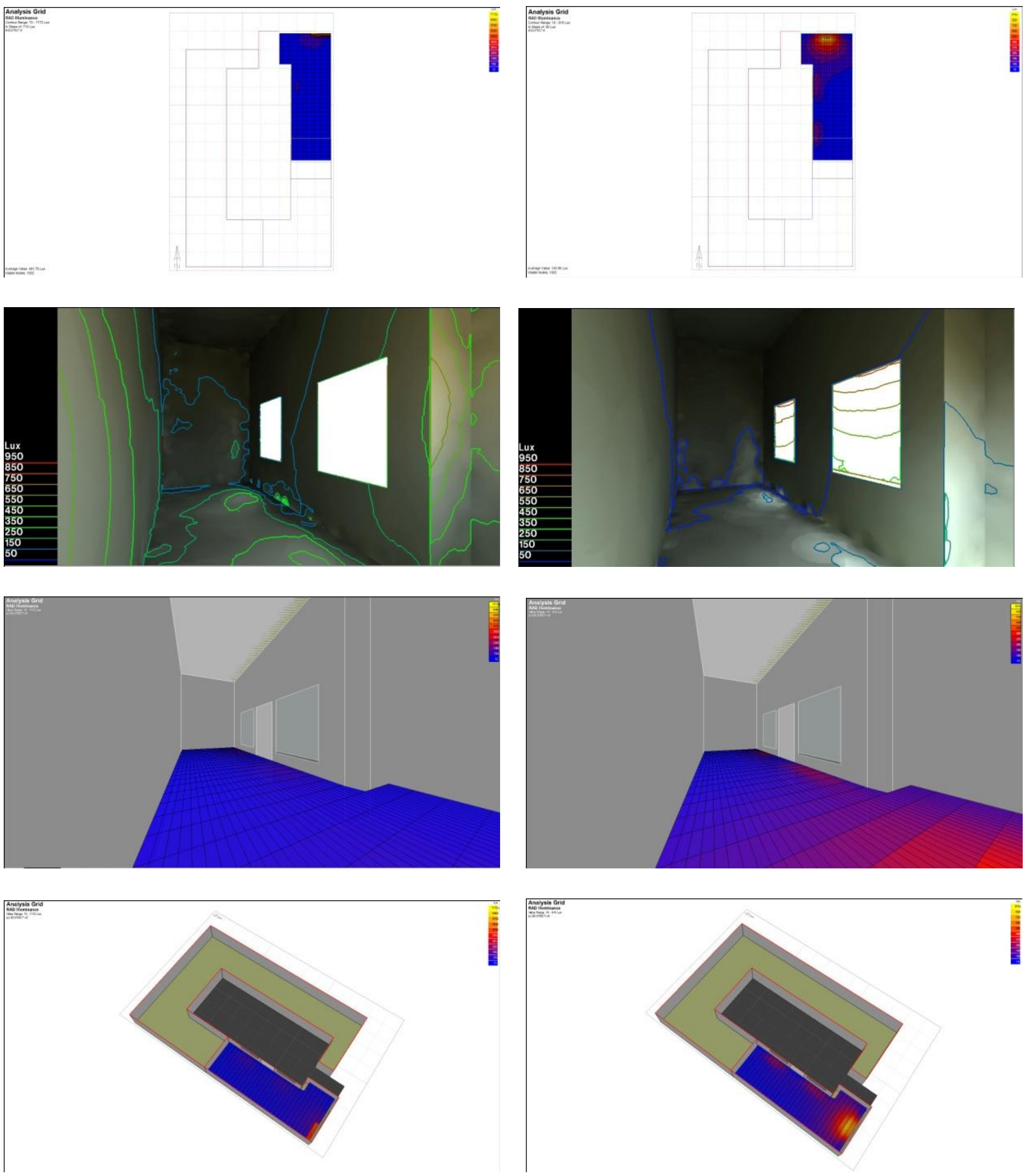
JUNE DECEMBER



***Courtyard-S*-C-N**

Radiance Simulation from Ecotect and Radiance: 3 p.m. in June and December

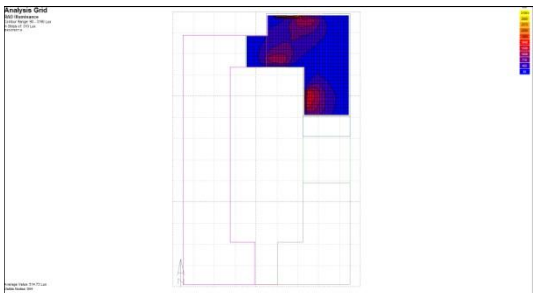
JUNE DECEMBER

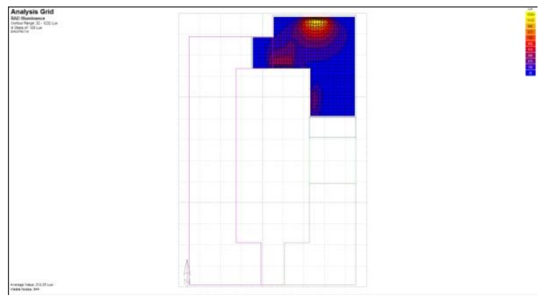


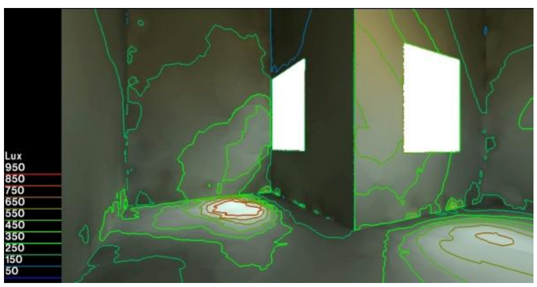
***Courtyard-S*-C-S**

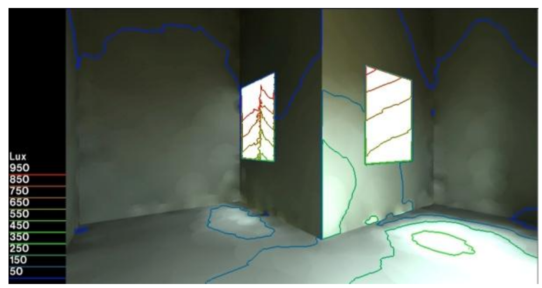
Radiance Simulation from Ecotect and Radiance: 9 a.m. in June and December

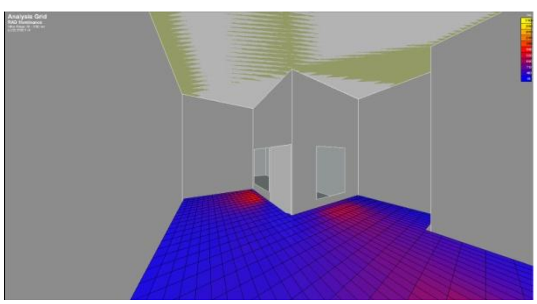
JUNE	DECEMBER

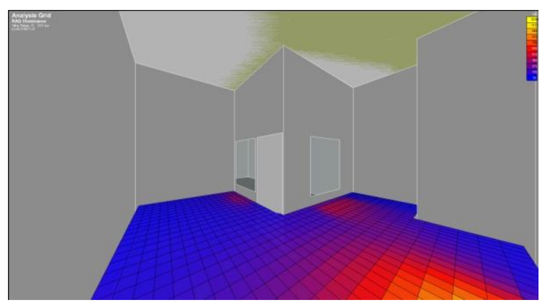


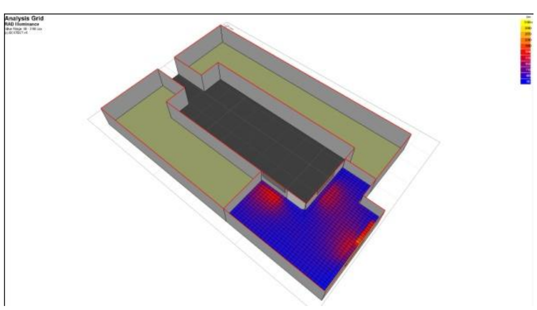


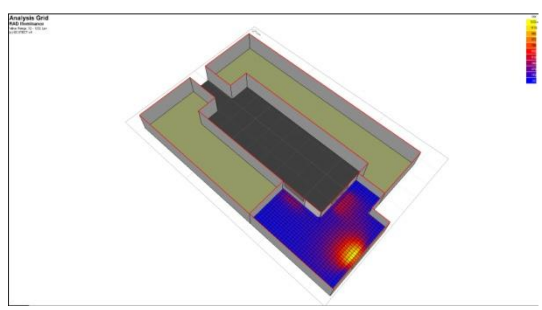








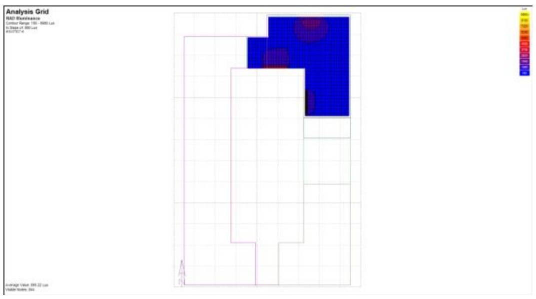


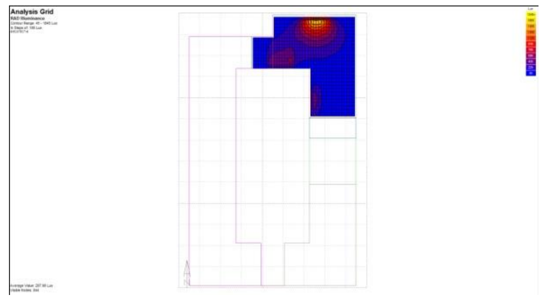


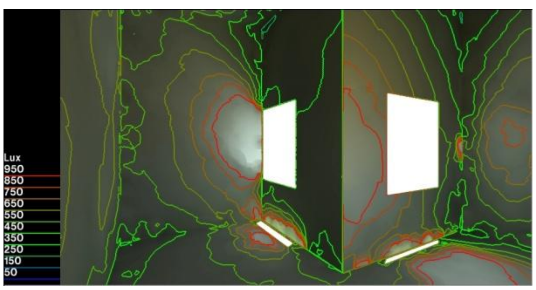
***Courtyard-S*-C-S**

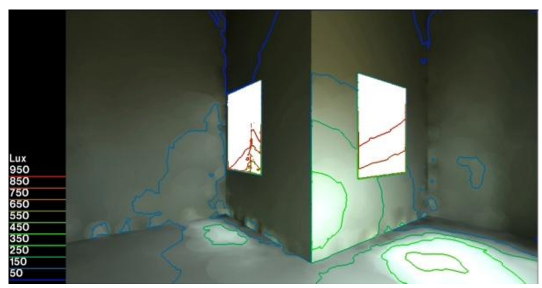
Radiance Simulation from Ecotect and Radiance: 12 p.m. in June and December

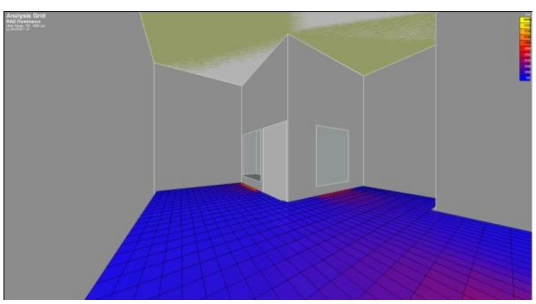
JUNE DECEMBER

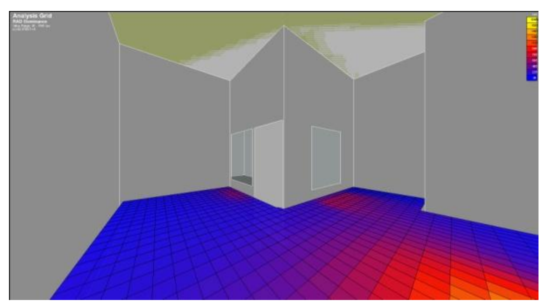


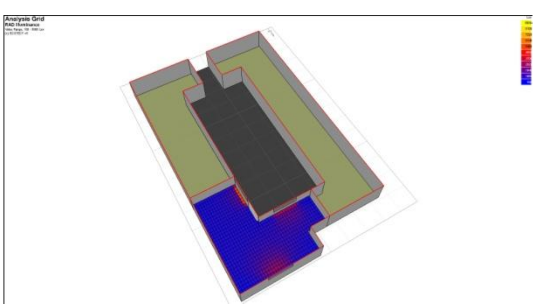


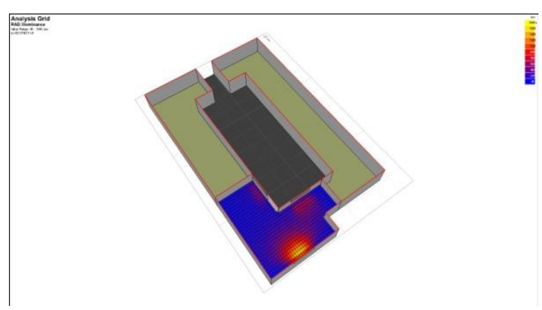








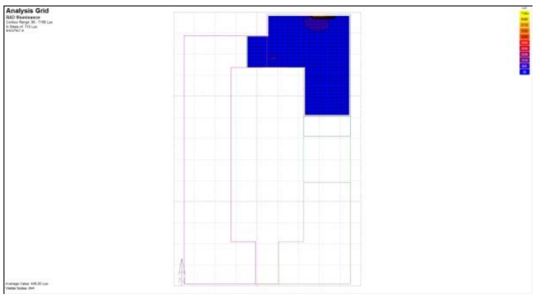


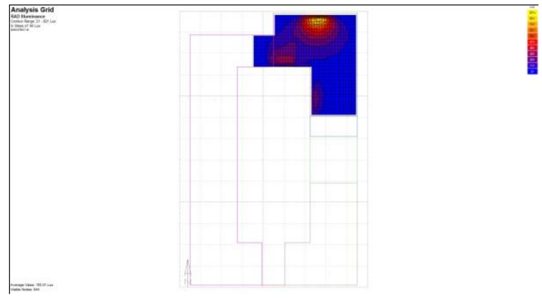


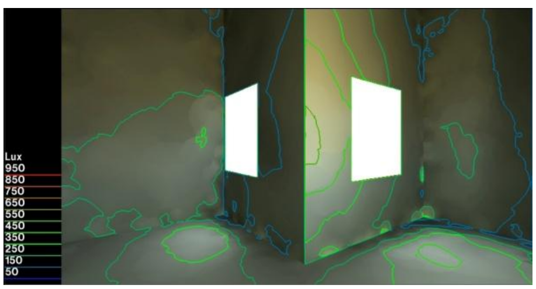
***Courtyard-S*-C-S**

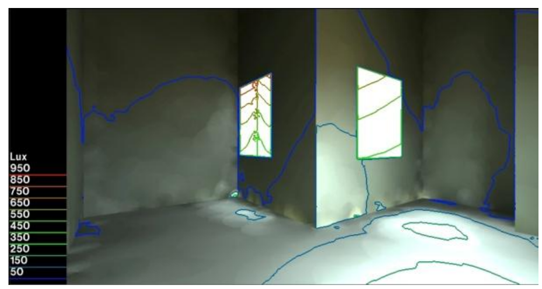
Radiance Simulation from Ecotect and Radiance: 3 p.m. in June and December

