Towards Nearly Zero Energy Buildings in Lebanon: Bioclimatic Design and Experimental Strategies

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TOWARDS NEARLY ZERO ENERGY BUILDINGS IN LEBANON: BIOCLIMATIC DESIGN AND EXPERIMENTAL STRATEGIES

By

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Abstract

In the coastal climate of Lebanon, summer internal comfort relies heavily on air-conditioning. Lebanon also suffers from a chronic shortage in electricity supply, where unorganized private sector provides up to 28% of the needed power, through what are referred to as neighbourhood generators.

Within this context, numerous local and international bodies are promoting low energy construction by issuing specific construction codes. Although they aim at reducing energy consumption within new builds, each publication recommends different envelope U-values.

Located on the eastern shores of the Mediterranean, Lebanon coastal climate is placed under the general category of warm temperate climates where summers are hot with minimal to no precipitation. The built environment in Lebanon is largely comprised of heavyweight materials such are concrete, stones, and/or their combined derivatives. This is an important observation, since heavyweight construction is usually recommended in hot climates for attenuating internal summer heat.

A review related to building studies focussed on reducing cooling or heating loads reveal at least four research methods including monitoring of actual structures; software simulation; calibrated simulation; and monitoring of purpose-built models. For similar or hotter climates, the majority of publication claim that externally-placed wall insulations have better effects on internal temperature than internally-placed ones. In contrast, a highly and internally-insulated house in Lebanon has won local and international sustainable awards by claiming that internal peak temperatures with no mechanical cooling are considerably cooler than the outdoors peak temperature.

The combination of all these factors raises the fundamental research question of finding the best performing wall-construction composition and materiality that will minimise internal overheating, and thus reduce or eliminate cooling energy loads for summer comfort in apartment buildings in Lebanon.

To reach this aim, the research starts by monitoring existing apartment buildings, followed by calibrated software-based temperature simulation. Next, in order to reduce the uncertainties found while monitoring the apartments, three test cells with different double masonry walls and insulation configurations are built and their internal temperatures are monitored for a full summer season. They are maintained under a strictly-controlled environment. Later, these test cells are computationally simulated and calibrated.

Results show that the best method for studying heavyweight construction is through full scale test cells, since each of the applied methods showed different results for the best performing construction with the least summer overheating. More so, performance ranking of the different constructions is not consistent throughout the different methods. As seen in the literature, temperature software calibration method is feasible but requires initial data to be modified.

Final results, based on the test cells, showed that the un-insulated double masonry wall test cell did lead to minimum overheating when compared to the three test cells with different insulation locations within similar double masonry walls. The outer insulated, which in the literature review is always seen as the better performing, ranked only second with a 40% difference when using the overheating degree hours above 30ºC as a performance indicator. This is due to the increased capacity of the unobstructed (un-insulated) double masonry walls to store and release heat into the room and the outdoor.

The contribution to knowledge is threefold: (1) a thorough understanding of the summer temperature behaviour of heavyweight construction in Lebanon; (2) a detailed assessment of temperature software allowed showing both their expectations and limitations in simulating heavyweight construction; (3) finally proving that un-insulated double masonry wall can provide least summer overheating when compared to differently insulated double masonry walls in the climate of Lebanon.

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Acknowledgments

Long before deciding to venture into a PhD, from an academic talk I retained two expressions "*it's lonely up there*" and "*why go into a PhD, when it's lonely up there? But it is the highest academic achievement*" these were my very first London words that stuck to my eager mind at the start of my master's degree. It is where my amazing London experience started, I was further fortunate to have Rosa as our team advisor for two terms. A couple of years later, from a relatively casual London chat with Rosa, the first idea of a PhD research emerged, and, out of the blue all the perfect settings were there: Rosa could be my director of studies, and it could be done from by home country Lebanon, studying the local built environment, with frequent visits to the University… a few encouraging shoves from Rosa, and it all begun!

I cannot express enough my gratitude to Rosa! She has been a great mentor and a perfect advisor. With her south Italian stamina she would slowly, calmly, but surely convince me that I needed to look at one or another issue from different perspectives and re-question my pre-set (stubborn) ideas. The live (and skype) discussions we had, were always a sheer intellectual pleasure!

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Author Declaration

NUMBER OF WORDS

39205 (Abs + Text)

43156 (Abs + text + Appendices)

DECLARATION

"I declare that all the material contained in this thesis is entirely my own work and that any quotation or paraphrase from the published or unpublished work of others is duly acknowledged."

DATE and SIGNATURE

Philippe H. Saleh

1 Introduction

Air-conditioning is extensively used to provide internal comfort in the coastal area of Lebanon during summertime. Even with scarce statistics, a visual inspection shows the extensive add-on window types or split units on a large number of buildings, old and new. The available energy figures for the commercial sector show that up to 31% of its overall consumption is for summer cooling (MoEW/GEF/UNDP, 2015). Another figure shows that the overall combined energy consumption of both residential and commercial sectors adds up to 31% of the overall national generated energy (Jouni and Mortada, 2013). In addition to that, Lebanon does not hold any oil and gas reserves; hence all its required fuel is imported.

Lebanon endures chronic power shortage where regular and recurrent blackouts are part of every-day routine. This is due to the combined effect of decrepit distribution grids and generating plants as well as ever increasing demands. Although numerous upgrades have been and are still implemented, the current energy situation relies on an un-organized private sector supplying up to 28% of the required energy through what are referred to as neighbourhood generators. This situation imposes on the end user two separate electricity bills per month: one for the governmental power provided by Electricité Du Liban (EDL) and the other for the neighbourhood generator.

Because of this energy supply problem and the extensive reliance on air-conditioners, numerous public and private, local and international, Energy Conservation organisations are trying to promote low energy construction. They are doing so by various methods, trying to appeal to the concerned parties. These methods vary from: (1) issuing free interest loans for developers, (2) granting local green building certification, or (3) just encouraging low energy construction by working on implementing passive design strategies. For that, specific guidelines for building envelope U-values and energy benchmarks have been published since 2005, however with each publication showing different values.

Beirut, Lebanon 33°N, 35°E is situated on the eastern shores of the Mediterranean, with a total north-south length barely exceeding 200km and a maximum width of 80km. In this small area, four distinctive climatic zones are defined. This study is concerned with the coastal area, where the capital Beirut, and more of the larger urban centres, are located. The climate of this coastal zone is placed based on the Koppen-Geiger (Kottek et al, 2006) world climate classification under the general category of warm temperate climates. The summers are long and hot with minimal to no precipitations, starting in June and extending until mid-October, while winters are short and mild. Looking at a typical year (Meteonorm 7), August mean temperature is 28.1°C with daily peaks between 30°C and 35°C, and January mean temperature is 14°C.

Heavyweight materials are the main construction material shaping Lebanon's built environment, all sectors included: residential, commercial and institutional. These materials comprise concrete, stones, and their combined derivatives. This type of construction has high density with the capacity to absorb, store and release heat, within a certain time lag. For these reasons, heavyweight construction is usually recommended for hot climates in order to reduce internal temperature fluctuations and keep them relatively cooler than the outdoors (Littlefield, 2007; Szokolay, 2004; Koch-Nielsen, 2002).

At least four different or complementary research methods are identified when going through similar studies engaged in building heating or cooling energy load reduction. These include direct observation of existing buildings; software simulation; calibrated simulation; construction and monitoring of physical models. Furthermore, similar studies done in comparable or hotter climates claim that walls with externally-placed insulation will perform better in terms of cooler internal temperatures when compared to internally placed insulation. Contrary to this argument, one BREEAM excellent award and first Lebanese Architecture Award recipient for a local house in Lebanon with internally highly insulated (low U-value) walls claims to considerably reduce peak temperature between inside and outside.

Research Aims and Objectives:

The combination of all these factors leads to the fundamental research question*:*

What is the best thermally performing wall composition (materiality and construction) producing minimal internal overheating and cooling loads, for improved comfort in summer in apartment buildings in Lebanon?

To answer this fundamental question, the research will further expand on the following related objectives:

1-*Improve the understanding of heavyweight construction temperature performance of local constructions during Lebanon's summers.*

2-*Show the expectations and limitations of thermal software when simulating heavyweight construction in hot climates.*

The two fundamental hypotheses are:

1-Externally placed insulation on double masonry walls will provide the least internal summer overheating, when compared to inner, middle and non-insulated similar walls.

2-Calibrated software simulations are expected to show similar results as the test cells, specifically when it comes to comparing the outcomes of the different construction types in terms of best and worst performing with least and most overheating.

Research methodology

This research uses four different methods to answer the fundamental questions and the various objectives. It starts off by monitoring the summer temperature of existing apartment buildings in various conditions of occupancy and air-conditioning usage. The following step consists of taking one of the apartments as a baseline and making a valid calibrated temperature-based software model out of it. This is achieved by comparing the software simulated temperatures with the recorded ones until acceptable indices were reached; this is done for two different weeks based on recorded hourly temperatures. This step relied on apartment monitoring showed considerable levels of uncertainty where outcomes did not correspond to expected literature based results. This problem was countered by the construction of three test cells with different double masonry walls and insulation configurations; they are maintained under a controlled environment with the advantage of simultaneous temperature monitoring which facilitates comparative studies under similar conditions. Temperature monitoring lasts an entire summer season. Later, these test cells are software simulated with various envelope alterations and internal gains increases. The final step consists of turning these software models into calibrated versions.

The experimental set up only deals with different walls and insulation configurations under unchanged and similar roof structures. Hence, this study's aim is not to find the best test cell with summer internal temperatures within acceptable comfort range. Rather, it will show the best wall and insulation configuration with minimal overheating, when compared to other walls. The main reason behind this is that in any given building of multiple floors, the top floor with its roof is limited in numbers and surfaces. Intermediate floors with external walls are considerably more numerous. The other reason takes into account timing and logistics. A study that deals with both walls and roof proceeds in two phases. The first phase consists of studying one element while the second is kept unchanged. After a reasonable amount of observation, the best construction in terms of least overheating is established, and sequentially duplicated onto the other test cells. Eventually, the second phase of testing the second element is initiated for another extended period. However, the study of roof performance was outside the scope of this study and cost and time limitations meant that attention was given to the study of the wall-construction only.

Structure:

The research is divided into two complementary parts. Part one includes chapters 2 and 3 where the local context of the research as well as the terminology, definitions and literature review are outlined. The second experimental part includes chapters 4, 5, 6 and 7. It starts with the monitoring of the summer temperature of existing apartments and their corresponding calibrated model software simulation. It continues with the construction of three purpose-built full-scale test cells that are monitored for temperature during summer, similarly followed by the corresponding software calibration and simulation. Figure 1.1 gives a concise graphical overview of the thesis structure with the main question and its corresponding answer along with each chapter main content.

Chapter 2 Context: from Lebanon's geography and climate to heat transfer in heavyweight construction

This chapter defines the context of the research by highlighting the problem and the reason for the research. Following a geo-climatic overview of Lebanon with its hot summers, the perpetual problem of energy supply is put forward in addition to a description of the built environment of heavyweight materials. It carries on showing how different local, regional or international bodies are promoting low energy construction in Lebanon. The combination of these different factors gives the purpose of the research of finding a low to no energy construction method for internal summer comfort.

Chapter 3 Definitions and literature review

This chapter sets both the theoretical background and the methodology to be followed: the needed terminologies are defined and previous researches that have dealt with similar cases are reviewed and consequently analysed. The first part expands the physics of heat transfer, alongside relative terminologies for quantifying heavyweight materials. Next, the EDSL TAS thermal software is reviewed with a focus on its heavyweight simulation, along with the organizations that validate its outcomes as reliable. Finally, the chapter defines software calibration and the different parameters needed by available protocols. Once the definitions and the theoretical background are set, the chapter reviews four types of previous researches that have focused on (1) the calibration issue, (2) theoretical or software-based studies for wall performance, (3) experimental studies for both roofs and walls, and specifically studies dealing with (4) thermal mass performance.

Part one has put forward the problem and defined the terminology and the available methods used in similar research, it also suggested that the outer-insulated walls provide the better option for reduced overheating and consequently reduced cooling loads.

Chapter 4 Temperature monitoring in residential buildings

The objective of the first chapter in the experimental section (part two) of the research is to assess the first methodology and to highlight its learning outcomes. It deals with the first method available in similar cases based on actual internal temperature monitoring in different apartments during an extended summer period. The monitoring highlights their summer internal temperature behaviour within Lebanon’s coastal climate. Furthermore, the monitoring provides valuable data on users’ living patterns, lighting and equipment types and schedules. This data will be incorporated into the consequent software simulations.

Chapter 5 Apartment’s software simulation and calibration

The objective is to resume assessing two other research methods and finding the best performing envelope in relation to overheating during Lebanon’s summers. With the data gathered from the better performing apartment, this chapter uses software simulation to build on the study using EDSL TAS software. It starts with a calibrated software model, where basic data are modified to allow the model to be calibrated based on existing protocols. Simulation runs test for proposed envelopes upgrades with varying internal inputs.

Chapter 6 Full scale test cells

All the variable results found in the previous chapter drive the research to build three full scale test cells with the objective of assessing double masonry walls with different insulation configurations under the same conditions and variables within a strictly controlled environment. This would ensure a significant reduction of any liable uncertainties in the previously monitored apartments.

Chapter 7 Test cells software-based studies

This chapter takes the data generated from the test cells for software studies based on a calibrated model to check to what extent such simulation results will be in coherence with the experimental observations.

Chapter 8 Discussion and conclusion

This portion summarises all the different results, and answers the fundamental question of the thesis, alongside the different objectives. It further identifies the limitations of the current study and proposes future research with further practical recommendations.

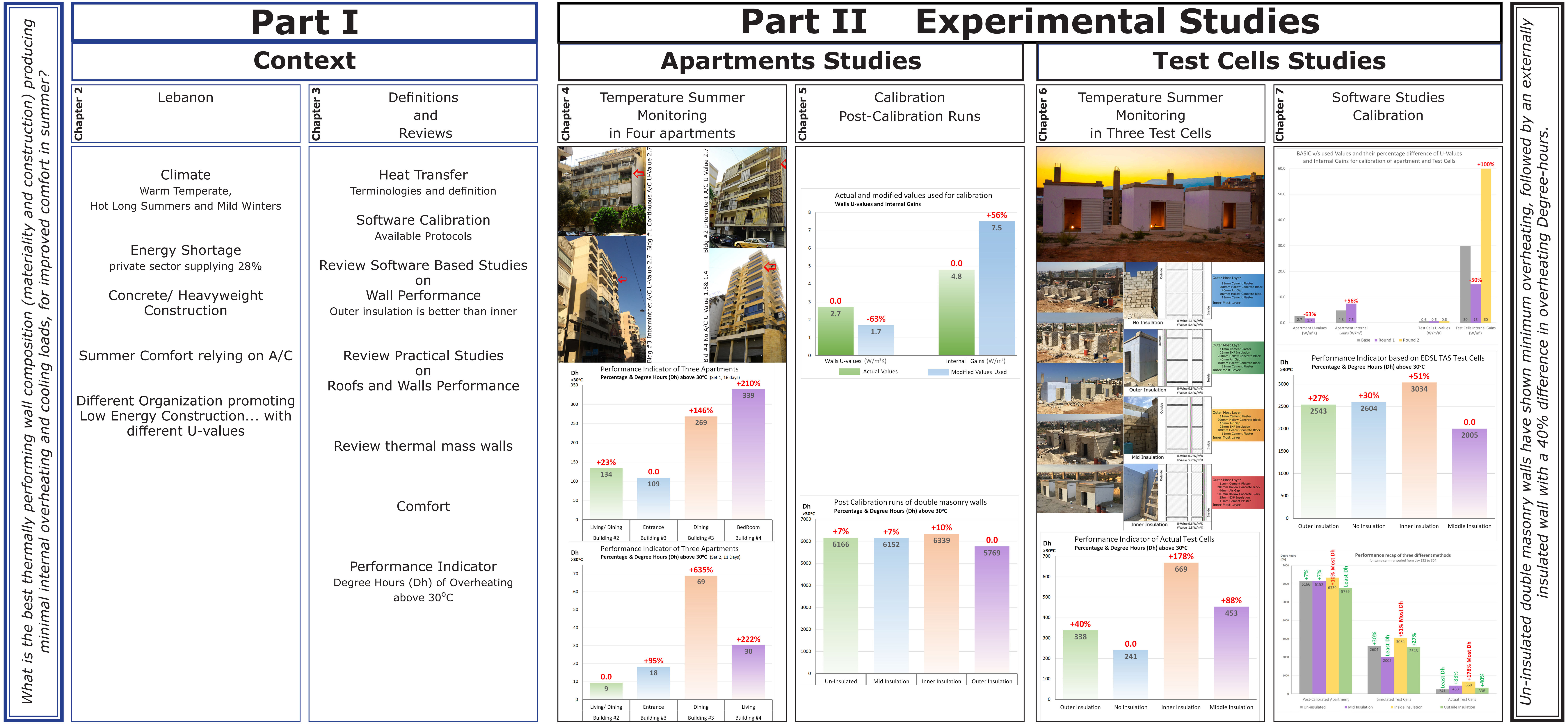


Figure 1.1 A concise visual abstract showing the structure of the thesis, the main question and findings within each chapter

2 Context: From Lebanon's geography and climate to heat transfer in heavyweight construction

2.1 Introduction

The main research question as defined within the introductory chapter is to find the best wall material and construction that will minimise internal overheating, and thus reduce or eliminate cooling energy loads. This first chapter sets the problem of the research question by defining its context comprised of both the geographic and climatic aspects of Lebanon as well as how local organizations are dealing with the issue. The chapter starts with a short description of Lebanon's rugged geography that gives way to four climatic zones. The coastal area being the research location is further defined within the overall warm temperate climate, where summers are long, hot and humid, but with no precipitation, while winters are short with mild precipitation. While reviewing proposed climatic responsive strategies, the chapter highlights that, within the combined summer high humidity and low diurnal temperature difference, heavyweight construction is not expected to have a major role in improving summer internal comfort. The chapter carries on showing the long-term unreliability of energy supply where shortage of electricity is a chronic, common problem with private electricity generator compensate the lack of power. What follows is the description of the built environment in terms of typology and heavyweight material used before moving onto showing that summer comfort heavily relies on mechanical cooling. In the last part, the chapter reviews the different institutional, public and private energy conservation awareness campaigns and more specifically their controversial publications each recommending different construction in terms of envelope U-values.

2.2 Geographical Description

Lebanon is situated on the eastern coast of the Mediterranean Sea (fig. 2.1; 2.2). Its geography is best described as two parallel mountain ranges running average 25^{o} Eastern, north/south direction, parallel to the Mediterranean coast line to the west at a total length of 200Km. Squeezed within those two mountain ranges is an expanse of inland; elevated, narrow plateau. The remaining coastal zone is narrow (fig. 2.3) with some sporadic mountains dropping directly into the sea. The western mountain range culminates in its northern part at 3066m above sea level, whereas the eastern range culminates in its southern part at 2800m. The inland plateau has an average altitude of 900m. The maximum width of all the above does not exceed 80km (fig. 2.4), yet this topography gives way to four distinct climatic zones.

Figure 2.1 Eastern Mediterranean basin and Lebanon (after Google Earth 7.1.5).

Figure 2.2 Lebanon Map (Source: Google Earth 7.1.5).

Figure 2.3 Typical Urban View of Lebanon (City and Bay of Jounieh) showing the narrow coastal zone lying just below the mountains/hills

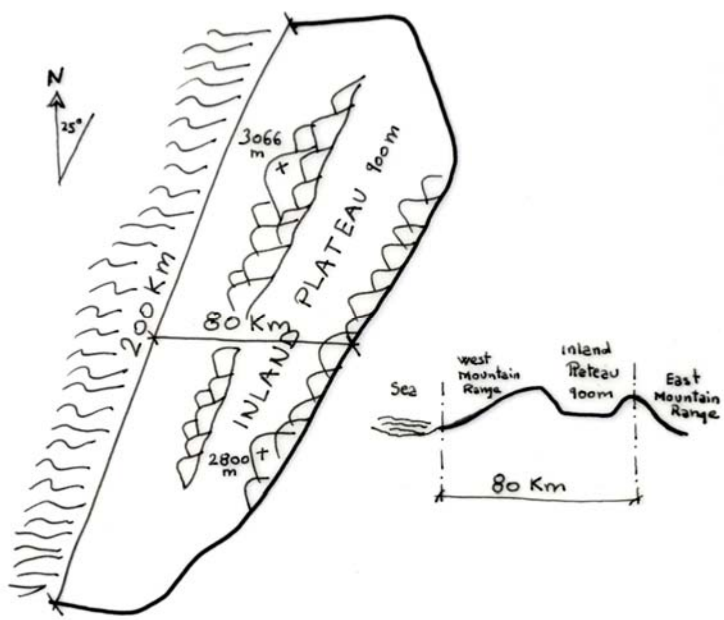


Figure 2.4 Schematic diagram explaining the topography and division of Lebanon

2.3 Climatic Classification and Analysis

The characteristics of Lebanon's climate are described in three complementary local publications: The Climatic Zoning for Buildings in Lebanon (Republic of Lebanon, 2005), Passive Design Strategies in Lebanon (Republic of Lebanon, 2005), and Thermal Standard for Building in Lebanon (Order of Engineers, 2010). Within these, four climatic zones are defined according to the altitude (fig. 2.5), as well as their heating and cooling degree day threshold brackets (table 2.1; 2.2): (1) the coastal zone, (2) the medium altitude on western mountain slopes, (3) the high mountains and (4) the inland plateau. Furthermore, the coastal zone is divided into two sub zones: the lower part (zone 1A) reaching up to 400m in elevation and the higher part (zone 1B) above 400m. The winter in zone 1A is described as warm and short whereas zone 1B as cold and its lengths increasing with altitude. Summer in both zones is hot and humid, but the maximum daily temperature for the higher part (zone 1B) is slightly lower. The daily gap between day and night temperatures is small all year round for both zones. The current research is located within climatic zone 1A.

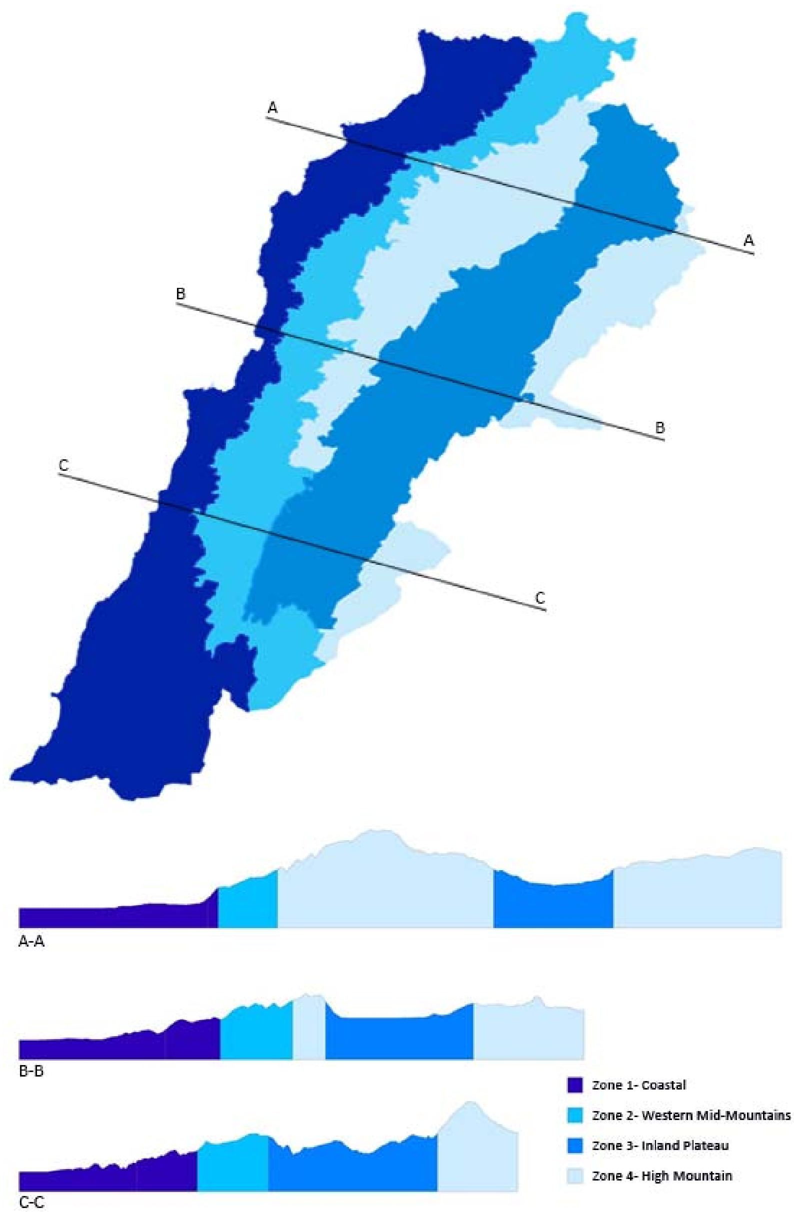


Figure 2.5 Map of Lebanon with the different climatic zones based on altitude. Also corresponding cross section showing the different climatic zones within the attitudes. Source: after Climatic Zoning for Building in Lebanon (2005)

Table 2.1 The four climatic zones of Lebanon based on altitude and Heating Degree Day (HDD) and Cooling Degree Day (CDD). Source: Climatic Zoning for Buildings in Lebanon (2005).

Climatic Zone	Approximate Altitude range	Approximate HDD(18) and CDD(21) Thresholds
Zone 1: Coastal	0-700 m	300 < HDD < 1200 120 < CDD < 1050
Zone 2: Western Mid-Mountain	700-1400 m	1200 < HDD < 2000 0 < CDD < 120
Zone 3: Inland Plateau	700-1150 m	1200 < HDD < 1800 120 < CDD < 600
Zone 4: High Mountain	Littoral side +1400m	HDD > 2000 CDD = 0
	Inland side +1150 m	HDD > 1800 0 < CDD < 120

Table 2.2 The different characteristics of the four climatic zones in Lebanon. Source: Thermal Standard for Building in Lebanon (2010).

Climatic Zone	Climatic Sub-zone	Winter	Summer	Daily Gap
1 Coastal	**1A** Altitude < 400 m	Warm and short	Hot and humid	Small all year
	1B Altitude > 400 m	Cold and long increasing with altitude	Hot and humid with maximum daily temperatures differing slightly from 1A	
2 Western Mid Mountain	No Sub-zone	Cold and long increasing with altitude	Cool and Moderate summer	More pronounced than the daily gap of zone 1
3 Inland Plateau	No Sub-zone	Colder and longer than the winter at same altitudes in zones 1 & 2 (min temperatures lower than zones 1 & 2)	Hot and dry summer, but cool at night. The min temperatures are lower than zones 1 & 2 and the max temperatures are higher. Very low humidity.	In summer the daily gap is high and varies according to the year.
4 High Mountain	No Sub-zone	Long and rigorous	Cool	Moderate to high in Eastern Mountain

Besides the local sources, two more sources are used to define the Beirut Climate: (1) the Koppen-Geiger and (2) ASHRAE.

According to the Koppen-Geiger world climate classification and the specific coordinates (Kottek et al; 2006), Lebanon falls into the **Csa** & **Csb** zones, as explained in the table 2.3 below and the explanatory notes which are based on the Homepage of Encyclopædia Britannica Online: ***Mediterranean climate***.

Table 2.3 Characteristics of the Koppen-Geiger Climate classification applied to Lebanon

	Main Climates	Precipitations	Temperature	Notes
C	Warm Temperate			Warmest Month >= 10°C Coldest Month -3<T<18°C
s		Summer Dry		Driest Month <30mm & <1/3 wettest month
a			Hot Summer	Warmest Month >=22°C
b			Warm Summer	four warmest months >10°C or Warmest Month <22°C

ASHRAE does not specifically classify Beirut in its international listing of climate. To find Beirut’s climate based on ASHRAE, two short studies are done: comparison to neighbouring cities and zone extrapolation from the available bracket given for cooling degree days.

In the first case, displayed in figure 2.6, neighbouring and regional cities are shown with two prevailing climates: Zone number 2 or the Hot and Humid, and Zone number 3 the warm and humid. Beirut should fall within these two zones.

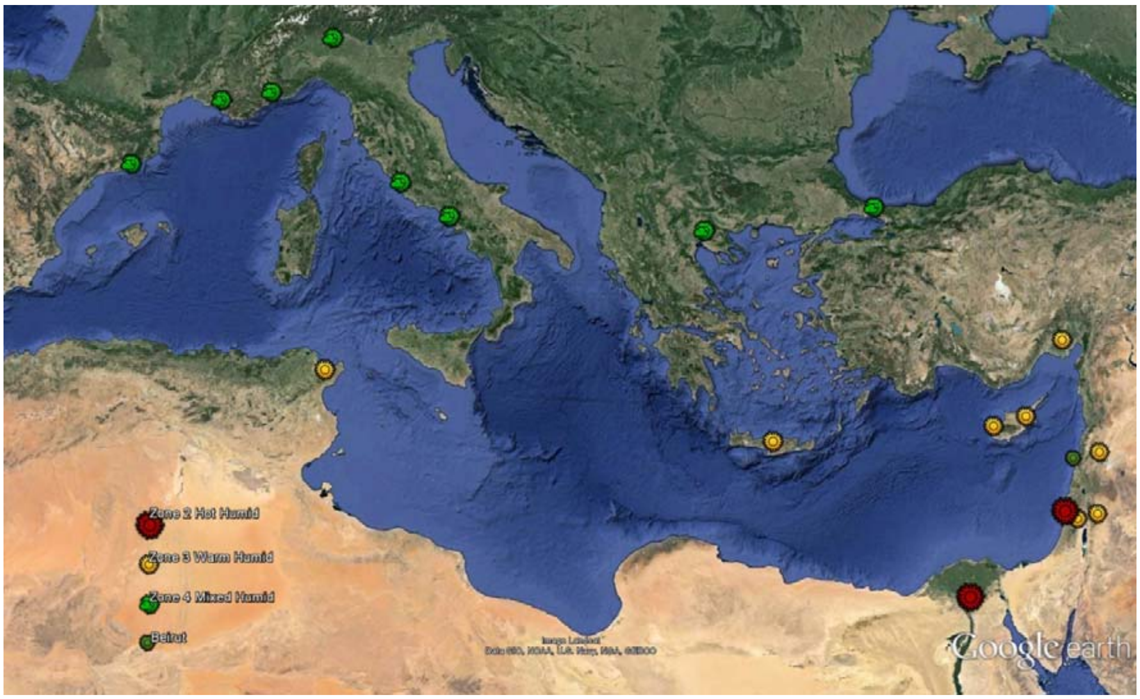


Figure 2.6 Different climatic cities on the Mediterranean Basin based on ASHRAE classification, with the exception of Beirut (Source: after Google 7.1.5).

For the second case study based on ASHRAE 90.1 (2007), thermal criteria for zone definition based on the Cooling Degree Day (CDD) and climate for zone 2 falls within:

$$3500 < CDD10^{o}C < 5000$$

Using the available climate file for Beirut (meteonorm 7), the calculated value is 4047; best-fitting for Zone 2.

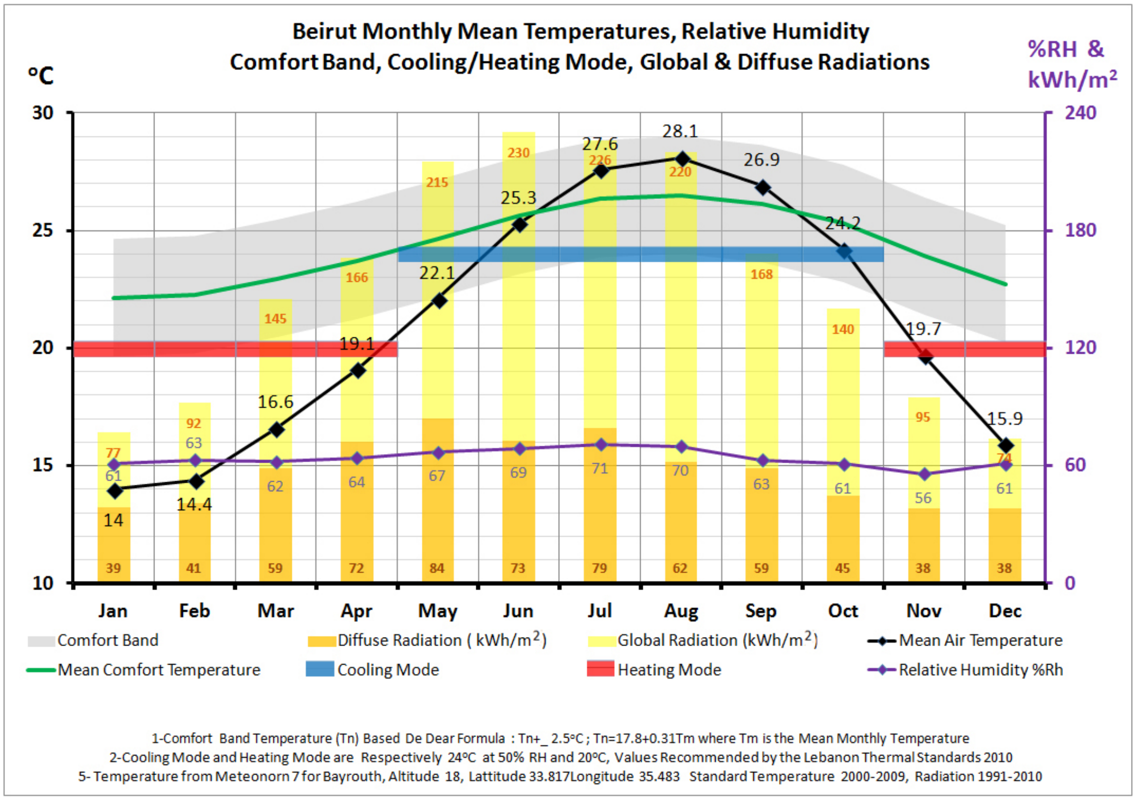


Figure 2.7 Beirut Monthly mean standard temperature, relative humidity, global and diffuse radiations, as well as comfort band, cooling and heating mode. Source: based on data from meteonorm 7.

For this research, the weather file data (meteonorm 7) is shown in figures 2.8, 2.9 and 2.10. These data are based on a standard average year calculated for the temperatures between the years 2000-2009 and for the solar radiation between the years 1991-2010, collected at the Beirut Airport. The latter's location is described by Oke (2006) and repeated in the World Meteorological Organization (2008) as open fields with data expected to be different from urban zone; in addition to that, the airport is located directly on the sea.

Figure 2.7 shows the monthly values of solar radiation, temperatures and humidity, while figure 2.8 traces the hourly and daily values of the above for the entire year comprised of short and mild winters, and long warm and sunny summers, with high humidity throughout the year. Figure 2.9 adds to these previous monthly data the wind velocity, the diurnal difference, the rain falls, and the hours of sunshine.

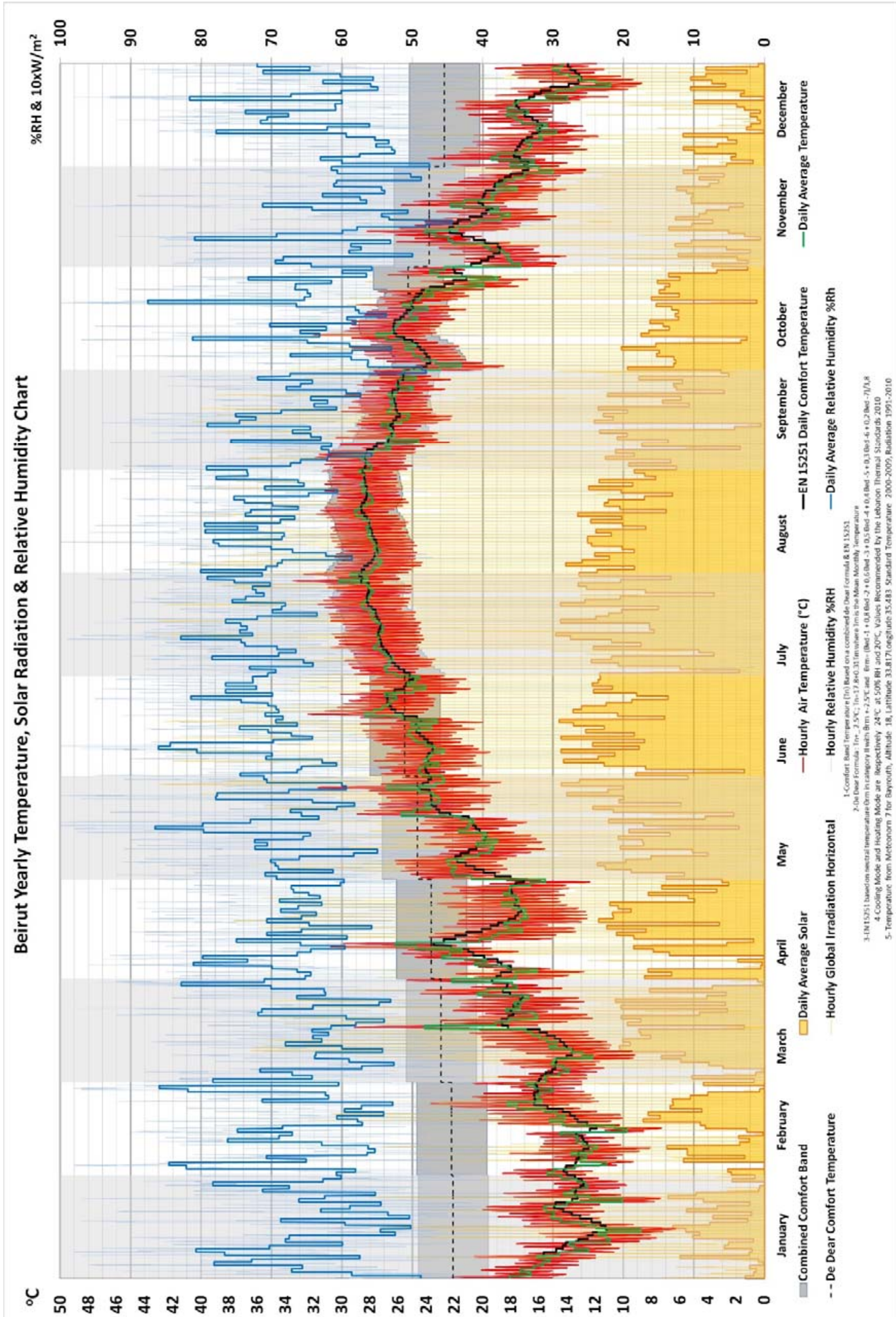


Figure 2.8 Beirut hourly and daily temperatures, relative humidity and solar radiations, in addition to a combined comfort band. Source: based on data from meteonorm 7.

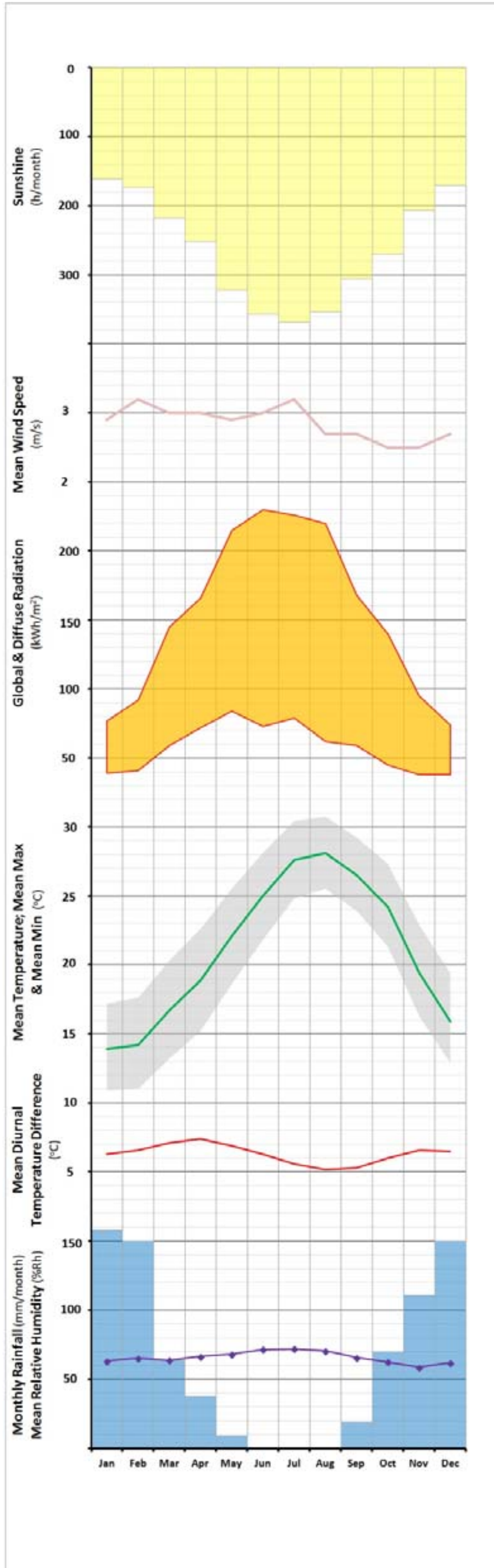


Figure 2.9 Combined weather graphs for Beirut.
(Source: based on data from meteonorm 7).

2.4 Climate Responsive Strategies for Lebanon

Lebanon's overall weather (figure 2.10) fits within the general category of warm temperate climate. Further characteristics based on the Koppen-Geiger world climate add that summers are hot with no precipitation; long hours of sun that provide considerable solar radiation, with relative humidity varying between 60 and 70% average. The main passive strategies consist of sheltering from the sun during the hot season, while trying to be exposed to it during the short mild winter. The psychrometric chart (fig. 2.10) compiled by Szokolay (2004) evidently demonstrates the solar benefits for the mild winter season. However, in order to counter the summer's high humidity, none of the passive design strategies of (1) combining thermal mass and night ventilation; (2) convective cooling through wind reaching 1.3m/s; or (3) direct evaporative cooling will have any impact on the long hot summer months. Climate & Comfort (2005) refers to the psychrometric chart for Beirut and states that although the temperature and relative humidity are beyond the summer comfort band, the use of thermal mass will extend the comfort zone to 33ºC. It also adds that carefully integrated air movement could stretch the comfort limit to 38ºC. Finally, the diurnal difference ranging between 5-7K (fig. 2.9) is quite low for any potential cooling from combined night ventilation and thermal mass (ref chapter 3.2).

As for the set cooling temperature, The Thermal Standard for Buildings in Lebanon (2010) recommends it at 24ºC. Whereas in an energy audit study of nine large scale commercial centres in Lebanon, LCEC (2010) recommended cooling temperatures between 25.5 and 26.6ºC for energy saving.

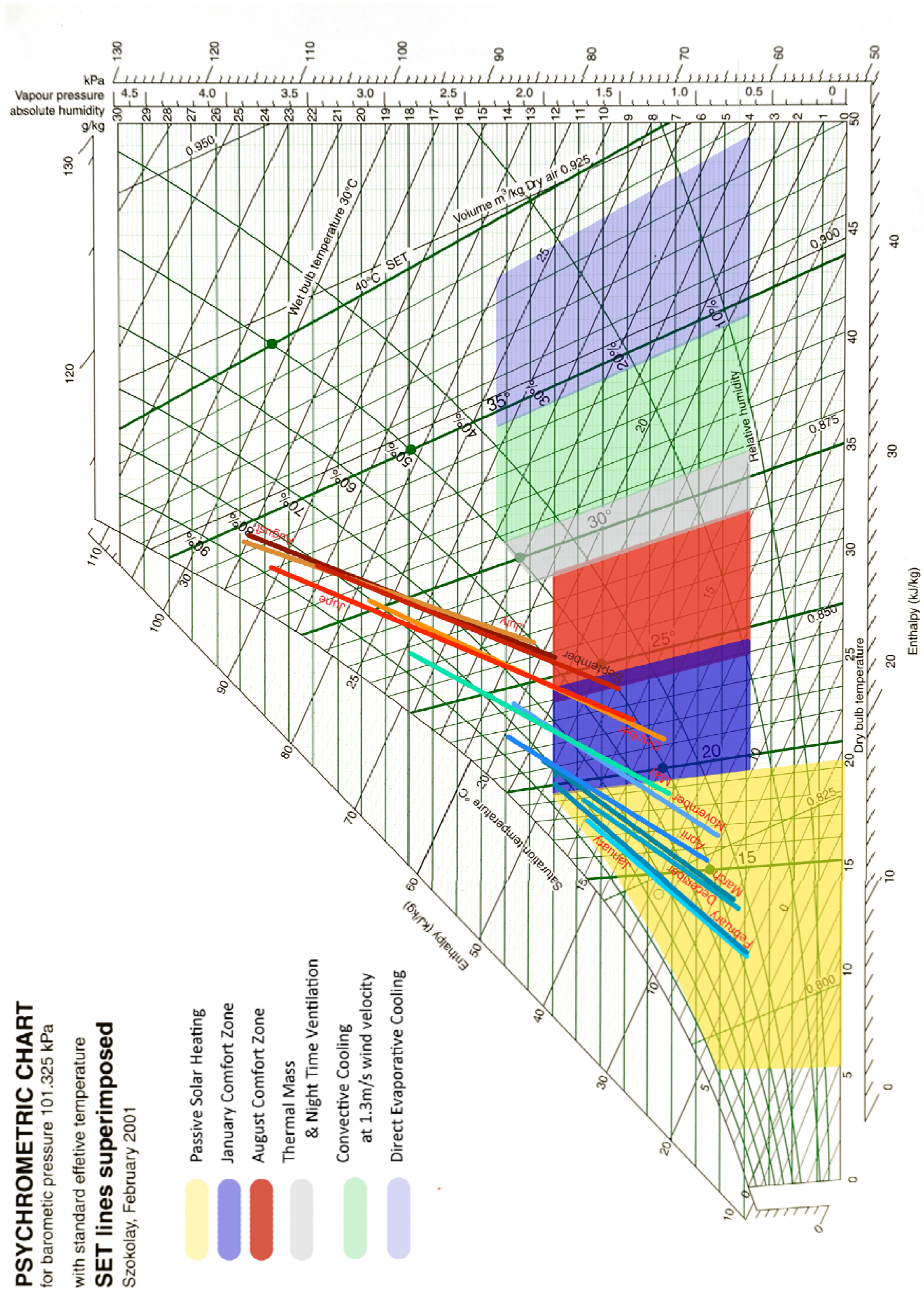


Figure 2.10 Psychrometric chart showing the potential of different passive design approaches over each month's maximum and minimum temperatures (Source: after Szokolay, 2004).

2.5 Lebanon's Energy Problem Context

Since the end of the local conflicts (1975-1990) in the early 1990's, the reconstruction phase of Lebanon included more than doubling the national electrical production from 953MW to 2038MW between 1996 and 2001 (EDL web page), yet there was never a time of uninterrupted and continuous power supply. The demand always exceeded the supply, and following a major political turmoil, in 2013 a new plan was unanimously adopted by all parties of leasing two power generating barges for a limited period of two years, giving enough time for the overhauling of two of the main power stations (fig. 2.11). Yet the two Turkish generating barges have been docked for over two years now with no updates regarding the status of the local power stations. The political promise was that by the end of 2015 electrical supply will be uninterrupted and continuous (24/7). In early 2018, up two four of the existing power plants were upgraded, adding an extra 715 GW generating capacity. Yet this was still not sufficient when taking into account the large number of Syrians that have taken refuge in Lebanon estimated at more than one and a half million; requiring alone an energy consumption of almost 500 GW (MoEW, 2017; AEMS, 2017). In addition to this ongoing process, historically unprecedented short and extended blackouts started to occur on a regular daily basis during the war. The main reasons behind those blackouts were the ageing power stations that did not receive any proper maintenance, along with a growing demand exceeding the available supply (Chbat, 2011). Those blackouts became so common that privately owned power generators were a necessity for many –private- households and businesses alike. Since then, the only improvement that happened to ensure a quasi-continuous power supply is those privately owned and operated power generators were replaced by privately owned power plants servicing entire nearby neighbourhoods.

Figure 2.11 The two Turkish leased Power generating ships:"*Fatmagul Sultan*" (left) at the Zouk (12Km north of Beirut) power plant and "*Orhan Bay*"(right) at the Jiyeh (22Km south of Beirut) power plant.

Local private investors buy one or more power generating units, use or rent an available plot of land near the area to be serviced, use the available low voltage electrical poles as carriers for their own cables, and thus distribute power to the surrounding neighbourhood by adding an electric meter. Once the main power is off, the neighbourhood generator automatically starts within few seconds to a minute and power is back again, without any end user intervention for change or, switching from one supply to another. Same procedure applies once the main power is back, another much shorter power break happens this time to allow the neighbourhood generator to turn off and to switch back to the main power supply.

2.6 National Official Production

Based on the available statistics (ALMEE, 2011) covering the year 2011, the governmental and only power producer known as Électricité du Liban (EDL) produced 65% of the overall electric power needed, importing 4% from Syria and 3% from Egypt, and the remaining 28% was produced by the private sector through the neighbourhood generators (fig. 2.12a, b). It should be mentioned that from the power produced by EDL, only 7% is generated by hydro power (fig. 2.12c), whereas the remaining is based on 74% imports of fuel and diesel oil, and 19% natural gases (Chbat, 2011) (fig. 2.12d). A recent, yet more confusing publication (MoE/GEF/UNDP, 2015) calculated the divisions of electricity sources of the overall generated power from 2012 and shows that Syrian import sums up to 3% whereas hydro power is 10.7%; showing less than the previous 4% from Syrian import, but more from hydro production.

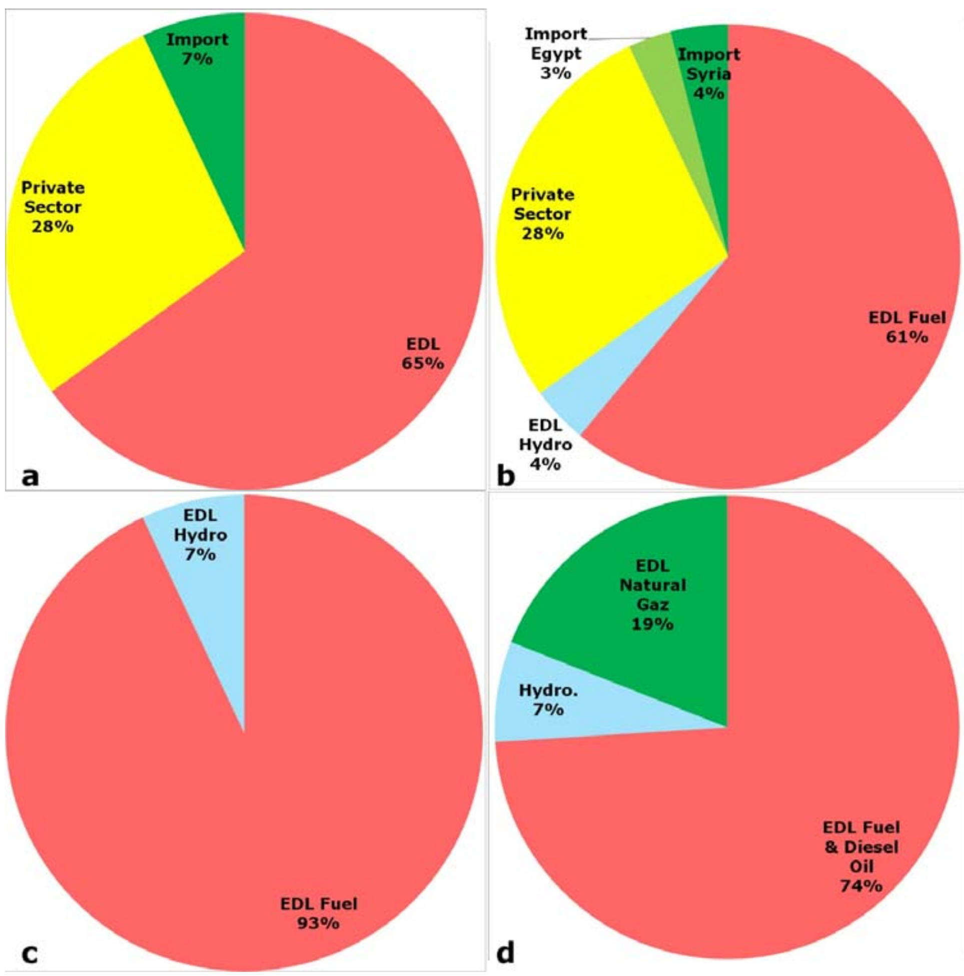


Figure 2.12 The local power status where (a) shows the production shares, (b) the details of the both imports and the main EDL sources, (c) the EDL hydro/Fuel proportion, and (d) the natural gases, fuel and hydro from EDL. **(Source: After ALMEE 2011)**

The reasons for the unreliable services of EDL are explained by Chbat (2011); they are about the proper generation, the transmission, and the distribution (MoEW, 2017). Within the generating issues, Chbat explains that the demand is increasing while the maximum available capacity has already been reached, moreover the average production cost of the kW.h is double than the average kW.h sold at 18c production and 9c sold, leading to annual losses of some 1.1B USD. Some 15% losses are further due to the transmission technical issues; similarly, considerable losses occur from the ageing network.

Jouni & Mortada (2013) show the values of final and overall energy consumption for 2000 and 2010. They report (figure 2.13) a 24% overall energy consumption for the residential sector and 7% for the commercial/offices in 2010, showing a small increase from the 2000 values of 19 and 6% respectively. Further to that, a breakdown of energy per each sector is also reported (table 2.4).

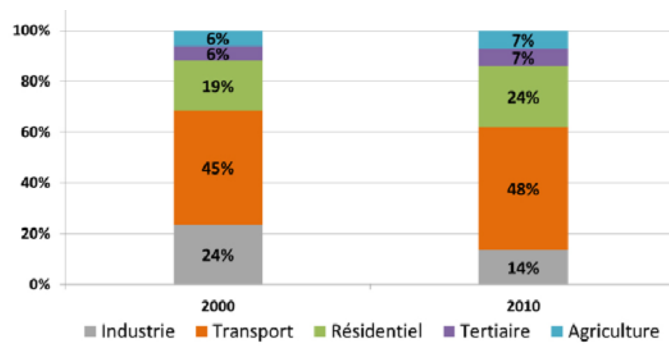


Figure 2.13 Energy consumption per sectors in 2000 and 2010. (Source: Jouni & Mortada 2013)

Table 2.4 Cooling and Heating percentage in residential and non-residential sector for 2010. (Source: Compiled after Jouni & Mortada 2013)

		Cooling		Heating	
	Overall %	Specific %	Overall %	Specific %	Overall %
Residential	**24**	5	**1.2**	49	**11.8**
Commercial/Office	**7**	22	**1.5**	13	**0.9**
Combined	**31**		**2.7**		**12.7**

The latter is among the few limited publications with detailed energy figures. Nonetheless, the report does not specify whether the values account for the entire country in all its four-climatic zonings. In another source, which is cited as the reference for these figures (Dib et al., 2011), the introduction specifically states that the data collection was difficult not due to the lack of coordination/cooperation from the different bodies involved in the study, but from the unavailability of the data, particularly the energy related ones. Furthermore, in the same source, displayed in a table, data shows that only 21 questionnaires/forms were distributed and collected for energy usage within the residential sector, whereas for businesses and offices, only 8 out of 28 distributed questionnaires were returned and assessed. Contradicting themselves, Jouni & Mortada (2013) show the increase from 16 to 50% in mechanical cooling in households from 2000 to 2010. **Furthermore, those values are in contrast with the energy benchmark proposed by the NEEREA (LCEE, 2014) for cooling and heating demands for the coastal climate of Lebanon at 115k.Wh/m^2 and 3 kWh respectively**. Finally, those figures do not relate from any perspective to the climatic properties of Lebanon. Hence, although it is the only source that has mentioned a detailed energy distribution, it is still an unreliable source and the figures cannot be taken into consideration. A recent study, by MoE/GEF/UNDP (2015) based on a survey of almost 900 commercial outlets and inclusive of all regions, found that cooling loads in the coastal area amount to 31% of the energy within the commercial sector, whereas the heating load is at 14%. A visual inspection of buildings, with all social classes combined, shows the excessive added-on window types or outside compressors. Some articles would even report that summer without A/C is not liveable.

2.6.1 Types of Energy Used for Heating and Cooling

Based on local knowledge, old buildings in the coastal area of Lebanon would rarely have heating, whereas they would have mechanical cooling in the form of split units or window type A/C. In recent constructions, diesel boilers might also be incorporated. The situation is different in the mid-mountain climatic zone, where heaters with diesel fuel boilers are common in old and new buildings. Recently, air conditioning units started to be incorporated into both old and new constructions. In the upper mountains climatic zone, the heating options are numerous starting from diesel boiler-based heaters, to fire places, diesel stoves, wood stoves, and wood pellet stoves and boilers. While not as common as heaters, mechanical cooling might be found in a few locations. For the inland plateau climate, both cooling and heating are available and installed. Heating would be available in a variety of modes similar to the high mountains climate.

2.7 Lebanon’s Built Up Stock and Typologies

There are no official statistics, references or documents that methodologically and numerically describe Lebanon’s built up fabric. Upon contacting the Order of Engineers and Architects, the *Lebanese Center for Energy Conservation* (LCEC), or any engineering and architecture university faculty, the reply remains that statistical data are missing, and other than very limited exceptions, the overall built-up environment of all climatic zones is made out of reinforced concrete for structures and slabs, and concrete and/or stone-related materials for non-structural elements and envelopes. Recent and old statistics of national cement production show an ever-increasing production, with limited periods of less production (Saliba, 1998; Sibline, 2015). Nevertheless, it should be mentioned that few authors did handle the issue from different perspectives: Skaff (2001) undertook a journalistic photo survey to emphasize the extent of the “concrete jungle” as he puts it in both the urban and rural context of Lebanon. Whereas Kassir (2003) in his socio-cultural history of Beirut, mentions at different instances its concrete built up fabric. Finally, Fischfisch (2011) re-mentions the concrete nature of the Beirut built up fabric in his book related to his Ph.D. thesis; he also states that concrete replaced the old wood construction from the middle to late XIX century.

The three main typologies of commercial/office blocks, residential, and institutional have their entire vertical structure, cores and slabs made out of reinforced concrete. The difference within typologies is evident within the facades. Only recently, and in the specific high-end area of down town Beirut, some all-glass residential buildings are the exception of the residential typology, usually with opaque walls and limited punctured windows. Since 2006, based on the new Building code (Republic of Lebanon, 2006), the walls are double cavity walls, constructed using concrete masonry units (CMU) also referred to as Hollow Concrete Blocks (HCB). The inner wall is plastered, whereas the outer wall can be both plastered and painted, or clad with natural stone, depending on the local zone's building code.

One of the main residential typology is the availability of balconies. Also, opaque facades with limited window openings are another characteristic of the residential typology (fig. 2.14). On the other hands, office typology seldom has balconies and is more often curtain glass or alternating horizontal glass and opaque continuous strips (fig. 2.15). Some mixed residential/offices are available as well, and some initially residential blocks are turned into offices (fig. 2.16).

2.7.1.1 Individual Houses or Apartments

Based on the statistics of the Atlas du Liban (2004), apartment buildings exceeded individual houses in number; increasing from 63% to 73% between 1970 and 1997. No further recent statistics are available.

Two main types of residential units prevail in Lebanon: the individual independent house type and the apartment building. The independent houses considerably vary in size and even name, from a small house, a villa, to a palace, and are relatively less frequent in number compared to apartments within buildings.

Within those buildings, the total number of floors is relative to the zone's own construction codes (fig. 2.17), but usually any building will have a minimum of four floors. The number of apartments per floor varies considerably from one per floor as a sign of luxury and high-end standards, to two per floor as the normal expectation. For more than two per floor, it is considered as social housing. As for the areas, the average small size would not be less than 80sqm, labelled as a studio with one bedroom and one living room. The average apartment is between 120sqm to 220sqm for two and three bedrooms respectively. As for the space allocation, a typical apartment will have a private area with bedrooms and a family den, in addition to a living and dining area. A kitchen and up to 2 WCs would also be available. The final element available, usually extending from the living area is the balcony which tends to be glazed and transformed into a conservatory for extra space.

Figure 2.14 A selection of medium height residential buildings with the balconies always present, some of which have been glazed to gain extra space, while others have only external awnings. Also, some façades are not stone clad (a; c; d & h). Example (g) from downtown Beirut is an atypical all-glass residential building.

Figure 2.15 Selection of office buildings showing the typical typology: no balconies, with either full glazed façade or alternating glass and opaque strips.

Figure 2.16 Typical mixed use or shifted function from residential to office: balconies are present, some of which have been glazed to enlarge the internal space. Advertisements are clearly exposed to promote the business.

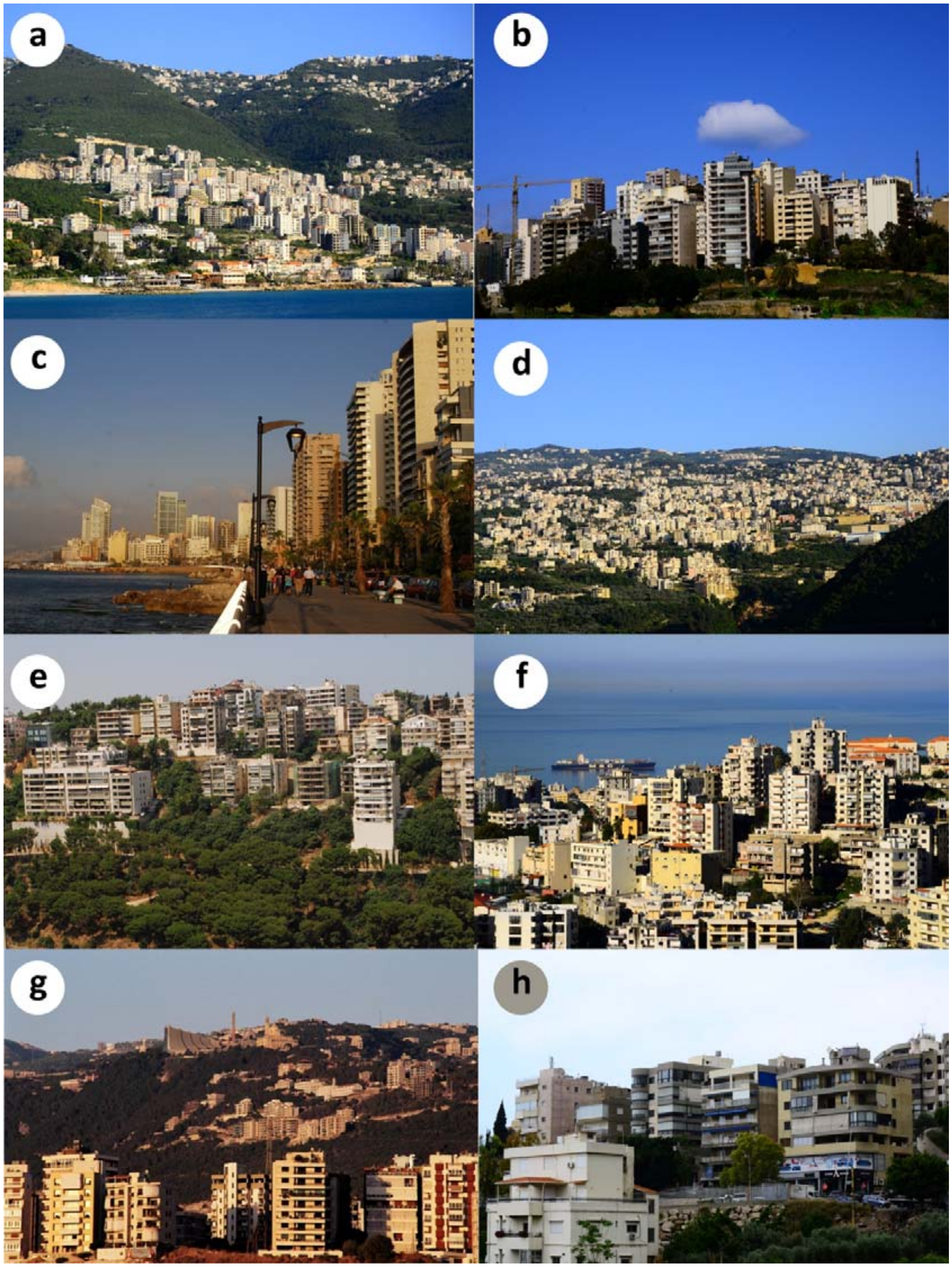


Figure 2.17 Typical view of constructed agglomerations showing the dense built up fabric adjacent to large green spaces.

2.8 Institutional, Public and Private Energy Conservation Awareness

Around the year 2000, concerns and awareness about energy conservation started to be a major issue in the local Lebanon scene. That period witnessed the emergence of the official governmental *Lebanese Center for Energy Conservation* (LCEC) under the auspices of the Ministry of Energy and Water (MoEW). The long-established Order of Engineers and Architects of Beirut[1] issued practical incentives to encourage the implementation of double cavity walls and pushed it until it became an abiding law. In parallel, non-governmental organizations like the *Association Libanaise pour la Maitrise de L'Energie et de l'Environnement* (ALMEE) [The Lebanese association for mastering the energy and the environments] backed by the French *Agence de l'Environnement et de la Maitrise de l'Energie* (ADEME) [Agency of the Environment and the mastering of the energy] continued to publish regular studies on the local subject in hand. In support of these initiatives, The *Lebanon Green Building Council* (LGBC) was established as well. All these bodies worked in parallel or together to produce general and/or specific guidelines for a better future with less dependency on fossil fuel energies.
The most collective and influential works completed include the Thermal Standard for Buildings in Lebanon (2005) commissioned by the *United Nations Development Program* (UNDP), the General Directorate of Urban Planning under the Ministry of Public Work and Transport. Within the same framework, *Climate and Comfort*, *Passive Design Strategies for Lebanon* (2005) as well as Climatic zoning for Building in Lebanon (2005) were published. In 2010, an updated edition of the Lebanon Thermal Standards grouped larger numbers of contributors: The order of Engineers and Architects, ALMEE, LGBC, and others. In 2011, a review of both editions was commissioned by the World Bank (Singh *et al.*, 2011).