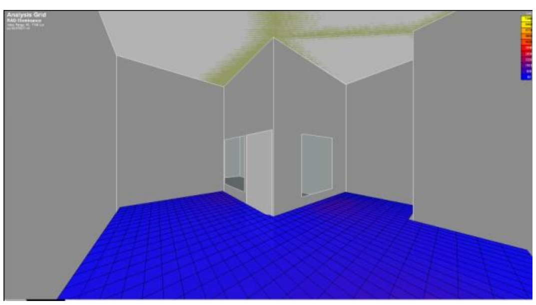
JUNE DECEMBER

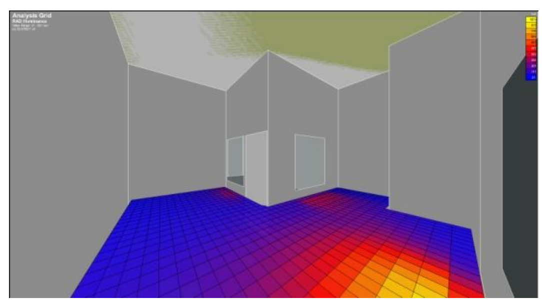


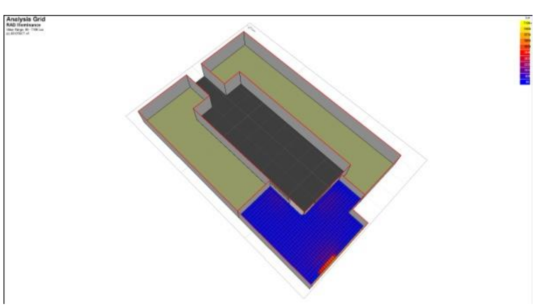


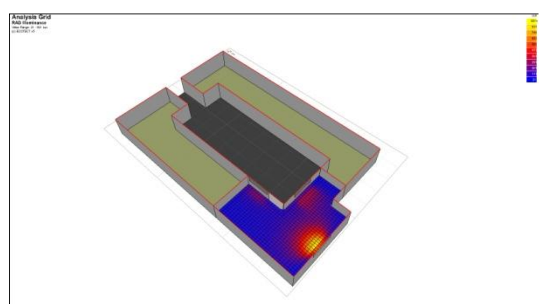








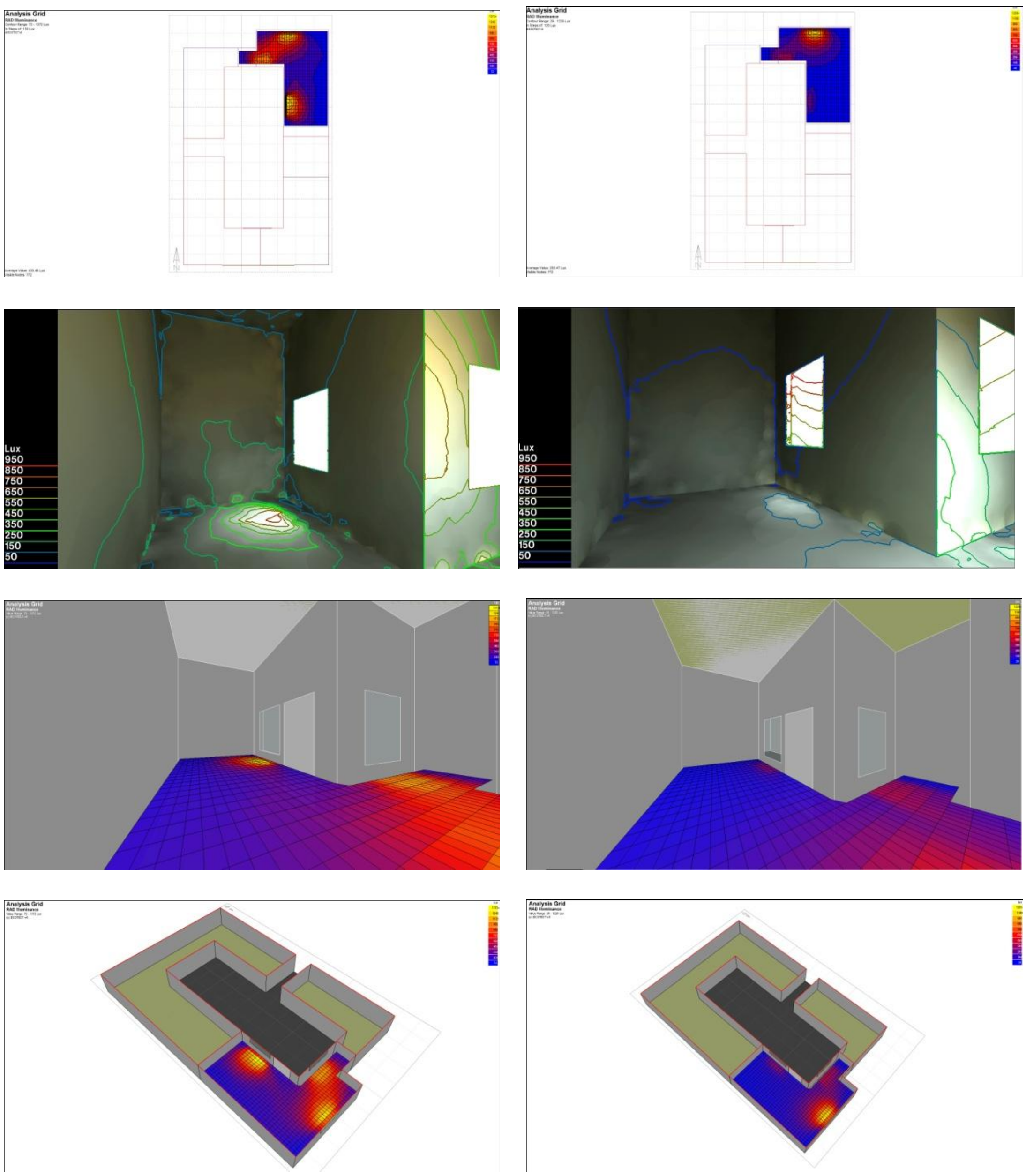




Courtyard-S-C-W

Radiance Simulation from Ecotect and Radiance: 9 a.m. in June and December

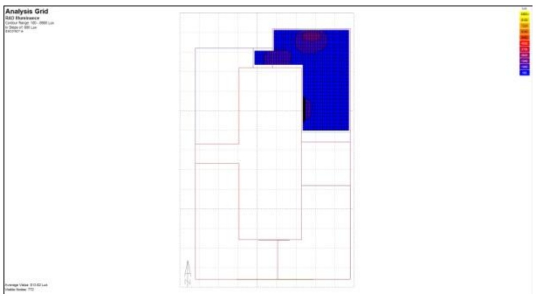
JUNE DECEMBER

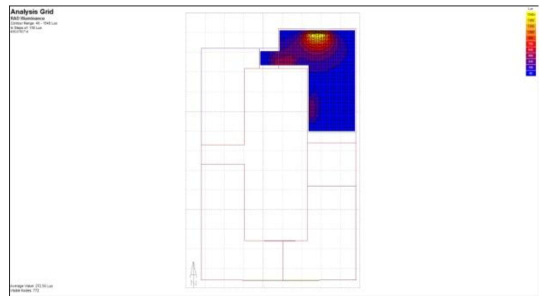


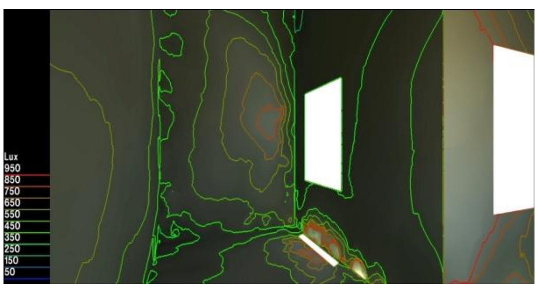
***Courtyard-S*-C-W**

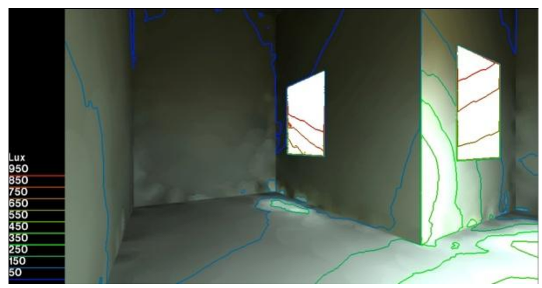
Radiance Simulation from Ecotect and Radiance: 12 p.m. in June and December

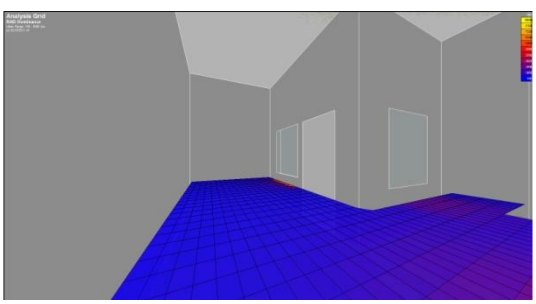
JUNE DECEMBER

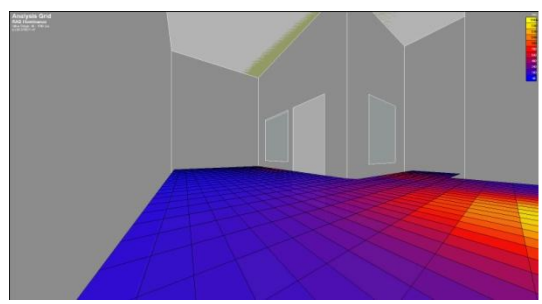


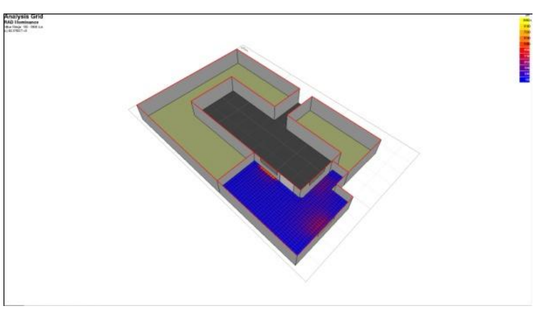


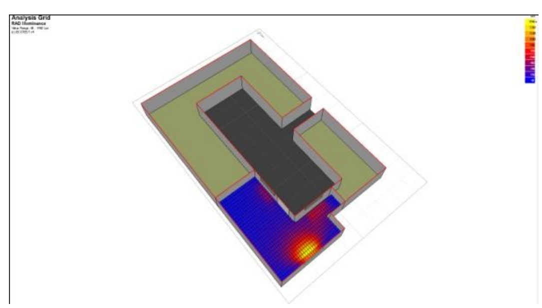








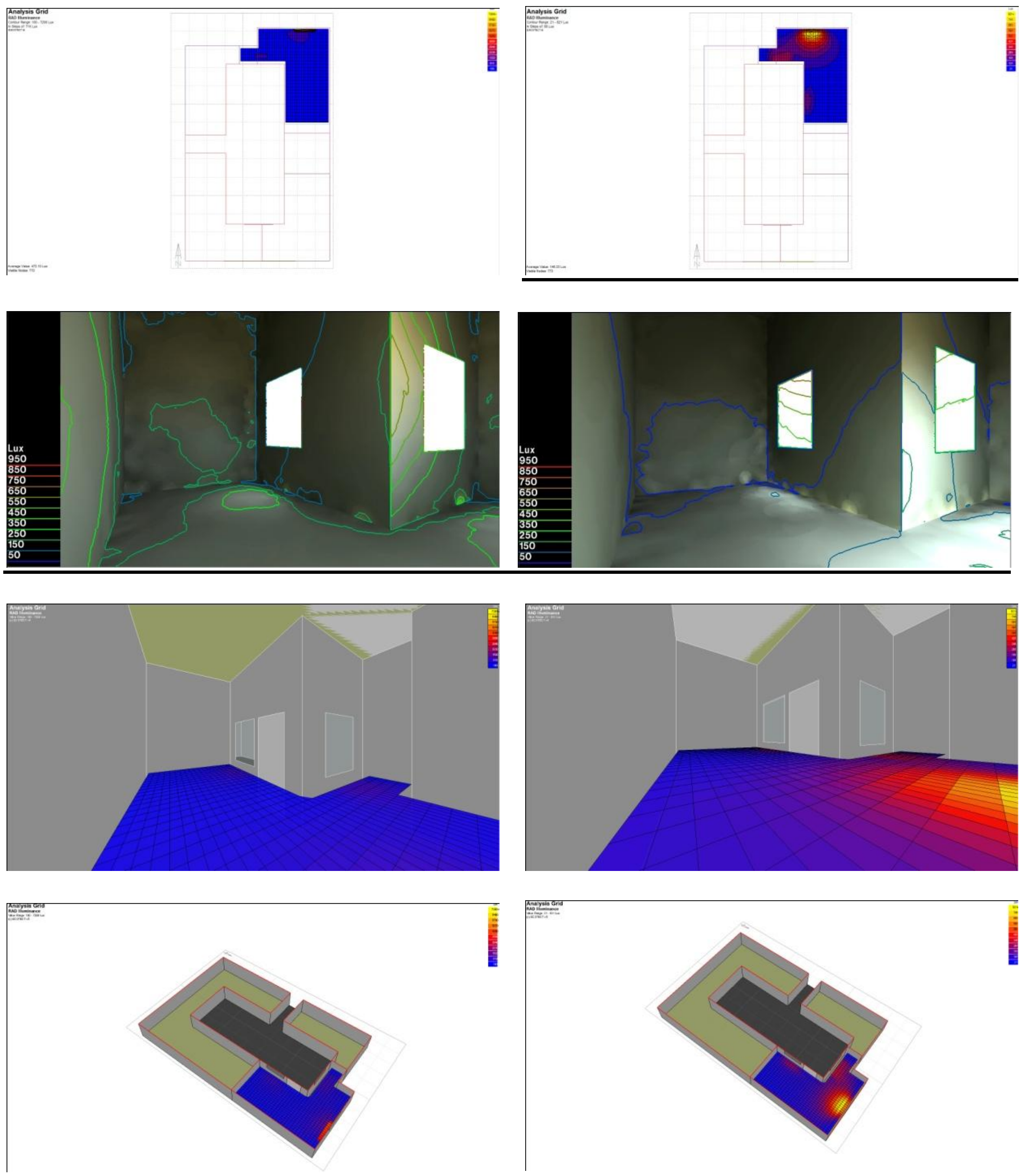




***Courtyard-S*-C-W**

Radiance Simulation from Ecotect and Radiance: 3 p.m. in June and December

JUNE DECEMBER



Appendix C

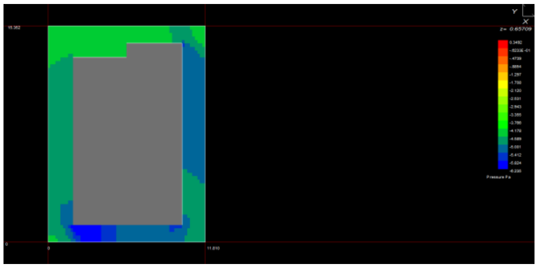
WinAir CFD Simulation

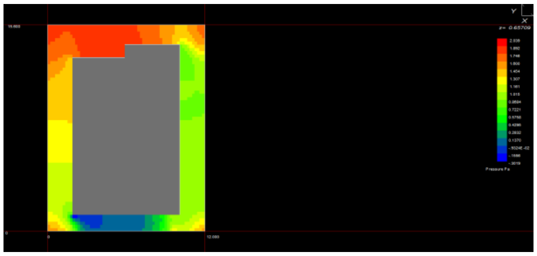
Courtyard-T

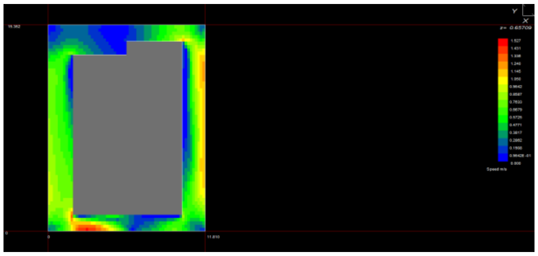
WinAir Pressure and Speed Simulation in the Month of June and December

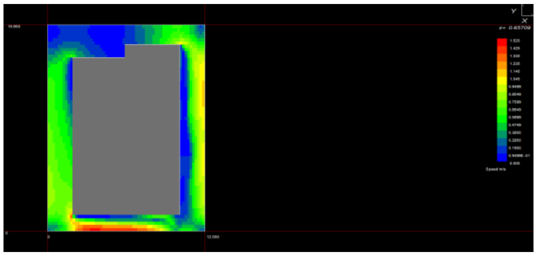
JUNE

DECEMBER





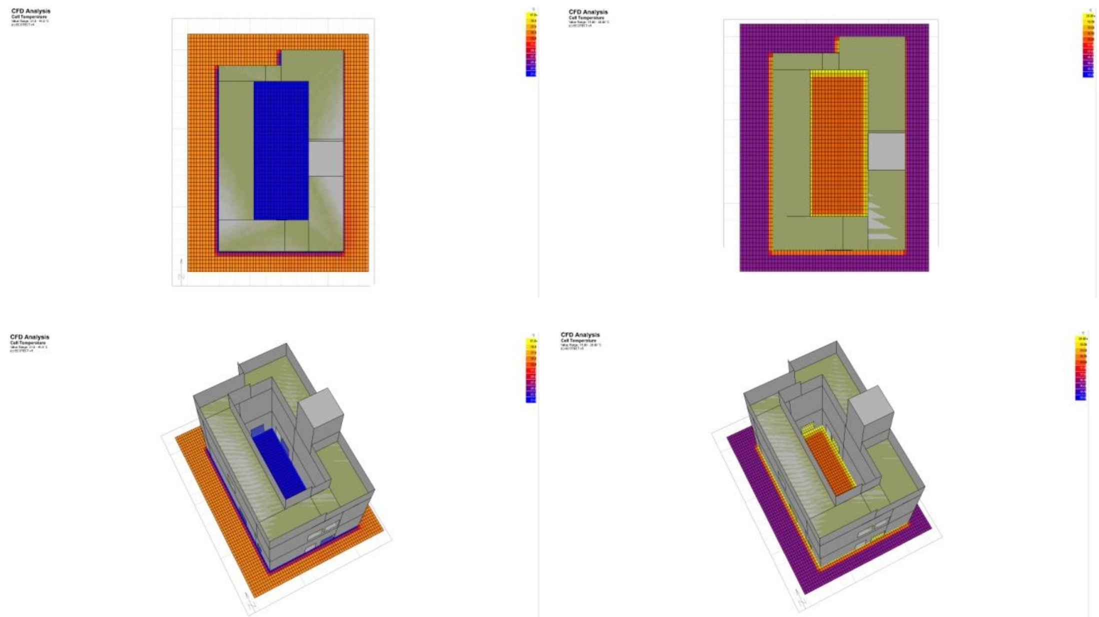




Courtyard-T

Cell Temperature Simulation in the Month of June and December

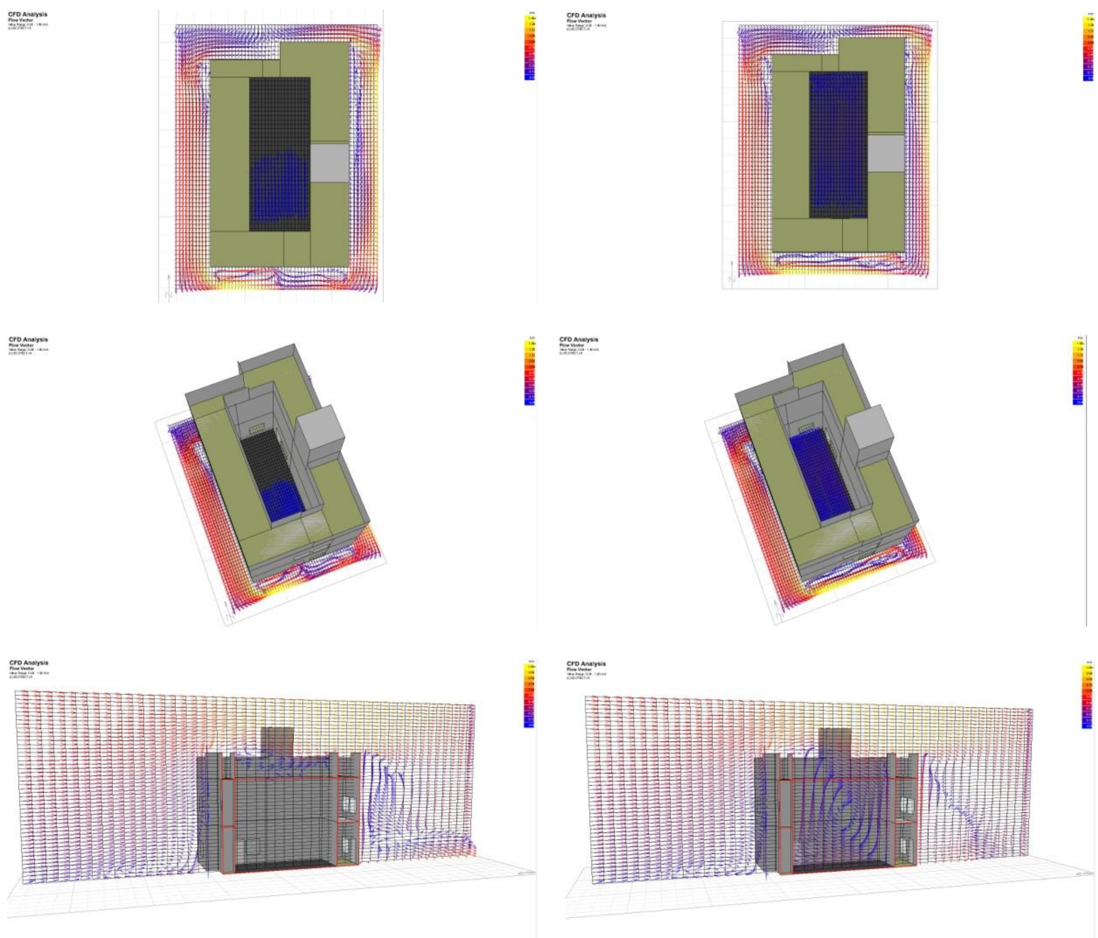
JUNE DECEMBER



Courtyard-T

Flow Vector Simulation in the Month of June and December

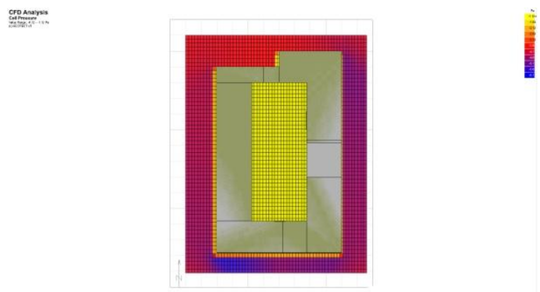
JUNE DECEMBER

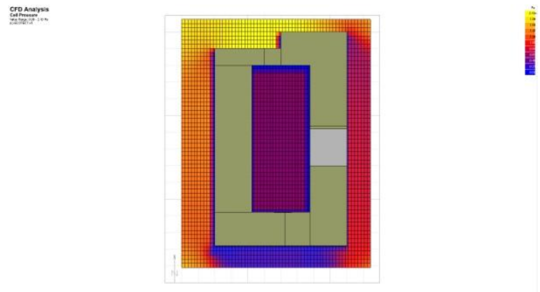


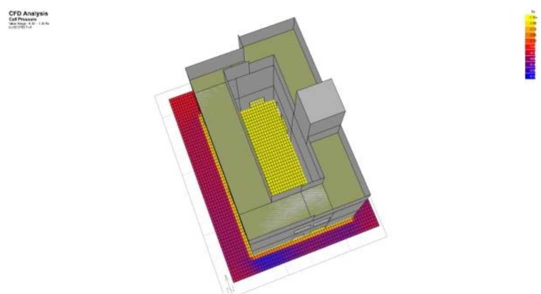
Courtyard-T

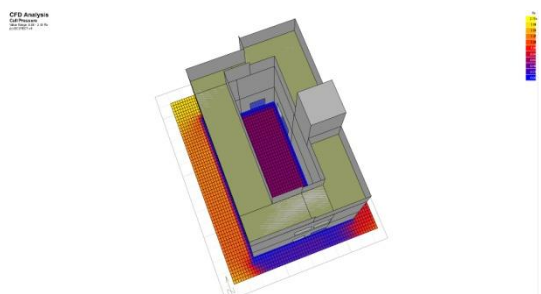
Cell Pressure Simulation in the Month of June and December