The Thermal Standard for Building in Lebanon (2005) is the first reference work published by governmental bodies (UNDP and the Ministry of Public Work and Transport) that gives specific and clear numerical values for the envelope properties for newly built residential and commercial projects within the four different climatic zones of Lebanon. The envelope properties also include the U-values and the window to floor area ratio.

Within the same context; up to three different building energy ratings are now available: the ARZ[2] rating issued by LGBC for existing office buildings and the CEDRE[3] rating issued by the local Industrial Research Institute (IRI). The GRASS rating issued by ALMEE is the newest addition, claiming to be the most Lebanese focused rating system (Mortada *et al.*, 2014).

Finally, in a recent development, the LCEC published guidelines (2014) on how to submit a holistic building energy report to get free interest funding loans. Those reports which should be submitted during the design phase, apply for both residential and commercial buildings. They consist of a percentage check point dealing with envelope U-values compared to pre-set ones, as well as

[1] Both Architects and Engineers are grouped in one order.
[2] ARZ is the Arabic name of the cedar tree, the symbol of Lebanon, represented on its flag.
[3] CEDRE is the French name of the cedar tree.

overall building energy consumption: 20 to 40% reduction of overall energy benefit from 20 to 70% interest free loan for the project's envelope cost. This program is named as the National Energy Efficiency and Renewable Energy Action (NEEREA), backed locally by the central bank and the Ministry of Energy and Water, and internationally supported by the United Nation Development Program (UNDP). The proposed U-values are the lowest compared to other locally and internationally issued standards for similar climatic zones. One drawback to these guidelines, explained by the Technical consultant to the LCEC Ms Sorina Mortada, is the lack of specific schedule of occupation and internal gains. **Nevertheless, regardless of this issue, the main point of the mandatory energy simulation is for the applicant project to show that it has achieved energy reduction within the same pre-conditions of occupancy, equipment, and internal gain.**

Within this context, U-values from different local and international sources for each of the external walls, the roof and the windows are listed in table 2.5. The values are considerably different from one source to another: the roof U-values range from 0.1 to 0.75 W/m^{2}K and the external walls from 0.18 to 1.62 W/m^{2}K. In both cases, the lowest values are provided by LCEC guidelines (2014), which did not specify any values for the windows. Otherwise, those windows U-values range from 1.81 to 6.2 W/m^{2}K which encompass triple glazing with low-e coating, single glazed windows, or intermediate double glazing. When the source specifies the values in imperial units for U-factor, a conversion factor of 5.678 is used to change into SI units to U-values (ASHRAE, 2013).

The yearly cooling and heating energy demand benchmarks from different sources (when available) are shown in table 2.6. The standard values are defined by the LCEC (2014) as "business as usual" in reference to any typical building without energy consideration; it is set for residential types at 118 kWh/m^2 per year out of which only 3 are for heating. On the other hand, the benchmark value for a building to start being considered as energy efficient is 80 kWh/m^2 per year.

It should be noted that there are no available local resources that give accurate U-values or R-values for the typical common local building materials and construction. The alternative for that is to exhaustively search lists of U-values or R-values for materials and construction types, from international references such are CIBSE guide A (2006) and books on sustainability Szokolay (2004) and try to estimate which description fits best the available local materials.

For internal gains, it is only in the LCEC guidelines (2014) that the occupancy internal gains are mentioned to be 5 W/m^2 for residential and 14 W/m^2 for offices. Whereas for lighting, the overall yearly energy is said to be 13 and 17 kWh/m^2 for residential and offices respectively. LCEC does not mention any internal gains from equipment. CIBSE specifies values for all three gains from occupants, lightings, and equipment for offices only. Those are expected to range between 28 and 33.7 W/m^2 (table 2.7).

Table 2.5 All U-values from different local and foreign sources expressed in W/m²K

	Title	Year	Roof	Walls	Window	Notes
Lebanon	**Thermal Standard for Buildings**	2005	0.57	2.1	6.2	
	Thermal Standard for Buildings	2010	0.71	1.6	5.8	Till 25% Window to Wall area ratio (WWR)
				1.6	4	For 26 -35% WWR
				1.26	3.3	For 36-45% WWR
	Thermal Insulation Market in Lebanon [1]	2011	(3.2cm)	(1.2cm)	N.A.	Data given in thickness
			0.58-0.74	1.59-1.62		Calculated U-value
	LCEC Guidelines on Preparing Technical Proposal for Non-Certified High Energy Performance Building	2014	0.1-0.15	0.18-0.31	N.A.	
Mediterranean	**RT2005 H3**[2]	2006	0.34	0.45	2.6	
	Tunisia ZT1[3]	2008	0.75	1.2	6.2	Low Window to Floor area ratio (WFR)
				1.1	6.2	Medium to High WFR area ratio
				0.8	3.2	Very High WFR area ratio
Int'l Codes	**ASHRAE 90.1.2007 (Zone 2 A, B)**	2007	0.27	0.70	4.26	Window U-value for up to 40% Wall Area
	International Energy Conservation Code [4]	2015	0.15	0.71-0.44	1.98	Values of Roof & Walls converted from R-values, converted to SI[5] U-values of Windows converted to SI

[1] Calculated U-value based on XPS insulation thickness. Density 26-75Kg/m³ and R=0.026-0.037 W/m.K
[2] French Thermal standards for H3 Zone: Mediterranean area of south France
[3] Tunisian Norms for Private Buildings ZT1 zone which is the Mediterranean area of North East Tunisia
[4] R-Values Converted to U-value by U=1/R; Value of Windows given in U-value
[5] All U-values converted to metric value by multiplying by a conversion factor 5.678

Table 2.6 Yearly energy values in kWh/m²/year standards and benchmarks for residential

Title	Year	Residential Standard	Residential Benchmark
RT2005 H3*	**2006**		80**
Thermal Standard for Buildings (Lebanon)	**2010**		80
LCEC Guidelines on Preparing Technical Proposal for Non-Certified High Energy Performance Building (Lebanon)	**2014**	118	80

* French Thermal standards for the H3 Zone: Mediterranean area of south France
** Based on fossil fuel heating (as opposed to electrical heating which has higher values)

Table 2.7 Internal gain values and ranges of values including totals expressed in W/m² from LCEC and CIBSE

Source	Type	Occupants	Lighting	Equipment	Total
LCEC	Residential	5	1.5*	n.a.	**6.5**
LCEC	Offices	14	1.9*	n.a.	**15.9**
CIBSE	Offices	5-6.7	8-12	15	**28-33.7**

* Values Calculated from 13 and 17 kWh/m²/year

2.9 Conclusion

The main research question is to find the best wall material and construction that will have minimal internal overheating and thus reduce or eliminate cooling energy loads. This first chapter exposed the different issues that outline the problem: Lebanon's summer comfort relies heavily on mechanical cooling, exacerbated further from the fact that the country already suffers from a long term and chronic power supply shortage. Added to this, the minor and overdue upgrades and improvements of the power generating, and supply infrastructures are rendered futile because of the 1.5 million Syrian refugees' basic electric needs. Based on the climate, a review of adequate climatic responsive strategies shows that the combined effect of high level summer relative humidity and the small temperature difference between day and night compromise any attempt of reducing the mechanical cooling needs for summer comfort by heavyweight construction. Following the definition of the problem, the chapter carried on showing how a large array of institutional, public and private energy conservation organisations are trying, to promote low energy construction, but in an uncoordinated manner. This initiative is encouraged by issuing free interest loans for developers, local green building certifications, or just promoting low energy construction by recommending specific guidelines for envelope U-values and proposing energy benchmarks for low energy buildings. Nonetheless, the overall outcome is a variety of incomplete schemes that are quite different from one another. The recommended wall U-values vary from 0.2 to 2.1 W/m^2K according to different local sources, while international code values for similar climatic zones vary between 0.4 and 1.2 W/m^2K. Similarly, following the yearly energy benchmarks stated at 80 kWh/m^2, LCEC attempts to standardize the gains from users in terms of W/m^2 but the lighting gains in overall yearly power consumed are reported in terms of kWh/m^2 with no specifications regarding gains or overall consumption generated from equipment.

Hence the chapter sheds lights on the local good intentions for reducing general energy consumption within Lebanon's built environment, and more specifically energy consumption allotted for summer comfort. However, this movement remains unstable due the unorganized fashion of the involved parties and the incoherence of the proposed values that are not calculated from actual experiments, rather imported and adopted from similar climatic zones. This further reinforces the valuable contribution the research will bring in terms of testing through different methodologies to establish which wall construction and configuration best fits the local climate of Lebanon for minimal summer overheating. The different methodologies employed for the experiment will be the focus of chapter 3.

3 Definitions and Literature Review

3.1 Introduction

In order to achieve summer comfort, there is an excessive reliance on mechanical cooling while electricity supply is already insufficient and suffering. This problem is further exasperated with the un-coordinated manner numerous local bodies are dealing with the issue, without any solid scientific base. This chapter sets both the theoretical background and the methodology to be followed; needed terminologies are defined and previous researches that have dealt with similar cases are reviewed. The definition portion expands on heavyweight construction and its expected temperature behaviour. It carries on with a review on heat transfer within heavy and lightweight construction, in addition to all the parameters that are used for quantifying thermal mass. These parameters are: time lag, decrement factor, admittance or Y-value, K-value or thermal capacity, and Thermal Mass Parameter (TMP). Lastly, a review is provided on EDSL TAS thermal software used in the research. The purpose of the review is to ensure the reliability of the software by understanding how heavyweight temperature behaviour is simulated, and at the same time checking the organizations that validate the outcomes of this software. Following software selection, the chapter defines the process and purpose of calibration, alongside the three available protocols that define the criteria of what makes a good calibrated model. In the second part, the chapter reviews calibration-based studies and continues with a literature review of theoretical studies about wall manipulation and energy performance. This is followed by a review of practical research of either existing or purpose-built structures that are monitored and studied. The literature review raises more questions than answers; however, it does inform the research of the different available methodologies followed in similar cases. The chapter then proceeds to look at specific thermal mass and energy studies in Cyprus and Greece that have similar climate and heavyweight construction as in Lebanon. The chapter ends by discussing thermal comfort, and its related performance indicators that better suit heavyweight construction temperature behaviour.

3.2 Basic Heat Transfer Definition and Terminologies

Lightweight construction materials are lighter, of low density, and have very little to no thermal capacity or storage. Therefore, their reaction to temperature fluctuations is instantaneous. The most commonly used lightweight construction materials are timber, glass, and all types of metallic structures such as aluminium, steel, stainless steel, and weathered steel. Insulated materials in particular expanded or extruded polystyrene (EPS/EXP), also fall into the lightweight category.

The term ‘thermal mass’ refers to any material with the capacity to absorb, store and release heat (Littlefield, 2007; Szokolay, 2004). Meanwhile, concrete, masonry walls and stone finishes are high-density materials that at the same time have high thermal capacity; hence the term ‘heavyweight’ refers to that type of construction. In his general climate description and corresponding passive design strategies, Szokolay (p.69; 2004) points out a 20K average diurnal difference in hot/dry climate where thermal mass can have a considerable influence. In contrast, a 5K typical difference available in warm/humid climates will considerably reduce the effect of thermal mass. In warm/humid climates, construction should be well-ventilated and lightweight to ensure the interior space is not hotter than outside. Szokolay's detailed climate review (p.50; 2004) reports a number of sources that imply the successful impact of the mass effect at as little as 8K to 10K in diurnal range. As seen in Chapter 2 and figure 2.10, the mean diurnal summer difference for Beirut only ranges between 5K and 7K.

Theoretical (or lab base setting) steady state heat transfer consists of studying heat dynamics that flows from outside to inside (through an envelope) without any input from internal sources, while transient heat transfer takes into consideration both inside and outside variables at the same time.

Temperature performance of heavyweight construction in hot climates is described as taking longer to warm up when exposed to solar gains and slower to respond to temperature variation (Littlefield, 2007; Szokolay, 2004). With the same reasoning, it would take longer to cool down and lose the extra heat. This stored heat would dissipate during the night due to lower night time temperatures (fig. 3.1). This situation is ideal to maintain a comfortable indoor temperature when the temperature difference between day and night is considerable. Furthermore, Szokolay (2004) considers this method a practical free-running solution to keep internal conditions within acceptable comfort levels. Littlefield (2007) and Szokolay (2004) both add that the practical effect of thermal mass lies in its surface area rather than in its thickness, therefore a 24-hour cycle of heat absorption and release can be easily inscribed within a thickness of 50 to 120mm. The latter can be available in any exposed reinforced concrete construction and its elements including slabs, walls and even floor finishes.

Koch-Nielsen (2002) states that the process of cooling down thermal mass, or heat dissipation, cannot be achieved without added and enhanced night-time ventilation for hot and dry climates. He does not comment on hot and humid climates but specifies that for warm and humid zones with little temperature fluctuations, thermal mass should not be applied. Instead, the better choice would be opting for well ventilated lightweight construction.

The 2013 Residence Compliance Manual (2014) issued by the California Energy commission states that a 200 to 300mm concrete wall will have a combined thermal dampening time delay between 6 and 10 hours (fig. 3.2). Furthermore, the amount of thermal mass with an evident effect is explained as a building "*having 30% of the conditioned slab floor exposed and 15% of the conditioned non-slab floor exposed with the equivalent of 50mm thick concrete*."

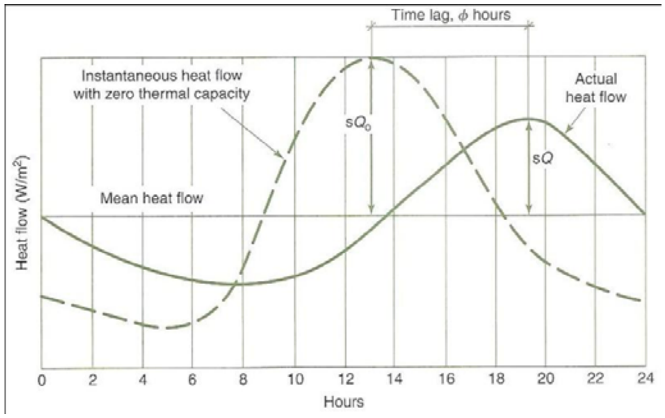


Figure 3.1 Heat flow through a real wall and a zero-mass wall. (Source Szokolay, 2004)

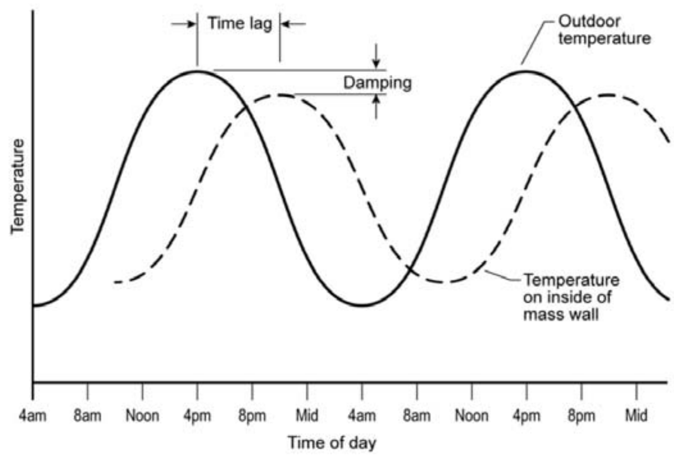


Figure 3.2 Thermal mass thermal performance as illustrated in the California 2013 Residential Compliance Manual (2014) and sourced itself from the California Energy Commission.

When it comes to expressing the thermal properties of thermal mass, the U-value (thermal transmittance) is no longer relevant. Instead, the time lag, decrement factor and delay, admittance or Y-value, K-value or heat capacity (de Saulles, 2012; BRE, 2011), and diurnal heat storage (Balcom, 1983) are more appropriate for such materials.

(a) The **time lag**, expressed in hours, is the delay between the peak external temperature and the peak temperature of the space where thermal mass is applied.

(b) The **decrement factor** is the ratio of the actual heat reaching the thermal mass and the heat that would be post-emitted (since it is a ratio it is non-dimensional). The **decrement delay** is the actual time between the heat peak and the emitted peak, expressed in hours.

(c) The **admittance** or the **Y-value** expresses the thermal mass ability to store heat within itself while ambient temperature fluctuates. The earliest mention of the Y factor goes back to Balcom (1983) who labelled it as the 'diurnal heat capacity' or DHC. It is expressed in W/m^2K. Although it shares the same unit with the U-value, it describes a different physical property; the larger it is the less internal temperature fluctuation is to be expected, K being the unit that expresses the difference between average internal temperature and the temperature at a specific time (de Saulles, 2012). Szokolay (p.131, 2008) gives the formula to calculate the admittance of a solid homogeneous element as the square root of the product of the periodic cycle:

$$Y = 0.5117\sqrt{\lambda \rho c}$$

λ: conductivity **(**W/mK); **c**: the specific heat (Wh/kg.K); **ρ**: density (kg/m^3)

(d) The K-value or 'heat capacity' is the product of the thickness **d** of a layer (mm) multiplied by its density **ρ** (kg/m^3) and its specific heat **c** (J/kgK) expressed in units of kJ/m^2K.

$$K = 10^{-6} \times \Sigma\, (\mathbf{d}.\, \boldsymbol{\rho}\, .\mathbf{c})$$

It is used as a compliance tool for building regulations within the UK. Its simplified formula is explained as such: *"they are measured from the inside surface stopping at whichever of the following occur first: (1) halfway through the construction element; (2) an insulating layer (thermal conductivity less than 0.08 W/mK); (3) a depth of 100mm."* (de Saulles, 2012)

(e) The Thermal Mass Parameter TMP (BRE, 2011) or 'diurnal heat capacity' of a building (Balcom, 1983) is the summation of all K-values multiplied by their respective areas, divided by the Total building's area (TBA).

$$TMP = \frac{\Sigma\, (\kappa \times A)}{TBA}$$

The TMP values are claimed by the UK BRE (2011) to be a good indicator of thermal mass based on the following (table 3.1):

Table 3.1 Thermal mass indicator based on the TMP values (Source: BRE, 2011)

Thermal Mass	Thermal Mass Parameter -TMP- **(kJ/m^2K)**
Low	100
Medium	250
High	450

It should be noted that for Lebanon, where the prevailing form of construction is with thermal mass (compared to the relatively limited heavyweight construction in the UK), no local sources of guidance exist for any of these thermal mass indicators.

3.3 EDSL TAS Software

Environmental Design Solutions Limited-Thermal Analysis Software (EDSL-TAS) is a commercial software whose manufacturer claims that it offers full thermal solutions based on dynamic simulation for existing or new buildings from simple small forms to large complex ones. The included parameters such as fully integrating natural ventilation, mixed mode with integrated stack, wind pressure and air flow analysis, allow the comparison of different heating and cooling strategies, along with the corresponding energy demands. It also claims to compare alternative façade designs impacting occupant temperature comfort and to accurately predict CO_2 emissions and operating costs in addition to cooling and heating equipment sizing. TAS Engineering v9.3 (the software version used in this research) was "approved for EPC and part L 2013 for England by DCLG on 01/05/2014" (www.edsl.net, June 2018).

TAS has three complementary parts: (1) 3D model, (2) building simulator, and (3) result viewer.

I- The 3D modeller allows the drawing of the building under study in 3D and the different internal spaces are assigned to specific zones.

II- The building simulator includes:

1- A specific weather file is assigned to the project, with the following variables:
   - a- Global solar radiation W/m^2
   - b- Diffuse solar radiation W/m^2
   - c- Cloud cover (from 0 to 1)
   - d- Dry bulb °C
   - e- Relative humidity %Rh
   - f- Wind Speed m/s
   - g- Wind direction ° from north

2- Each drawn building component of the 3D model is assigned to a specific construction. These constructions can be built one element/layer at a time to reach the needed value or taken from existing pre-set construction files.

3- Each zone is assigned with a specific internal condition with the following parameters each expressed in terms of W/m2 where the area is the specific zone's area. These are labelled internal gains, expressed in term of sensible and latent heat.
   - a- Ventilation and infiltration rate and schedule, expressed in air exchanges per hour (ach)
   - b- Lighting gains and schedule, expressed in W/m^2
   - c- Number of users and their schedule in terms of W/m^2 expressed in terms of sensible and latent heat
   - d- Number of equipment and their schedule, in W/m^2, expressed in terms of sensible and latent heat
   - e- Pollutant generation, expressed in litres $CO_2/hr.m^2$

4- Windows and shading opening schedules.

5- Thermostatic control where the cooling, heating and relative humidity levels are assigned with their corresponding schedules.

III- The result viewer that can be simulated hourly for any specific period generates the results that include:

1- Cooling loads
2- Heating loads
3- Dehumidification loads
4- Temperature performance

EDSL TAS is validated by the following bodies

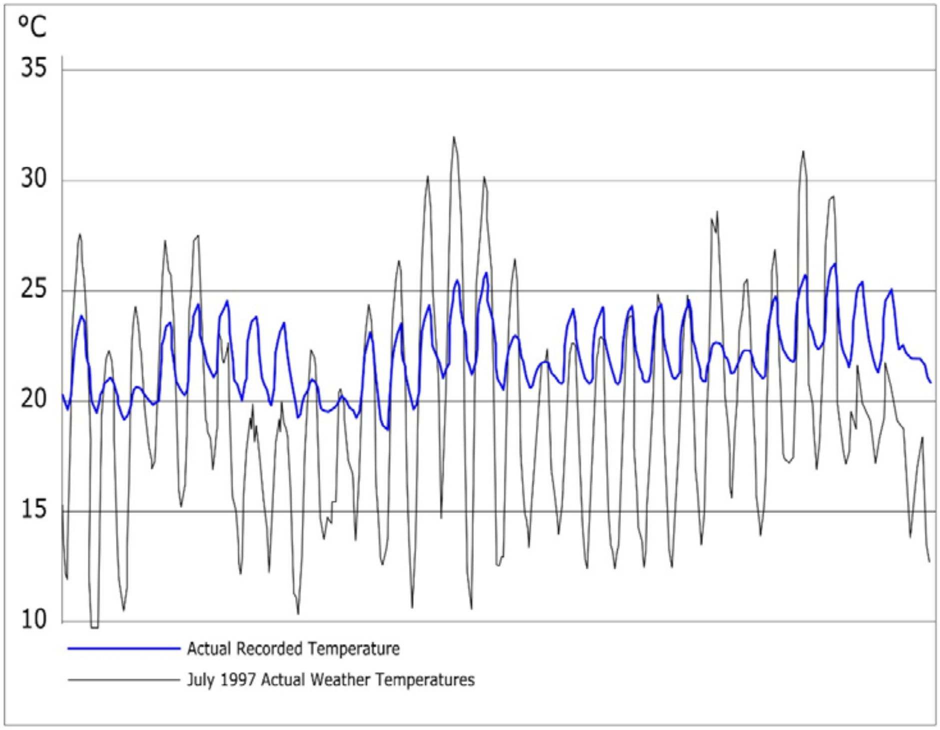
1- EPC and Part L2, as well as building assessment for level 3, 4 and 5
2- Building Energy and Environment Modelling (BEEM) suitable for performance and energy prediction
3- ASHRAE 140-1 where TAS successfully passed all the performance test for both edition 2004 and 2007
4- EN ISO Standards where TAS 9.3.0 is compliant with standards 13791, 13792, 15255, and 15265

EDSL TAS has also successfully passed the comparative CIBSE Guide A test for heat loss, summer temperature and cooling loads calculations.

In the theory manual provided on request by email by EDSL, the text is written in such a way as to keep the outcome true in a general sense but without any mention of expected accuracy "[…] *whose influence (thermal mass) A-TAS allows the user to investigate*." (p.4); where 'investigating the influence' does not necessary imply any specific level of accuracy in simulation, it may refer to an overall temperature/energy behaviour specific to thermal mass.

It also appears TAS considers thermal mass as add-ons onto initially lightweight structures, in contrast with construction that have the slabs, structures and sometimes envelopes made with heavyweight materials: "[…] thermal mass is not neglected in cases where a significant amount is present in lightweight component of large areas." (p.9)

In the older version of their website (accessed February 2018), there is an example of a temperature simulation for the EDSL headquarters' building (built in 1994 in Garston) which had heavyweight elements integrated within the building for better overall temperature and energy performance. The simulated graph is reported to have a good fit with the actual temperature behaviour. Looking closely at the graphs in figure 3.3 the following can be noted:



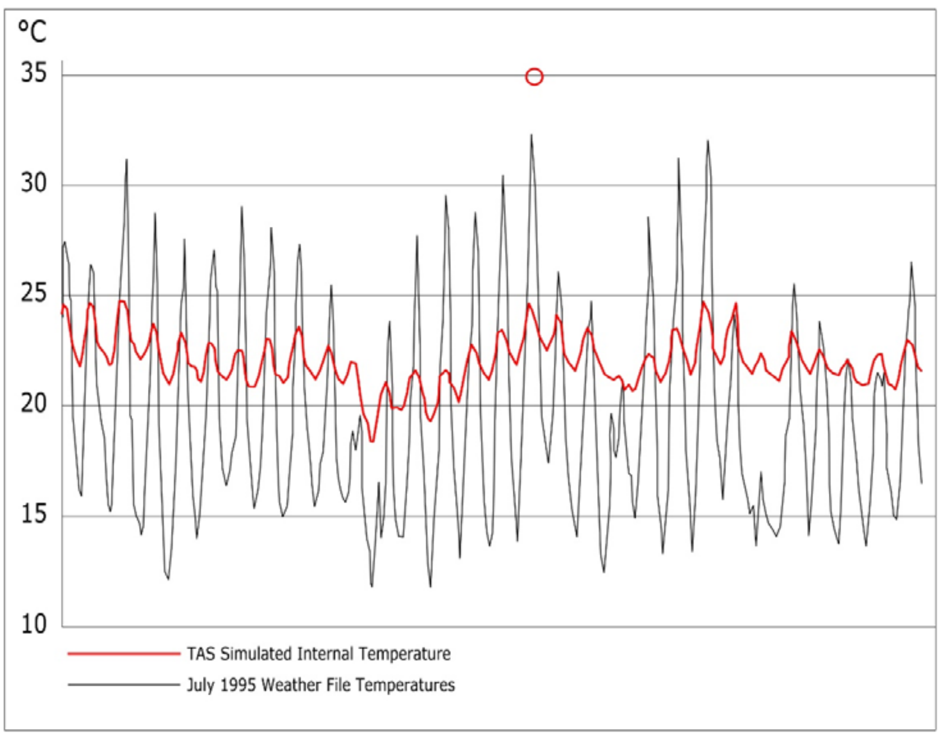


Figure 3.3 Temperature calibration of the Environmental Building headquarter of EDSL TAS based on actual recorded weather and internal temperature of July 1997 (upper) and simulated data with 1995 weather file (after: www.edsl.net, accessed February 2018)

1- The overall trend of the internal temperature in both recorded and simulated temperatures appear to be well matched as internal day temperatures are cooler than the outdoors and the night temperature are warmer than the outdoors.
2- The difference between the actual recorded internal temperature peeks and the external actual peeks is larger compared to the simulated ones with 4-5K for the first and 2-3K for the later.
3- Night-simulated temperatures appear to better fit the recorded ones, with what looks like the same difference between the minimal internal and the night coolest external temperatures.
4- The difference between the internal temperature maximum and minimum (diurnal range) is larger for the actual recorded temperature at 4-5K whereas the simulated difference stands at 2-3K.
5- Where there is a major change in the overall actual day to day temperature, the simulated version seems to be responding faster than the actual recorded. The actual temperatures are maintaining at least the minimal temperature similar to the previous night, but the day's peak is reduced.

Based on the above visual observations, EDSL TAS appears to be a valid thermal software which would simulate the features of heavyweight temperature performance with a reliable level of overall accuracy. Nevertheless, when daily temperature fluctuations or temperature differences between inside and outdoor are an issue, the results appear to be more indicative.

3.4 Calibration

Calibration consists of inputting all the data pertaining to the building's envelope, users' behaviour, equipment and lighting loads and schedules, along with the recorded weather data, into the thermal software. Data of cooling and heating equipment are entered as well. A 3D model of the building is produced, and the software generates via simulation monthly or hourly energy requirements. These simulated energy needs are compared to existing values through specific protocols. When simulated values do not fit the requirements, alterations are done on some of the initial data for another round of testing and the new values are compared again. This is repeated until a model and its corresponding values are acceptable. Three protocols are available from: ASHRAE Guidelines 14-2014; the International Performance Measurements and Verification Protocol (IPMVP); and the Federal Energy Management Program (FEMP). The main calibration of uncertainty measurement indices recommended in these references are: The Coefficient of Variation of the Root Mean Square Error (CVRMSE) and the Normalized Mean Bias Error (NMBE). Calibration should use at least one of these indices.

$$CVRMSE = \mathbf{100} \frac{\sqrt{\frac{\sum_1^n (\boldsymbol{Ts} - \boldsymbol{Tr})^2}{(\boldsymbol{n} - \boldsymbol{p})}}}{\boldsymbol{Tm}}$$

$$NMBE = 100 \frac{\sum_1^n (Ts - Tr)}{(n-p) \times Tm} m$$

Ts simulated temperature at time n

Tr recorded temperature at time n

Tm arithmetic mean of all recorded temperatures

n total number of individually recorded temperature

p number of parameters in the baseline (considered 1)

To have an acceptable calibrated model, the range of these indices for a model based on monthly figures is a maximum of 15% for the CVRMSE and 5% for the NMBE. For an hourly-based model the ranges increase to 30% and 10% respectively in both FEMP and ASHRAE protocols, whereas for IPMVP, the hourly value indices are lower at 20% for the CVRMSE and 5% for the NMBE. Alternatively, for both ASHRAE and IPVM, calibration verification may be through the coefficient of determination R^2.

Mean Bias Error (MBE) and the Goodness of Fit (GOF) are sometimes used in calibration research (Ruiz & Bandera 2017) but are not found in any of the above protocols. Table 3.2 summarizes all the available indices.

Finally, and most importantly, it should be noted that in all three references; ASHRAE, IPMVP and FEMP, there is no mention of any specific time frame and/or minimum number of simulated values for a valid model as long as the hourly or monthly protocol indices are used for validation.

Table 3.2 The available uncertainty measuring indices recommended or used, along with the acceptable range (if available) for monthly or hourly studies.

	ASHRAE		FEMP		IPMVO		Others
	Hourly	Monthly	**Hourly**	Monthly	**Hourly**	Monthly	
CVRMSE	**≤30**	≤15	**≤30**	≤15	**≤20**	n/a	
NMBE	**±10**	±5	**±10**	±5	**±5**	20	
R2	≥0.75		n/a		≥0.75		
GOF							yes
MBE							yes

Table 3.3 summarizes the different nomenclature of software runs, including the differences between each one. The simulation runs are generic runs that could be done without any reference to an existing case study. The calibrated process starts by inputting all the specifics, which eventually might be altered to reach a calibrated model. The post calibration runs use the already altered values of the calibrated model to carry on with further studies.

Table 3.3 Software run nomenclature and typical methodologies

Data		Simulation	Calibration First round	Calibrated Model Last Round	Post Calibration
Weather File		Default*/ Historical**	Historical	Historical	Historical/ Default
Envelope	Plan/ area/ orientation/ dimension/ windows	Generic/ Specific***	Specific	Specific	Specific
	U-values & physical properties	Generic/ Specific	Specific	Altered**** Specific	Further Upgrades on the Altered
Users details	Schedule	Operator's Choice can be based on Generic or Specific	Specific	Specific	Specific
	Numbers & Heat emissions		Specific	Altered Specific	Specific
Lighting details	Schedule		Specific	Specific	Specific
	Numbers & Heat emissions		Specific	Altered Specific	Specific
Equipment details	Schedule		Specific	Specific	Specific
	Numbers & Heat emissions		Specific	Altered Specific	Specific

*Default Weather file represents a typical year of the area under study. In contrast to
**historical file presenting the actual recorded data of the studied period in the specific area of study.
*** Specific stands for all data based on observation and believed to be the most accurate, based on the operator's judgment and expertise
****Altered are modified values beyond their specific, as observed values, specifically for the purpose of calibration

The following papers show the many validation indices used within various researches to prove the energy study under question is properly calibrated. The papers are grouped by similar indices, in chronological order. The purpose of this review is to show that even with the available calibration protocols and their recommended indices, there are many other alternatives used in energy-based research and are still accepted as valid.

The papers below use MBE and CVRMSE:

In the first paper based on the energy calibration of a HVAC system for a large building in Ireland, P. Raftery *et al.* (2011) recommended reducing both MBE and CVRME to 5% and 20% respectively instead of 10 and 30%. The reached values were -4.2% and 7.8%.

Pisello *et al.* (2012) completed three rounds of energy calibration for a multifunctional building to reduce the MBE from an initial value of 8 to 6 and finally reached 0.06 with the corresponding CVRMSE at 0.09. It is important to highlight that the percentage sign is missing from both values, along with the plus/minus sign for the MBE.

Tulsyan *et al.* (2012) simulated the energy performance of six different buildings in India, based on total yearly energy. They managed to get the Mean Bias Error (MBE) between 10% and 19% and the CVRMSE between 9% and 18%. Based on the values from table 3.2, the CVRMSE for annual and/or monthly values should be less than 15% and the NMBE less than 5%; in the case they are considered similar to the MBE, the range should also be considered similar. Nonetheless, all the MBE values of this study would be out of the acceptable range.

G. Mustafaraj *et al.* (2014) working on a heat pump for a heated building in Ireland included recorded weather data along with data based on measured temperature and occupant surveys. Although the authors complete two rounds of calibrations, the second round consists of inputting more fine-tuned data since they are deduced from actual measurements, specific schedules, and user patterns. The simulation and calibration included hourly values of heat pump electrical load. Both MBE and CVRME values are calculated and fit between -6.5% and 11.4% for the first round, and 12.3% and 33.5% for the second.

M. Royapoor and T. Roskilly (2015) in their well written and structured research investigate energy and temperature simulations where the recorded weather file of the studied year 2012 is integrated into the calibration process. They introduce more verification indices such as 'Mean Bias Error' (MBE) and 'Coefficient of Variation Root Mean Error' (CVRME) in order to simulate gas and electrical power usage and claim 'good values' of 0.9% and 9.9% respectively. For a heated building, they provide a temperature simulation graph that allegedly shows a good fit with the actual monitored recorded values. They plot the monthly means, minimums and maximums, compare them to the recorded ones, and show overall results of 0.7% and 1.9% using MBE and CVRME. They note that the accuracy is found to be within ±1.5°C difference in 99.5% of the recorded values. This is interesting to see, since this is the only identified research that has dealt with temperature calibration using monthly values. But without any previous references or protocols to compare to, the difference of 1.5K seems major when it comes to temperature changes. When it comes to UK winter, while comfort temperatures are at 19°C, the simulated values would fall between 17.5°C and 20.5°C which differs almost 8%. Their research recommends some practical amendments, following a previously published paper, to reduce the MBE and CVRME to 5% and 20% respectively instead of the 10% and 30% (Raftery, P. *et al.*, 2011).

The following papers are using percentage difference between various measured and simulated values to claim that they have reached a calibrated model.

B. Dong *et al.* (2014) refer to the fact that the calibration process has a long history: "*calibrated energy models have received more and more attention for better building operation in the last two decades.*" They used a manual energy calculation model to validate the energy performance of a large size army barrack based on monthly cooling and heating energy loads. Using the percentage difference between measured and calculated loads, they accepted the model to be calibrated at ±15%.

F. Stazi *et al.* (2015) worked in Mediterranean climate in central Italy where a single-family house of two floors with different construction technics (heavyweight ground floor, lighter weight upper floor) was studied. Calibration is done with surface temperature, weather parameters, and users' data during the observation period. The validation criteria used is the percentage differences of surface temperature between monitored and simulated that varied between 1.3% for internal surface and 2.7% for external.

M. Hurnik *et al.* (2018) studied energy calibrated models based on a house located in Poland. Calibration is done over 18 day's period, where all the energy and outdoor ambient air temperatures were recorded. Final calculated values are compared to the measured values with percentage varying between 0.1% and 3.1%. The research included four steps of energy upgrades, among them walls insulation and better performing windows. Performance indicators used yearly energy value reductions based on the initial base case.

M. Jradi *et al.* (2018) studied energy performance of 4 day-care centres in Aarhus, Denmark. The study started with a calibrated energy model based on monthly bills. The index used is just the percentage difference between the calculated energy values and the billed values, which should fall less than ± 20%. All calculations show that the actual difference ranges between 5% and 7%.

In this final set, further different indices are used.

J. Vesterberg *et al.* (2014) report that even though energy calibrations have been going on for a couple of decades, there is still no consensus for specific guidelines. They recommend spot measurements for different logged variables to ensure logged data accuracy and consequently achieve better model accuracy. In their research on energy needs for the heating of two family houses located in Sweden, they manually calculated the energy demand from first principles and achieved a good agreement with the recorded data using Goodness of Fit when regressed variables were integrated within the calculations.

P. De Wilde, (2014) reviews the performance gap between predicted energy usage and actual energy consumption. The research starts by a literature review and moves to a pilot project. According to the authors, the culprits to blame for the gap between the actual and predicted values vary from the construction gap, the impossibility of predicting users' behaviour, and the weather. The research looked at the recorded gas and electrical consumption during two years (2011-2012) and compared those to simulated data. Their research intention was not to complete actual calibration, rather to review the various reasons behind those gaps.

L. Harmer and G. Henze (2015) emphasize the importance of a calibrated energy model while acknowledging that it is not an easy task. They apply three verification protocols: The Normalized Mean Bias Error (NMBE), the Coefficient of Variation Standard Deviation (CVSTD), and the Goodness of Fit. Although they refer to ASHRAE guidelines 14, neither CVSTD nor Goodness of Fit are mentioned therein. Nevertheless, they apply the same acceptance range used for CVRMSE. Their initial values for both NMBE and CVSTD are 9% and 33%, yet they later calculate the

Goodness of Fit for each of these errors with what they claim as "weighted factors" to have the final Goodness of Fit CVSTD at 28% and Goodness of Fit NMBE at 1.4%. The plus or minus signage that should be available for the NMBE are not shown.

G. Allesina *et al.* (2018) proposes a new energy calibration methodology known as the "energy signature", which they claim is based on the correlation between outdoor factors and consumed energy using high-performance graphical software that would test multiple variables to reduce the uncertainties to the minimum. Both monthly gas heating consumption and electricity are studied. Furthermore, the paper uses another new error index; the Safety Aimed Error (SAE), along with the Root Mean Square Error (RMSE) that reached around 1%. The simulations run by the software JEPLus are for a large-scale superstore in northern Italy.

The final paper by Ruiz & Bandera (2017) is a concise overview on calibration, with a thorough review of the main three available protocols ASHRAE, FEMP and IPVMP, alongside a detailed explanation of the different measuring uncertainty indices. Based on an exhaustive list of papers, the authors show the most common mistakes that occur in calibrated based research. The three main indices are the Normalized Mean Bias Error (NMBE), the Coefficient of Variation of the Root Mean Square Error (CVRMSE) and the Coefficient of Determination R^2, in addition to these they also explain the Mean Bias Error (MBE) since it is related to the other indices. One of their recommendations is to use both the NMBE and CVRMSE together.

Table 3.4 summarizes all the details of the reviewed paper with the wide variety of methods with a focus on energy studies.

Table 3.4 Overall summary of papers that have dealt with calibration.

Authors	Year	Location	Building Type/size	Specific Method	Index Factor Used	Values (pre*) achieved
Vesterberg, J. *et al.*	2014	Sweden	2x family house 862sqm & 925 sqm	hourly energy supply	Coefficient of determination R2	>0.96
Dong, B. *et al.*	2014	Illinoi, USA	barracks 149875sqft (13923 sqm)	Monthly cooling/heating Energy loads	Percentage difference between measured and simulated heating/cooling loads	±15%
De Wilde, P.	2014	Plymouth Uni, UK	9 floors academics building	NOT about calibration Just mention the gap between simulated and measured, based on two years of gas and electrical energy.		
Harmer, L. and Henze, G.	2015	Uni of Colorado, USA	180000sqm, 2006 multifunctional	Energy model	Goodness of Fit, CVSTD & NMBE	CVSTD 33%; NMBE 9%
Royapoor, M. and Roskilly, T.	2015	Newcastle Uni- UK	8365sqm 500 staff concrete slabs+ glazing	Gas and electric power & temperature simulation	MBE and CVRMSE	Yearly Energy MBE 0.9% CVRMSE 9.9% Monthly Temperature MBE 0.7% CVRMSE 1.9%
Raftery, P. *et al.*	2011	Ireland	30000sqm 4 floors building	HVAC system energy	MBE & CVRMSE	MBE -4.2% CVRMSE 7.8% (monthly figures)
Mustafaraj, G. *et al.*	2014	Cork, Ireland	4500sqm	hourly heat pump electrical consumption	MBE & CVRMSE	MBE -6.5-11.4% CVRMSE 12.3-33.5%
Pisello *et al.*	2012	NY, USA	73019sqm	overall Energy consumption	MBE & CVRMSE	MBE 8; 6 and 0.06 CVRMSE 0.09
Tulsyan *et al.*	2012	Jaipur India	6 large size buildings	Energy need, through electrical power	MBE & CVRMSE	MBE 10.6%-19.16% CVRMSE 9.7-17.94
Stazi, F. *et al.*	2015	Central Italian	1 family house, two floors	surface temperature & hours of overheating	% percentage difference of internal and outer surface temperature	between 1.3% and 2.7%

Hurnik, M. *et al.*	2018	Poland	1 family house, two floors	total building energy system		% percentage difference of 8 days averaged energy consumption	between 0.1% and 3.1%
Allesina, G. *et al.*	2018	Northern Italy	superstore	monthly heating gas, and electrical consumption	Energy signature	Safety aimed error (SAE) and RMSE root mean square error	1.206×10^4 RMSE 0.011 SAE
Jradi, M. *et al.*	2018	Denmark	4, day care centres	Monthly electrical and heating loads		percentage difference between bills and calibration values,	between 5% and 7%
Ruiz, G.R. & Bandera, C.F.	2017			Overall Calibration Review			

* values between () are pre-calibrated simulation runs

3.4.1 Overview

The goal of the different available calibration protocols is to assess the energy efficiency of the cooling and/or heating systems within a building to be built, or one that has gone through retrofitting for energy upgrades. Although calibration protocols also deal with water and costs, the reviewed research is concerned with energy. While assessing cooling and heating energy loads of a given construction, one assumes by default that it is not free-running and relies on specialized energy consuming equipment such as boilers for heating, and/or compressors for cooling. Furthermore, it is contained in a controlled environment where the interaction of the building's internal spaces and the outdoor is considerably reduced. The latter is achieved when insulation or low U-value materials are added to the building's envelope. The problem emerges when the aim of the current study is solely based on temperature performance, with the goal of finding a free-running construction solution that does not require any cooling equipment for summer comfort. In such a case, the internal environment interacts with the external and becomes considerably influenced by it, more specifically by the hourly temperature fluctuates and the different temperature trends during daytime and night. All these factors are not considered in energy-based protocols.

The main concerns of this current study are that regardless of the numerous methods followed to reach a good fit or a calibrated model:

(1) Calibration studies are more often done for overall energy studies, and in particular for cooling and heating loads, in contrast to specific temperature-based studies, which are still done under cooling or heating modes.
(2) Specific guidelines and protocols are available for energy studies which include CVRMSE and NMBE as variation indices; highly recommended and more often used.
(3) Calibration methodologies vary between simple and complex, yet they all agree that some inputted data need to be modified to reach good calibration.

3.5 Theoretical Studies Based on Wall Performance.

The following papers have studied the energy or temperature performance of different walls and insulation configurations using software simulations. The review shows that the final outcome of the best wall insulation location varies from one paper to another.

E. Kossecka and J. Kosny, (2002) investigated the best location for insulation within a massive wall. The study is based on both mathematical formula and the DOE-2.1E thermal software. Simulations are done for six different U.S. cities/climates for a one floor ranch plan. Both calculations and software-based methods reached the same conclusion that the best energy conservation for continuously used buildings is placing the massive walls in the interior in order to keep the insulation layer at the exterior. The research observed that the opposite case of having the insulation on the interior will fit better in a non-continuously used building. Looking at the simulated ranch mode, the one floor building has a large pitched attic with no thermo-physical description except for an overall roof value insulation; no details on usage patterns or internal gains are mentioned.

In another paper based on temperature simulation within the Italian city of Florence using ANSYS software, C. Balocco *et al.* (2008) record surface temperatures of an externally insulated model. It is not clear if the 3-D model is an actual three-dimensional room, or only a wall. Internal gains are not mentioned. While the study looked at heat flux, the conclusion states that the external insulation will reduce the cooling loads for average (north) latitudes between 40º-45º, described as *"moderately hot climate with 1821 heating degree days"* and with significant solar gains. There is no mention of any performance indicator regarding the percentage of reduced energy or the temperature reduction.

Based on an expanded literature review by O.T. Masoso and L.J. Grobler (2008), the effect of excessive wall insulation is seldom taken into consideration in temperature and energy research. The authors use what they describe as a well calibrated temperature model. This model includes a wall with middle-insulation. The simulation shows that at a certain point where cooling temperature is fixed, and internal gains are increasing, the energy for cooling will increase.

In another paper by S. Al-Sanea and M.F. Zedan (2011), a mathematical formula was used to calculate the best location and thickness of insulation in Riyadh, Saudi Arabia. Result shows that a double cavity hollow block (2 x 100mm) with three layers of same insulation thickness (3 x 26mm) placed on the outside, inside and in the middle, will considerably reduce energy cooling loads. Within the same city and two of the previous authors: S. Al-Sanea *et al.* (2012) are looking for the best configuration that combines thermal mass and insulation to reduce cooling loads. Based on a mathematical model, they found that insulation positioned nearer to the outer surface, combined with a massive wall, will require minimal cooling energy, especially if the building is continuously cooled.

Within the same insulation layering studies, but this time in a theoretical frame work, D.E.M. Bond et al. (2013) reconfirmed the previous statement that three layers of insulation equally distributed within a thermal mass are the best solution for minimal cooling energy loads.

Set in the Italian weather, F. Stazi *et al.* (2013), start by defining three types of walls: capacity walls (massive one-layer wall); stratification walls (cavity walls); and resistance walls (double cavity with outer insulation). Later, three dwellings in different areas are chosen, each as one of the described types. The cases are monitored at the same time during both winter and summer. The paper does not provide any information on how the calibration is done, except that it took into account the actual recorded climate file, the different users and equipment schedules. Parametric runs that include adding insulation are carried on. Results show that for summer time, stratified or cavity walls tend to have the highest internal temperatures compared to both massive and resistance walls. Whereas, during winter time, resistance walls tend to have higher internal temperature compared to the other two walls. All internal temperatures are below winter comfort within the studied area. The study concludes that adding insulation on a capacity or mass wall at any location (inside or outside) is not good for summer times. Externally added insulations have some positive impact for winters only. As for the stratified or layered wall, the ideal solution is a combination of a ventilated and externally insulated façade for best performance for both winter and summer seasons.

F. Stazi *et al*. (2015) studied a single-family house of two floors with different construction technics (heavyweight ground floor, lighter weight upper floor) in the Mediterranean climate in central Italy. The study consists of five different new walls with different layout configurations to enhance temperature and energy performance. Hours of overheating, cooling/heating loads and surface temperatures are simulated with the EnergyPlus software during winter and summer. Software retrofitting shows that summer cooling loads are the least for the as built, whereas the combined minimal cooling and heating is for a vented wall. The latter consists of combination of a massive internal layer with a well-ventilated gap and a high insulated external layer. The gap can be closed during winter time and opened during summer.

Located within the sub-tropical and Mediterranean climate of Valencia, Spain; I. Guillén *et al.* (2014) show strong correlation between observed and calculated temperatures. This study is dealing with different types of insulated and ventilated facades during a 24 hours period while the air conditioning system is continuously running. With little solar radiation, the internal temperature followed the variation of the external air temperature. However, when solar radiations became more intense, a large decrease between inside and outside temperature (inside being cooler) was recorded. The study explains that this temperature difference is due to the ventilated multilayer façade where there is an increase of temperature within those layers. Thus, the study concludes that a ventilated layered facade within warm climate would imply consistent reduction of energy without the need to increase the thermal wall mass.

3.5.1 Overview

Within research focusing on walls, conclusions vary between externally located insulation, multiple layers of insulation, and ventilated façade for less cooling and heating energy loads (Table 3.5). It is worthy to note that none of the papers recommend internally placed insulation.

Table 3.5 Various papers that have dealt based on software studies, with walls, and more specifically location of insulation for reduced cooling energy loads.

Authors	Year	Location	Notes	Conclusion/Best Location of Insulation
Kossecka, E. and Kosny, J.	2002	6 US cities climates		External for continuous usage Internal for non-continuous usage
Balocco, C. *et al.*	2008	Florence; Italy		External
Masoso, O.T. and Grobler, L.J.	2008		Mentions Impact of Over Insulating	Central
Al-Sanea, S. and Zedan, M.F.	2011	Riyadh, KSA		3 Layers
Al-Sanea, S. *et al.*	2012	Riyadh, KSA		External (for continuous usage)
Bond, D.E.M. *et al.*	2013			3 Layers
Stazi, F. *et al.*	2013	Italy		Ventilated cavity wall with external insulation Massive wall external or internal insulation is not advised
Guillen, I. *et al.*	2014	Valencia		Multi-layered ventilated, low mass façade
Stazi, F. *et al.*	2015	Italy		Ventilated cavity wall with external insulation

3.6 Experimental Approach Based on Roofs and Walls

The following researches are model-based studies; sizes vary from a shoe box lab setting to a large habitable module. The review shows the various purposes and methodology of observations.

In a chronological viewpoint, the starting point of the literature review starts with D.M. Ogoli (2002) who worked on four full scale rooms built in Nairobi, Kenya; two of which have stone walls and the other two timber walls. The dimensions are 2000 x 2000 x 2000 mm in addition to a 1997mm pitched roof. The study shows that internal temperature peaks in closed thermal mass rooms are considerably lower than in light-mass rooms. The research is interested in finding a regression formula for predicting internal maxima for light and high mass rooms.

The next paper by B.M. Suman and V.V. Verma (2003) located in Roorkee, India, deals with two full sized rooms;2700 x 2700 x 2700mm and 5800 x 3660 x 3250mm with doors and openings. These rooms have different types of roofing: Asbestos cement, galvanized iron and 100mm reinforced concrete. The observation was in two phases (not at the same time) with the roofs having either a washed thermal coating applied to their exposed surface (treated) or not. The conclusion shows that internal air temperatures are always lower when the roofs are treated. Nonetheless, without simultaneous observation, no accurate comparison can be made for the different types of materials.

In the next research located in the Guadeloupian tropics, T. Soubdhan (2005) works with four small insulated test cells of 1220 x 1220 x 500mm where roofs are made of corrugated metallic sheet with different types of insulation as well as ventilated or non-ventilated cavities. The concise conclusion is that a ventilated air gap has a major influence on reducing heat transfer. Also, in non-ventilated air gaps, polystyrene insulation performs better than fibre glass and radiant barriers in reducing heat transfer.

A full-scale model in Greece (Dimoudi, A., 2006) is investigated for roof performance with one internal common space and one large pitched roof divided into different zones with different types of elements. Each roof part has a dimension of 2400 x 2700 mm with an internal height of 3600 mm. The internal temperature is maintained the same, while sensors record the surface temperature of the roof's different elements. The typical roof is a concrete slab of 120mm with 50mm insulation and a 250mm precast slab. The experimental versions had an air gap addition of 60mm and 80mm. Results show that the ventilated roof performed better than the non-ventilated one. The radiant barrier significantly enhanced daytime performance yet not as efficiently for the night time. Nevertheless, its installation is recommended when considering a full day. Regarding the air gaps, the smaller (60mm) performed better only without the radiant barrier. The different experiments were again not completed simultaneously, and the authors pointed out that "*direct comparison between the different layouts could not be made and thus, only qualitative results can be derived*".

In another research (Hien, W.N. (2007), measurements are taken on an existing roof parking in Singapore before and after a green roof is added. The upshot is that up to 18K is reduced in surface temperature on the planted part. The study focuses on what is happening above and, on the roof, rather than below it. Measurements are recorded on typical days, within a long drought period, and following two days of rain. After precipitation, the surface temperature of the substrate turned out to be warmer than the concrete surface. A plausible explanation could be taken from B. Givoni (2007) in his unpublished study where permanently shaded soil has a higher temperature than the surrounding exposed surface due to rain falling on the exposed hot surface and flowing into the shaded soil and heating it. The paper seems to have missed many opportunities obvious when looking at the picture of the said roof: it is clear that the green areas did not cover the entire roof surface and hence simultaneous measurements could have been taken at different locations with different finishes in order to reduce uncertainties.

In his work on handling cooled soil strategies, B. Givoni (2007), describes experiments dealing with two sets of full scale rooms: the first located in Israel, Rosenfield (2006) consisted of two test rooms 2500mm high, four square meters of roof, and a 100mm parapet around it. A layer of soil is added, topped with another layer of gravel. At a later stage, the entire roof is shaded: the recorded data show that internal temperatures performed best with when the wet soil was protected by the also shaded gravel layer.

Another experiment in Saudi Arabia (Al Hemiddi, 1995), described in Givoni's same paper (Givoni, B., 2007) experiments with a full size four single-story rooms with an un-insulated concrete roof and different passive cooling devices, of which the best performing internal temperature is with a cooled soil roof.

In a lab study, J.L. Alvarado and E. Martinez (2008) experiment with an extremely reduced size of 286 x 381 x 102mm, made out of casted cement and solar radiation (simulated by a fixed 500W lamp). Corrugated aluminium foil is used with different orientations as well as with different thickness insulation beneath it. Total testing time lasted seven hours. It was concluded that up to 70% of the temperature load can be reduced by an adequately designed and insulated roofing system; still the authors added that further real sized studies should confirm the conclusions.

Another non-simultaneous and reduced scale study (Yu, B.F., 2008) was conducted in Xian Jiaotong, inland China, with a three-floor built up model, of 1200 x 1200 x 1800 mm, with 115mm walls, slabs and roofs (although said to be 100mm; yet drawn as 50mm). Walls are covered by a 25mm cement plaster. It is not clear whether the monitoring and data are averages calculated for an entire season, still the graphs show data for less than a day. In the test, different materials are used on the walls, but the temperature difference is the only key criteria for the model performance. It appears from the paper that the measured internal temperature is for the second or intermediate floor. With different types of external coating used in both summer and winter, the results show that the higher the albedo (explained as closer to white colour), the larger the temperature difference during both summer and winter, and reciprocally, the lower the albedo (explained as closer to darker colour), the smaller the temperature difference during both seasons.

The next experiment located in Sri Lanka (Halwatura, R.U. and Jayasinghe, M., 2008) is staged in two phases; starting with four small scale reinforced concrete roof cells and moving to a larger existing but un-occupied room. The research does not describe in detail the physical characteristics of these cells in terms of overall dimensions or types of supporting walls, it does however describe the thicknesses of each of the different layers that make the slabs. Furthermore, from the picture that is shown within the article, the following issues might have had some unexpected and confounding impacts on the study: the cells seem to be quite closely located to one another, hence some concerns might arise due to overshadowing; a nearby large container might add further shadowing to all or to some of the cells. When it comes to the larger full-scale room, insulation materials are added above the existing roof and protected with a layer of screed. Soffit temperature monitoring prior and later to the addition of the insulation is the key for this comparative study. Internal gains from equipment, users, as well as direct solar gains are not accounted for. From the picture, it is clear that on one of the façade, a large glass door is fixed above appear to be three narrow horizontal ventilation strips. On another façade, another opaque door exists (not clear if timber or steel door). The conclusion states that well protected insulation over concrete slab provides an acceptable indoor temperature.

M. D'orazio *et al*. (2010) mention the "box effect"; explained as the effect of overinsulation leading to overheating. Located in Italy, the experiment consists of four types of insulation roofs covering a single internal space. Both the heat flux and the surface temperature are monitored to conclude that insulation thickness reduces the effect of traditional passive cooling.

K.S. Ong's (2011) simple and straightforward on-field experiment in Malaysia consists of six inclined over an attic small-scale models (2000 x 1000 mm, 15º inclined and 300mm above ground). Although the test lasted several weeks, only less than 24 hours of data are reported.

Roof temperatures as well as attic ambient temperatures are recorded. The best results for both surface and attic temperatures are with a ventilated attic below a solar collector. Additionally, insulation directly below the inclined tiles performed better than insulation over the attic floor.

Nearby Jordan, four test cell of 1000 x 600 x 1000 mm steel box with insulated edges are studied (Hamdan, M.A., *et al.*, 2012). The cover (considered as a roof) is made out of different local roofing materials: (1) bare reinforced concrete (reference/control cell); (2) white washed cement cover; (3) glass embedded tiles; and (4) layer of clay over the entire reinforced concrete. The clay covered slab performed the best, and a further test showed that 50mm of clay would be the best thickness. Some of the issues within this test include: actual observation seems to have been for only four hours; test cells are too closely located raising concerns on overshading.

In the next paper, P. Chaiwiwatworakul *et al.* (2013) check the relevancy as well as the best location for wall insulation in the hot and humid climate of Thailand. The research combines an actual model of 3000 x 3000 x 2650 meters with a south window of 60% of the total wall area. Walls are 80mm brick cement plastered on both sides. On the south wall, below the window, one part of the wall is insulated from the outside; another part from the inside and the third part has no insulation. The conclusion states that for prolonged night usage with no windows, internal insulation will enhance temperature performance, while in the same scenario, an externally placed insulation will not be cost effective. While with windows; only the internally placed insulation will enhance the cooling load whereas the externally placed insulation will tend to increase it. It should be noted here that the study is based on the surface temperature of the different parts of the wall, and direct solar gains can enter the room through the windows.

This review by Al-Obaidi *et al*. (2014) is an observation of a single full sized actual model of some 4000 x 5000 x 3000mm pitched roof building in Malaysia, monitored three times, three days each. Each time an additional aspect is altered or added. Since the monitoring is not simultaneous, the study is based on the temperature difference between outdoors and indoors. The conclusion is that a ventilated non-insulated attic performs best in comparison to an attic or without one.

Located in Shiraz, Iran, the paper (Sabzi, D., 2015) does not clarify whether the test cells were built or not and their number. No photos are available of any of the test cells. Nevertheless, the dimensions are defined at 800x800x1000mm to study four different types of roof cooling techniques. A mathematical simulation is validated against experimental data with an error less than 18% (type of error is not specified). The employed performance indicators are temperature increases between the different test cells as well as percentage cooling load increase. Results show that the addition of a water pond will have the best cooling performance, whereas a water jacket, (sealed water pond) has the least.

To study temperature effect of roof ponds in the subtropical climates of Brazil, E. Krüger (2016) made two considerably reduced scale models of 305 x 680 x 680mm and completed three rounds of testing. The paper does mention the limitations of reduced scaling but adds that observation came in agreement with the available literature. The performance indicators used were cooling degree days, temperatures, and cooling loads; they showed that the indirect evaporative roof cooling technique provides a good overall internal cooling.

The work completed by A. Albatayneh (2016) is the most relevant for the current research. Four 6000 x 6000 x 2400mm test cells are built in the moderate climate of New South Wales, Australia, with four different wall configurations and three different roofing systems which already compromise the comparative results. The rooms are monitored for 12 months in the same conditions: continuously closed with no inside activity no users, lighting and equipment, only the sensors. The performance indicator used is percentage of hours of comfort. The four walls tested are (1) insulated (not clarified, but most likely within the cavity) cavity walls made out of two 110mm bricks and 50mm air gap;(2) internally insulated reverse brick veneer, fibro-cement sheets, insulation,, an air gap, and a 110mm brick wall; (3) insulated brick veneer or internal timber frame wrapped with reflective foil, insulation, an air gap, and a 110mm brick wall; (4) cavity brick module or just a double 110mm brick wall with a 50mm air gap. The same flat ceiling is fixed in all four rooms, but above that, three different roofs are installed with either clay tiles, concrete tiles, or coated corrugated sheets. Results from an entire year of observation show that the insulated cavity walls perform better in terms of maximum hours of comfort, and the room with the least hours of comfort is the cavity brick module. However, while looking at the monthly performance graphs, the cavity brick did perform better than the insulated cavity during the months of March, April, November and December. The results are compared to Accurae sustainability rating tools and are found to be in accordance.

D.G. Leo Samuel (2017) studied eight different building structures with no common plans or dimensions. Each of these structures is composed of different wall and roof configurations and different passive design features. They are monitored in a three-phase process for 3 days in Hyderabad, India, within the transitional season after summer and before the monsoon. The performance criterion is temperature comfort level, and study concludes that massive walls and roofs reduce the internal air temperature by 0.9K compared to lightweight structures.

A recent study on roof cooling techniques (Kachkouch, S., 2018) located in Marrakech, Morocco, experiments with four fully-sealed 1000 x 1000 x 1500mm test cells. Only one test cell is used as a reference. The performance indicators are temperature graphs and differences. Results show that white roofs reduced ceiling surface temperature by up to 13K, unshaded insulated roofs by 9.9K, while shaded roof by only 8.9K.

3.6.1 Overview

Research based on actual buildings or test cells show a wide range of used scales, varying from as small as 300mm shoe box dimensions to a full scale of up to 6000m width and 2500m internal height. The purpose of these studies varies considerably as well; ranging from heat flux transfer analysis, impact on energy load, to temperature outputs. Table 3.6 shows the simplified details of these studies.

Among those studies, only few are completed with parallel comparison of the different models. They are commonly based on the temperature difference between inside and outside for one specific model and period, consequently altered and monitored for another period. Although solar radiation and wind have major implications on the outcome, they are not taken into account.

Table 3.6 Overview of papers of actual models of various sizes with emphasis on walls, roofs, or both.

Author	Year	Location	Size (mm)	Notes	Conclusion
Ogoli, D.M.	2002	Nairobi, Kenya	2000x2000x2000mm plus 1997mm pitched roof		Internal temperature peaks in closed thermal mass rooms are considerably lower than in the light-mass rooms
Suman, B.M. and Verma, V.V.	2003	Roorkee, India	2700x2700x2700 & 5800x3660x3250	Asbestos Cement; Galvanized iron; 10cm RC	Washed thermal cooling enhances internal cooling
Soubdhan, T. *et al.*	2005	Guadeloupe, Tropics	1220x1220x500	Corrugated metal roof; ventilated; insulated	Ventilated air gaps have a major positive impact
Dimoudi, A. *et al.*	2006	Greece	2400x2700x3600	3 types of roof for one internal space	Ventilated roof with no more than 60mm performed best without radiant barrier
Hien, W.N. *et al.*	2007	Singapore	Planted roof top parking		Up to 18K reduction in surface temperature with green roofs
Givoni, B.	2007	Israel KSA	4sqm x 2500 four 4 full size rooms	Cool Soil	Roofs covered with wet soil, gravel and shaded provide best protection
Alvarado, J.L. and Martinez, E.	2008	Lab	300x400x100		Insulation could reduce 0% of cooling load
Yu, B.F. *et al.*	2008	Zian Jiaotong, China	1200x1200x1800 3 Levels		Reflective white coating on walls and roofs have a positive impact
Halwatura, R.U. and Jayasinghe, M.	2008	Sri Lanka	4 RC roofs cells + large room		Well protected insulation over concrete slab provides an acceptable indoor temperature
D'orazio, M. *et al.*	2010	Italy	insulated roofs	Box effect & Thermal Decoupling	Passive cooling application loses effect when using insulation.
Ong, K.S.	2011	Malaysia	2000x1000x300, inclined 15° roof		Inclined roof with a ventilated attic insulated from below performs best
Hamdan, M.A. *et al.*	2012	Jordan	1000x600x1000	x 4 RC roof Cells	Clay covered RC slab performs best
Al-Obaidi, K. *et al.*	2014	Malaysia	4000x5000x3000 pitched roof	non-simultaneous observation	Ventilated, non-insulated, attic performs best
Sabzi, D.	2015	Shiraz, Iran	800x800x1000	roof cooling technics	Water pond (open) is best, while water jacket (sealed) is worst for providing coolness
Kruger, E.	2016	Brazil	305x680x680	Roof ponds for indirect evaporative cooling	Proof of good cooling method
Albatayneh, A.	2016	New South Wales, Australia	four 6000x6000x2400	hour of comfort over the entire year	Best performing (descending order): (1) insulated cavity walls (2) internal insulated reverse brick veneer (3) insulated brick veneer (4) cavity brick module
Leo Samuel, D.G.	2018	Hyderabad	eight random structures with passive cooling strategies		Massive walls and roof reduce the internal air temperature by 0.9K compared to lightweight structures
Kachkouck, S.	2018	Morocco	1000x1000x1500	surface temperature reduction between outer and inner roof	Reduction of: 13K from white paint 9.9K insulated roof 8.9K shaded roof

3.7 Thermal Mass Performance Studies

Moving now to specific papers that deal with heavyweight construction.

P.A. Fokaides *et al.* (2017) present an interesting paper of a neighbouring country, Cyprus, with similar climate and construction techniques to Lebanon. The group investigated energy improvement of a social housing construction by implementing the European directive for improved temperature performance. The technique consisted of lowering U-values (adding insulation) over three distinct periods. The paper introduced a new parameter for energy other than the commonly used kWh/m^2; the kWh/m^2 per capita and per hour, hence combining both number of users and length of time used. The study showed that with this factor, the oldest construction with the highest U-values consume the most energy for cooling, while the newest with the most insulation and lowest U-values have the least cooling loads. One issue that is not clear in the paper is how the U-value was reduced; they have only mentioned that it can be achieved by a layer of insulation (without specifying its location within the wall) or with a specific 300mm brick element.