JUNE | DECEMBER





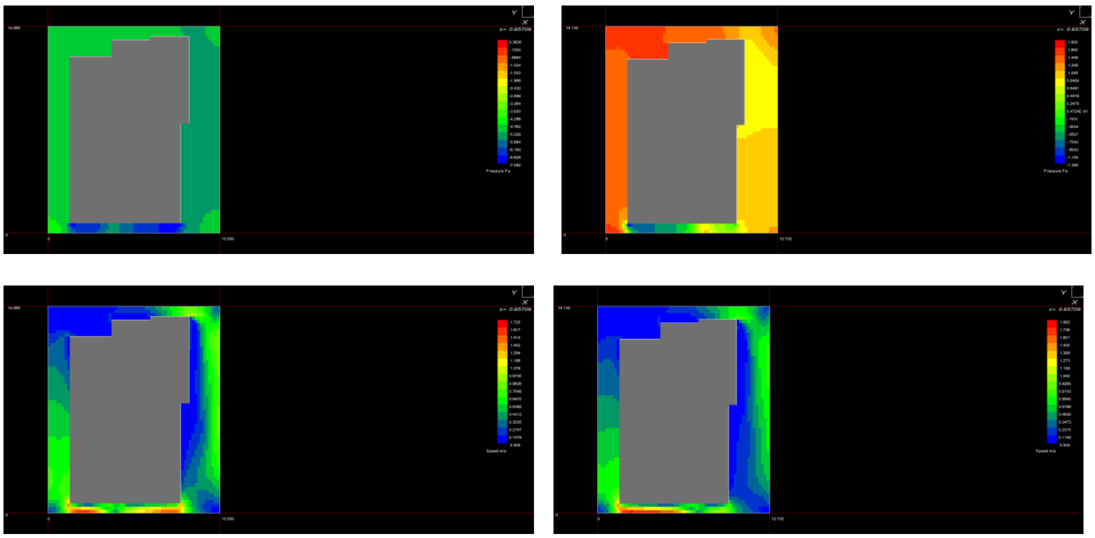




***Courtyard-S*-U-N**

WinAir Pressure and Speed Simulation in the Month of June and December

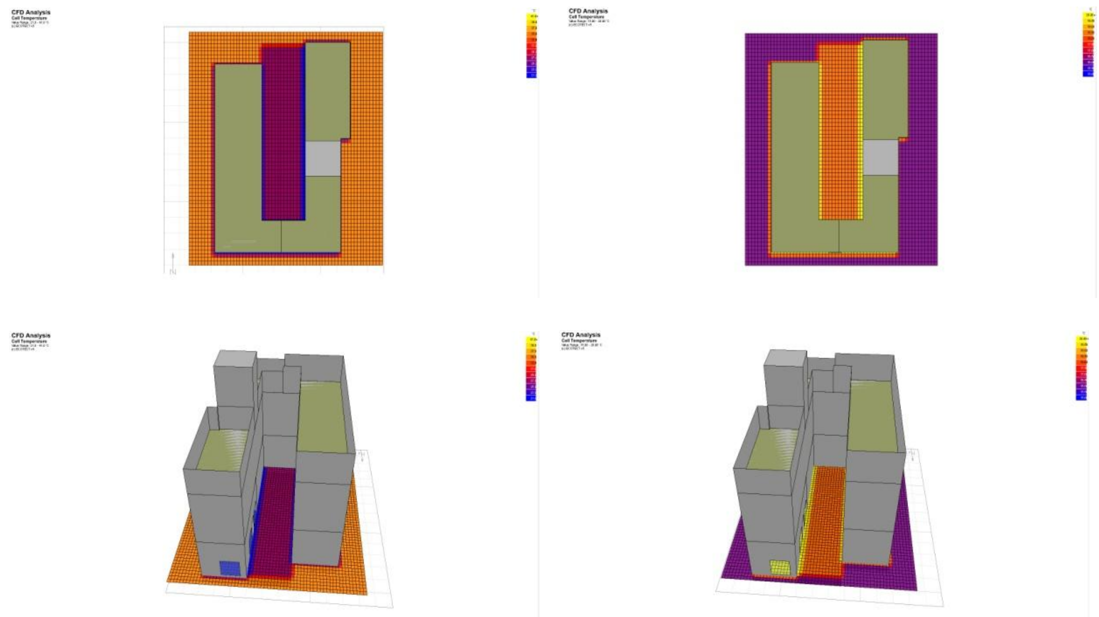
JUNE DECEMBER



***Courtyard-S*-U-N**

Cell Temperature Simulation in the Month of June and December

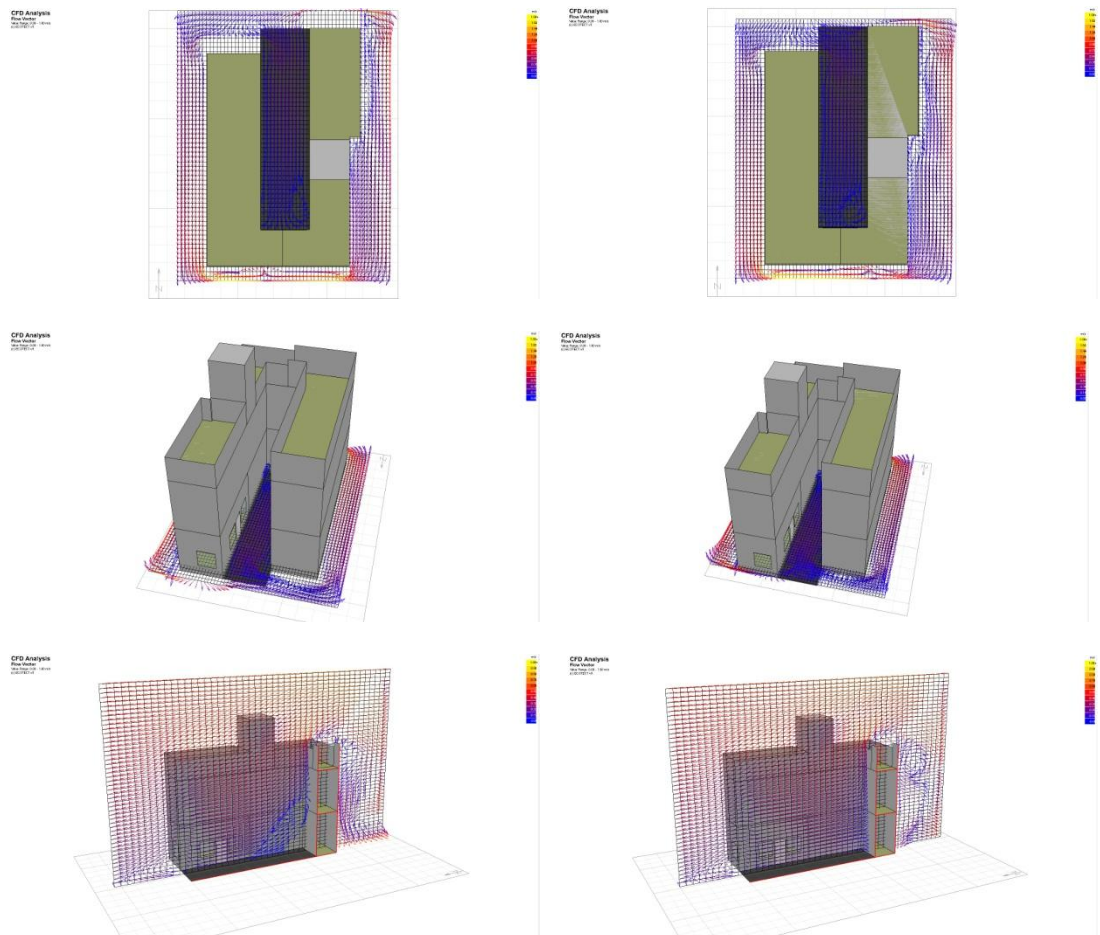
JUNE DECEMBER



***Courtyard-S-*U-N**

Flow Vector Simulation in the Month of June and December

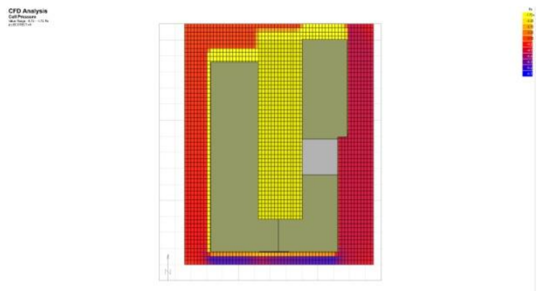
JUNE DECEMBER

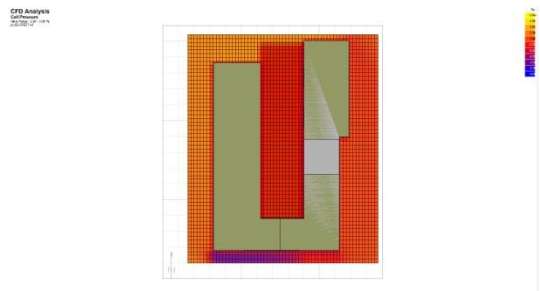


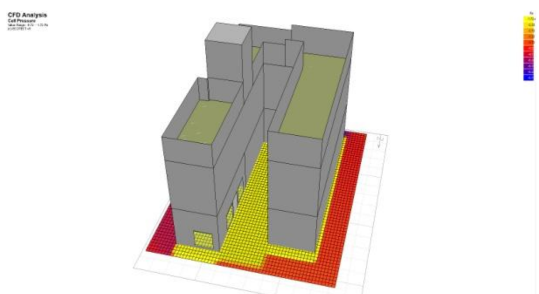
***Courtyard-S*-U-N**

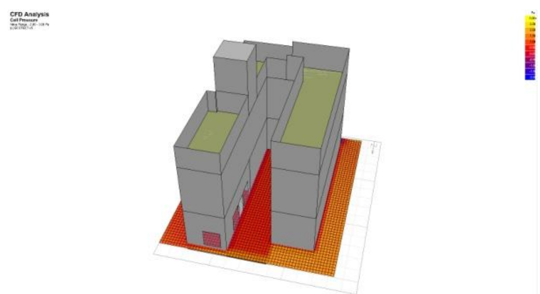
Cell Pressure Simulation in the Month of June and December

JUNE DECEMBER





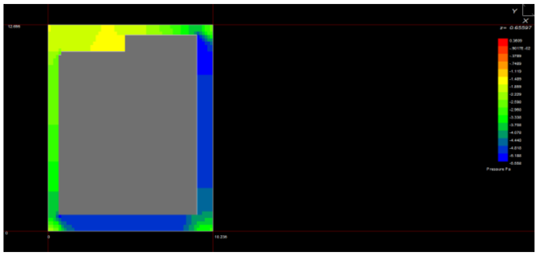


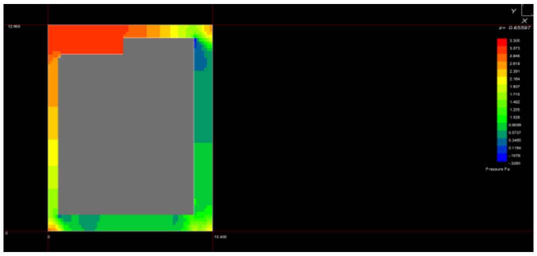


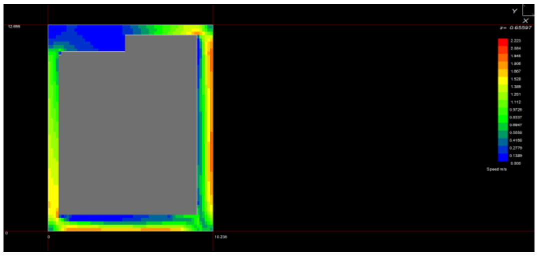
***Courtyard-S*-U-S**

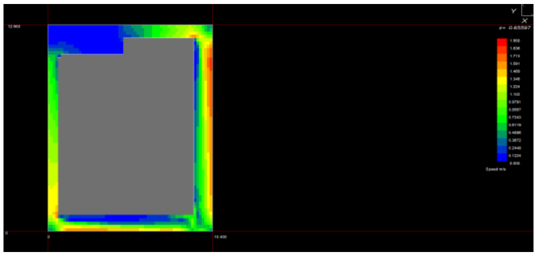
WinAir Pressure and Speed Simulation in the Month of June and December