Similar to the case of Cyprus, A.G. Gaglia *et al*. (2017) review the effect of the same European directive for improved temperature studies in Greece. Two buildings, an older built with less/no insulation and a newly built with high insulation/low U-value are software simulated for energy loads. The four distinct climatic zones of Greece are checked, and results show that within the hottest climatic zone, the lower U-values with 50 to 70mm insulation reduce the heating load, but the cooling load, which is initially low, has actually increased.

Still in Greece, D. Anastaselos *et al.* (2017) simulate more than 20 different construction layouts in the four different climatic zones of Greece. Each of these layouts harbours different types and location of insulation within the walls. The criteria of comparison are not only the expected cooling and heating energy, but also, economy, effect on environment (pollutant), and attained comfort level. When looking at zone A (the hottest and most similar to Lebanon's coastal climate), the energy outcome for both cooling and heating loads barely varies across the variables proposed for the construction layout. Also noted, cooling loads are almost double the heating loads.

A study (Reilly, A. and Kinnane, O., 2017) states that there are a limited number of research that focus on exact performance and properties of thermal mass. Otherwise, researchers deal exclusively with thermal resistance and conductivity. Furthermore, even codes and general guidance references discuss thermal mass in a general manner grading overall temperature performance as good or bad without getting into specifics. For that, the paper considers Madrid with its prominent day and night temperature difference for a case study on transient heat flow within one wall. The findings coincide with the available literature, but there were no comparative elements.

A thorough review (Verbeke, S. and Audenaert, A., 2018) on thermal mass properties and construction states that relying solely on the U-value is not enough to describe the temperature performance of heavyweight elements. It also states that the layering of material within the envelope is important. The paper adds that there are limited researches that deal with actual studies, instead they rely on software. Based on the findings of the study, the effects of shading and ventilation are important in such a construction. Finally, the paper concludes that available researches usually focus on the effect of energy from thermal mass buildings with no reference to the overall life cycle energy of these materials. Although the latter is considerable according to the paper when compared to other materials. The paper carries on saying that with modest energy savings from heavyweight construction, focus should be made for overall life cycle.

3.7.1 Local Example

Among the few published studies on local building temperature performance (other than the researcher's previous publications) is the recently renovated building advertised as the first BREEAM excellency award winner and recipient of the Lebanese Architects Award (LAA) for best green building named casa Batroun. In the PLEA 2014 conference, Aldabra (2014) uses the peak temperature comparison between the outdoors and the internals to assess which of the night and day time ventilation is performing better in terms of coolness.

The research shows that for an outdoor peak temperature of 35ºC, internal peaks with night time ventilation vary between 26 and 29ºC in the different monitored floors and rooms. On the other hand, with day time ventilation, a 36ºC peak in the outdoors results in an internal temperature of 29ºC. These observations are based on 8 days of monitoring: the building is shaded, and venetians blinds are placed on some of the windows (not specified when open or closed); occupants are in the house only during the night. The three upper floor rooms, made of timber, register a sudden drop one hour after the night time ventilation starts. Whereas the lower floor masonry constructed rooms do not show any sudden drops. The outdoor temperature disclosed to be within the mid 30ºC for, and for eight consecutive days in the first half of the month of September is not convincing, specially when no details are provided regarding methodology, sources, and year.

The paper uses kelvin hour and kelvin hours reduction as performance indicators to show which of the day or night time ventilation performs better. It is not clear if the values are based on one-day observation or an extended ventilation period. Summation of the data at the half hours are also not clear.

Referring to another presentation by the architect (Nasrallah, 2014), the U-values of the walls and roofs are said to be between 0.33 and 0.42 W/m^2.Kfor the walls, and 0.22 W/m^2.K for the roofs. From the pictures, the insulation is placed on the inner part of the walls and roofs. Thus, in opposition to all available previous studies, the study showed good results with internal peaks considerably below day's peak. According to the above remarks and unclarities, the study appears to be unreliable.

3.7.2 Un-insulated Construction

Within the extensive focus of research on insulation, it is worth noting one researcher's controversial view point against insulation. Kiel Moe's Insulating Modernism (2014) strongly criticizes and takes a stand against buildings' insulation practices to promote the usage of thermal or heavyweight construction. With all his rigorous research on the historical, qualitative and numerical description of insulation, his conclusion regarding heavyweight construction remained descriptive, subjective, without any qualitative analysis. His main argument is that insulation was imposed on architects from the HVAC trades as an idealized solution, not open for debates or revisions. Architects were discouraged of experimenting with different materials and construction to reach constructions with internal comfort based solely on material performance. In another book, Thermally Active Surface in Architecture (Moe, 2010), he proposed circulating cool water in thin pipes along the heavyweight surface as a practical way to flush away the night excess heat.

3.8 Comfort and Performance Indicators

Before diving into performance indicator, a short remark on temperature comfort is needed to show the various approaches, as well as the changeable values, per month or season. Different comfort approaches, formulae and standards are available: Szokolay (2004) presents a few of them ranging from the 1970's (Humphreys, 1978; Auliciems, 1981; Griffiths, 1990; Nicol & Roaf, 1996) to end up with deDear *et al.* (1997). They all take into account that the comfort temperature (Tn) is a direct factor (α) of the monthly mean temperature (Tm) added to a constant (C):

$$\mathbf{T}_n = C + \alpha \mathbf{T}_m$$

Different values were proposed in each of the different studies. This is further elaborated by deDear & Brager (1998a) with an exhaustive literature review of all preceding works related to comfort. In one study (McCartney & Nicol, 2002) completed in five European countries, results showed that no single general formula could be applied in different countries, especially when those countries are lying north or south of Europe. On the other hand, deDear & Brager (1998b; 2000) showed that the range of comfort in a naturally ventilated space would be larger than in a space relying on mechanical cooling; the reason being that higher performance rating is expected from a mechanically cooled building versus a naturally ventilated one. Staying within similar comfort views (ASHRAE 55-2004) and as explained by Olesen & Brager (2004), although no similar formulae are given for the comfort temperature, ready-made graphs with comfort zones ranging from 80 to 90% acceptability are shown and explained, in relation to the monthly mean temperatures.

The EN-15251 European Standard (2006) and Olesen (2007) continue with the above similar equations using slightly modified values for free-running buildings. Unique values of 25.5, 26 and 27°C are given for mechanically cooled buildings with an expected acceptability of 90, 80 and 65% respectively. It's a rather unique yet confusing contribution when it comes to its logistics or applicability; especially with the fact that comfort temperature is in direct relation with the preceding day's mean temperatures, and no longer with the month's. Below are the formula of (1) deDear and (2) EN-15251 for monthly comfort; they show the same overall approach, but with different variables both at ±2 °C for 90% acceptance.

$$\mathbf{T}_n \pm 2^{o}C;\ \mathbf{T}_n = 17.8 + 0.31\mathbf{T}_m \qquad \mathbf{(1)}$$

$$\mathbf{T}_n \pm 2^{o}C;\ \mathbf{T}_n = 18.8 + 0.33\mathbf{T}_m \qquad \mathbf{(2)}$$

$\mathbf{T}_m$ is the mean monthly temperature

$\mathbf{T}_n$ is the comfort or neutral temperature

Previous sections and table 3.2 have reviewed the different performance indicators used within some of this research. This section discusses the degree hours (Dh) and the overheating hours above a benchmark temperature.

The degree hours (Dh) is defined as the summation of the number degrees on an hourly recording above or below a certain benchmark temperature (Szokolay 2008).

The comfort, discomfort or overheating is the summation of hours where temperature is beyond a set benchmark. Within different comfort approaches and its monthly variations, it is better to use a common benchmark temperature such as overheating in this case and compare the portion to overheating hours. The example in figure 3.2 used for illustration purpose only, is not based on actual data, shows the differences between those different approaches:

Degree hours will have decimals whereas the hours of overheating are integer numbers.

At day 1; the green line has the most overheating hours above 30°C at 18Dh followed by the blue line at 16 only. Whereas looking at the degree hours of the blue line is now the highest at 19.3 whereas the green is at 15.7Dh.

At day 2; both hours of overheating and degree hours correspond with both showing that the blue is performing worse.

Days 3 and 4; the green and the blue line have the same hours of overheating, yet the degree hours clearly show that the blue line is performing better than the green.

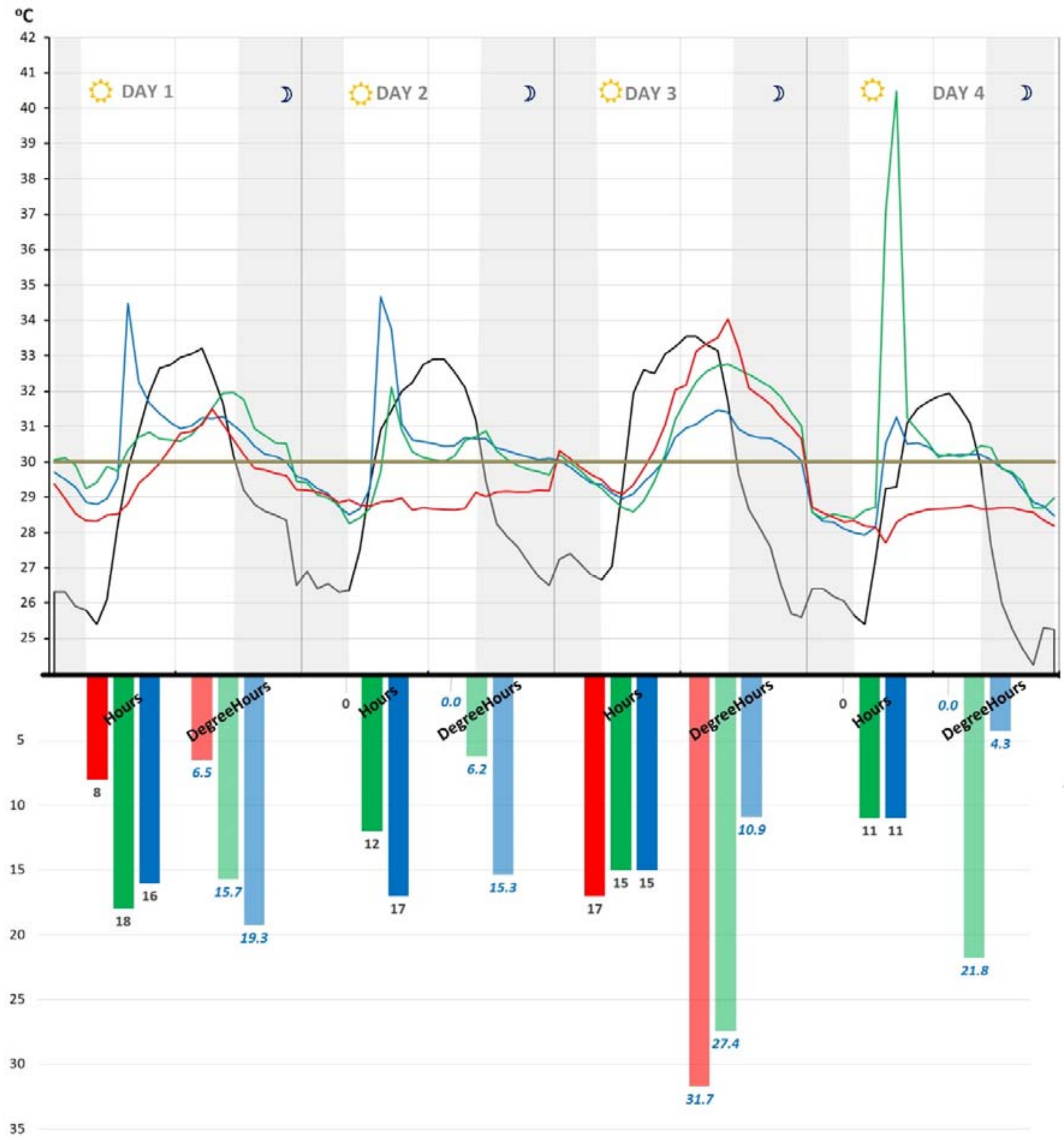


Figure 3.4 Temperature graph for illustration purposes only, showing random days with the corresponding hours of overheating above 30°C and the degree hours above 30°C

This example shows that for comparative temperature performance, using degree hours over a certain temperature is a better performance indicator since it takes into account more temperature nuances than using the hour of overheating or comfort which are likely to confuse the results.

3.9 Conclusion

Excessive mechanical cooling for summer comfort is the main problem to be addressed, especially when electricity supply is already unstable. The uncoordinated manner the numerous local bodies are dealing with this issue is further exacerbated because of lack of any solid scientific basis. This chapter sets the theoretical background of the study by defining the needed terminologies along with a review of previous research that have dealt with similar cases. The chapter starts by defining heavyweight construction and its expected temperature behaviour. It carries on with a review on heat transfers within heavy and lightweight constructions. and all the parameters that are used for quantifying thermal mass. These parameters are: time lag, decrement factor, admittance or Y-value, K-value of the capacity, and the Thermal Mass Parameter (TMP). Next the chapter reviews the EDSL TAS thermal software which is used within the research showing how it works and its different components with a detailed explanation on how each one functions, as well as the various parameters that can be inputted into the study. More importantly, the different UK and international bodies that validate its temperature and energy studies are listed. In an attempt to decipher the algorithm used for simulating heavyweight construction, the few references found are vague, varying between simplified calculation methods that take into account admittance match to the SAP 2012 guidelines. Those references discuss heat capacity and thermal mass parameters but not admittance, and their theory manuals address the specific response factors to be used to ensure that thermal mass is included in the calculations. Taking these into account, in addition to an example from their website, the chapter states that EDSL TAS is a reliable thermal software which simulates light and heavyweight temperature performance with a good level of overall accuracy. Nonetheless, when daily temperature fluctuations or differences between inside and outdoor temperatures pose an issue, the results appear to be more indicative, with smaller differences in the simulated version, as well as more minor differences between the simulated peak and the day's peak temperature. Consequently, the process of calibration is defined and based on three verification protocols: the ASHRAE guidelines 14, the IPMVP, and the FEMP. The common points shared by the three are that the calibration is completed for energy models with either monthly or hourly figures. For the latter, the two recommended verification indices are the CVRMSE and the NMBE which should be less than 30% and 10% respectively as mentioned in ASHRAE and FEMP, whereas IPMVP proposes a lower range of 20% and 5% respectively. A review of previous studies shows the common denominator among all the researches is their inclination for energy studies, in contrast to temperature-based studies. Furthermore, and more critically, previous studies show that basic data of various parameters are modified to reach a good validation. Many of these wall performance researches agree that external insulation is the best location. Following the theoretical or software-based studies; the research carries on with a review on purposely built models. These actual models vary considerably in both scale and purpose; the scale can range for as small as a 300 x 300mm shoebox studied under lab conditions or as large as a 5000 x 6000 mm test cell. The larger part of these studies has focused on roof performance, with purposes varying from heat flux transfer, impact on energy loads, to temperature performance. Regarding thermal mass studies, previous researches near Cyprus and Greece (similar climate to Lebanon's) focus on the inevitability of adding insulation and finding the best location for it; many directives and recommendations advise lower U-values/high insulation construction. Before explaining the subtle difference between degree hours and hours of comfort or overheating, the chapter reviews the different approaches to comfort. The degree hours of overheating above 30°C is adopted for the research as the main performance indicator. The various research methods used within the previous studies can be categorised into four types: (1) solely based on actual observations, (2) software-based that could be extracted from previous observation and are either (2) calibrated or (3) not, and finally, research based on (4) purposely built models that can vary in size from small shoebox to full liveable sizes.

The problems and questions highlighted in this chapter can be summarized in the following statements:

1- Thermal software generates indicative results for heavyweight temperature simulations.
2- Calibration is possible but requires the modification of various basic parameters.
3- Conflicting results are found in similar/related studies.
4- Four types of methods are used.

The above suggest that no one method should be taken the most suitable due to a lack of consensus. Furthermore, choosing one method over the other could be a compromise; therefore, it is imperative for the research to include the four available methodologies.

Chapters 2 and 3 have defined the problem and relevant terminologies. It has also described the methodology to be followed. **Lastly, it concluded following previous research that outer insulation is expected to provide the least internal overheating**.

4 Temperature Monitoring in Residential Buildings

4.1 Introduction

Part one has put forward the problem and defined the terminology and the available methods used in similar research. It also suggested that the outer-insulated walls provide the better option for cooler interiors or consequently less cooling loads.

This first chapter in the experimental portion (part two) of the research deals with the first method for similar experiments based on actual internal temperature monitoring in different apartments during an extended summer period. The objective of this chapter is to assess the first methodology and to highlight its learning outcomes. Four apartments located in a Southern Beirut neighbourhood are monitored for various lengths during the summer of 2015. They vary in age from recent (less than 10 years old), 30 years old, and reach to up to 50 years old. Some are inhabited, others are not, with either continuous cooling, intermittent cooling, or free-running (not mechanically cooled). They all are made of heavyweight construction where some have single masonry wall, while others have double masonry walls clad with natural stones. The monitoring will highlight their summer internal temperature behaviour in the coastal climate of Lebanon. More so, the monitoring will provide valuable data on the users' living patterns along with lighting and equipment's types and usage schedules. These data will later be incorporated into the software simulation.

Observations of summer internal temperature behaviour of heavyweight construction show the slow response to external fluctuations due to heat storage in the building mass. Furthermore, warmer night's internal temperatures are explained and compared to the cooler outdoors night temperatures; **low wind velocity is insufficient to flush away the excess stored heat from the heavyweight structure**. Surface temperature observations will show the relationship between internal and external surfaces, and the factors influencing the time difference between both peaks, as well as the considerable gap between them. With different usage in each apartment, the chapter also shows that for best monitoring outcome, choice of the apartments plays a major role for preferred scenarios.

The first method for comparing the effect of different wall constructions is not straightforward since various variables can interfere in such cases such as: different mechanical cooling schedules for each apartment; living patterns of users; or even window and shutter closure/opening schedules. However, the extended observation period, spanning for more than two months, allows singling out the different days when no mechanical cooling is used, and eventually when windows are closed. Thus, it is possible to establish performance ranking based on high U-value walls (single masonry wall) and low U-values walls (double masonry walls). In parallel to that, the effect of the low Beirut wind velocity is also studied.

4.2 Collected Fieldwork

Form August until late October 2015, four different apartments are monitored for internal ambient air and dry bulb temperature for different lengths of time (10 days to three months). The apartments are located within one of Beirut's suburban neighbourhood Ain Er-Remeneh (figures 4.1, 4.2). The historical weather files for the entire monitored period is available from the main official weather station located some 3 to 4 Km away from the airport. Each of the different apartments has its own occupancy pattern (one apartment is empty) and cooling strategy varying from (1) full time or continuous cooling; (2) free running mode or no mechanical cooling; and (3) mixed mode or non-continuous cooling. Table 4.1 resumes the details of the four apartments including the main orientation of the living areas, the cooling mode, habitation, number of users, as well as the period of monitoring and the total number of weeks. More details of the apartment can be seen in appendix 1.

Figure 4.1 Overall aerial view of Beirut's southern suburb, with the airport runways showing on the lower left. The main location of the official weather station is shown at left-centre. Apartments 1 and 4 are shown as one due to their proximity, whereas apartment 2 and 3 are shown further away (Source: After Google Earth 7)

Figure 4.2 A closer aerial view distinctly showing the four different apartments in the Ain Er-Remmeneh, Beirut South Suburbs. (Source: After Google Earth 7)

Table 4.1 Detailed summary of each apartment

		Apartment #1	Apartment #2	Apartment #3	Apartment #4
Year of Construction		1960s	1960s	1980s	2010s
Main Orientation		East	South/West	South	East
Cooling Mode		Full Time A/C	Mixed Mode	Mixed Mode	Free Running
Occupancy Status		Occupied	Occupied	Occupied	Un-Occupied
Numbers of Users		Family of 3	Family of 4	Family of 5	None
Observation	**From Date**	15-Sept	01-Aug	01-Aug	01-Aug
	From Week	37	31	31	31
	To Date	30-Oct	30-Oct	30-Oct	30-Oct
	To Week	43	39	43	43
	Total Weeks	7	9	13	13

4.2.1 Temperature Data Loggers

Two sets of data loggers are used in the different monitored apartments. All are of the same brand; Tiny Tags data loggers for temperature and relative humidity (fig. 4.3). One set is newer (2015) then the other set (three years old):

12 data loggers for temperature and relative humidity (6 new, 6 old)

4 data loggers for temperature and relative humidity with probe (old)

16 data loggers for surface temperature (new)

The data loggers used are Tiny Tags Plus 2; TGP-4500, described as “rugged and suited for outdoors monitoring”. They have a 10K NTC thermistor and an internally mounted sensor. The temperature reading resolution is at 0.01^{o}C ranging between 10 and 50^{o}C, the accuracy being between 0.4 and 0.5^{o}C.

Figure 4.3 All the data loggers (old and new; Tiny Tag) and surface temperature and temperature probes.

4.2.2 Ventilation within Apartments

When looking at the plans and layout of the different apartments the following was noted: the living area plan of apartment #1 is an open plan with a balcony on one end and a window on the other end. Apartment #2 has at least one window and one window-door in every space. This sensitive approach to natural ventilation is missed in apartments #3 and #4 where open floor plans are losing their unity by the addition of structures and discontinuous external walls. Even in the case of an attempt with cross ventilation, the windows are not on the same line (apartment #4). Using Szokolay's (2008) and Brown's (2001) methods to calculate the air exchange within the different apartments give higher air exchanges for the older apartments (figure 4.4) (more calculation details in appendix 3). The window and plan configurations in the older apartments (#1 and #2) are treated in a sensitive way allowing for better ventilation.

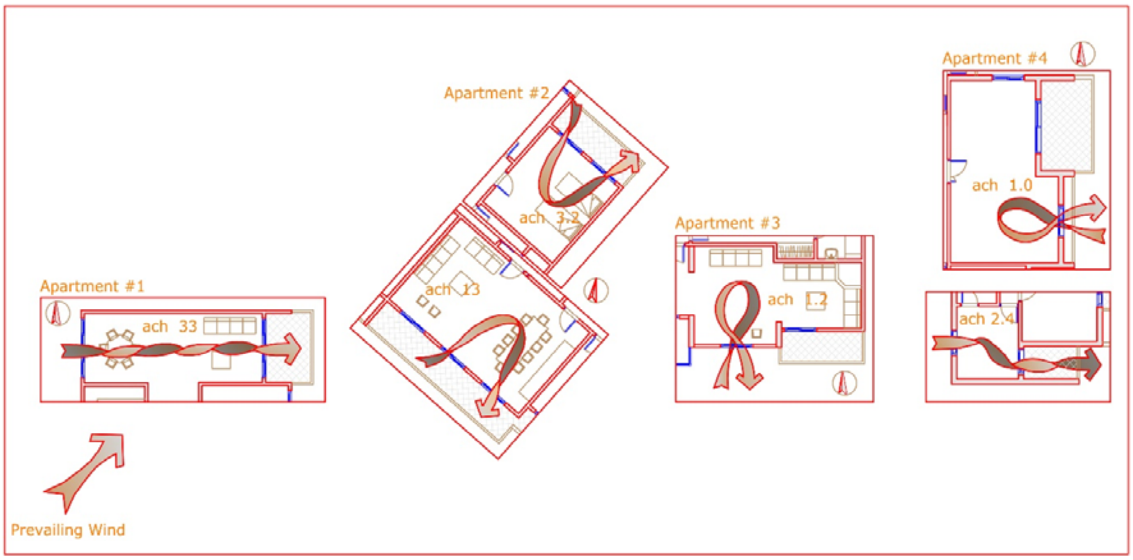
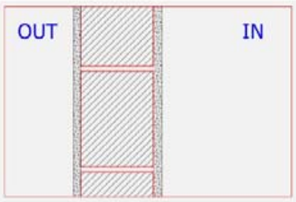
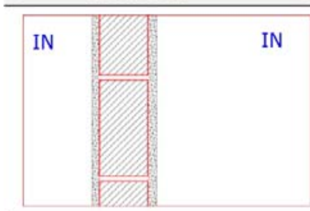
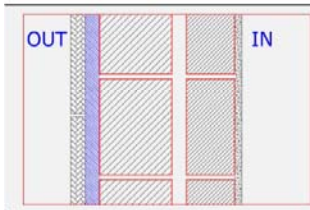
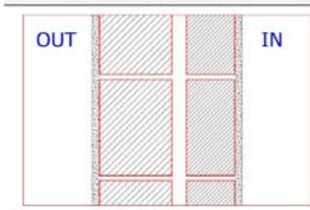
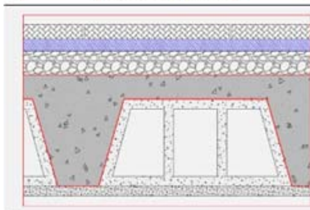


Figure 4.4 Various window configurations within the apartment buildings, showing the sensitive approach of the older apartments compared with the newly built ones.

4.3 Buildings Thermal Properties

Table 4.2 summarizes the building's thermal properties from envelope construction to U-value and Y-value. The U-values are from the EDSL TAS software since these are the values that will be used in the software in the later simulation runs. Since EDSL TAS does not show admittance values, (ARUP U-value calculator shows them), the values shown are taken from this reference.

Table 4.2 Recap on all the envelope's physical and thermal properties

Constrcution Type		Building	U-Value* (W/m^2k)	Admittance Y-Value** (W/m^2k)
	21mm Ext render + 150mm Hollow Concrete (dense) Block + 21mm Int Plaster	1; 2 & 3	2.7	3.4
	21mm Int Plaster + 100mm Hollow Concrete (dense) Block + 21mm Int Plaster	1; 2; 3 & 4 (internal Partitions)	2.9	3.7
	30mm Stone Cladding 25mm Cement Mortar 150mm Ext Hollow Concrete (dense) Block 30mm Air Gap 100mm Int Hollow Concrete (dense) Block 21mm Int Plaster	4 East	1.4	3.4
	25mm External Render 150mm Ext Hollow Concrete (dense) Block 30mm Air Gap 100mm Int Hollow Concrete (dense) Block 21mm Int Plaster	4 West	1.5	3.4
	30mm Stone Tiling 25mm Cement Mortar 50mm Aggregates 230mm Hollow Concrete Slab Cast in-Situ 21mm Int Plaster	All	1.9	5.4

* The U-values are calucated based on the EDSL TAS software

** The Y-values are calucated based on ARUP u-value calculator

4.4 Summer 2015 Beirut Weather

Figure 4.5 gives a brief description of the recorded summer data recorded from the Beirut Airport official station. Recordings show the mean wind velocity at 2m/s with the maximum at less than 3m/s; mean relative humidity above 60% with a maximum above 80%; and average temperature slightly below 30ºC for August and September with peaks of 34ºC. The day-night gaps vary between 8.5K and 8K.

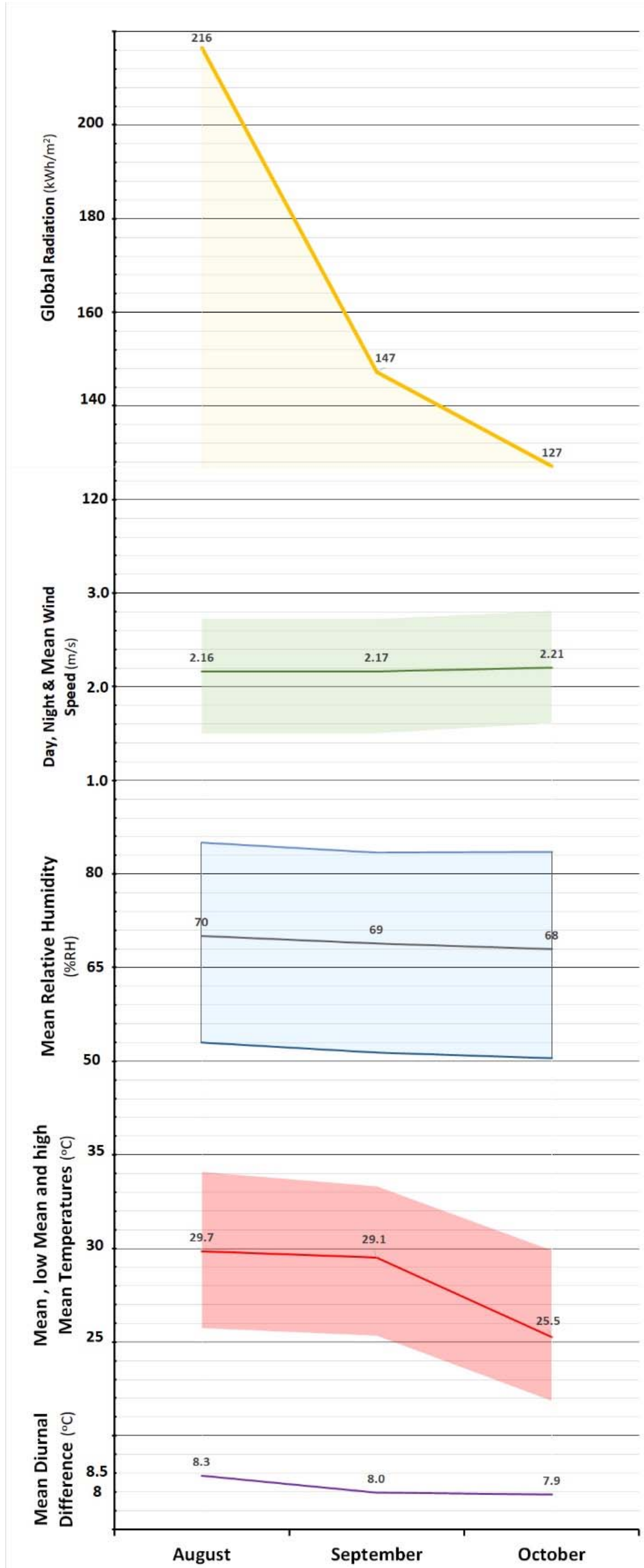


Figure 4.5 Summary of summer 2015 weather

4.5 Results

All temperatures are for the dry bulb temperature of both external ambient air and internal ambient air.

4.5.1 Apartment #1: Full-time cooling

In brief: East orientation; full time cooling mode; family of three; monitored for 7 weeks from September 15 (week 37) to October 30 (week 43)

Three areas are monitored in apartment #1: the entrance, the open dining area, and the external shaded balcony with the east orientation (fig. 4.6). Apartment #1 has the A/C on full-time, but still, internal dry bulb temperature (DBT) does fluctuate between a low of 26 and high of 30ºC, with the entrance temperature showing a minor lower temperature. More so with the old steel windows and the expected high infiltration rates, the dining area temperature shows relatively higher peaks (when compared to the entrance) of up to 1K in the early afternoon, when the sun starts hitting the west dining area wall. Furthermore, while looking at the entire set of temperature graph, it is clear that the overall cooling temperature trend is following the external trend as well, hence it stays around 29ºC in September, then falls to an average 26ºC in October. There seems to be one evening where the A/C had been turned off, due to a probable power shortage, between day 268 to 269; resulting from the high infiltration combined with a high U-value of un-insulated walls, the temperature dropped in parallel to the outdoors temperature but remained 1K warmer. The shaded balcony DBT, that holds the A/C compressor, shows huge fluctuations during the day with peaks up to 8K above the day's peak. The balcony's night temperature is always warmer than the outdoors but no more than 2K.

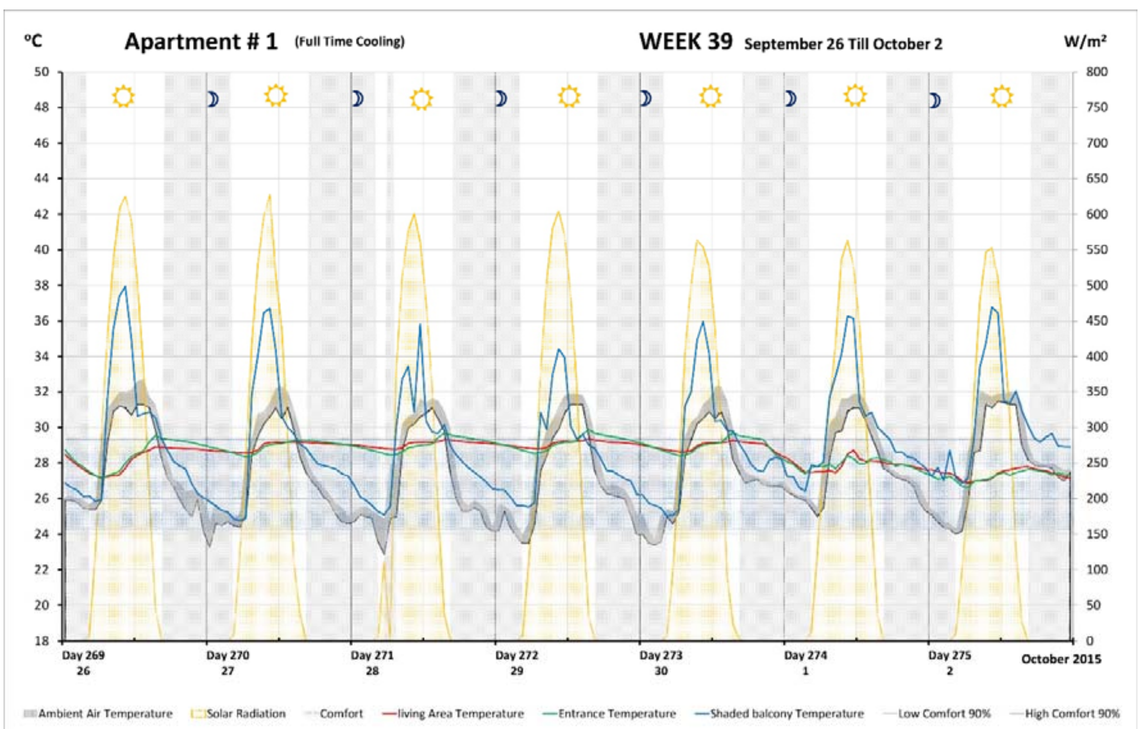


Figure 4.6 Apartment #1 continuous cooling, week 39, days 269-275, September 26, October 2, 2015. DBT of dining area, entrance, and shaded balcony.

4.5.2 Apartment #2: Mixed-mode cooling

In brief: South-West orientation; mixed mode cooling; family of four; monitored for 9 weeks from August 1(week 31) to October 2 (week 39)

In apartment #2 with the mixed-mode cooling, three spaces are monitored: the bedroom, the dining area, and the clostra (sheltered semi-outdoor space), in addition to the external and internal surface temperatures at different walls and orientations.

Extended night mechanical cooling and limited daytime cooling provide the bedroom with temperatures lower than the external temperature, yet when the A/C is turned off, night internal temperatures are 2- 3K warmer, and proportional to the external temperature trend. During weeks 38 and 39 (fig. 4.7 and 4.8), the bedroom is a good example to investigate the free running mode behaviour since the A/C is seldom used. With its north two windows and the east blank wall, the morning to late afternoon DBT remains 3 to 4K cooler than the daytime's peak. During the evening and night, internal DBT drops but remains up to 2K higher than the night ambient/outdoor temperature. When the day or night ambient temperature drops suddenly for a short period of time, the internal DBT is unaffected its diurnal fluctuation is limited to up to 7K when the outdoors diurnal fluctuation is up to 14 or 15K.

When cooling in the dining area is available, it is limited to not more than a couple of hours. Thus, the temperature observations are more consistent: the day's internal DBT are always cooler than the outdoor and warmer than the night's. Occasionally, early afternoon internal temperature exceeds the outdoors by 2- 4K due to a shift in the wind direction. Otherwise, the low speed mid-day wind varying between 2 to 4 m/s is enough to inhibit sharp excess peaks. The diurnal fluctuation cannot be compared to the bedroom because of its extended cooling period; nonetheless it is still less than the outdoors by a maximum of 8K.

The clostra with the same orientation as the living area shows quite similar temperature trends: morning DBT is up to 2-3K cooler than the external and 2K warmer during the night. Overall, the clostra's peak is up to 1K or slightly warmer than the living area, whereas its lowest temperature is cooler to up to 2K. Thus, making the overall diurnal fluctuation between 9-10K. Similarly, as observed within the living area, the influence of the mid-day wind is also shown with peaks warmer than the day's peaks.

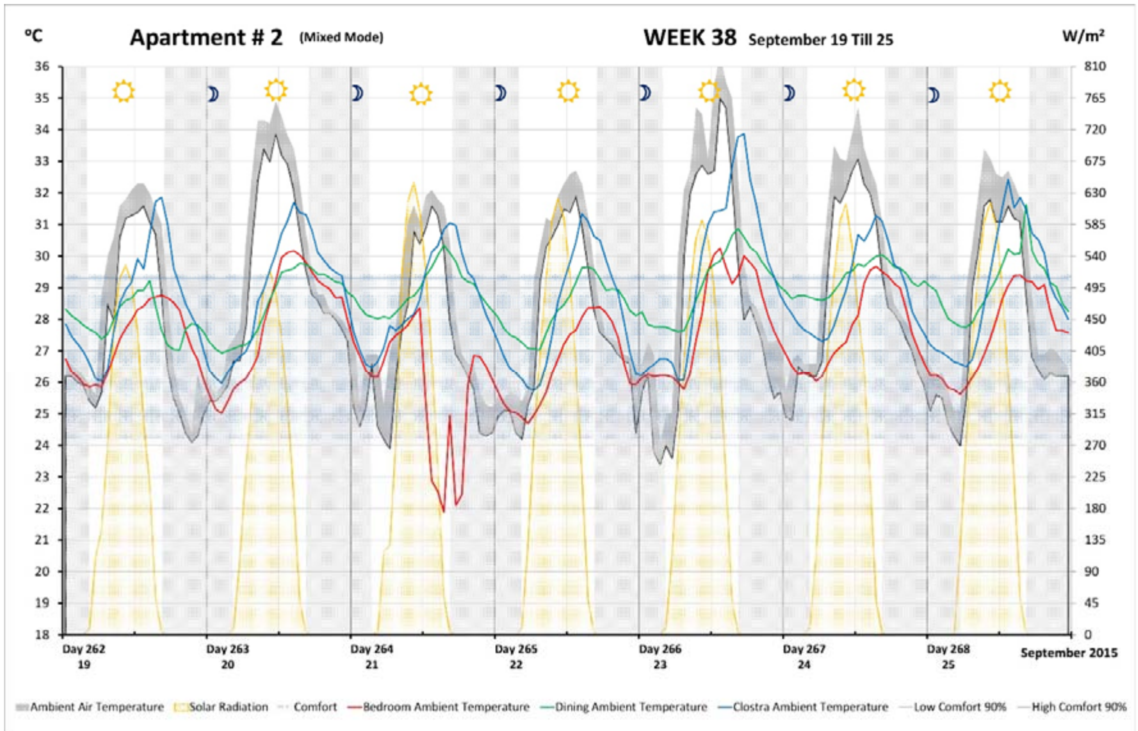


Figure 4.7 Apartment #2 with the mixed mode cooling, week 38, days 262-268, September 19-25, 2015. DBT of the bedroom, dining area, and clostra. A/C is only used on day 264 and 266.

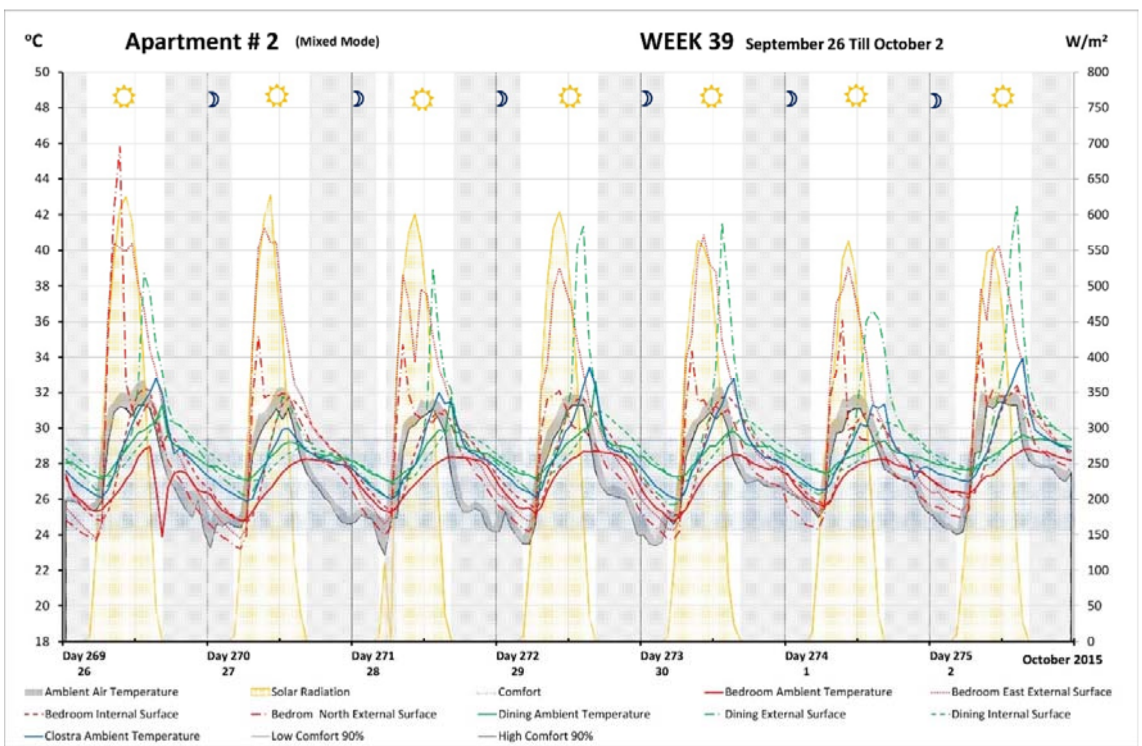


Figure 4.8 Apartment #2 with mixed mode cooling, week 39, days 269-275, September 26 - October 2, 2015. DBT of bedroom, dining area, and clostra. Surface temperature A/C is only used on day 269.

Further observations show that when outdoor DBT peaks are much higher than the previous day (day 228 or August 16) internal DBT and peaks remain relatively cooler (fig. 4.9). Whereas once the day DBT drops considerably lower than the previous day (day 248 September 5) the internal DBT remains warmer.

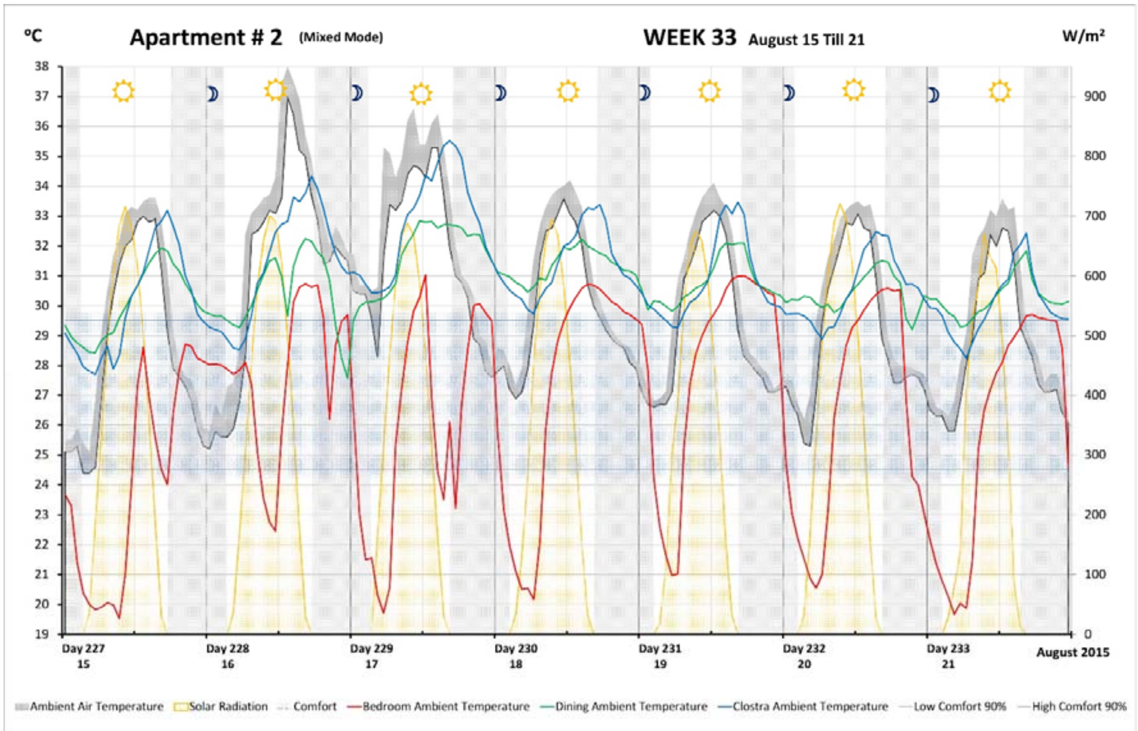


Figure 4.9 Apartment #2 with mixed mode cooling, week 33, days 227-233, August 15-21, 2015. Looking in particular at day 228 when the day's DBT peaked higher than the previous day, but internal DBT did not become considerably warmer.

Degree hours methods for analysis

Two methods are followed for Degree hours (Dh): cumulative temperatures above 30ºC for an entire day; or separated into daytime and night-time for a better appreciation of the temperature difference trends. The cumulative weekly Dh during night-time with the internal night temperature of the three different rooms (table 4.3) clearly shows that night internal temperature is warmer than the outdoors. At one instance (week 32), some night overheating occurred in the bedroom even with the A/C running frequently. As for day temperatures, a good example is at week 34 (table 4.4) where beside the running A/C only in the bedroom, both the dining area and the clostra underwent considerably less overheating than of the outdoors' ambient air. With the dining area summing up to 52.2 Dh while the outdoors is at 126.4 Dh, a difference of 41% is calculated. Last observation is during week 39 (September 16-October 2) when the A/C in the bedroom is off, and even though the ambient air overheating is at 33.4 Dh (least recorded of all previous weeks); the bedroom showed no overheating, and the dinning was only at 6.2 Dh (table 4.5).

Table 4.3 Night Dh: summed up as total per weeks, considerably more pronounced than the ambient air Dh. Even in the bedroom with the A/C running, one observation is slightly higher (week 32).

	Week 31	Week 32	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38	Week 39
	Night	**Night**	**Night**	**Night**	**Night**	**Night**	**Night**	**Night**	**Night**
Ambient Air	1.5	0.0	8.0	0.0	0.0	1.9	0.0	0.0	0.0
Bedroom	0.3	**2.0**	1.5	0.0	0.0	0.0	0.0	0.0	0.0
Dining	**19.3**	**6.0**	**24.5**	**0.6**	**2.7**	**9.9**	**3.5**	0.0	0.0
Clostra	**17.7**	**1.4**	**31.4**	**0.5**	**4.5**	**13.0**	**3.6**	0.7	0.0

Table 4.4 Dh of week 34: full day observations showing both the dining area (no A/C) and clostra area with considerably less Dh than the ambient air of the outdoors. The bedroom A/C is randomly run for 6 days (highlighted in red).

	Day 234	**Day 235**	**Day 236**	**Day 237**	**Day 238**	**Day 239**	**Day 240**	**Total**
Ambient Air	14.4	18.6	17.2	16.3	15.4	22.5	22.0	**126.4**
Bedroom	0.0	0.0	0.0	0.2	0.0	1.3	2.5	**4.0**
Dining	4.9	6.0	6.4	5.9	7.9	11.7	9.2	**52.2**
Clostra	5.8	9.5	10.2	8.2	12.5	21.1	19.2	**86.5**

Table 4.5 Week 39: A/C on for one day in the bedroom; both the bedroom and living area have considerably less Dh overheating than the outdoors, while the clostra has more.

	Day 269	**Day 270**	**Day 271**	**Day 272**	**Day 273**	**Day 274**	**Day 275**	**Total**
Ambient Air	7.6	3.5	3.2	4.7	3.0	3.5	7.9	**33.4**
Bedroom	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.0**
Dining	1.8	0.0	1.7	2.7	0.0	0.0	0.0	**6.2**
Clostra	9.3	0.0	6.3	10.0	7.9	4.0	13.3	**50.8**

Surface Temperature

Surface temperatures are influenced by both the internal and the external temperature, and accordingly, both internal temperatures of the bedroom east wall and the living area west wall can be seen as a summation of both. The internal bedroom temperature shows almost a similar trend as the internal wall when the A/C is turned on, warmer with a maximum of 3-4K. However, when the A/C is off, the internal surface peaks up to 4K warmer than the internal ambient temperature. Nonetheless, it always remains much cooler (6-8K) than the external surface peaks of the north and east walls. Also, this internal surface temperature peak is marked a couple of hours after both external walls peaks (fig.4.8).

Similarly, the internal surface temperature of the living area in the morning is cooler within a range of1- 2K, but warmer in the evening. More so, it peaks 1-2 hours after the external surface temperature peaks at up to 15K cooler. Peak surface temperatures reached 50^{o}C and 47^{o}C for the north bedroom wall and south living wall respectively. External temperature soars when the sun is directly hitting the surface, yet variable peaks are reached due to the combination of the sun intensity and the wind's velocity and direction; the latter can either help in increasing or decreasing the surface temperature.

A closer look of day 263 (week 38; September 20; fig 4.7) shows both the time lag and the decrement factor. The former is the time difference (horizontal axis) between the day's ambient peak temperature after midday (11am) and the clostra's, dining area's and room's peak a couple of hours later (2 & 3pm). The decrement factor is the temperature difference between the 34^{o}C peak ambient temperature and the 30-32^{o}C peak temperature of the dining area, clostra, and bedroom.

4.5.3 Apartment # 3: Mixed-mode cooling

In brief: south orientation; mixed-mode cooling; family of five; monitored for 13 weeks from August 1 (week 31) to October 30 (week 43)

In apartment #3 with mixed-mode cooling, three areas are monitored: the entrance, the living area, and the glazed balcony.

Limited A/C usage is further elucidating the temperature behaviour of this apartment (fig 4.10 and 4.11). Although the living area is seldom used, the windows are kept closed when not in use. This is clearly reflected in the night internal DBT trend that is warmer than the night DBT averaging to 5-6K. Nevertheless, the day's morning to early afternoon DBT is still up to 2K cooler than the outside, and the overall temperature fluctuation is within a 5-6K range.

The entrance DBT is somehow influenced by the adjacent living area when the A/C is turned on. Nonetheless, its fluctuation is limited at not more than 4K. Being quite enclosed, the entrance DBT daytime peaks are up to 4K cooler than the outdoors DBT peak. However, due to limited ventilation (no windows), night DBT is up to 5K warmer than the external, but still 1-2K cooler than the living area temperature.

As for the dining area adjacent to the glazed balcony, two temperature trends are apparent: when the internal shades are not used, and the windows are closed, internal DBT soar considerably above the outdoors DBT reaching above 40^{o}C sometimes. Meanwhile, the combination of opening the windows and closing the internal shades keeps the temperature only a few degrees warmer than the outside. With the use of the internal shades, the peaks drop 2K below the day's peak (fig 4.11).

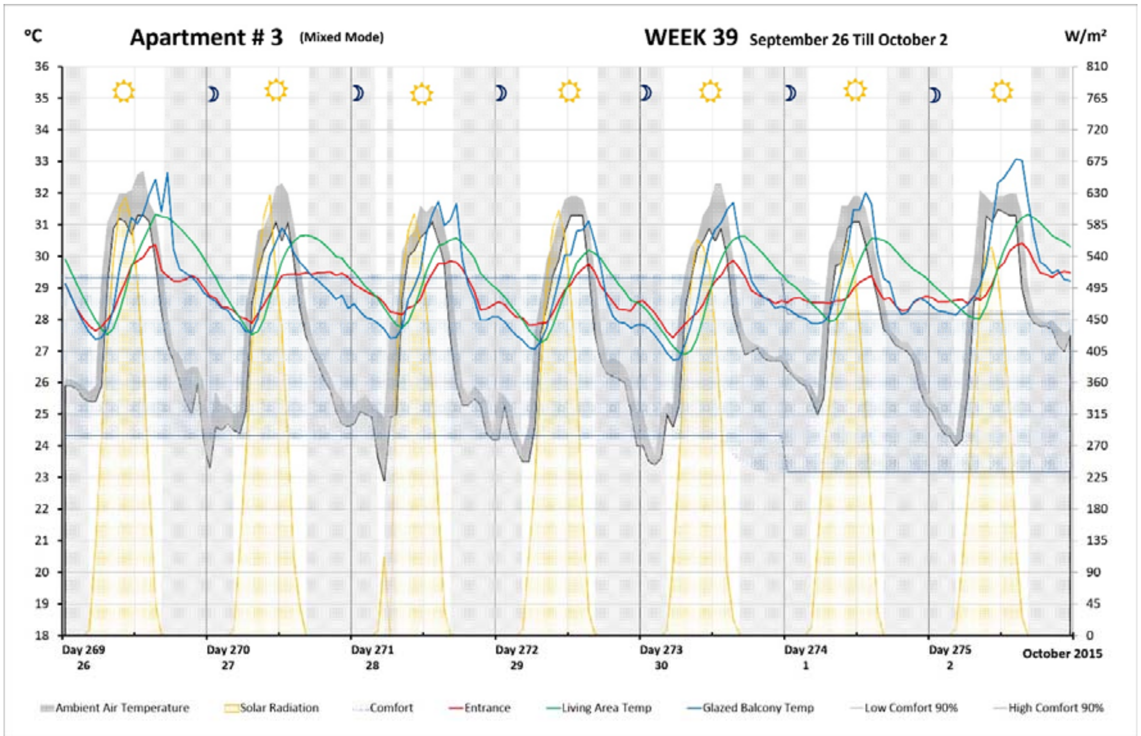


Figure 4.10 Apartment #3 with mixed-mode cooling: week 39, days 269-275, September 26 - October 2, 2015. DBT of the entrance, living area, and glazed balcony.

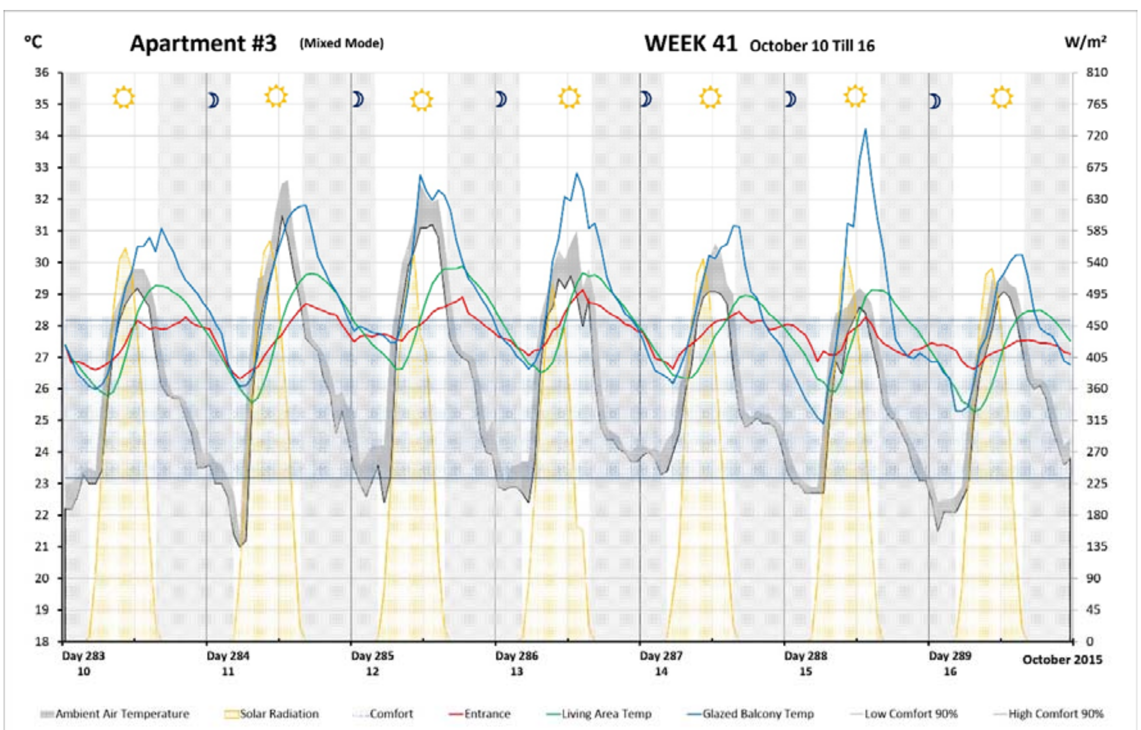


Figure 4.11 Apartment #3 with mixed-mode cooling: week 41, days 283-289, October 10-16, 2015. DBT of the entrance, living area, and glazed balcony. On day 268 in particular, glazed balcony temperature soars due to closed windows and no shading.

When it comes to overheating in terms of Dh above 30ºC, the entrance which is the least exposed to the direct sunlight as well as to wind, shows the least overheating for the overall observation period (10 weeks). The living area shows 14% less overheating than the outdoors. The glazed balcony is constantly overheating; almost doubling the outdoors' by some 228% (table 4.6). Night overheating (table 4.7) trends show that the glazed balcony is releasing the excess heat more easily than the living area. Nonetheless, all the rooms are overheating more than the outdoors' air (only at 11.4 Dh) for the entire nights, whereas the entrance which is cooler than the outdoors during the day, sums up to 105.7 Dh.

Table 4.6 Overall weekly Dh overheating above 30ºC for the entire monitored period, including the gross total

	Week 31	Week 32	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38	Week 39	Week 40	Week 41	Week 42	Week 43	TOTAL
Outdoors	155.3	141.7	197.7	126.4	124.0	115.4	105.0	94.8	33.4	8.1	7.1	10.2	0.0	**1119.1**
Entrance	N/a	9.6	143.8	38.8	64.0	51.7	115.0	22.1	1.8	0.0	0.0	0.0	0.0	**446.8**
Living	167.0	133.0	215.7	129.5	100.9	44.1	87.6	52.5	30.2	1.0	0.0	0.0	0.0	**961.4**
Dining	346.4	139.1	336.1	118.3	202.5	230.0	682.8	254.6	55.8	8.1	58.7	63.3	53.8	**2549.5**

Table 4.7 Overall weekly Dh overheating above 30ºC during the night for the entire monitor period, including the gross total.

	Week 31 Night	Week 32 Night	Week 33 Night	Week 34 Night	Week 35 Night	Week 36 Night	Week 37 Night	Week 38 Night	Week 39 Night	Week 40 Night	Week 41 Night	Week 42 Night	Week 43 Night	TOTAL Night
Outdoors	1.5	0.0	8.0	0.0	0.0	1.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**11.4**
Entrance	N/a	0.0	42.5	2.9	9.8	14.1	34.5	1.9	0.0	0.0	0.0	0.0	0.0	**105.7**
Living	49.0	23.7	66.9	25.5	18.5	11.2	19.8	6.2	1.7	0.0	0.0	0.0	0.0	**222.7**
Dining	31.7	0.0	33.5	9.2	24.2	14.0	75.7	6.2	0.0	0.0	0.0	0.0	0.0	**194.6**

4.5.4 Apartment #4 –Free running mode/ Unoccupied-

In brief: east orientation; free running mode; unoccupied; monitored for 13 weeks from August 1 (week 31) to l October 30 (week 43)

The bedroom and the living area are monitored in this apartment as well as the internal lobby (at the ground floor level) leading to the basement, in addition to the internal and external surface temperatures of both rooms. The monitoring of the apartment had two mistakes: the data loggers placed in the living area were directly hit by the morning sun (fixed after an entire month of monitoring) and the data logger in the bedroom was also hit by the sun.

Dry bulb Temperature in the living area is up 2-4K lower than the day's peak, regardless of the sun hit peak. The night DBT is much warmer than outside by up to 4-5K. At first the windows are closed, then open on week 34; this is reflected by a reduced night difference of 3-4K.

The bedroom has a window on the west wall and a glass door covers the balcony on the east wall. Even with both windows, whenever the sun reaches the room, a small temperature peak of 1-3K occurs. In the first three weeks when the windows are closed, the day's DBT are high, but not more than 2-3K cooler than the outside. The effect of closing the windows is clearly visible starting on day 213 (August 1; fig. 4.12). The temperature gap between internal and external shrinks from 4-5K (while windows are open) to 1-2K (after the windows are closed). Once the windows are open again, the gap goes back to 4-5K (fig. 4.13).

Similar observations apply for the bedroom night temperature with an increasing (warmer) gap until the windows are opened again.

Although the basement lobby has no windows, minimal ventilation can be passed through the main building gate. Its temperature graph shows a minimum day/night fluctuation of not more than 2K. Daytime temperature is up to 8K cooler than the day's peak, but up to 6K warmer than the night's. When calculating the average, it is almost the same as the daily ambient outdoor air average with not more than a 0.3K difference.

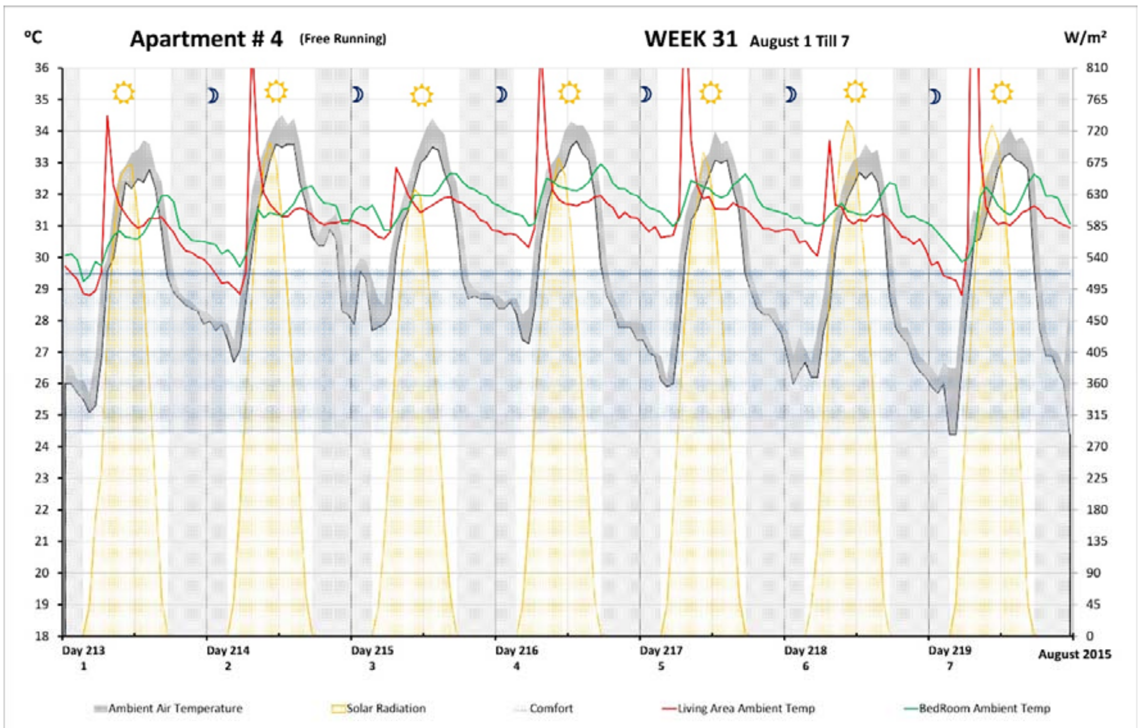


Figure 4.12 Apartment #4 with free-running mode and unoccupied: week 31, days 213-219, August 1-7, 2015. DBT of the living area and bedroom with decreasing gap between day's peak and internal peaks with the windows' closure. The excessive peaks during the morning in the living room are due to the sun hitting the data loggers, whereas the morning and afternoon shorter peaks in the bedrooms are due to the sun getting into the room for a limited time.

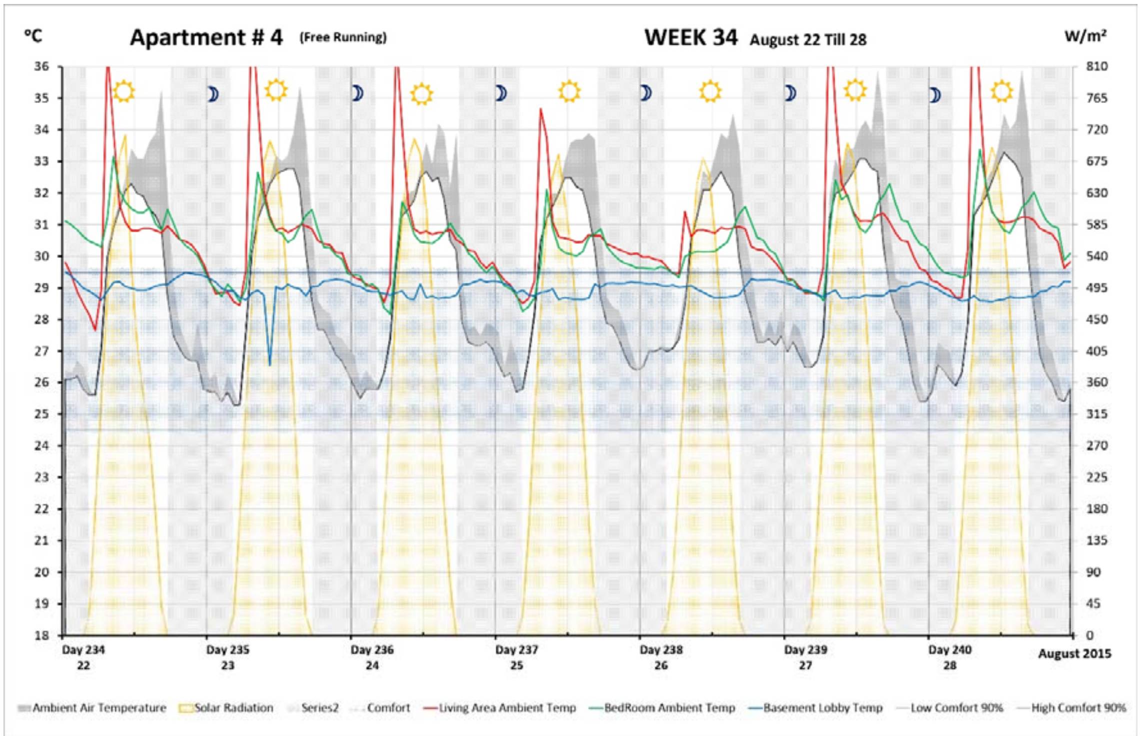


Figure 4.13 Apartment #4 free-running mode and unoccupied: week 34, days 234-240, August 22-28, 2015. DBT of the living area and bedroom with increasing gap between day's peak and internal peaks with the windows open. Also, the basement lobby's almost stable temperature is shown.