JUNE | DECEMBER





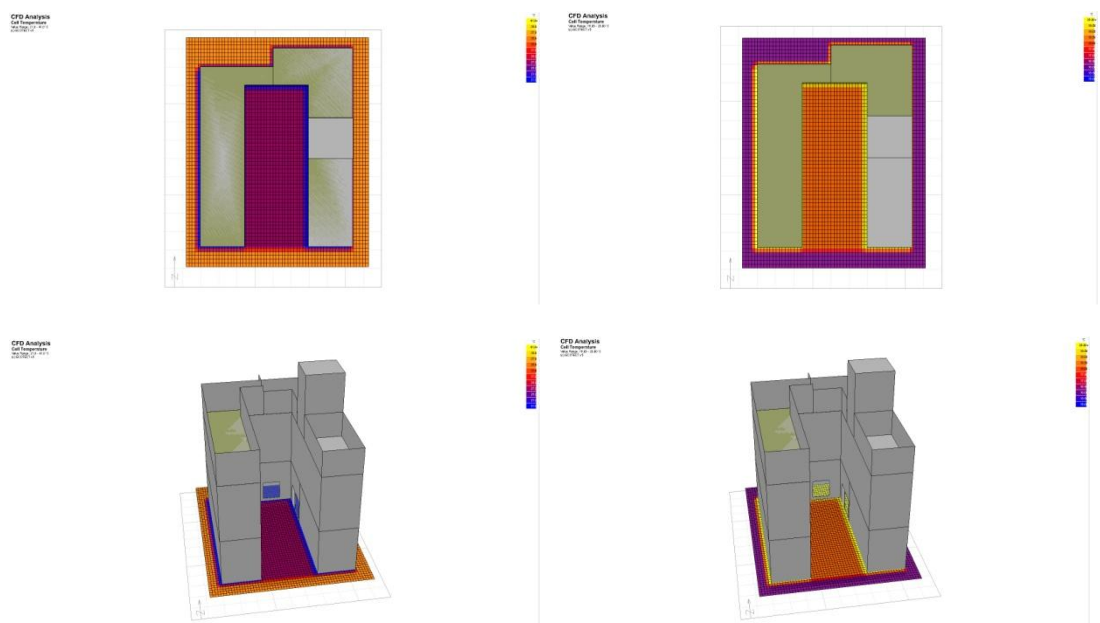




***Courtyard-S*-U-S**

Cell Temperature Simulation in the Month of June and December

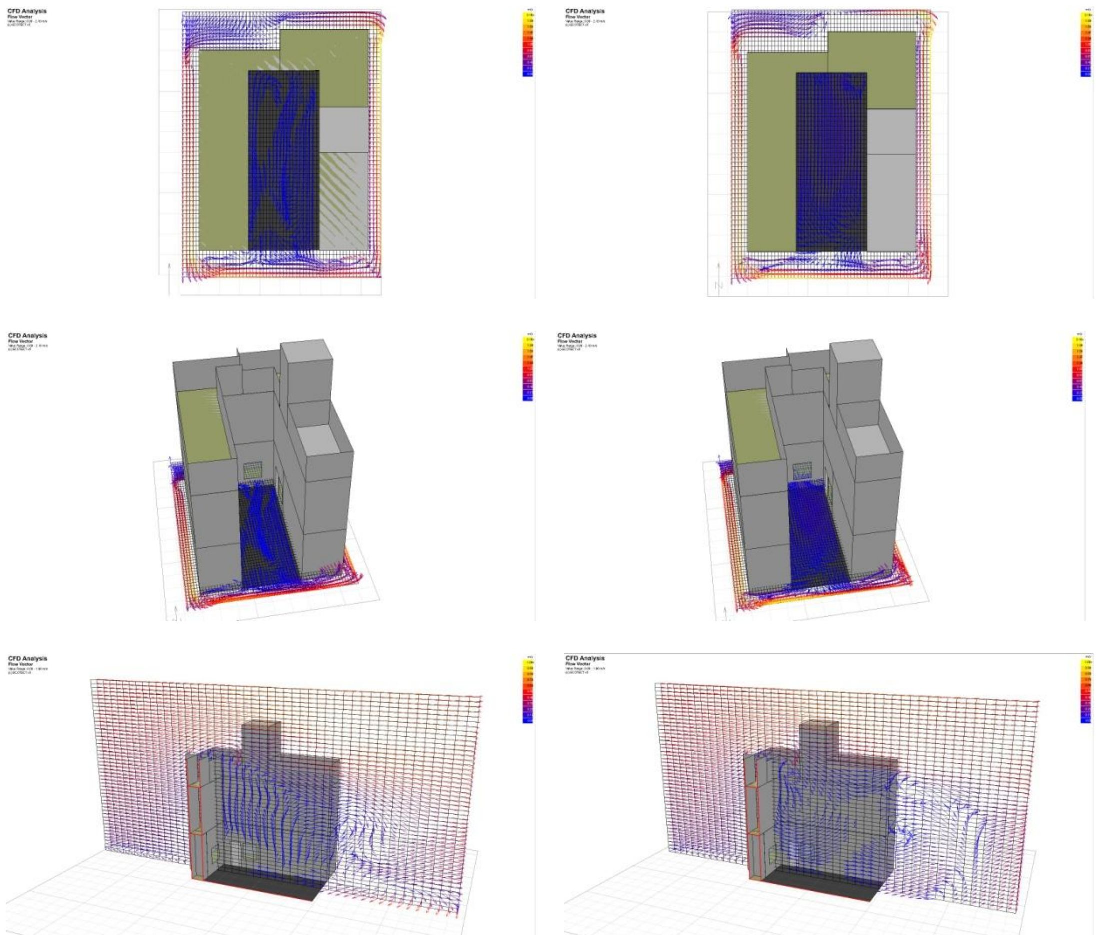
JUNE DECEMBER



***Courtyard-S*-U-S**

Flow Vector Simulation in the Month of June and December

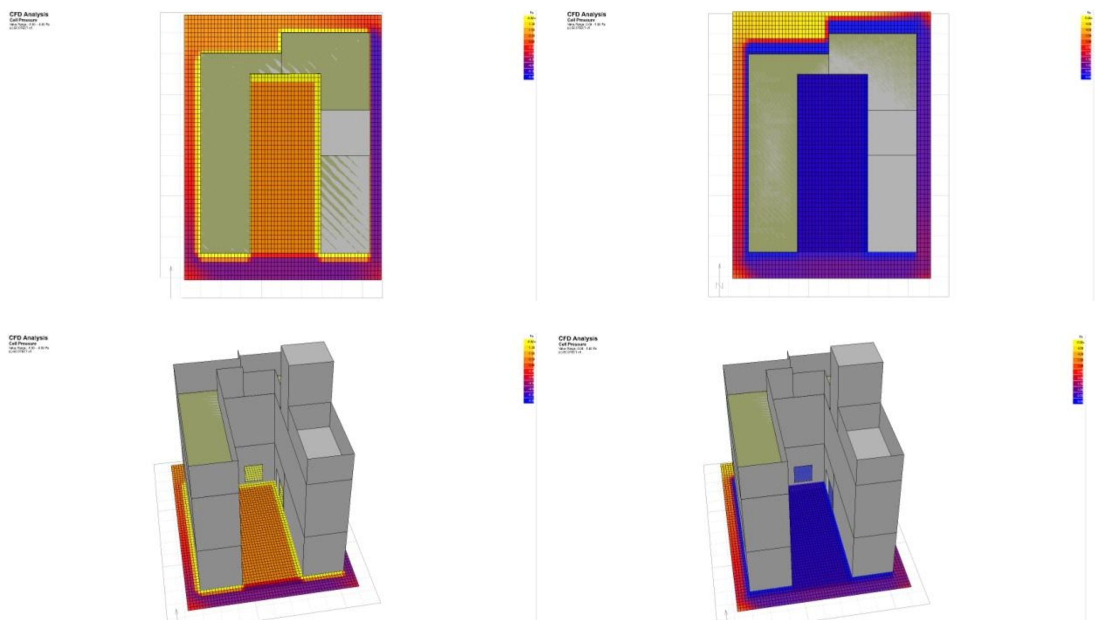
JUNE DECEMBER



***Courtyard-S*-U-S**

Cell Pressure Simulation in the Month of June and December

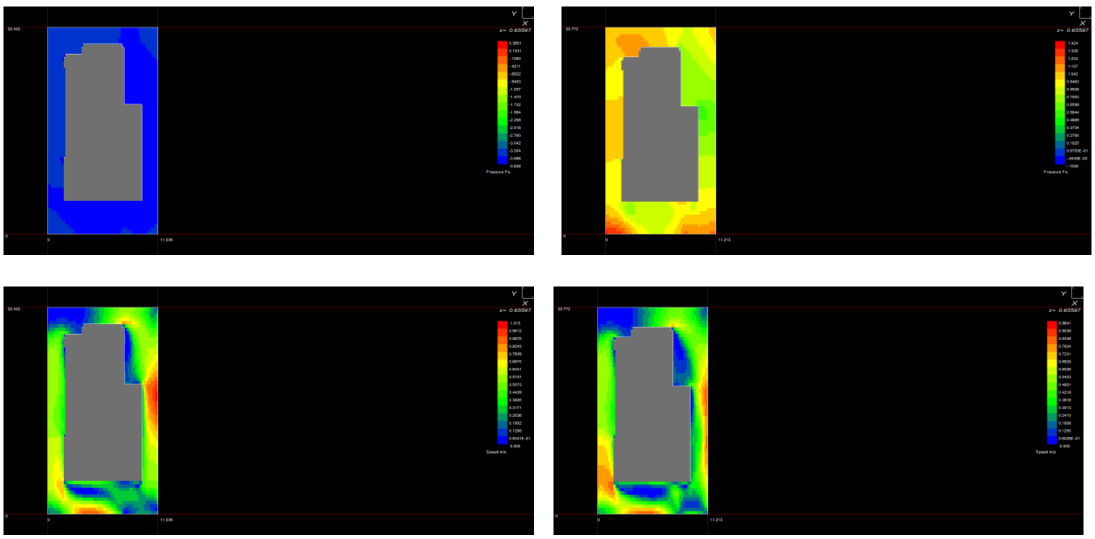
JUNE DECEMBER



***Courtyard-S*-U-W**

WinAir Pressure and Speed Simulation in the Month of June and December

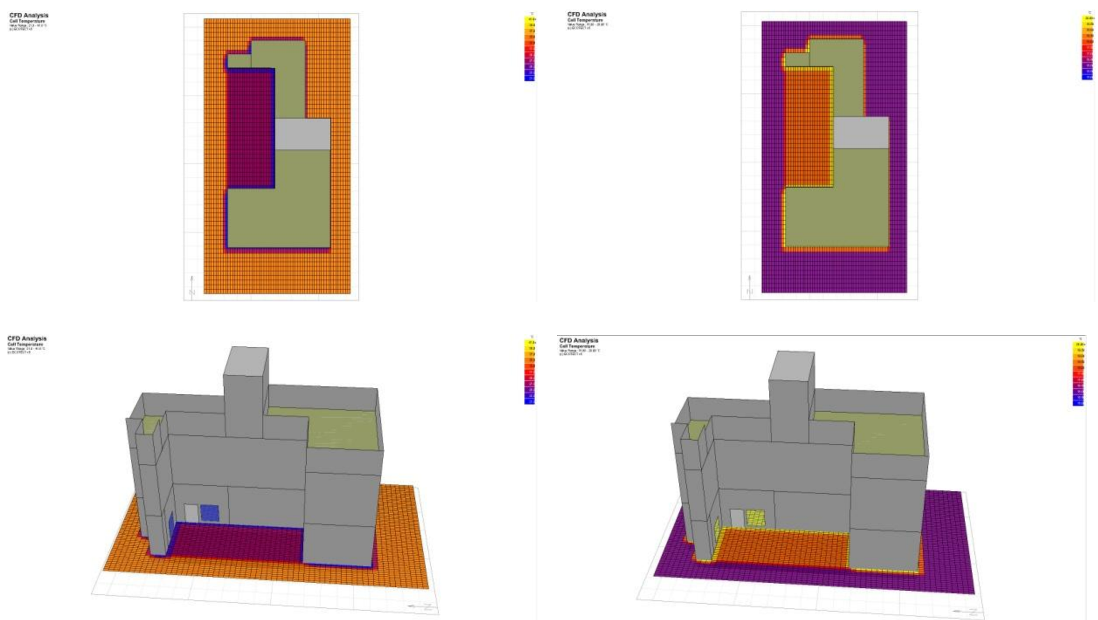
JUNE DECEMBER



***Courtyard-S*-U-W**

Cell Temperature Simulation in the Month of June and December

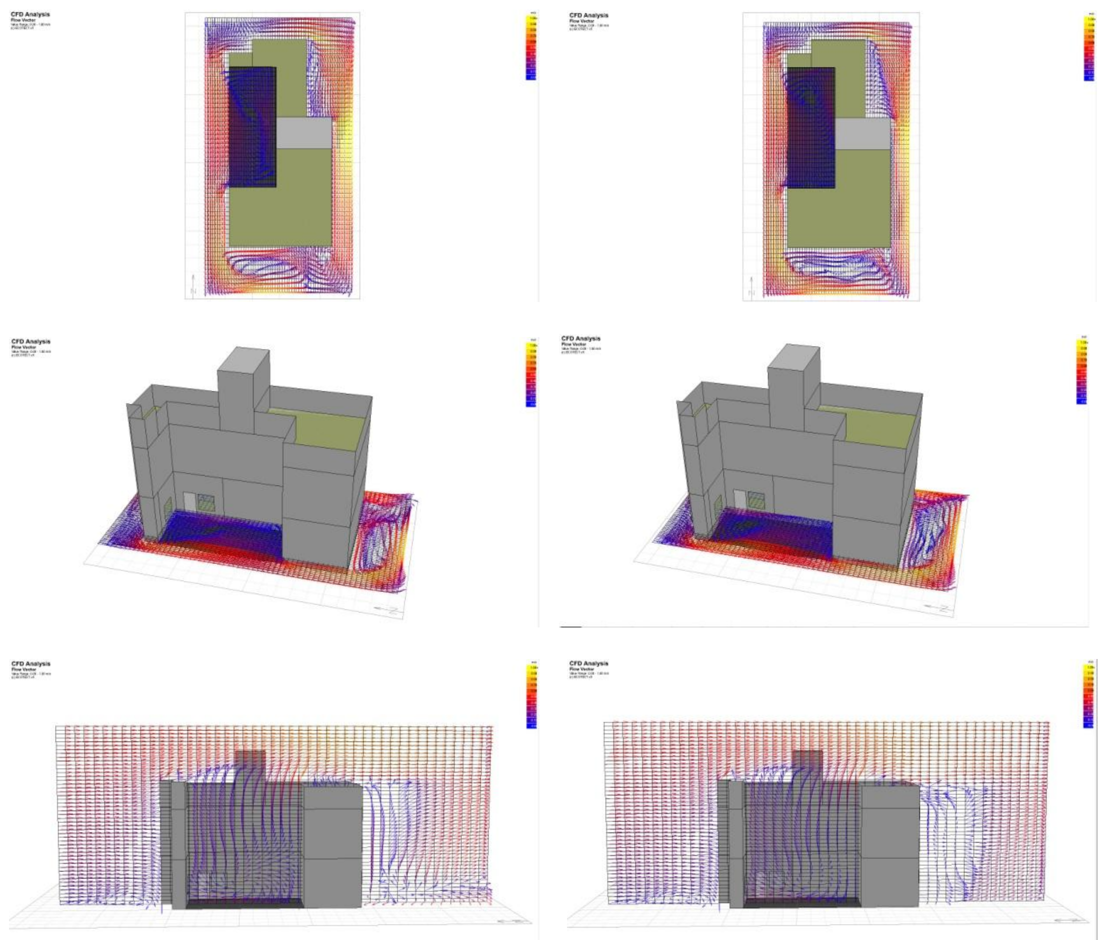
JUNE DECEMBER



***Courtyard-S*-U-W**

Flow Vector Simulation in the Month of June and December

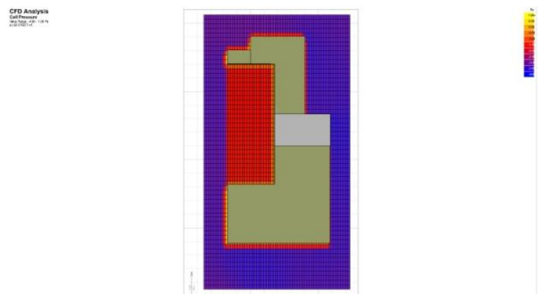
JUNE DECEMBER

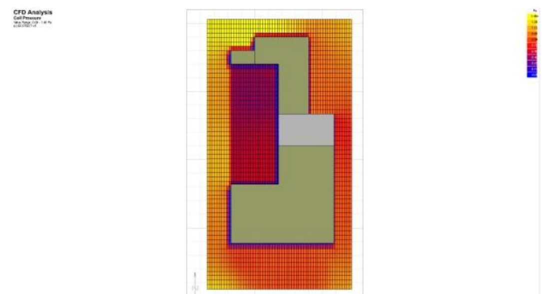


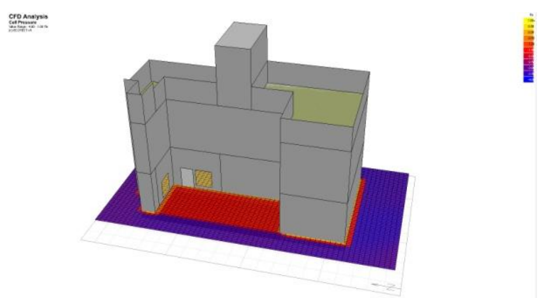
*__Courtyard-S__*__-U-W__

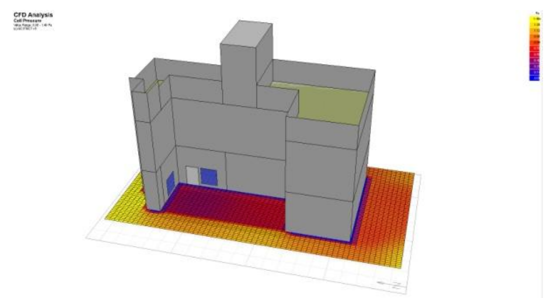
__Cell Pressure Simulation in the Month of June and December__

JUNE DECEMBER







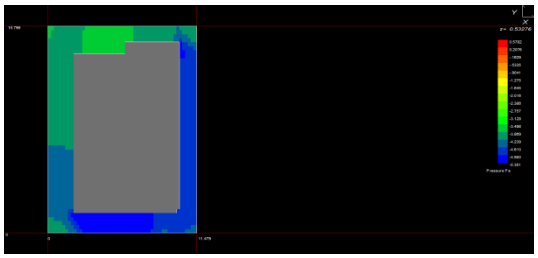


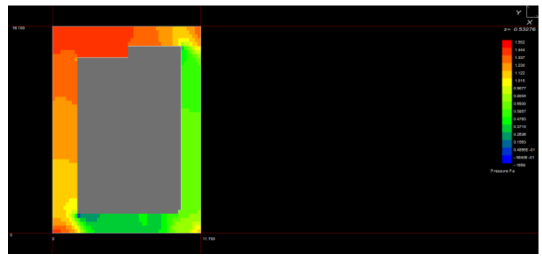
***Courtyard-S*-C-N**

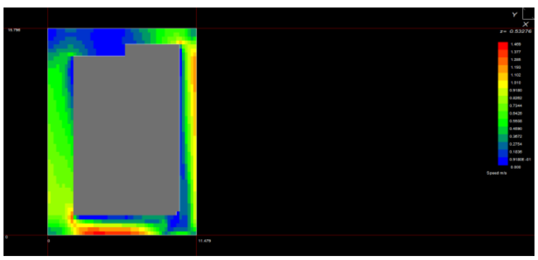
WinAir Pressure and Speed Simulation in the Month of June and December

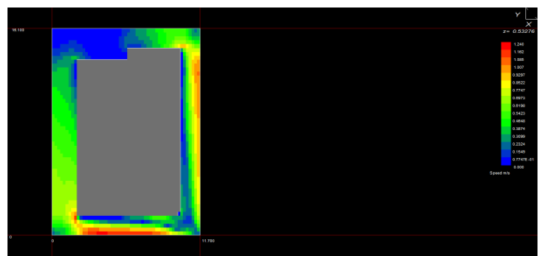
JUNE

DECEMBER







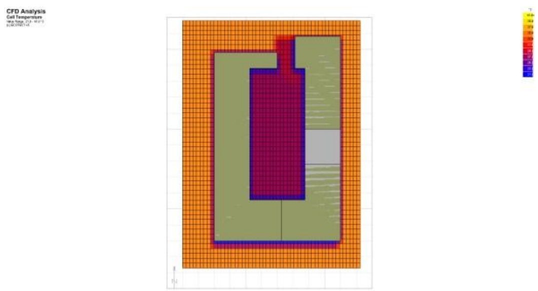


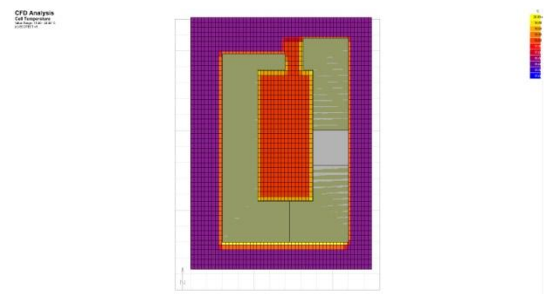
***Courtyard-S*-C-N**

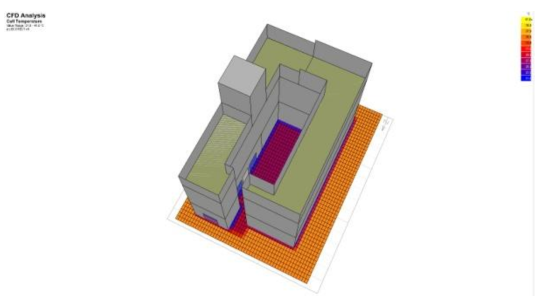
Cell Temperature Simulation in the Month of June and December

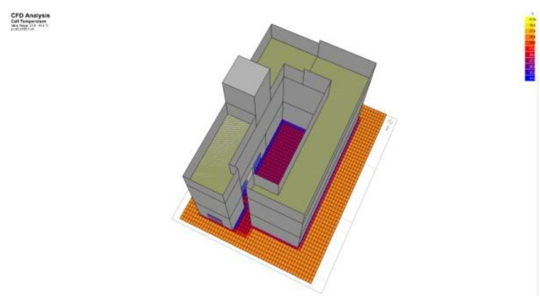
JUNE

DECEMBER





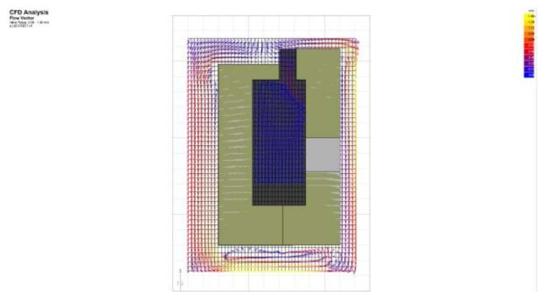


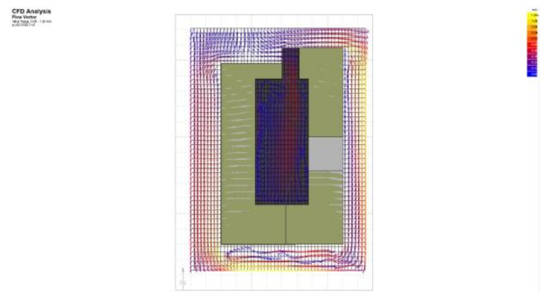


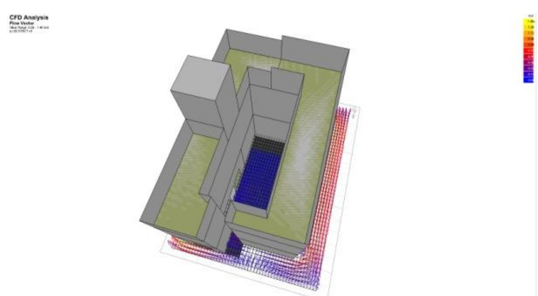
Courtyard-S-C-N

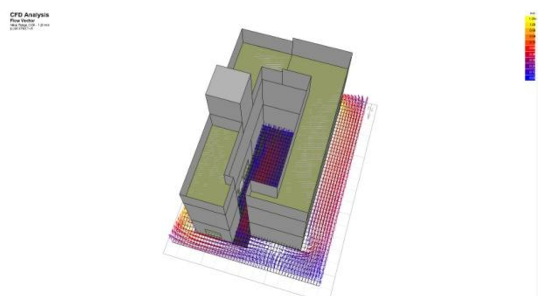
Flow Vector Simulation in the Month of June and December

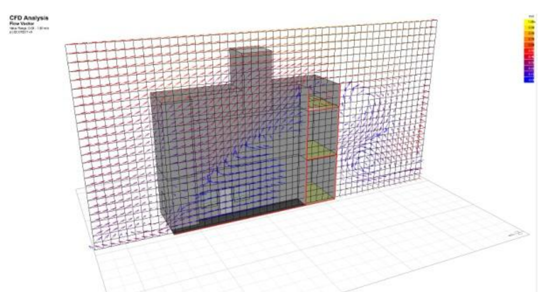
JUNE DECEMBER

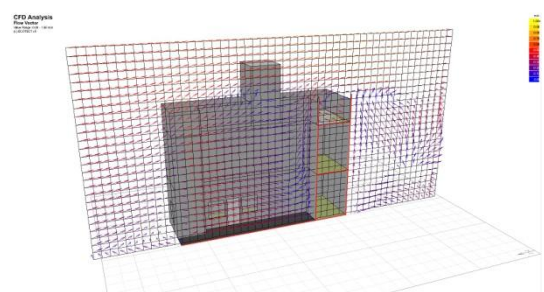








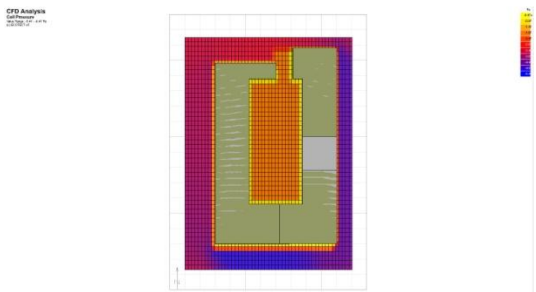


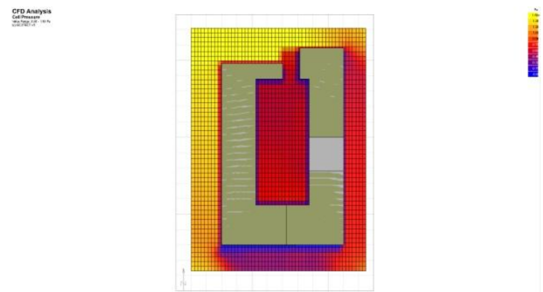


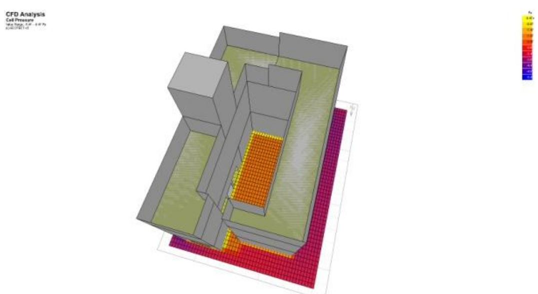
***Courtyard-S*-C-N**

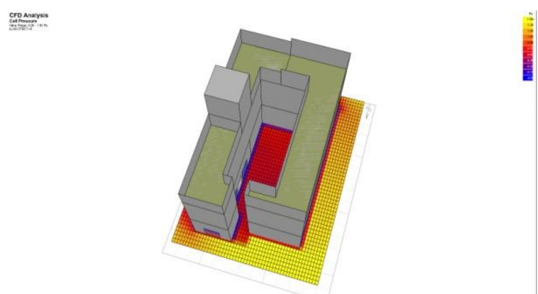
Cell Pressure Simulation in the Month of June and December