Regarding overheating, the most interesting part is the minimal, almost null overheating in the basement. Whereas the east oriented living room and the west oriented bedroom are overheating more than the ambient outdoor air (table 4.8).

Table 4.8 Overall full-day overheating over 30ºC Dh for the entire monitored period

	Week 31	Week 32	Week 33	Week 34	Week 35	Week 36	Week 37	Week 38	Week 39	Week 40	Week 41	Week 42	Week 43	TOTAL
Ambient Air	155.3	141.7	197.7	126.4	124.0	115.4	105.0	94.8	33.4	8.1	7.1	10.2	0.0	**1119.1**
Living	227.0	217.5	287.8	146.7	165.2	94.1	118.6	43.7	4.2	0.0	0.0	0.0	0.0	**1304.7**
Bedroom	248.5	234.0	370.5	105.5	139.9	115.1	159.1	185.8	84.1	13.4	19.1	0.3	0.0	**1675.4**
Basement	N/a	N/a	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	**0.8**

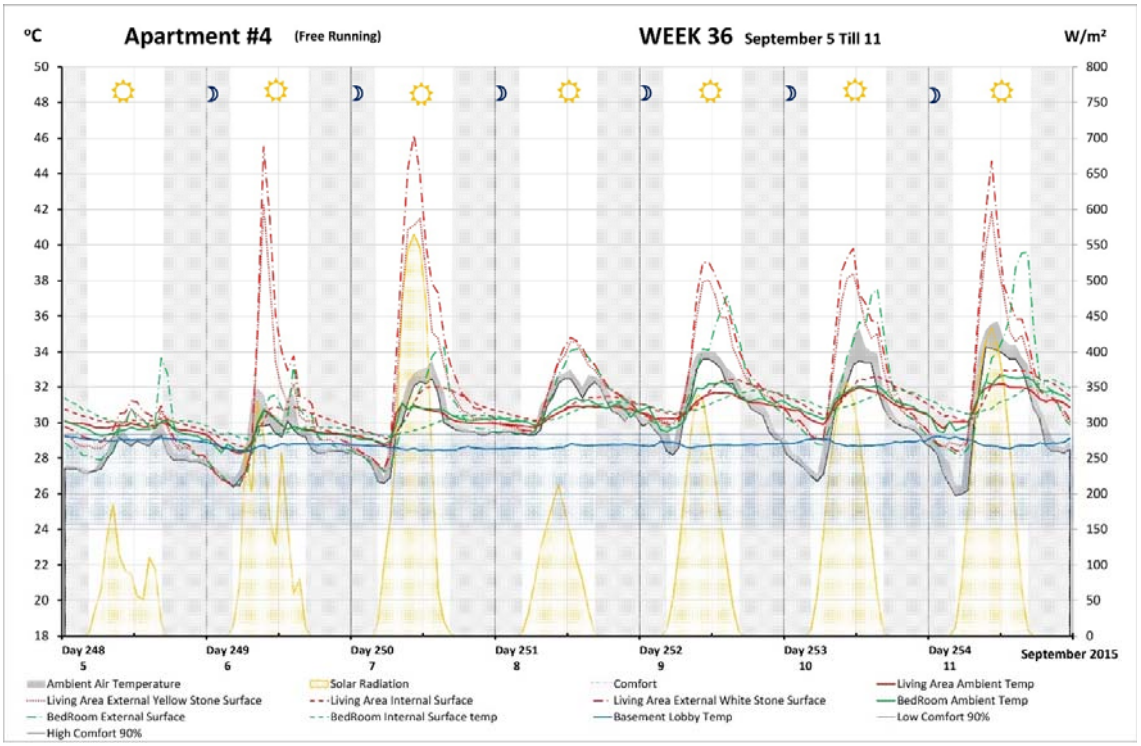


Figure 4.14 Apartment #4 with free-running mode and unoccupied: week 36, days 248-254, September 5-11, 2015. With DBT and surface temperatures.

Three external surface temperatures are recorded; two on the east façade and one on the west façade: one on a yellow stone on the east façade the other one on a white lighter stone, and the last one on the west façade painted a light grey colour. Week 36 is a good example to study surface temperatures (fig. 4.14): The morning sun hitting the east surface is raising both temperatures high, but the white stone is the one with the highest records; well above 40ºC and reaching 50ºC at some points. The yellow stones are at least 4K less with peaks not exceeding 45ºC. The west light grey painted façade receives the afternoon sun and is cooler than the white stone surface, but warmer at different times than the yellow stones with a few peaks between 46-48ºC.

Internal surface temperature is influenced by both inside and outside, and hence it peaks much cooler than the outside surface temperature but stays warmer than the internal air temperature. Night internal surface temperature is always warmer than the outside surfaces, and the day's internal surface temperature slightly cooler than the room's ambient air.

4.5.5 Relative Humidity

Summer humidity in Beirut ranges between an average low of 60% and a high of 90% with the lowest drop around the day's hottest hours, and the highest at the night's coolest hours. Similarly, the internal air is influenced by the external relative humidity, especially when the windows are open. It is quite common to hear that without the stickiness of high relative humidity; the temperatures would have been bearable. Additionally, the A/C is used more to dehumidify the internal air than to actually reduce temperature. The fans of various sizes in apartments #2 and #3 randomly used in the living areas will induce a low velocity breeze capable of alleviating the sensation of humidity on the skin.

4.6 Discussions

4.6.1 Internal Dry Bulb Temperature

All the observed apartments are made of heavyweight material, and their temperature outcome is the result of the thermal mass behaviour.

The less the internal space has direct exchange with the outside, the less the internal dry bulb temperature fluctuates between day and night. This is seen in the entrance of apartment #3, and the 4th building's basement lobby. In the latter, the DBT fluctuation is relatively flat with the calculated average slightly different from the entire day's average. The effect of thermal mass in absorbing and storing heat is visible in the day's internal DBT which is cooler than the day's outdoor DBT, ranging from a few hours in the morning to the entire day time. Similarly, the thermal mass's effect of releasing the stored heat of the day with a certain time lag makes night internal DBT always warmer than the night's DBT. The low response to the daily changes in the ambient air temperature is visible when external day temperature rises sharply compared to the previous day. When this happens, the internal temperature shows a slightly warmer temperature compared to the previous day's. Similarly, when the night external temperature sharply drops, the internal temperature remains as warm as the previous night. Practically, a sudden and limited temperature change (rise or drop) in the external DBT of 2-3K might affect the internal temperature by no more than 0.5K.

4.6.2 Ventilation

Ventilation combined with thermal mass should provide an acceptable internal temperature. However, the limited and low velocity wind in Beirut only reaches a monthly average of slightly above 2m/s, peaking at 4m/s, and many hours with no wind during September and October. Natural ventilation is not capable of sufficiently cooling the internal night temperature, thus inside remains warmer than the outside. This effect is well observed in apartment #4 when the windows are kept closed for some time and then opened; a clear drop of 1-2K is recorded in the internal night temperature.

4.6.3 Surface Temperature

External surface temperatures are directly influenced by the physical properties of the material as well as its colour. Meanwhile, internal surface temperatures are influenced by internal air temperature, external surface temperature, and the thermal properties of the wall itself. It was unexpected that a whitish stone was getting hotter than an ochre yellow stone, but that might have been due to the difference in stone type rather than only the colour. Similarly, the afternoon sun hitting a grey painted surface is cooler than the morning sun hitting a light-coloured stone (yellow or white). Internal surface peaks are considerably less than the outer surface peaks at either the same time or an hour later. During the night, internal surface temperature can be cooler than the internal air temperature, but at rare instances and for no more than one to two hours, it went even cooler than the outside air temperature. Internal surface temperature is also influenced by the wall's U-value, hence the temperature of surfaces with a higher U-value is more likely to be influenced by the day's warmth or the night's coolness.

4.6.4 Internal gain effect

It is difficult to accurately observe the effect of internal gains due to A/C usage, as well as to the lack of recorded data of when and how many people used the specific room. Regardless, unless it is a major internal gain, it has limited influence on the internal temperature observed by the small instantaneous peaks that disappear once the source is gone. Those are registered in the inhabited apartment where sharp rises of 1K are randomly observed. It was interesting to see two short peaks in the room with an east and west window (empty apartment #4) due to solar gains hitting the room (and not the data logger itself).

4.6.5 Comparative Studies

The four apartments underwent a prolonged period of simultaneous monitoring (table 4.1). Rooms with similar cooling behaviour and no temperature incidents are chosen for comparison. Cooling behaviour refers to days when no cooling is used (not even for an hour). Temperature incidents refer to direct sun rays hitting the data logger, thus creating an instantaneous surge in temperature. It should be noted that there are no consistent window schedules.

Taking the above into consideration, two sets of non-consecutive days are grouped from the 4 rooms from the three buildings to have their temperature performance compared:

Set 1:
- living/dining area of apartment #2
- Entrance of apartment #3
- Dining area of apartment #3
- Bedroom of apartment #4

Set 1 has been fitted to the criteria for 16 non-consecutive days of observation, while set 2 is found to fit the criteria for 11 non-consecutive days with one change in rooms for only apartment #4. The rankings are shown in figures 4.15 and 4.16 below.

Set 2:
- Living/dining in apartment #2
- Entrance in apartment #3
- Dining in apartment #3
- Living in apartment #4

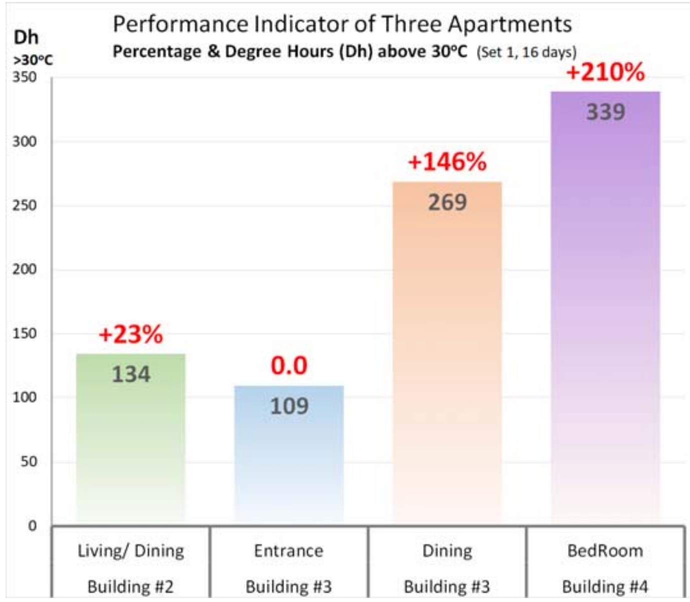


Figure 4.15 Results of cumulative degree hours above 30ºC for 4 rooms from the three different apartments when no mechanical cooling is used. Results from set 1: 16 non-consecutive days of observation.

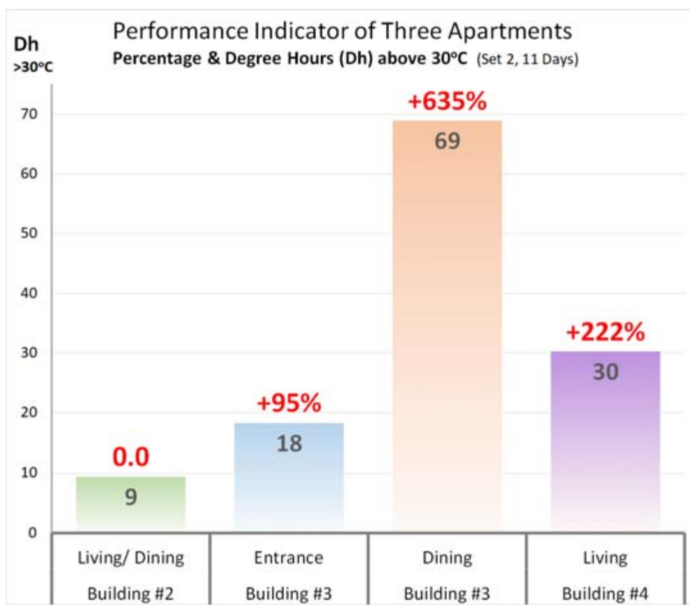


Figure 4.16 Results of cumulative degree hours above 30ºC for 4 rooms from the three different apartments when no mechanical cooling is used. Results from set 2: 11 non-consecutive days of observation.

The fact that the window schedules are not part of the study add a further layer of uncertainty onto the results. Nonetheless, the following can be noted:

1- An internal room with no direct sunlight will be relatively cool, but a cleverly ventilated room could outperform it. As seen in set 1 (fig. 4.15), the well-ventilated living/dining of apartment #2 is performing better than the internal entrance of apartment #3. In set 2 (fig. 4.16), the entrance performed better most likely because the living/dining area was less ventilated (by closed windows).

2- Any room adjacent to a glazed balcony performs badly (phase 1 of dining room in apartment #3). Clever ventilation and shading devices in this room, while no ventilation in the bedroom of apartment #4, will make it less overheated. Nonetheless, both undergo considerably more overheating when compared to the indoor entrance and the living/dining area.

3- In terms of external envelope, results show that the living/dining of apartment #2 with a high U-value of 2.7 W/m^2.K is performing better in terms of Dh overheating compared to two rooms with the double walls in apartment #4 of U-values 1.4 and 1.5 W/m^2.K.

4.6.6 Low Air Exchange

The above observations are the direct result of the thermal mass all those buildings share, combined with ventilation (figure 4.4). Combining the previous results in terms of degree hours above 30ºC and air exchange, high U-values with good ventilation produce less overheating than low U-value with low air exchange (additional notes in table 4.9).

Table 4.9 Comparative data for the dining room and living area, including set 1 and set 2 of non-consecutive days.

Apart	Room	Orientation	**Y-values** (W/m^{2}K) Walls	Slabs	Walls **U-values** (W/m^{2}K)	Air exchange (ach)	**Dh>30 Set 1**	**Dh>30 Set 2**
2	Living	South	3.4	5.4	2.7	13	**134**	**9**
4	Living	East	3.4	5.4	1.4	1.0	n/a	**30**
4	Bedroom	North	3.4	5.4	1.5	2.4	**339**	n/a

4.7 Conclusion

The first experimental chapter of the second part of the research used one of the four methods highlighted in the previous studies; internal temperature monitoring of four different apartments during summer 2015. This first method provided good insight into heavyweight temperature behaviour during Beirut's hot summers. It also showed that although delicate, comparative studies are still possible, but with an expected level of error.

The monitored apartments share the same thermal mass construction, yet they vary in wall construction, age, occupancy and cooling modes. The monitoring showed their temperature behaviour in terms of daytime internal DBT to be cooler than the outside, even with the open windows, while night internal DBT warmer than the outside. Both outcomes can be attributed to the combined effect of the thermal mass storing heat during the day and Beirut's low wind velocity unable to flush out the excess heat. Similarly, the slow response of internal temperature to sudden excess heat or temperature fluctuations is highlighted as well. In two instances, naturally ventilated internal spaces with low air exchange and no direct solar gains showed minimal temperature fluctuations with an average temperature almost equal to the day's mean temperature. Surface temperature peak between outside and inside varied considerably, and with a certain time lag, of up to a couple of hours. The external surface is directly influenced by the sun hitting the surface, as well as by the colour and type of material. Internal surface temperature is affected by the wall's physical and temperature properties and by the internal conditions, especially when the cooling is on. It is important to note that comparative studies require more attention to the details since although the apartments were monitored roughly within the same period, random A/C usage in some apartments, the occasional direct solar exposure of loggers, alongside random window scheduling (for ventilation) might have some effects on the results. Nonetheless, an extended period of observation helps in finding comparable days (with at least no mechanical cooling) and thus provides a good opportunity for comparative studies. Additionally, results show that low U-value (better insulated) cavity walls produces more overheating Degree hours (Dh) compared to higher U-value (less insulated) walls. Furthermore, well-ventilated and/or internal spaces with no direct solar gains have much less overheating than other spaces. More interestingly, comparative observations showed that high U-values combined with good ventilation result in less overheating than low U-value with low air exchange. The observation of apartment #2 with its occupants' feedback also provided valuable data of living patterns and behaviour and lighting and equipment types and schedules. All these led to a cumulative value for internal gains that can be used in the following software-based study. This calculated value of 4.8 W/m^2 (appendix 2) was less than the proposed value of 6.5 W/m^2 by LCEC guidelines. It is interesting to note that this LCEC value which is calculated for only users and lighting only (excluding appliances) should logically be even higher.

5 Apartment's Software Simulation & Calibration

5.1 Introduction

The previous chapter based on actual temperature monitoring of different apartments during the summer of 2015 provided the basic data to calculate internal gains. Taking into consideration the limitations of observation conditions, logged temperature data showed that the apartment (apartment #2) with the single masonry wall, but with a better ventilation strategy, has less overheating in terms of degree hours above 30ºC, as seen in both figures 4.15 and 4.16. This chapter uses the data from this apartment to do thermal software simulation

The objective of the chapter is to find the best performing envelope in terms of least overheating during Lebanon's summers using a calibrated software model. The different envelopes to be software-tested are double masonry walls with insulation placed at different locations. Since envelopes have an important impact on reducing cooling energy loads, this research expects these proposed envelopes to further reduce summer overheating.

The basic data used, correspond to both the apartment's physical properties as well as its usage patterns. The physical properties include floor dimension and layout, and envelope construction and thermal characteristics in particular its U-values. The usage patterns include the combined effect of users, lighting and equipment frequency, schedule and heat gain.

The approach makes the available software model into a valid calibrated one where the simulated outcomes will be compared to the recorded data. Given the results comply to ASHRAE 14, calibration protocol (as seen in chapter 3.2 and table 3.4) we can assume that the model's outcomes coincide with the actual data thus are valid for further studies. These would include upgrading the single wall into a double masonry wall, and adding further insulation at different locations: outer, middle, and inner sides.

5.2 Calibration Runs

Figure 5.1 shows the previously monitored apartment #2 (refer to Chapter 4, and Appendix 1).

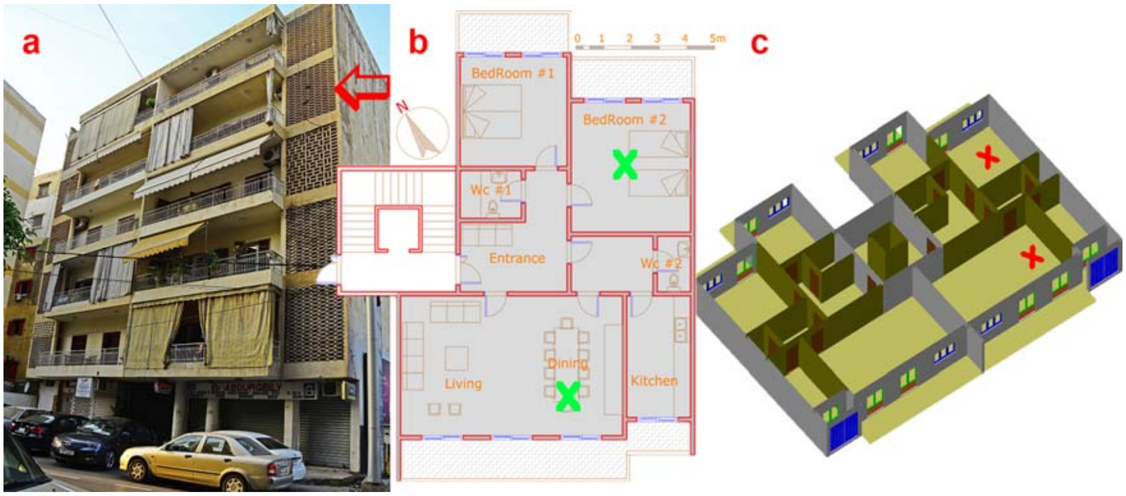


Figure 5.1 (a) Apartment #2 is used as a base for the simulation; (b) Typical plan of an apartment where both the dining/living area and bedroom are simulated; (c) 3D axonometric of the temperature model showing an entire floor of both apartments.

Based on the literature review and the available protocols reviewed in Chapter 3, the CVRMSE and the NMBE are calculated. In both the literature review and the protocol that are more based on energy rather than temperature calibration, margins of errors are calculated for the overall period of monitoring.

The EDSL TAS 9.3.2 thermal simulation software is used with the Bayrouth weather file 2000-2009 (Meteonorm 7). Four typical floors are modelled, each with the two adjacent apartments. The orientation is kept the same with the living areas facing South-West. The modelled apartment is on the 4^{th} floor.

The building's physical properties are inputted based on the observation, whereas its thermal properties are extrapolated from similar constructions and construction references. Similarly, the user living patterns as well as lighting and equipment usage are also inserted based both on observation and user feedback. Weather data is provided by the airport. Three rooms are simulated: the bedroom where the A/C is used more frequently (but without a predictable schedule); the living room with less A/C usage; and the clostra (the semi-enclosed space between the kitchen and the outside). Windows are assumed to be open when the A/C is not on.

Five rounds of calibration are completed for week 32 (days 213 to 219; August 1-7). data is inputted based on the operator's judgment. Considerations were taken to introduce an evidence based incremental adjustment to preclude unreliable trials and errors:

In the first round, the envelope U-values properties are the calculated value of 2.7W/m^{2}K. All user details, lighting and equipment schedules are inputted as they have been communicated or observed. The total compiled[4] internal gains are 4.8W/m^2.

In the second round, the internal gains are completely turned off.

Round three changes the U-values from 2.7 to 1.7W/m^{2}K while keeping internal gains null.

Round four keeps the U-values of 1.7W/m^{2}K but increases internal gains back to 4.8W/m^2.

Finally, the fifth round keeps the 1.7W/m^{2}K U-values but raises the internal gains to 7.5W/m^2.

Increasing gains beyond 7.5W/m^2 without the modified U-values was futile since the first round already showed warmer/higher simulated temperatures than the recorded ones.

Both the CVRMSE and the NMBE are calculated for each simulated room separately and then their combined weighted value is calculated as well. In this case, the study modifies one parameter at a time, which is a simple and valid method. This allows the study to focus on the impact of two major parameters: the internal gains and the envelope U-values.

[4] To get these unique values, all the schedule and the wattage are inputted, for all the rooms of the apartment, on three different schedules for weekdays, Saturdays and Sundays. Calculation is done for the total kWh for the entire year, then this value is divided by the full hours of the year and the apartment area to get the value of the internal gains in terms of W/m^2.

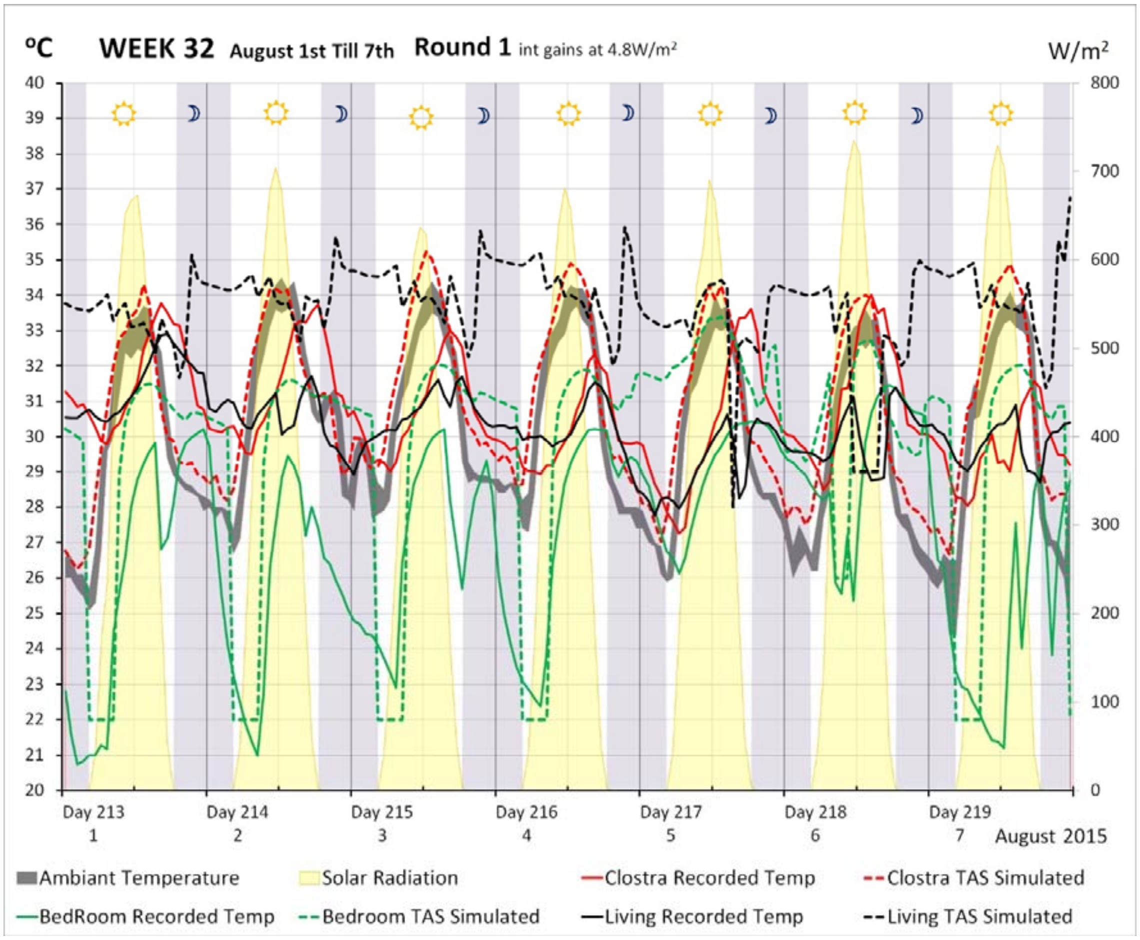


Figure 5.2 Temperature graphs of the three different rooms from week 32: the first round of calibration showing both the recorded and simulated data.

The first round shows that the simulated temperature in both the living area and the bedroom is considerably warmer than the recorded (fig. 5.2). Round two lacking internal gains shows good values for both the simulated living area and clostra. Meanwhile, the bedroom is still not in the acceptable range. Nevertheless, the weighted indices of all three rooms are within acceptable ranges; 26.4 for the CVRMSE and -2.7 for the NMBE.

When U-values are changed for round three (table 5.1) and internal gains are kept null, the living area shows a failed performance with the CVRME at 124, which impacted the weighted value to be above the acceptable levels of 49. Round four kept the modified U-values with 4.8W/m^2 for internal gains; all values were within acceptable ranges with the living area the highest at 29. The fifth and final round (fig. 5.3) further raised the internal gains to 7.5W/m^2 while keeping the modified U-values: all values were acceptable even within the IMPV less than 20 for the CVRMSE and less than ±5 for NMBE. Between round four and five, both bedroom indices rose, whereas they shrunk for the other two rooms. Table 5.2 shows all the five specific rounds and the both the CVRMSE an NMBE values.

Table 5.1 Initial values and updated values of the envelope's thermal properties used in the third calibration run, based on EDSL TAS material calculator.

Material		Thickness (mm)	U-value (W/m².K)	Conductivity (W/m.K)	Density (Kg/m³)	Specific Heat (J/kg.K)	Full Construction U-value (W/m².K)	Conductance (W/m².K)	Time Constance
Concrete Masonry Unit for External Walls	Modified Calibration Value	250	1.9	0.7	2300	3250	**1.7**	2.4	24.9
	Actual Value	130	3.2	0.9	2050	840	**2.7**	5.0	1.7
Hollow Concrete Roof	Modified Calibration Value	500	1.1	0.7	2450	3250	**1.1**	1.4	80.0
	Actual Value	345	1.9	1.0	1568	925	**1.9**	2.9	4.9
Hollow Concrete Slabs	Modified Calibration Value	350	1.5	0.7	2450	3250	**1.3**	1.6	60.7
	Actual Value	345	1.9	1.0	1568	925	**1.6**	2.1	9.3
Aerated Masonry Clostra	Modified Calibration Value	200	2.1	0.7	2450	3250	**2.1**	3.3	13.8
	Actual Value	200	3.1	1.3	2240	840	**3.1**	6.5	1.6
Concrete Masonry Unit for Internal Walls	Modified Calibration Value	100	3.2	0.7	2300	3250	**2.6**	4.7	6.4
	Actual Value	100	3.6	0.9	2050	840	**2.8**	5.5	1.4

Table 5.2 All the characteristics of the five different rounds of calibration with the corresponding values of CVRMSE and NMBE for each of the calibrated rooms and the mean value.

Rounds		IG 4.8 W/m² **1**	IG Nil **2**	IG Nil Modified U-value **3**	IG 4.8 W/m² Modified U-value **4**	IG 7.5 W/m² Modified U-value **5**
Living	CVRMSE	133.2	4.6	124.2	29.1	15.9
	NMBE	-10.3	-0.4	9.6	2.3	-1.2
Clostra	CVRMSE	5.2	3.0	7.9	5.2	4.5
	NMBE	-0.4	-0.2	0.6	0.4	0.4
Bed Room	CVRMSE	110.9	71.5	15.1	2.4	7.7
	NMBE	-8.6	-7.6	1.2	0.2	-0.6
Weighted	**CVRMSE**	**83.1**	**26.4**	**49.1**	**12.3**	**9.4**
	NMBE	**-6.4**	**-2.7**	**3.8**	**0.9**	**-0.5**

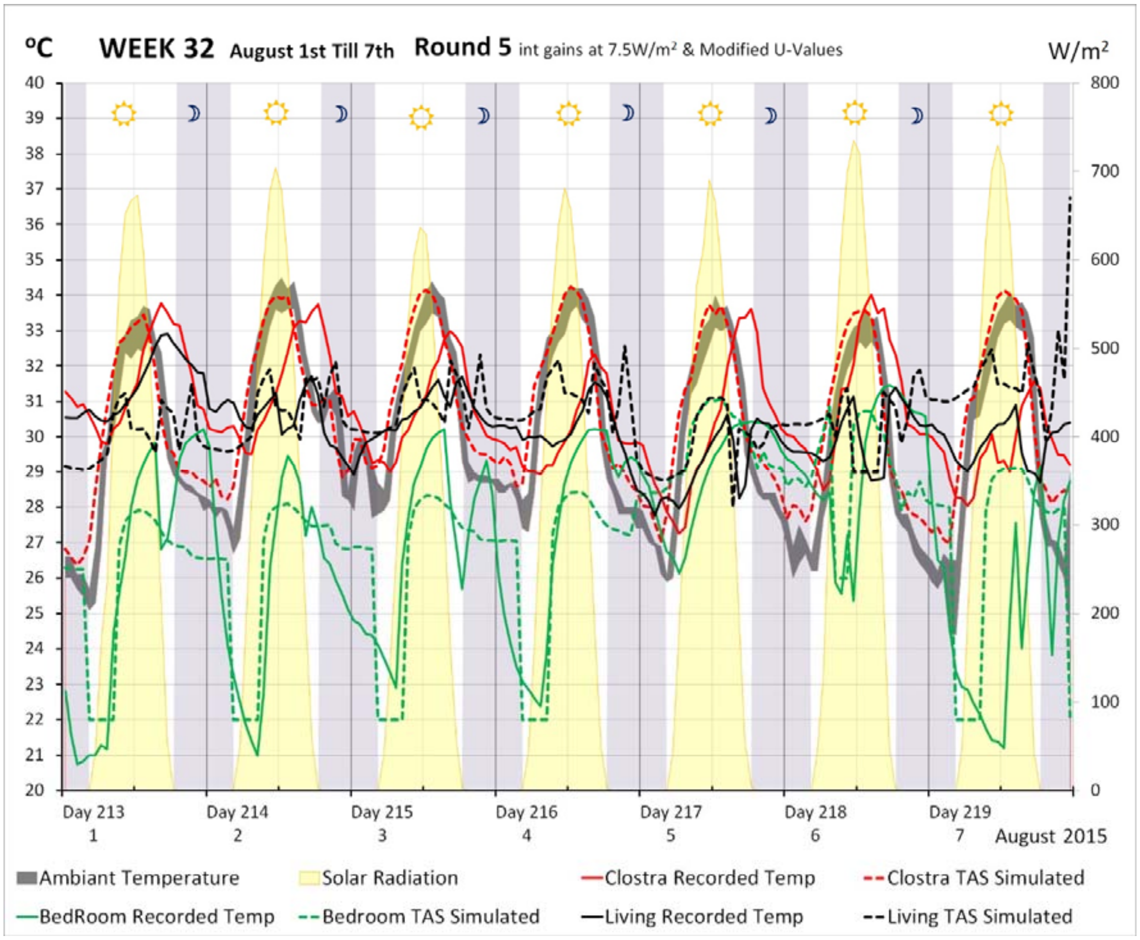


Figure 5.3 Temperature graphs of the three different rooms from week 32; final round five of calibration, when internal gains are raised from 4.8 to 7.5 W/m² and external walls' U-values reduced from 2.7 to 1.7 W/m².K but CVRMSE at 9.4 and NMBE at -0.5%.