JUNE DECEMBER





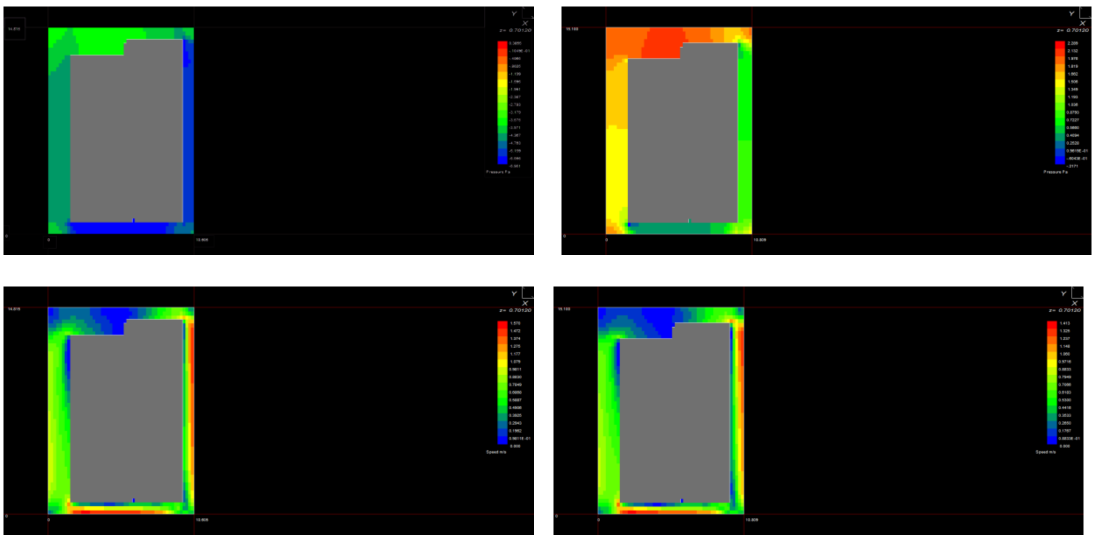




***Courtyard-S*-C-S**

WinAir Pressure and Speed Simulation in the Month of June and December

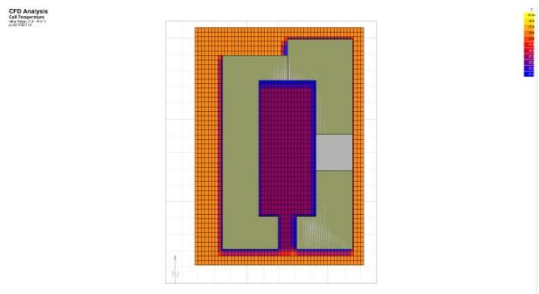
JUNE DECEMBER

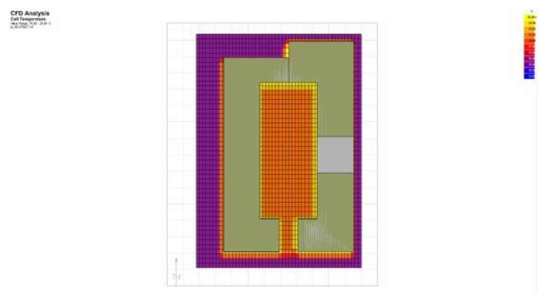


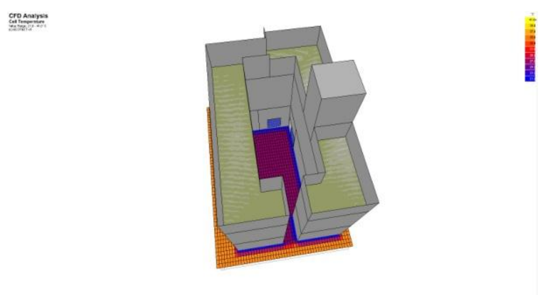
***Courtyard-S*-C-S**

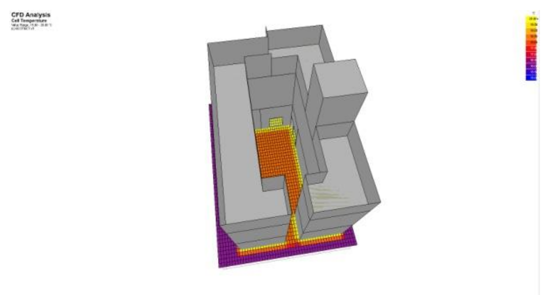
Cell Temperature Simulation in the Month of June and December

JUNE DECEMBER





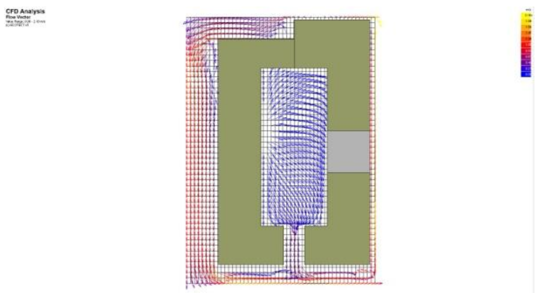


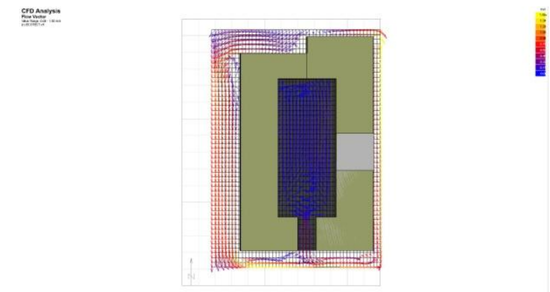


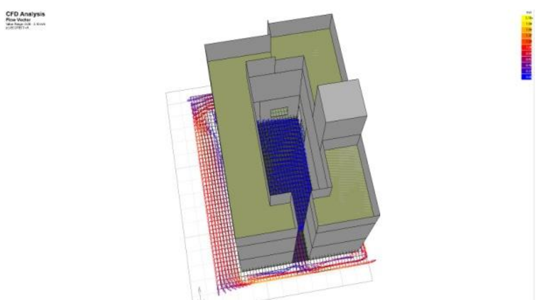
***Courtyard-S*-C-S**

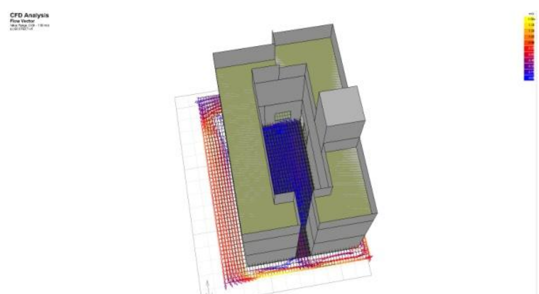
Flow Vector Simulation in the Month of June and December

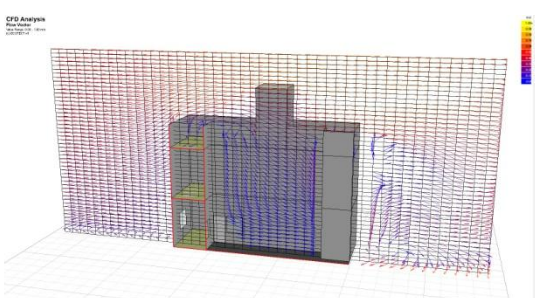
JUNE | DECEMBER

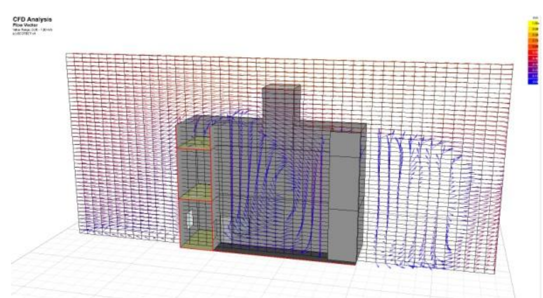








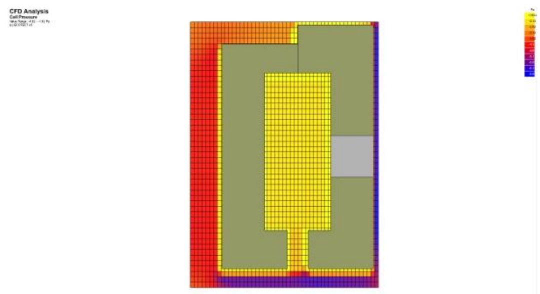


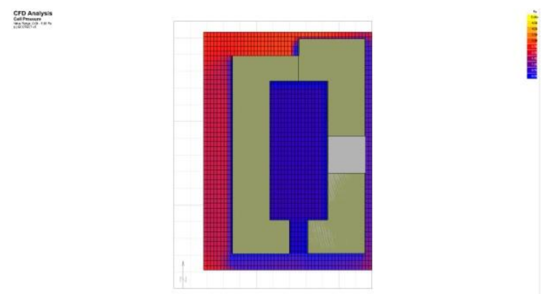


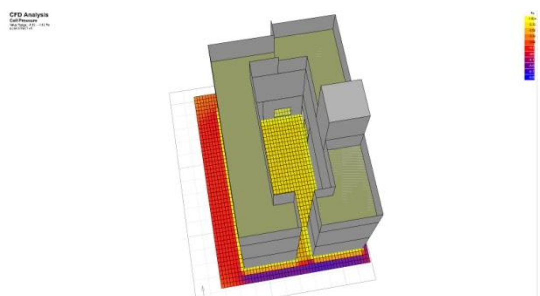
***Courtyard-S*-C-S**

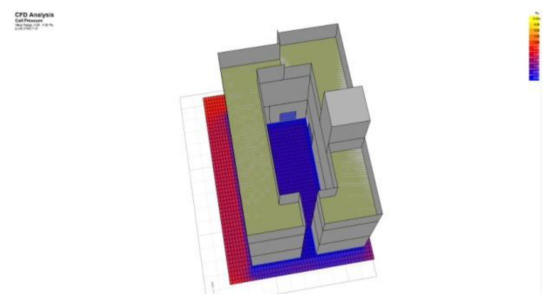
Cell Pressure Simulation in the Month of June and December

JUNE DECEMBER





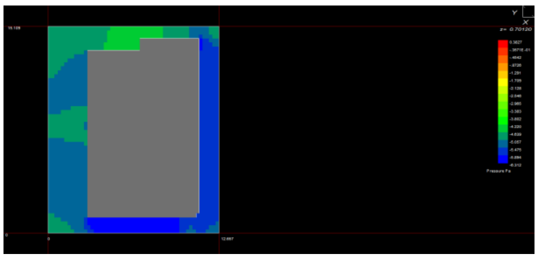
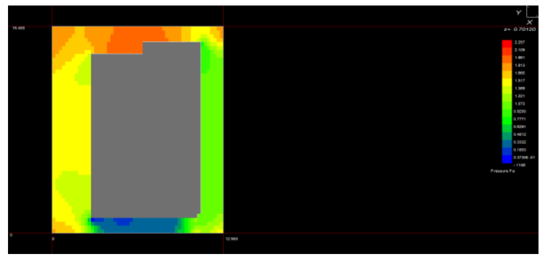
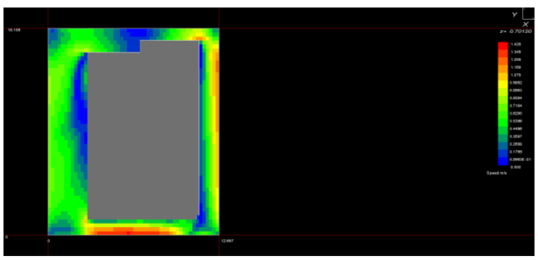
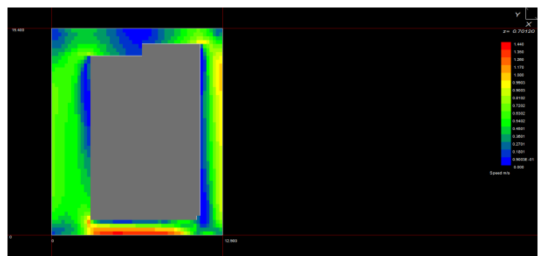




Courtyard-S-C-W

WinAir Pressure and Speed Simulation in the Month of June and December

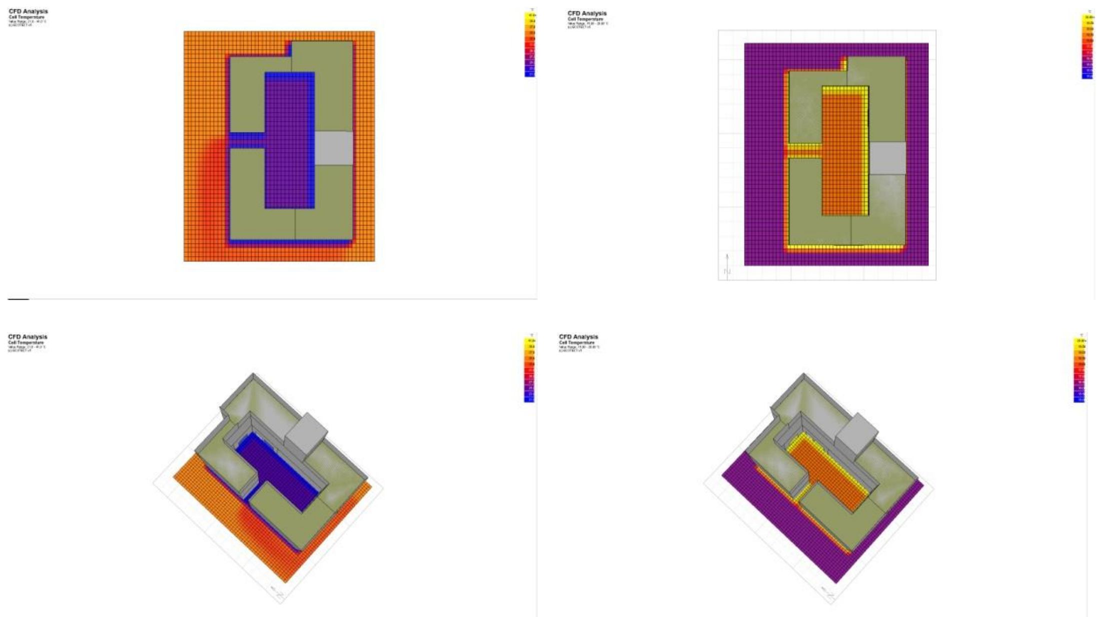
JUNE DECEMBER

***Courtyard-S*-C-W**

Cell Temperature Simulation in the Month of June and December

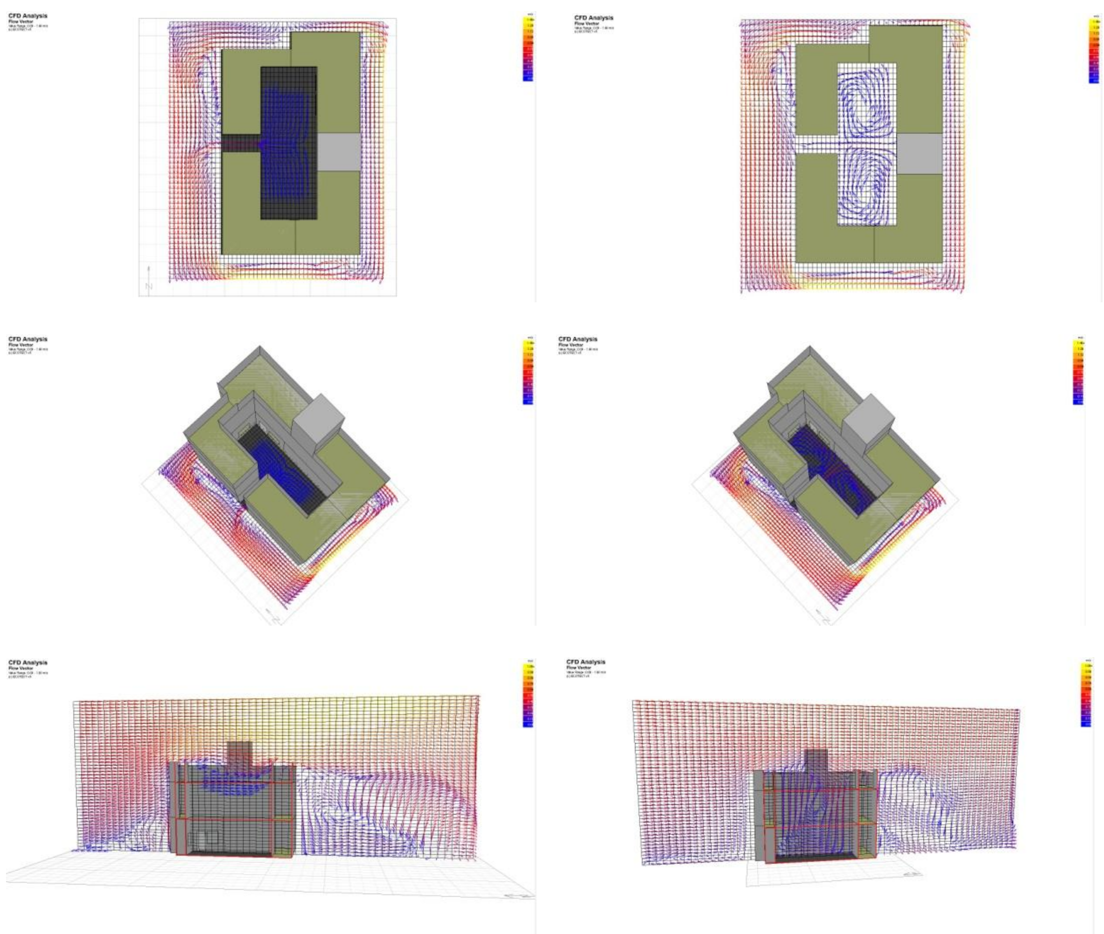
JUNE DECEMBER



***Courtyard-S*-C-W**

Flow Vector Simulation in the Month of June and December

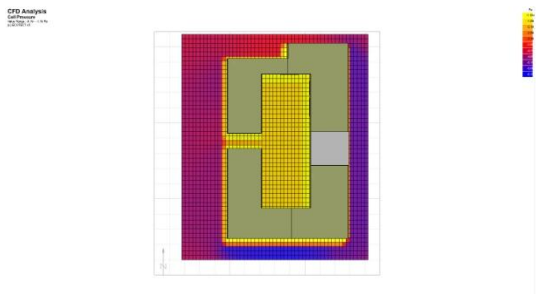
JUNE DECEMBER

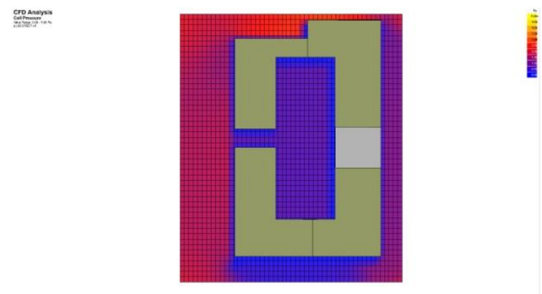


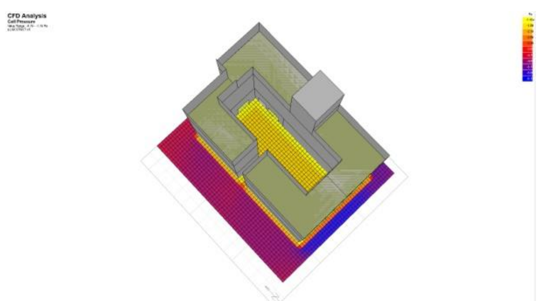
***Courtyard-S*-C-W**

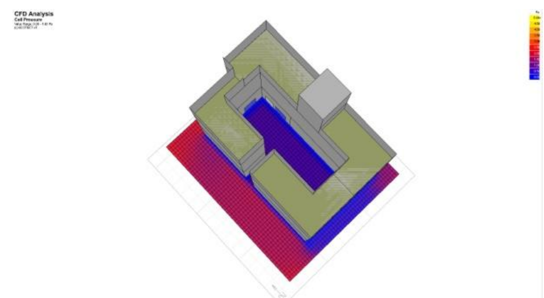
Cell Pressure Simulation in the Month of June and December

JUNE DECEMBER









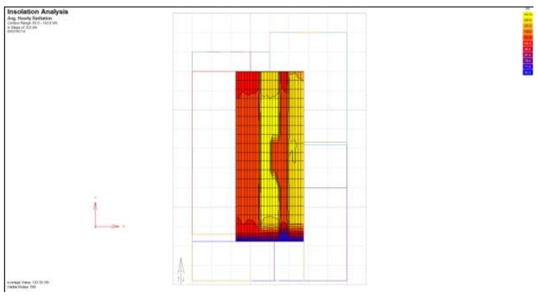
Appendix D

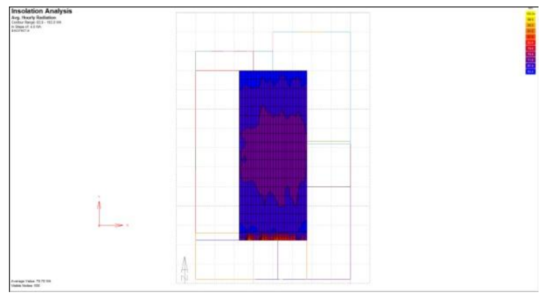
Solar Access Simulation

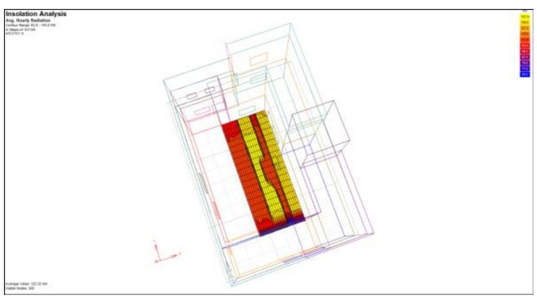
Courtyard-T

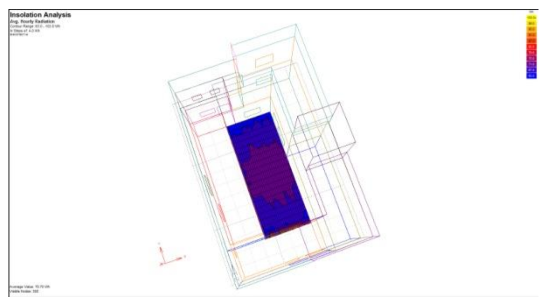
Insolation Analysis Simulation: in June and December

JUNE DECEMBER





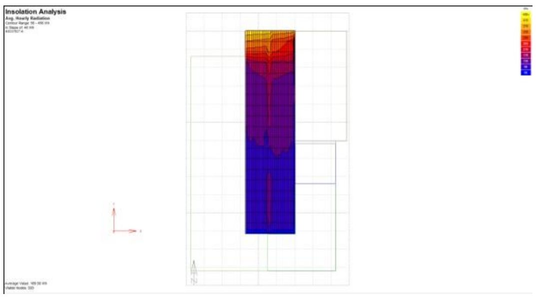


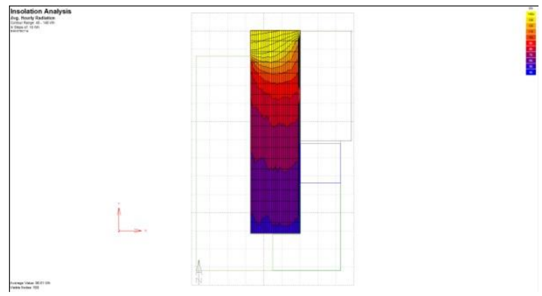


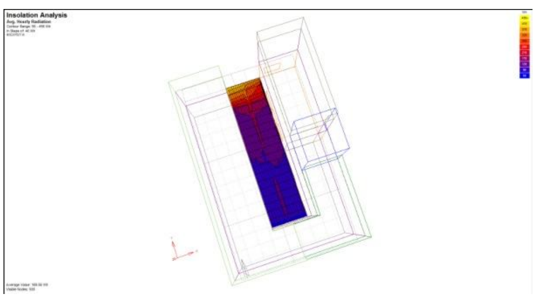
***Courtyard-S*-U-N**

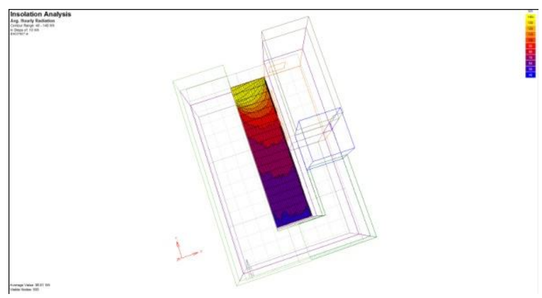
Insolation Analysis Simulation: in June and December

JUNE DECEMBER





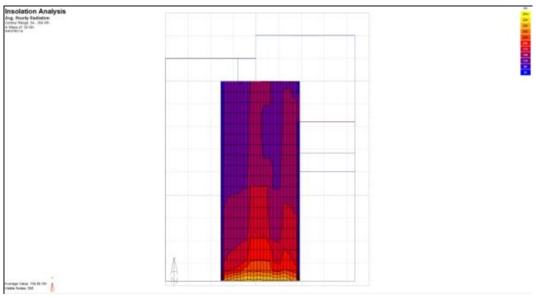


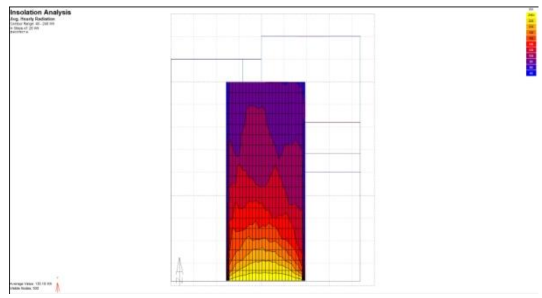


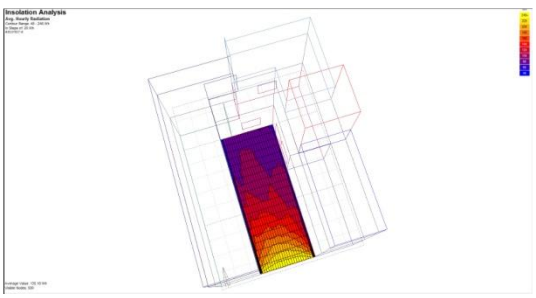
***Courtyard-S*-U-S**

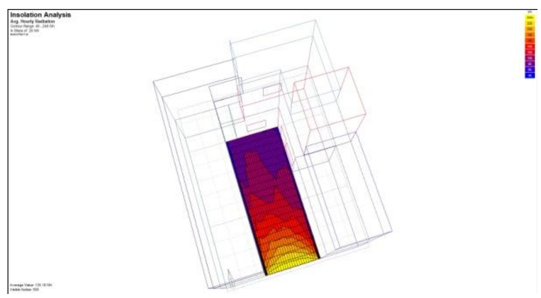
Insolation Analysis Simulation: in June and December

JUNE	DECEMBER





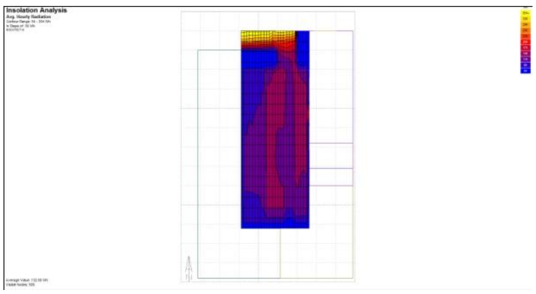


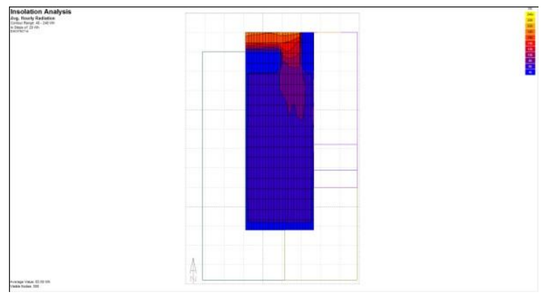


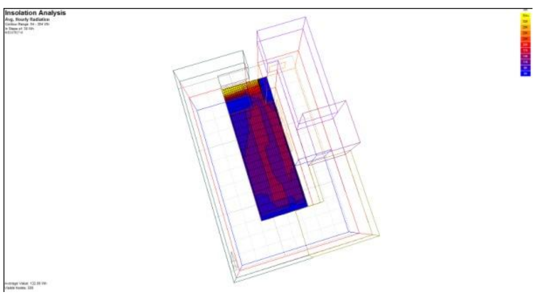
***Courtyard-S*-C-N**

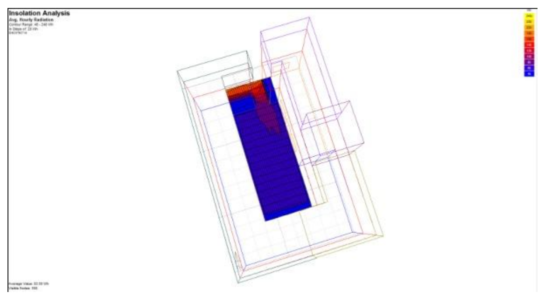
Insolation Analysis Simulation: in June and December

JUNE	DECEMBER





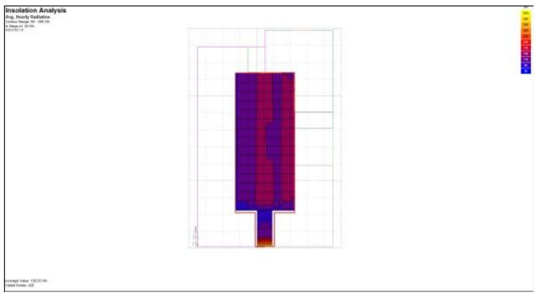


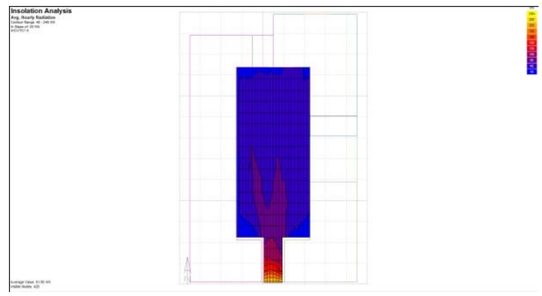


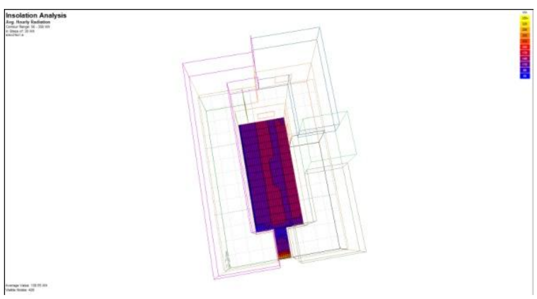
***Courtyard-S*-C-S**

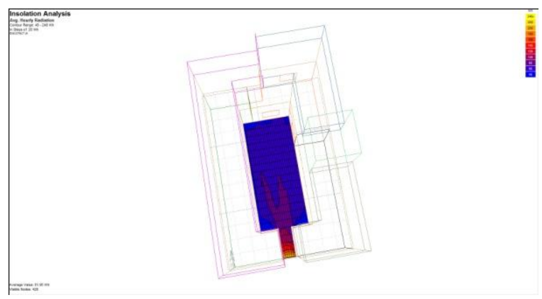
Insolation Analysis Simulation: in June and December

JUNE DECEMBER





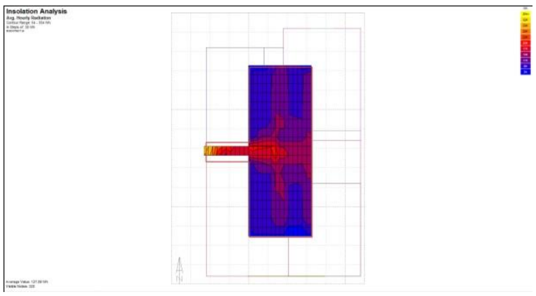


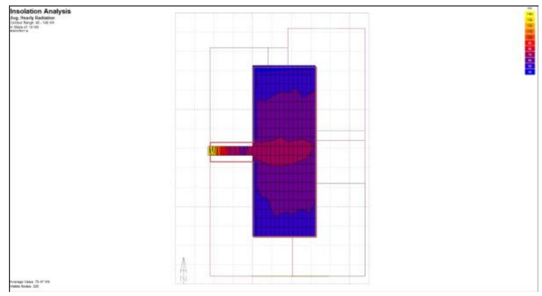


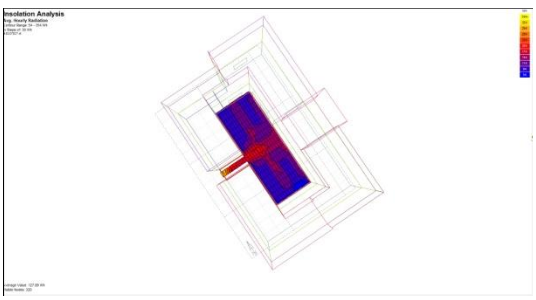
***Courtyard-S*-C-W**

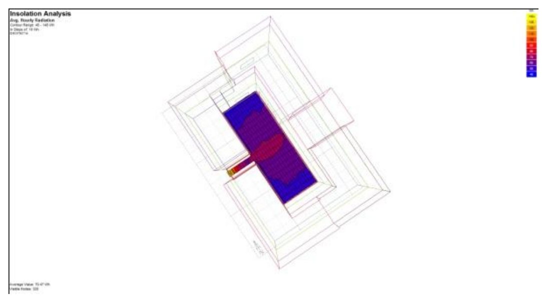
Insolation Analysis Simulation: in June and December

JUNE DECEMBER







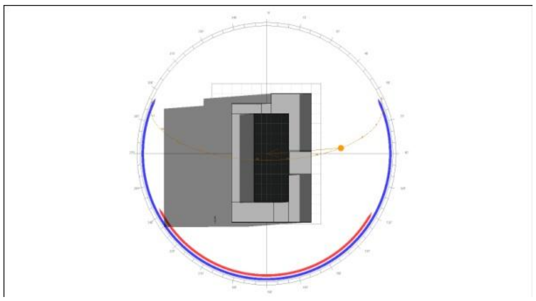
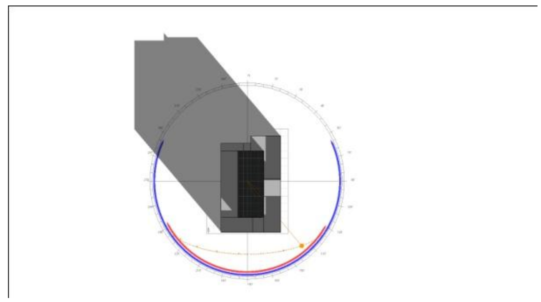
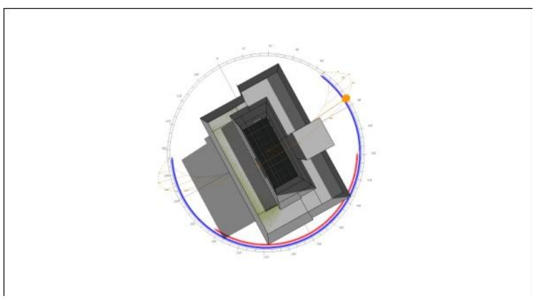
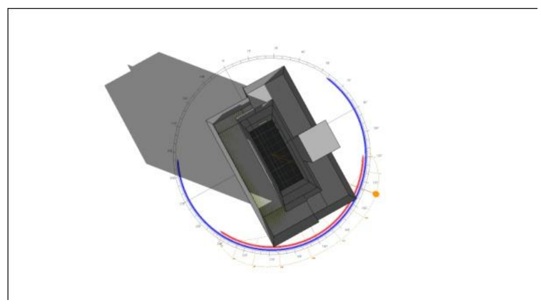


Appendix E

Shading Simulation

Courtyard-T

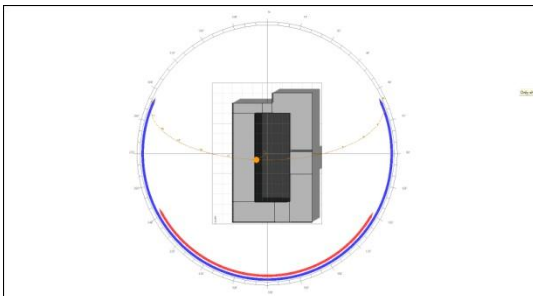
Shading Simulation: 9 a.m. in June and December

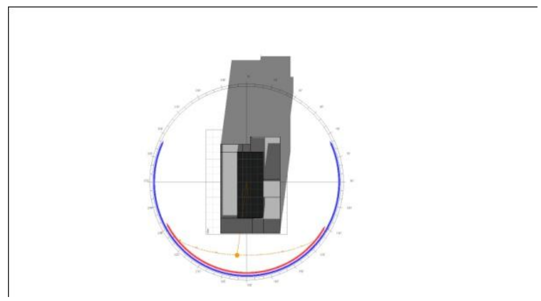
JUNE	DECEMBER
	
	

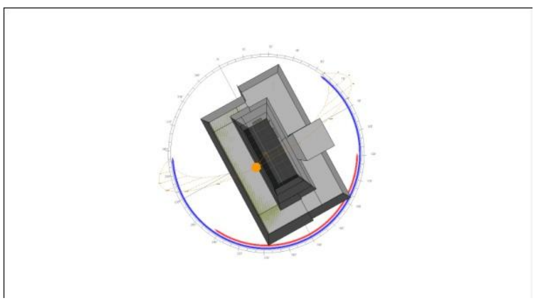
Courtyard-T

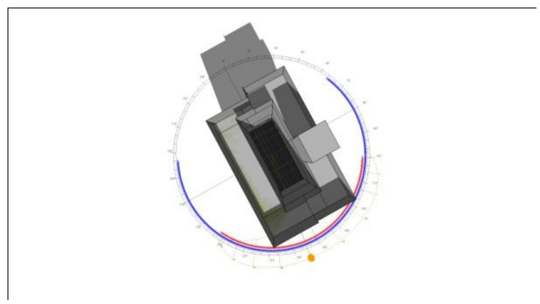
Shading Simulation: 12 p.m. in June and December

JUNE DECEMBER





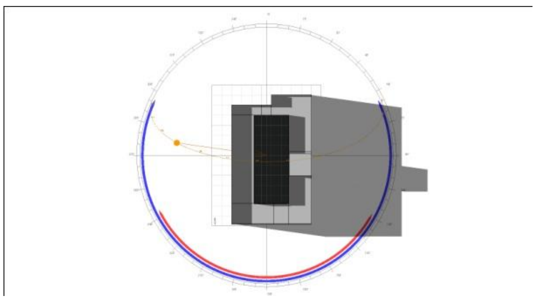


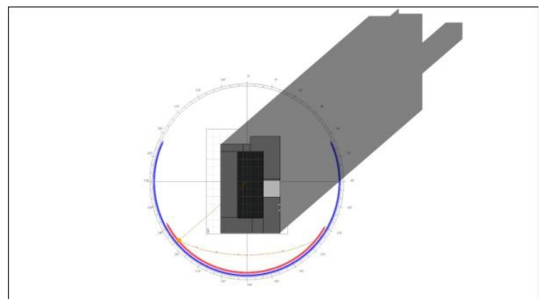


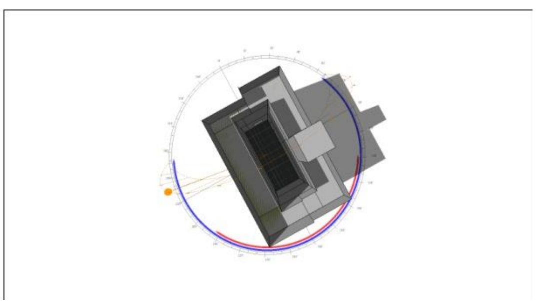
Courtyard-T

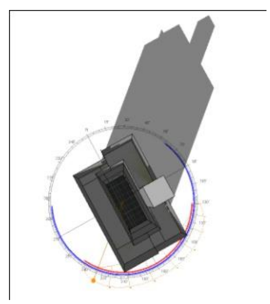
Shading Simulation: 3 p.m. in June and December

JUNE DECEMBER





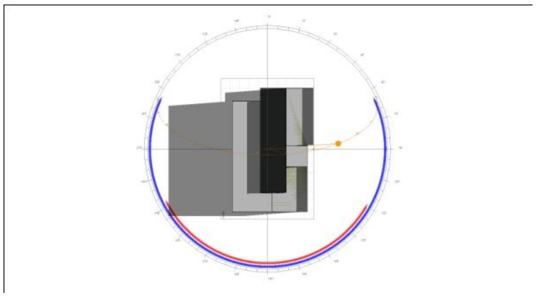
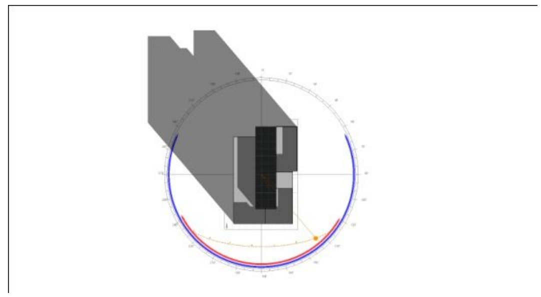


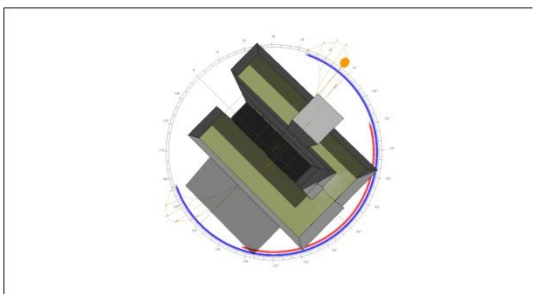
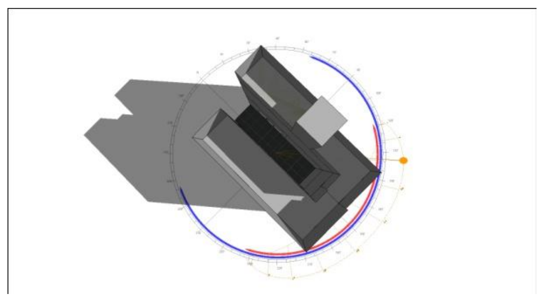


***Courtyard-S*-U-N**

Shading Simulation: 9 a.m. in June and December

JUNE DECEMBER

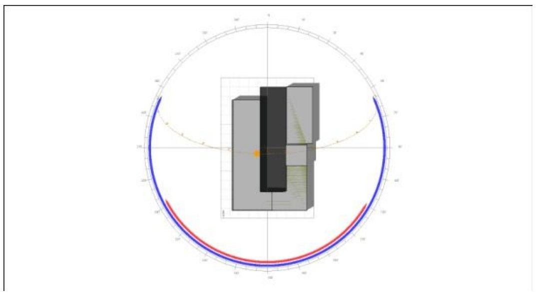



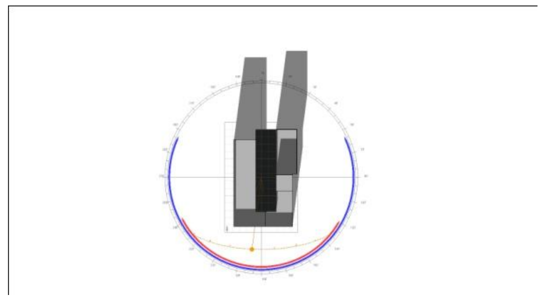
***Courtyard-S*-U-N**

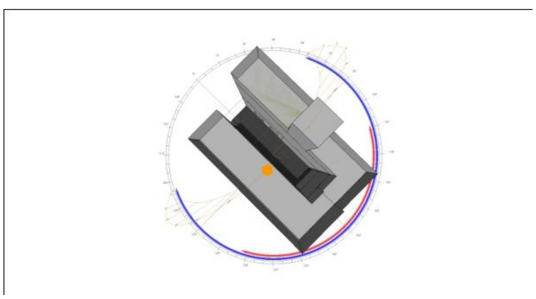
Shading Simulation: 12 p.m. in June and December

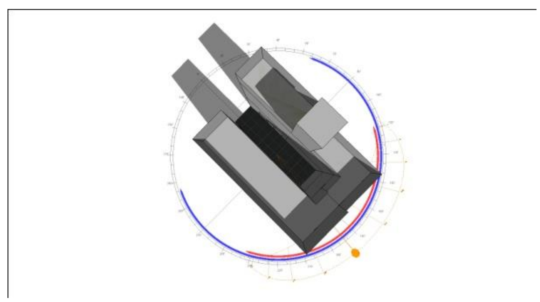
JUNE

DECEMBER





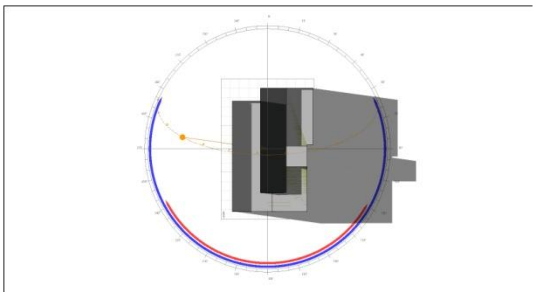


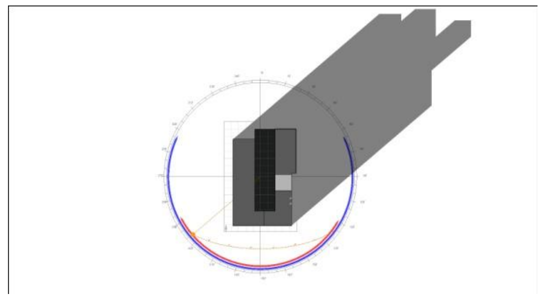


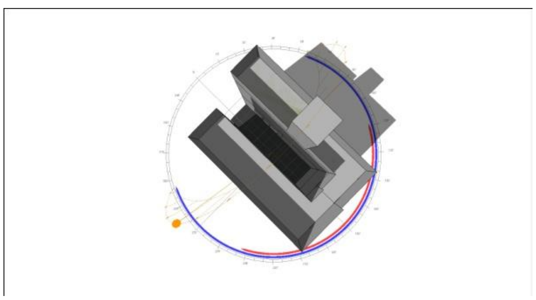
***Courtyard-S*-U-N**

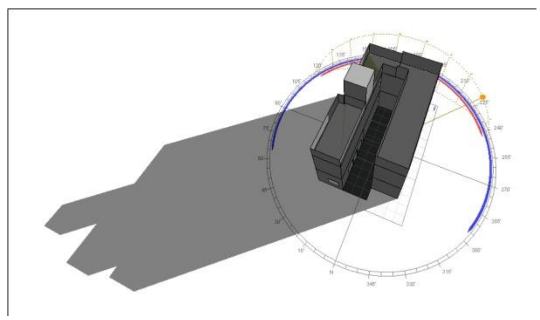
Shading Simulation: 3 p.m. in June and December

JUNE DECEMBER





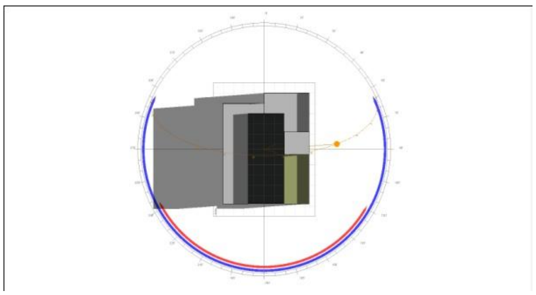


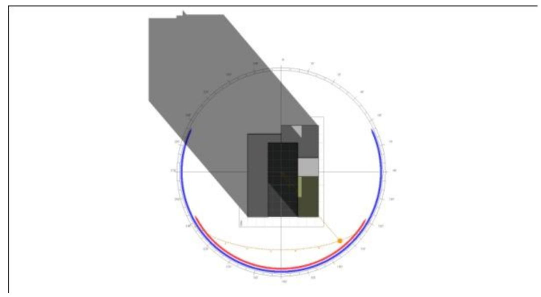


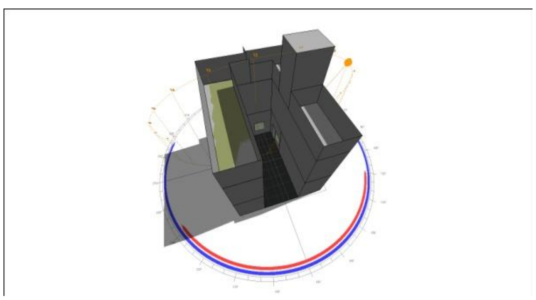
***Courtyard-S*-U-S**

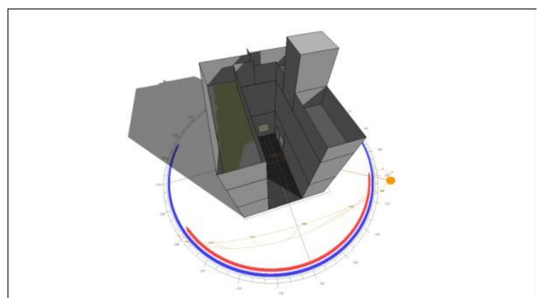
Shading Simulation: 9 a.m. in June and December

JUNE | DECEMBER





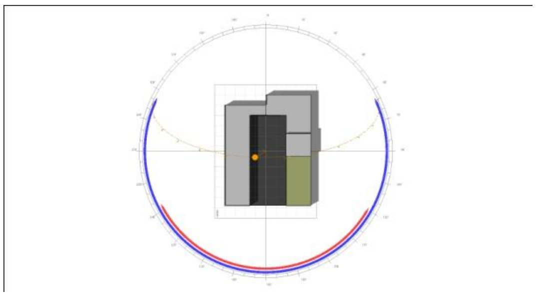


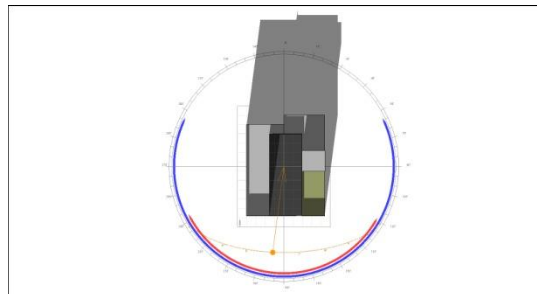


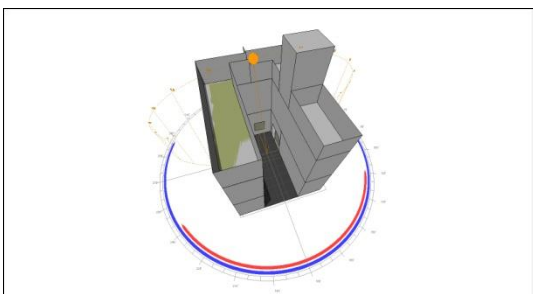
***Courtyard-S*-U-S**

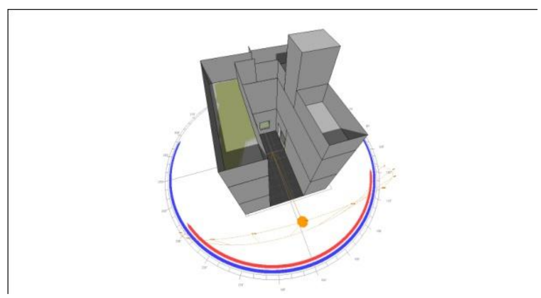
Shading Simulation: 12 p.m. in June and December

JUNE DECEMBER





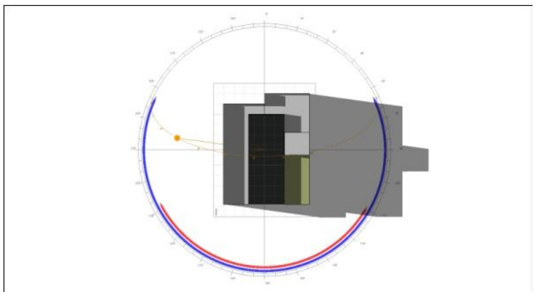


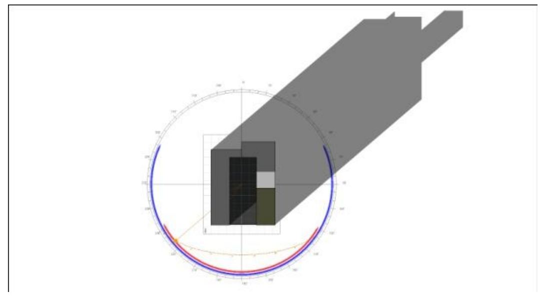


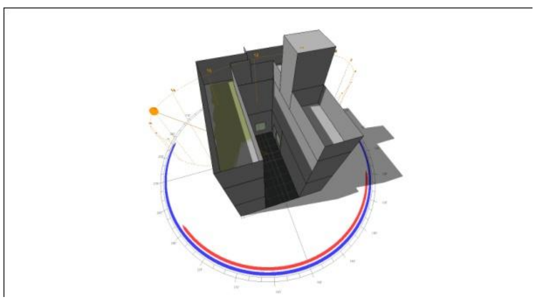
***Courtyard-S*-U-S**

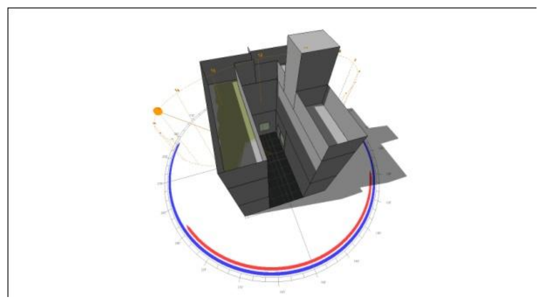
Shading Simulation: 3 p.m. in June and December

JUNE DECEMBER





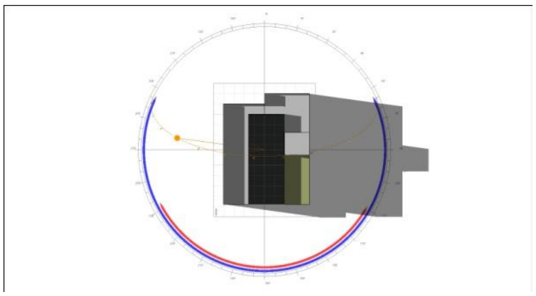
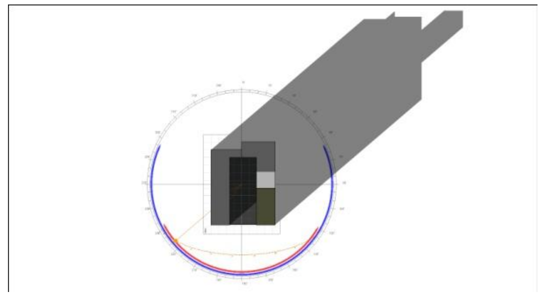


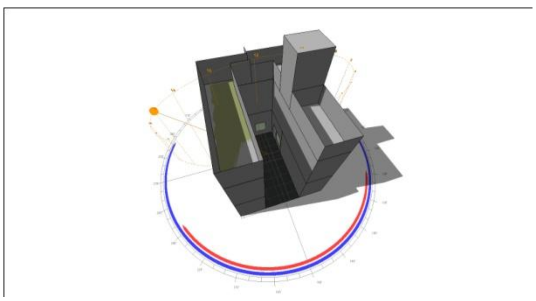
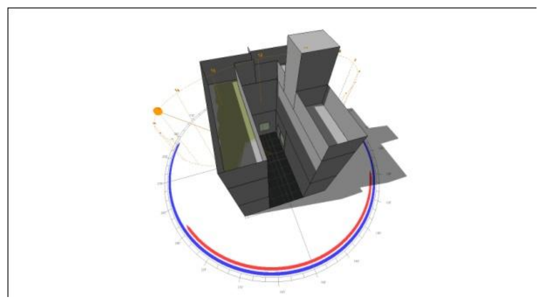


***Courtyard-S*-U-S**

Shading Simulation: 3 p.m. in June and December

JUNE DECEMBER

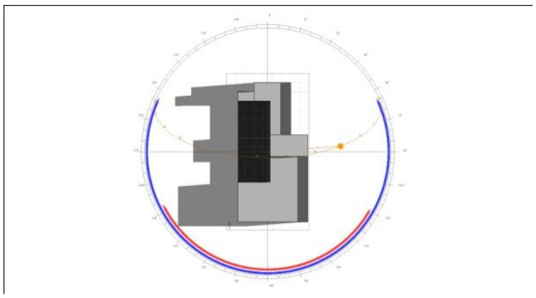



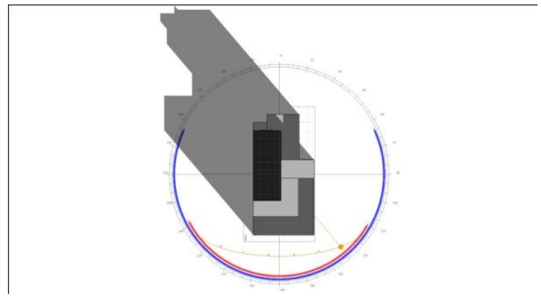



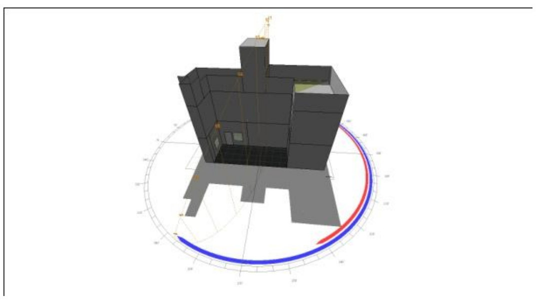
***Courtyard-S*-U-W**

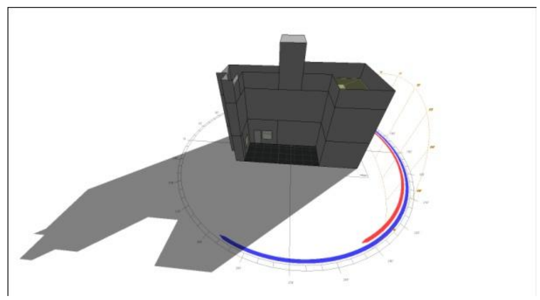
Shading Simulation: 9 a.m. in June and December

JUNE DECEMBER



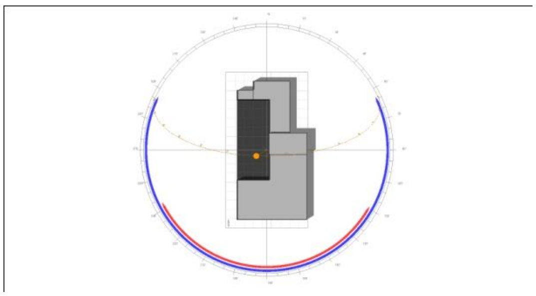
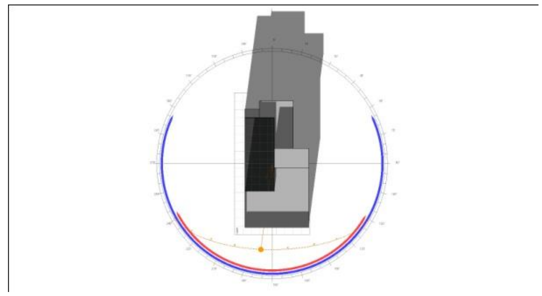
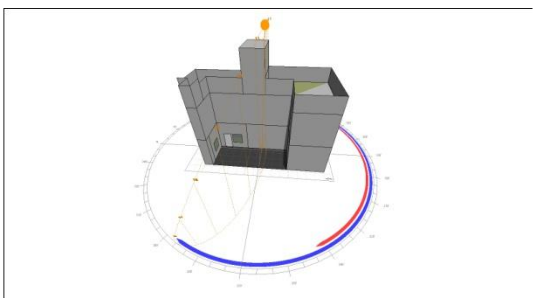
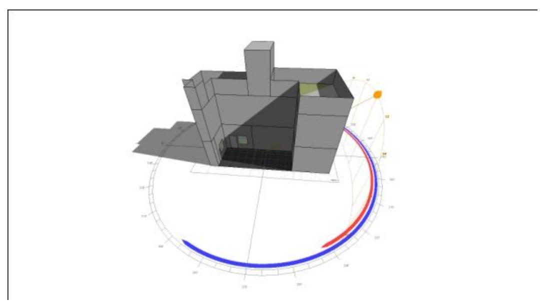






***Courtyard-S*-U-W**

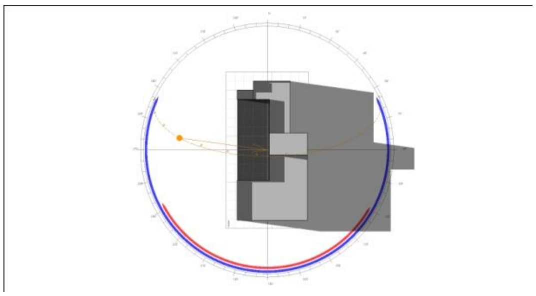
Shading Simulation: 12 p.m. in June and December

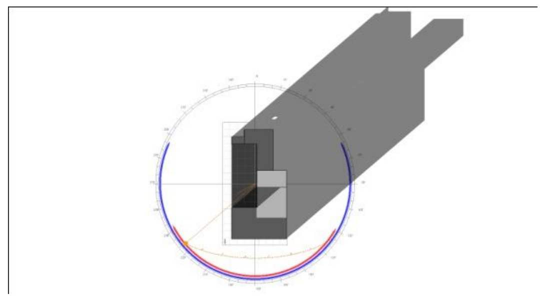
JUNE	DECEMBER
	
	

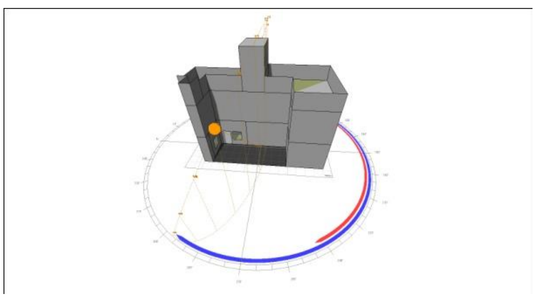
***Courtyard-S*-U-W**

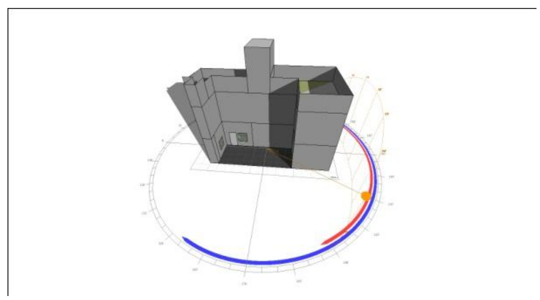
Shading Simulation: 3 p.m. in June and December

JUNE DECEMBER





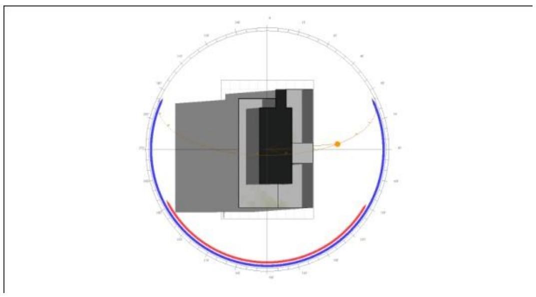


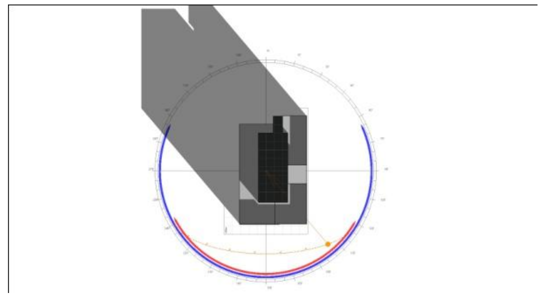


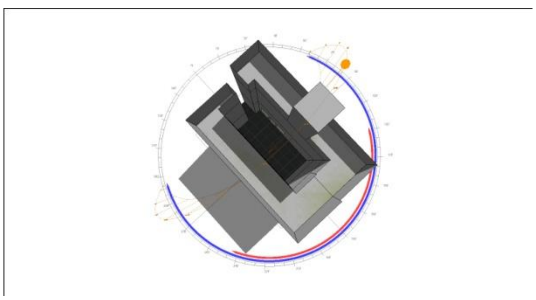
***Courtyard-S*-C-N**

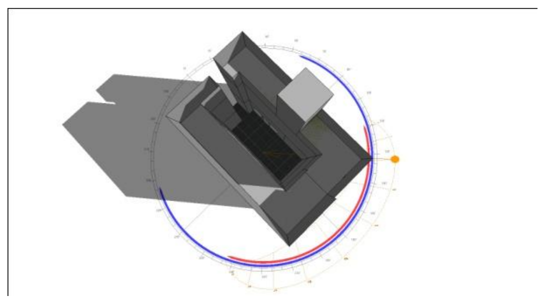
Shading Simulation: 9 a.m. in June and December

JUNE DECEMBER







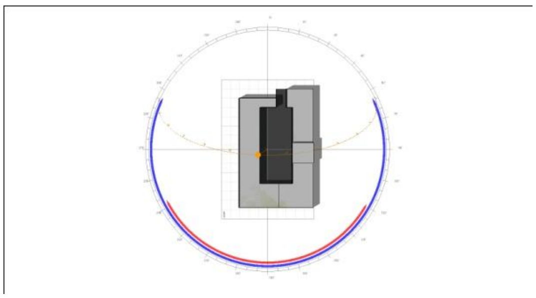


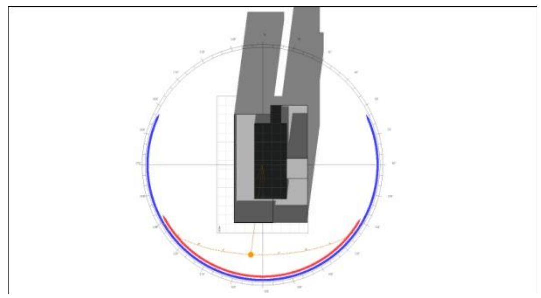
***Courtyard-S*-C-N**

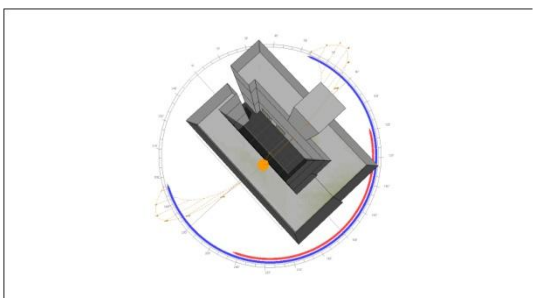
Shading Simulation: 12 p.m. in June and December

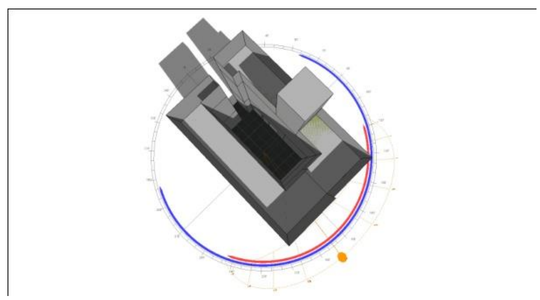
JUNE

DECEMBER





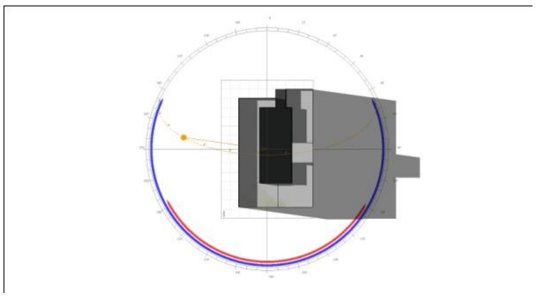


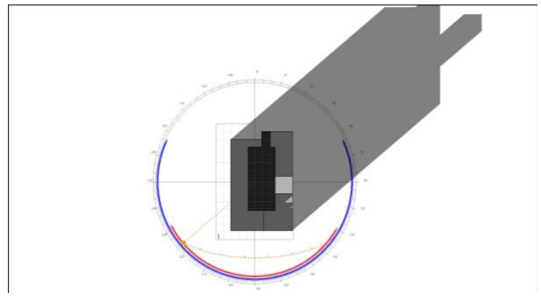


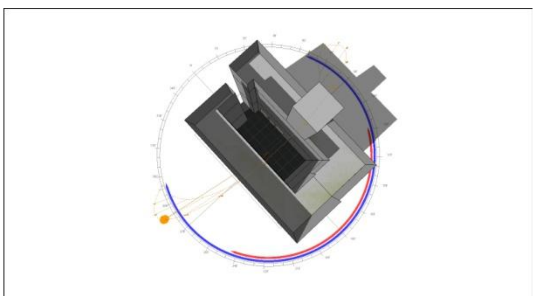
***Courtyard-S*-C-N**

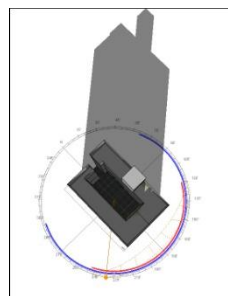
Shading Simulation: 3 p.m. in June and December

JUNE | DECEMBER





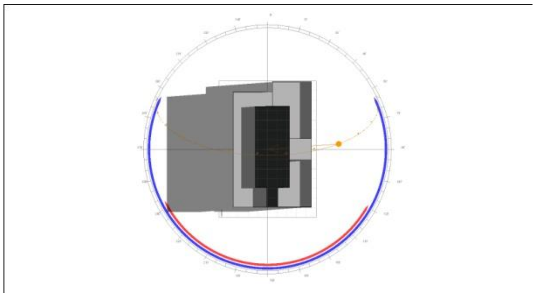


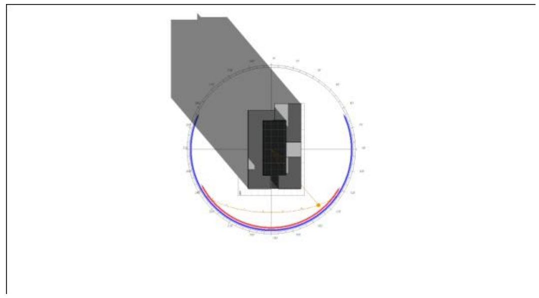


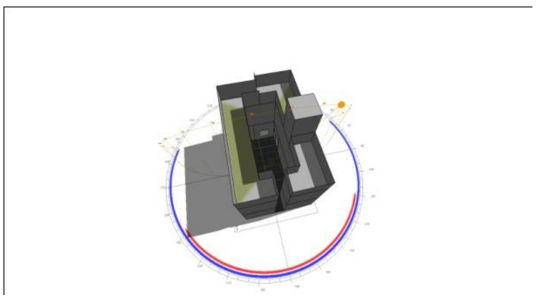
Courtyard-S-C-S

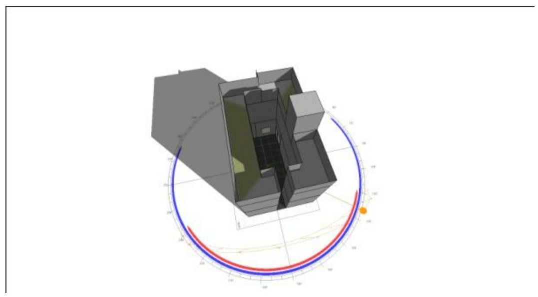
Shading Simulation: 9 a.m. in June and December

JUNE DECEMBER





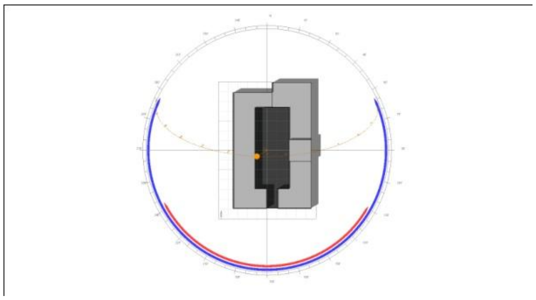


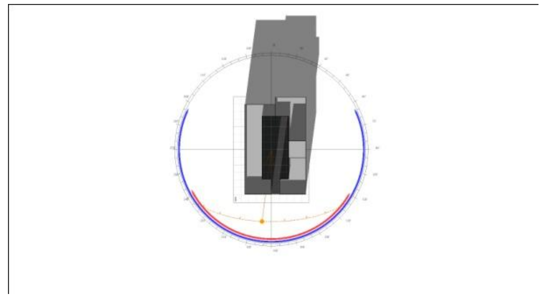


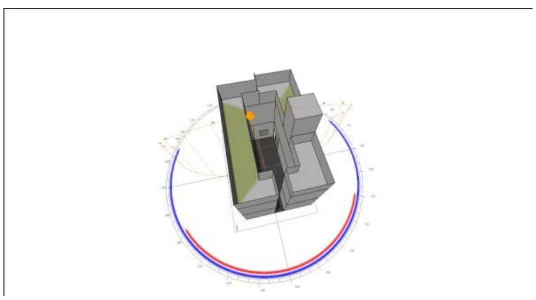
***Courtyard-S*-C-S**

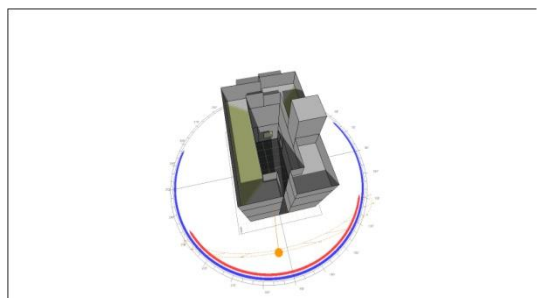
Shading Simulation: 12 p.m. in June and December

JUNE DECEMBER





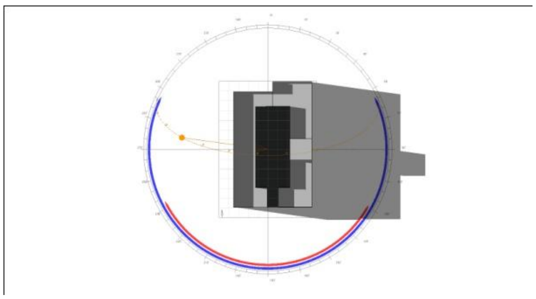


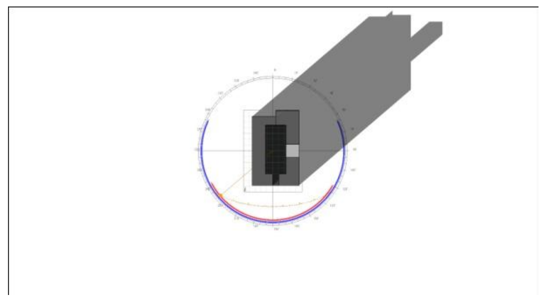


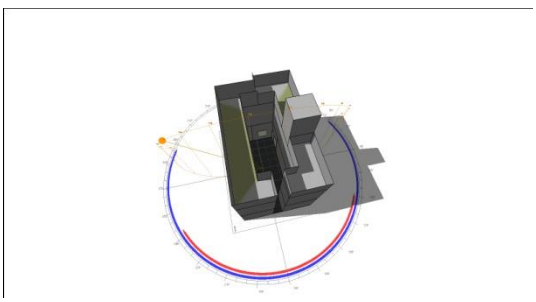
***Courtyard-S*-C-S**

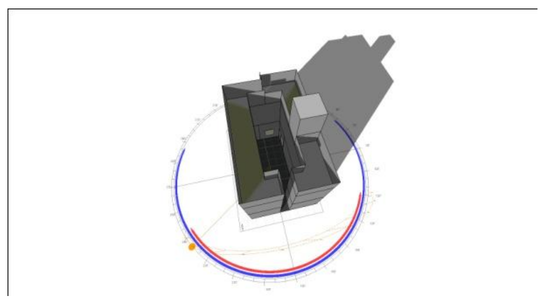
Shading Simulation: 3 p.m. in June and December

JUNE DECEMBER





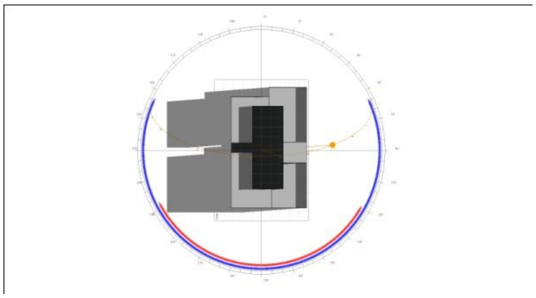


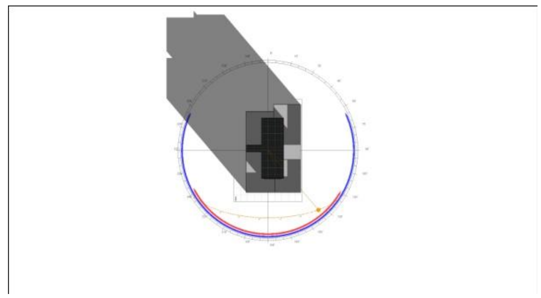


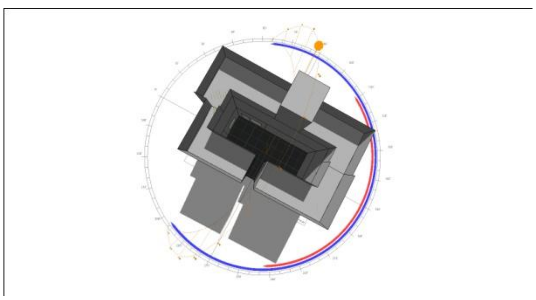
***Courtyard-S*-C-W**

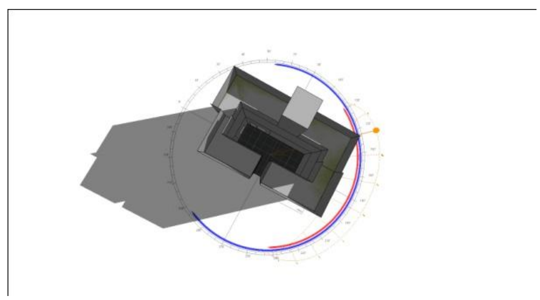
Shading Simulation: 9 a.m. in June and December

JUNE | DECEMBER



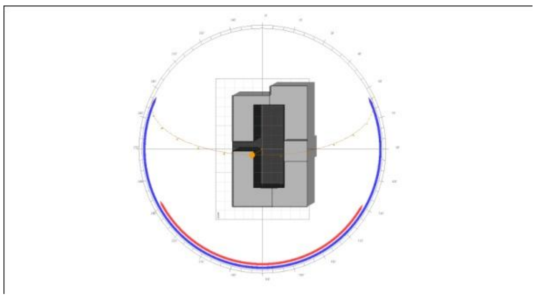
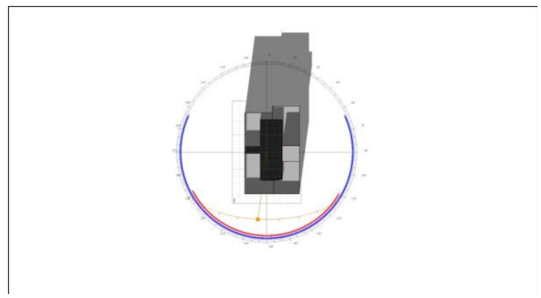
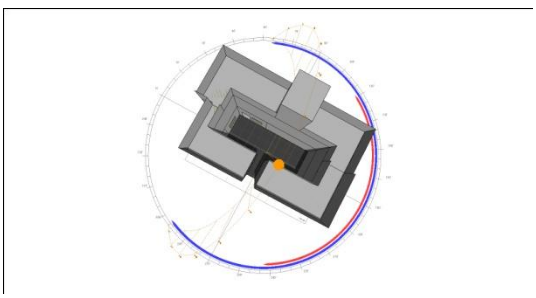
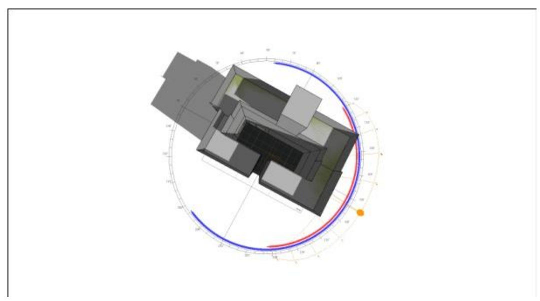






***Courtyard-S*-C-W**

Shading Simulation: 12 p.m. in June and December

JUNE	DECEMBER
	
	

***Courtyard-S*-C-W**

Shading Simulation: 3 p.m. in June and December

JUNE | DECEMBER