At this stage, and based on the indices values, the simulated temperature model is calibrated. Calibration required increasing internal gains and modifying envelope U-values. Looking closely at the temperature graphs of the final calibrated model, the following are noted:

1- In the clostra, the well ventilated semi-enclosed space, simulated temperature is never cooler than the ambient outdoors temperature, when its actual recorded temperature is cooler at least during the daytime.
2- In both the living area and the bedroom, peak simulated temperatures are cooler than the recorded ones.

This calibrated model is re-tested for week 40 (fig. 5.4), the only difference being that the air conditioning is completely turned off during that week, but otherwise internal gains and U-values is kept the same as the ones used for round five.

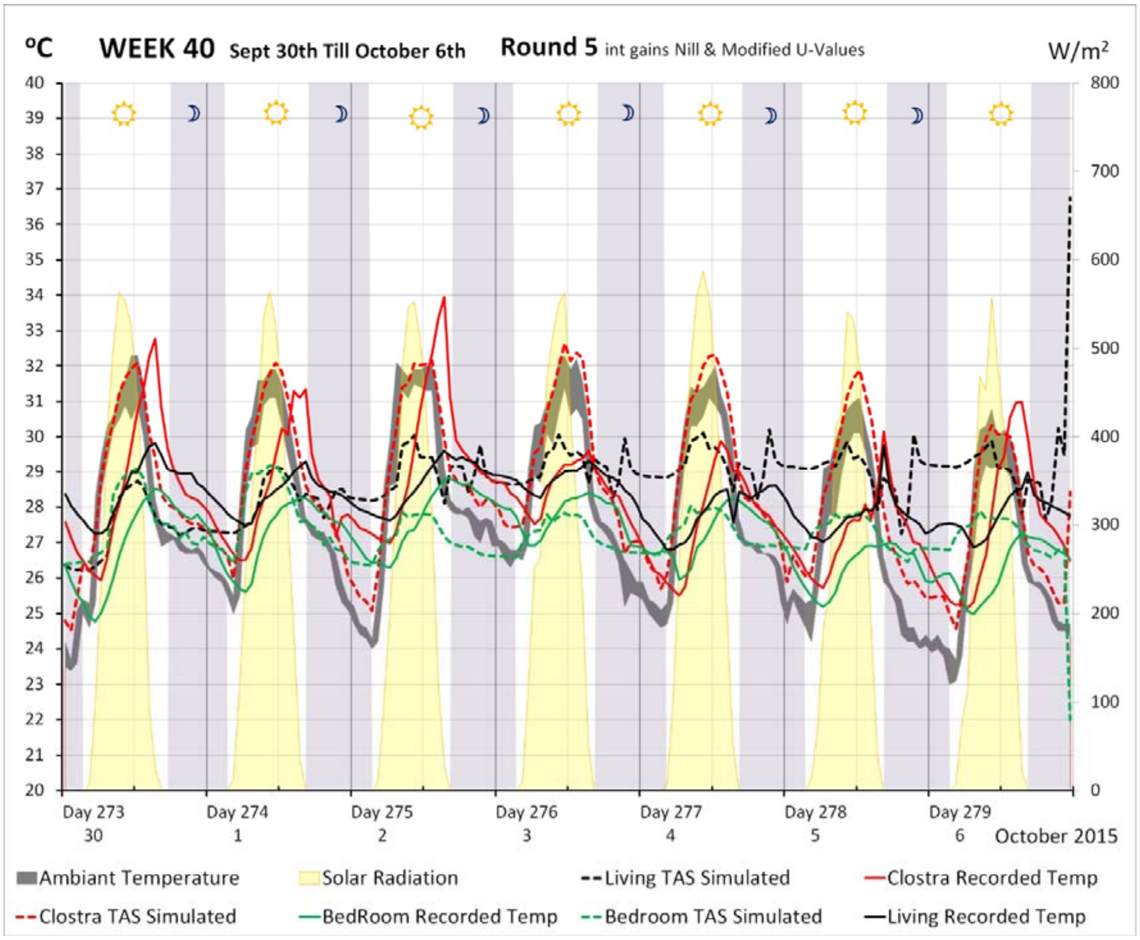


Figure 5.4 Temperature graphs of the three different rooms tested for a different week 40. The modified U-values are kept the same but CVRMSE is 16.3 and NMBE at -1.3%.

The indices show a good fit, even if the values are now higher than the previous reached values (table 5.3). The living area has jumped to 22 (above the acceptable range for the IMPVE), while the clostra showed the most change; from 4 to 17 CVRMSE even if it is not affected by any internal modifications.

Table 5.3 Values of CVRMSE and NMBE from the previous final calibrated round for week 32 and the corresponding values when simulated for week 40 with the same modified U-values.

	Rounds	5 /Week 32	5b /Week 40
Living	CVRMSE	15.9	22.3
	NMBE	-1.2	-1.7
Clostra	CVRMSE	4.5	17.5
	NMBE	0.4	-1.4
Bed Room	CVRMSE	7.7	9.1
	NMBE	-0.6	-0.7
Weighted	**CVRMSE**	**9.4**	**16.3**
	NMBE	**-0.5**	**-1.3**

This first calibration trial shows that temperature calibration can be achieved with good indices values. Furthermore, if the same model with the same input is tested for another period, values would change a little, but the model would remain as an overall valid calibrated temperature model. The next question becomes on how to continue the study with the purpose of finding a construction that will reduce internal summer heat. The U-values of the envelope are already modified beyond what they actually are, and similarly, internal gains are higher than they were (fig. 5.5). Both U-values and internal gains are increased up to almost 60% from their initial values.

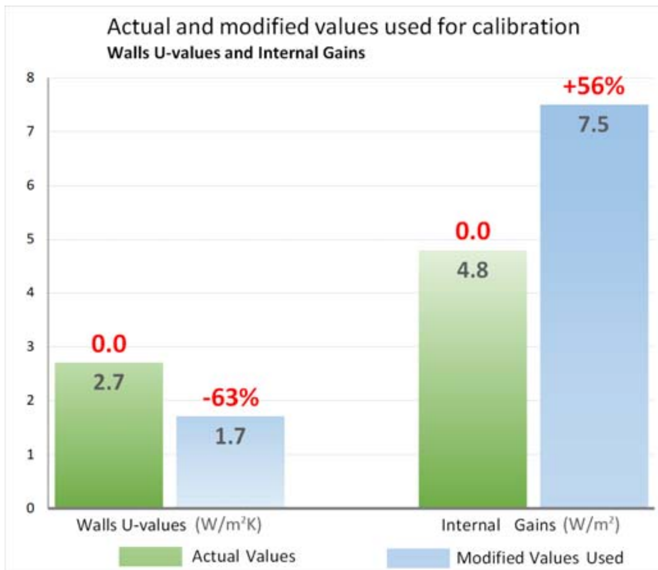


Figure 5.5 Modified values and percentage of wall U-values and internal gains needed to reach good calibration.

5.3 Post Calibration Runs

To proceed to the consequent simulation runs, the following are considered: the changed wall U-value of 1.7W/m^{2}K used in the calibration is considered as a single masonry wall of 150mm width. To simulate a double masonry wall, the same construction is doubled with the addition of a 20mm air gap and another addition of a 25 XPS layer on either the outside, middle, or inside of the wall. The new U-values of the post-calibrated walls are different from the calculated (table 5.4). Results shown in figure 5.6 indicate the cumulative temperature performance of the bedroom and living area combined.

Table 5.4 Values of wall U-values based on expected calculation vs. values used based on calibration process.

	Regular/Calculated U-value (W/m^{2}K)	Calibrated & Used U-values (W/m^{2}K)
150mm Single Wall	2.7	**1.7**
2x 150mm Double Wall +20mm Air Gap	1.3	**0.8**
2x 150mm Double Wall +20mm Air Gap + 25mm XPS	0.6	**0.5**

Furthermore, the same schedule for windows is used as the one for the calibration process. The calibrated model showed a clear difference reaching 7% and 10% among the four different wall constructions. The best performing with minimal overheating was the outer insulated double masonry wall. Both the middle-insulated and the non-insulated had 7% more overheating, and the worst performance was scored by the internally insulated double masonry wall.

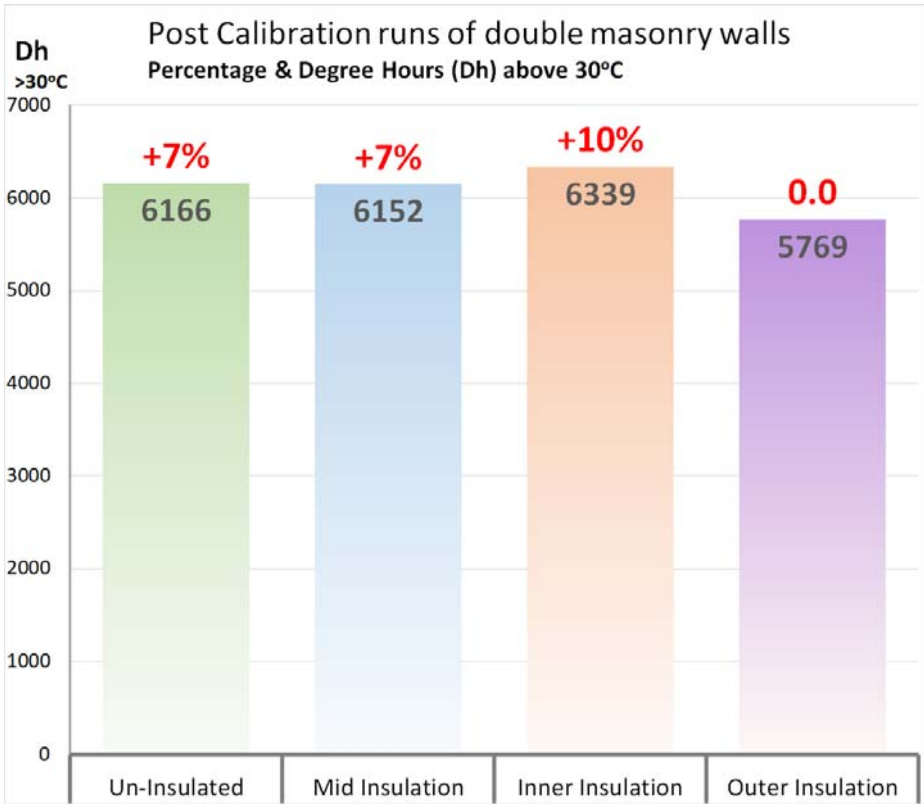


Figure 5.6 post-calibration results based for four different wall configurations. All are double 150mm masonry walls: one has no insulation while the others have a 25mm EXP insulation positioned at the outer, middle, or inner side of the wall. Results of the combined bedroom (north/east orientation) and living area(south/west) temperature performance are shown.

5.4 Conclusion

Following the previous chapter of studying actual temperature behaviour by observing different apartments during Beirut's summer, this chapter used the observed and collected data to carry on with further temperature software studies starting by making a calibrated model. The objective is to assess, based on calibrated model, the temperature performance of various proposed double masonry walls with different insulation location, in terms of least overheating degree hours above 30ºC.

A calibrated model of the previously best performing apartment in chapter 4, is used. Calibration is reached only when some parameters are modified. Internal gains were raised from initial and calculated 4.8 W/m^2 to 7.5 W.m^2 and the walls U-values were reduced from initial 2.7 W/m^{2}K to 1.7 W/m^{2}K. This allowed the calibrated model to fit well within the recommended uncertainty measuring indices of CVRMSE 9.4% and NMBE -0.5%. Furthermore, using the same values for another week gave more acceptable results, but with higher indices of 16.3 and -1.3% respectively. The following step was the post-calibration which took the calibrated values of what is basically a single masonry wall and doubled it to have a double masonry wall with a 20mm air gap in between, and added 25mm XPS insulation on the outer, middle or inner sides of the wall. Within the runs, results showed similar results as were consistent with the literature review: the outer insulation performing best and the inner insulation the worst with 10% more overheating.

Software simulation methods based on a calibrated model did not show convincing results in accurately representing the expected temperature performance of various heavyweight constructions in Beirut’s hot summer. This inevitably pushes the research to opt for experimenting with purpose-built test cells for more representative and valid conclusions.

6 Full Scale Test Cells

6.1 Introduction

So far, the research was based on actual apartment monitoring and software simulation from previously collected data. The data from the apartment observations were valuable to carry on to the software-based research; the limitations of the method were due to various uncontrollable variables within the apartments which might have compromised the comparison. The software simulation outcomes showed that comparative results are sensitive to various changes within the initial data, where reducing envelope U-values, window opening and closure, and increasing internal gains, considerably affect the comparative ranking results. Furthermore, both internal gains and walls U-values were changed to reach acceptable calibration.

All these factors combined (uncontrolled variables, comparative ranking results, modification of physical characteristics such as U-values) indicate the necessity for full-scale test cells as a more appropriate method than software models. The goal is to assess double masonry walls with different insulation configurations under the same conditions within a strictly controlled environment, where user-variables such as windows, shutters and lights can be applied to all cells simultaneously. This would allow the reduction of uncertainties encountered in the previously monitored apartments.

The chapter is focused on the construction, the monitoring and the thermal behaviour of three test cells. The characteristics of the measuring temperature data loggers and the on-site installation of the weather station are introduced. Before a list of all the physical and thermal quantification of the built test cells is included, such as their thermal mass parameter, the heat capacity the admittance or Y-values, and the U-value. The three test cells have the same internal area and roof, but their double cavity walls have different insulation configurations; placed on the outside, the middle, or the inside. By mid-summer, the middle insulation is completely removed. The test cells are located in the small town of Rasmaska, near the Town of Tripoli, on the coastal zone of Lebanon. The recorded four months weather is explained. The next step introduces different methods for non-simultaneous temperature behaviour comparison when variables are introduced at different stages: These variables are external white paint, windows, shutters, added light bulbs, and mechanical ventilation. The results are then discussed, including the performance of the internal and external surface temperatures, along with the effect of removing the middle insulation, the added internal gains from the light bulbs, and the added mechanical ventilation. The proposed methodology allows the research to show and quantify the temperature behaviour of different thermal mass wall configurations.

6.2 Construction

Construction of the three test cells started by mid-May, under the direct and continuous supervision of the researcher (more details for the land search in appendix 4). Figure 6.1 shows the finished test cells, and the technical maps of the three rooms on site and with all relevant details and dimensions are shown in Fig. 6.2 (Further details available in Appendix 5). On August 23rd, 2017 (day 235), three 100 W incandescent light bulbs are added in each of the test cells with the same configuration. During week 34 between August 29 and 31(days 241, 242 and 243) the insulation of the test cell #2 was removed from the middle of the cavity wall. Thus, the U-value for test cell #2 changed from 0.6 to 1.1 W/m^2.K.

Figure 6.1 The three completed test cells showing the internal lights on, just before sun rises from behind the mountains.

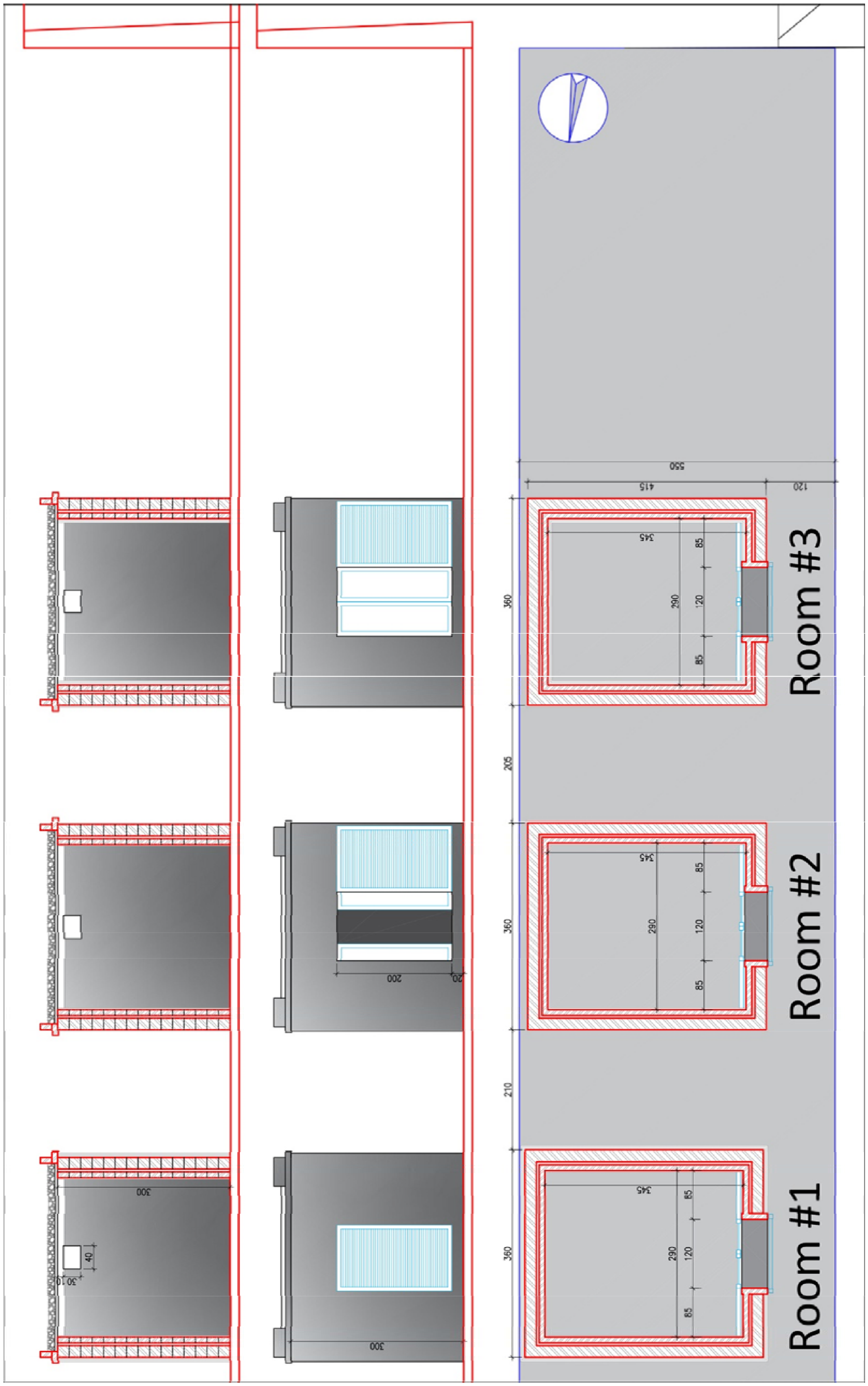


Figure 6.2 The technical maps, plans, sections and elevations of the three rooms

The finished test cells have the following physical characteristics:

a- Internal dimension 3450 x 2900 mm
b- External dimension 4150 x 3600 mm
c- Internal height 3000 mm
d- Internal area 10 sqm
e- Internal volume 30 cu.m
f- The main window is centred on the west elevation and is 1200 x 2000 mm, made of 2 horizontally sliding single panels 6mm transparent (colourless) glass, U-value 6.1 W/m^{2}K. Sliding rails are located inside.
g- The main west elevation has one louvered aluminium panel of 1300 x 2000mm sliding on horizontal rails located outside and to the right-hand side.
h- The east elevation has a centred small opening of 400 x 300 mm at a height of 2500mm.
i- U-value of walls in test cells 1 and 3 (external and internal insulation) is 0.6 W/m^{2}K.
j- U-value of walls in test cell 2 (middle insulation) is 0.7 W/m^{2}K.
k- U-value of non-insulated test cell is 1.1 W/m^{2}K.
l- U-value of roof is 1.5 W/m^{2}K.
m- U-value of the slab on grade is 4.0 W/m^{2}K

More thermal parameters are calculated and shown in table 6.1.

6.2.1 Avoiding pitfalls with simultaneous observation

Chapter 3.2 explained the difference between steady state and transient heat transfer, where in a lab setting steady state research look at the unidirectional heat transfer through a specific envelope (external to internal), with no consideration for any other internal heat source. Transient heat transfer research on the other hand, focus on all the heat sources, both internal and external.

within each test cells the internal heat sources are

1- The sun rays falling on the walls and floor through the window
2- The convective heat source of natural air movement going into the test cells through the shutters or the open windows.
3- The direct heat from the three-incandescent lights emitting a total of 300W

Also, within each test cells, heat transfer occurs through its envelopes as following:

1- Conductive heat transfer through walls and roofs:
   This happens when the outer layer of the envelope is heated, and heat is transferred to the inner layers through convection.
2- Radiative heat transfer through walls, roof and slab on grade:
   a. This primary reason is the result of direct sun rays falling on the walls and the slab on grade. These will store the heat and release it through radiation.

b. The secondary reason is the heat gained from the three-incandescent lights which will be stored and released from the walls, roof and slab on grade.
c. All surfaces will also radiate heat into the test cells, and into the outdoors as well

More can be said about the heat transfer within the double masonry walls and the air gap where a combined conduction (solid masonry and plaster) and convection (air gap) heat transfer occurs. The advantage of simultaneous observations is that while acknowledging that each envelope is worth a thorough study, and the results are the combined effect of all heat transfer from all the envelopes. Yet when one and only one envelope has different characteristics, results will specifically reflect these specific characteristics.

To further assert the above argument, it should be mentioned that simultaneous construction by same team of construction workers also add a further advantage to the study where same quality and eventually defaults would happen in all three test cells. This particularly could be critical in two cases: (1) the window installation and (2) the roof closing on the air gap within the double masonry walls. As such, for the window railings, same attention is given to the installation within the three test cells, and instead of insisting of a fully sealed structure, the aluminium window frame was made to keep an average gap of 8mm around all the three window openings. Similarly, for the roof air gap closure detail: the 49mm timber roof planks cross the 40mm air gap to rest on the outer 200mm walls, and a 160mm loose gravel bed covers those planks.

Thus overall, the results contained in the test cell study do reflect the heat transfer specifically within the different wall configurations.

6.2.2 The instruments

A Davis weather station is installed on the nearby elevated gate structure, and two data loggers for dry bulb and globe, or radiant air temperature are installed in the centre of each test cell on a thread linking the timber roof to a nail in the concrete floor. The ambient air data logger is at head height some 1600mm, whereas the radiant air Data logger is at 1350mm, both from floor level (fig. 6.3).

Furthermore, the west wall with the opening has an internal and external surface temperature data logger.

All data loggers used are **Tiny Tags +2**; recording data at the hour including minimums and maximums.

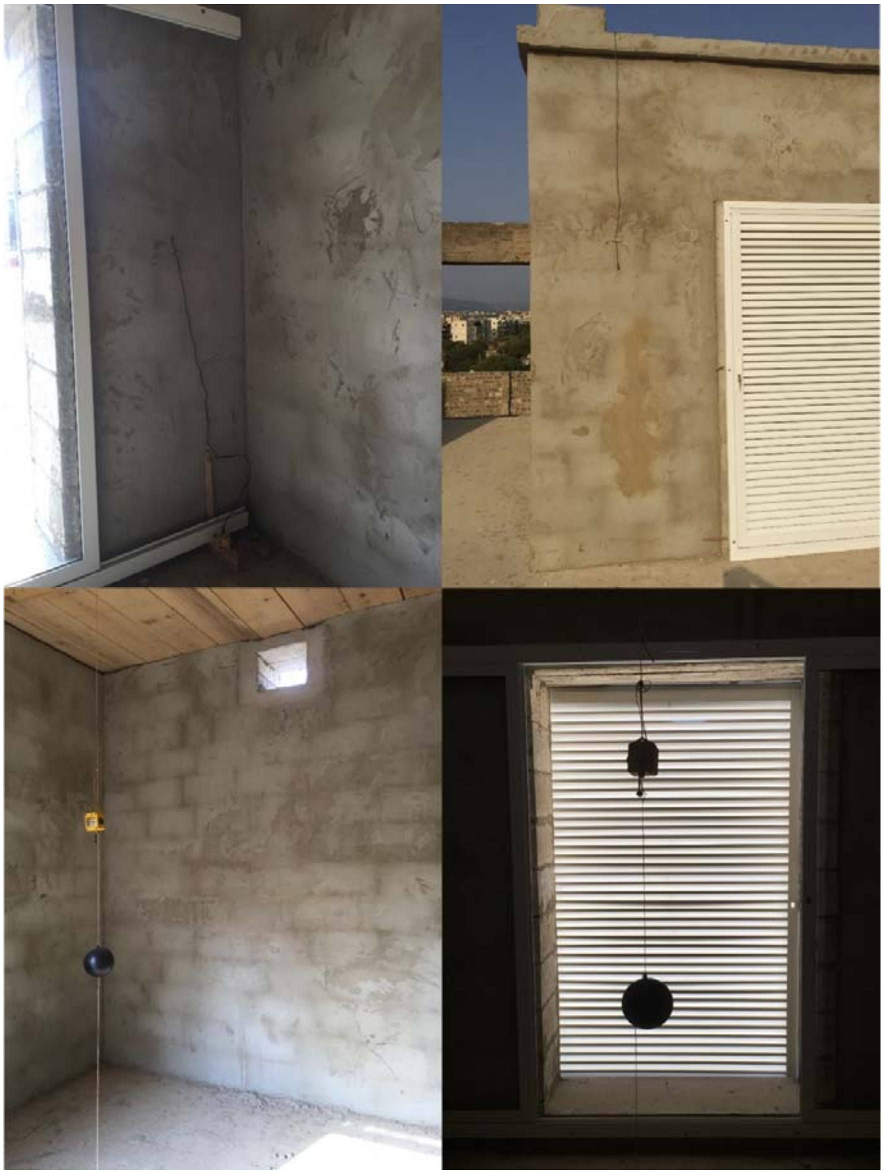


Figure 6.3 The tiny tags +2 data loggers with the inside and outside surface probes, and the ambient and radiant air temperature hanging on a thread in the middle of the room at different heights.

The Davis weather station (fig. 6.4) records the necessary data such as air temperature, relative humidity, wind direction and velocity, and solar radiation. These will be used both for the study and to prepare a partial weather file for issues encountered during comparative software *vs.* reality simulations, and eventually calibration. The weather station is also available live online on the link below. The weather station is set to record data at half hour intervals, yet the values of the hours are only used.

After scanning the weather link in the surrounding area, a couple of stations are located nearby. The nearest station is contacted for eventually missing data (except solar). Eventually, data are used for the following missing days:

(a) Week 25; Days 170-171-172; June 19-20-21
(b) Week 27; Days 186-187-188-189; July 5-6-7-8
(c) Week 31; Days 213-214-215; August 1-2-3

They will be noted as from a nearby station whenever they are used in corresponding graphs.

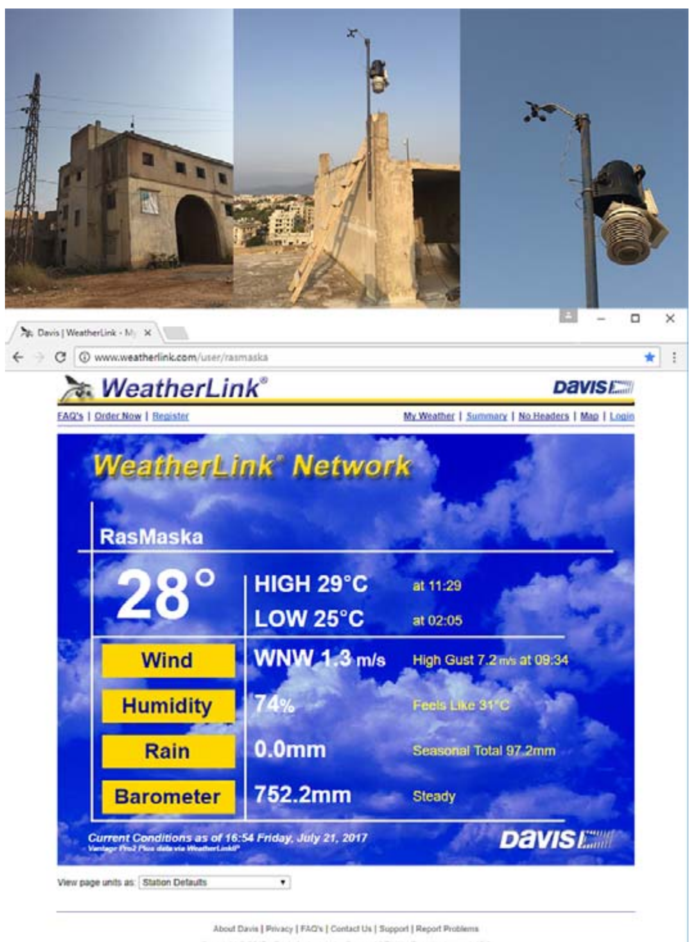


Figure 6.4 The location of the Davis weather station on the top of the adjacent structure, and the online link for the live data at www.weatherlink.com/user/rasmaska, available online since June 22, 2017

The Tiny Tags +2 data loggers are 2 to 4 years old and not factory calibrated ever since. The electronic ban on Beirut-London flights made re-calibration impossible, hence they were manually calibrated. However, a comparative and confirmation analysis of their accuracy was performed as follows:

Some 15 data loggers were put to record temperatures every 2 minutes, sequentially, they were put in a fridge, a freezer, and then in the outside shade for a total length of thirty minutes in each of the different locations. They are all positioned in a row, next to each other with the sensors facing the same direction.

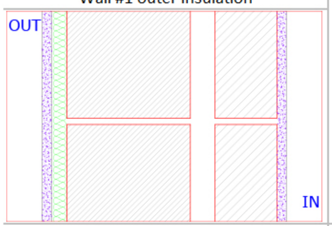
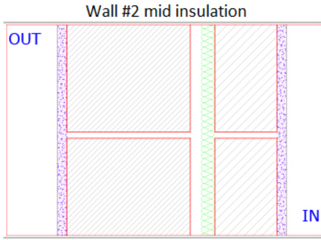
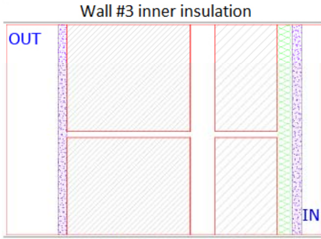
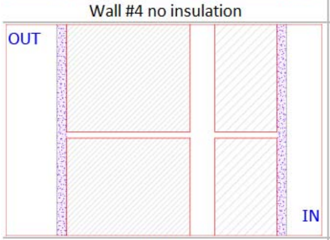
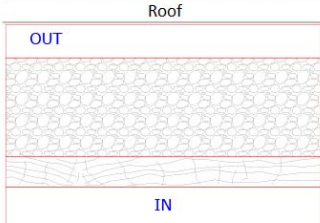
All recorded values were evaluated, and the best three nearest values were marked and given one mark/point, and the second top three were marked as well. Differences in values are within the second decimal only (100ths of a degree Celsius). After counting their points, the best three with the least differences were used as room ambient air data loggers, whereas the next three were chosen to be the test cells' radiant data loggers.

Same method is applied for the surface temperature loggers where the surface probe is properly fixed to the fridge's and the freezer's internal surfaces.

6.2.3 Quantifying the Test Cells

Table 6.1 shows different thermal parameters (refer to Chapter 3.2 for expanded definitions). They are calculated using the free downloadable dynamic thermal properties calculator from MPA, UK Concrete Centre (2010).

Table 6.1 Calculated U-values, admittance or Y-values, heat capacity of K-values, and thermal mass parameters of the construction elements of the different test cells. MPA dynamic thermal property calculator is used except for the U-values* where the EDSL TAS values are shown instead.

Construction	U-Value* W/m^2K	Y-Value Admitance W/m^2K	K-Value Heat Capacity kJ/m^2K	TMP Thermal Mass kJ/m^2K	Average U-Value (of Opaque Surfaces)
Wall #1 outer insulation 	0.6	5.4	219	1069	0.7
Wall #2 mid insulation 	0.7	5.7	219	1069	0.8
Wall #3 inner insulation 	0.6	1.3	14	339	0.7
Wall #4 no insulation 	1.1	5.4	219	1069	1.1
Roof 	1.5	3.5	188		

The parameters include: thermal mass parameter (TMP); heat capacity of K-value; and admittance or Y-value. The U-values shown are from EDSL TAS since MPA does not show these values.

Starting with the TMP, a heat capacity value of 100mm is used for the outer insulation (wall 1), middle insulation (wall 2), as well as for the no insulation (wall 4), whereas for the inner insulation (wall 3), it is left to the insulation layer only. TMP is calculated to be 1069 kJ/m^{2}K for walls 1, 2 and 4 (up to the cavity), and 339 kJ/m^{2}K for wall 3, with the former showing high to very high thermal mass compared to the latter of slightly above medium thermal mass.

Walls of Rooms 3 TMP 250 < **339** <<450

Walls of Rooms 1,2 & 4 TMP 450<<< **1069**

A higher Admittance or Y-value is expected to increase the Δt between the mean internal and external temperature, and consequently less fluctuation is to be expected. This is particularly shown in the inner insulated cell with the lowest value of 1.3 W/m^{2}K, whereas both outer insulated and non-insulated walls have the same value of 5.4 W/m^{2}K, and the middle-insulated wall at 5.7 W/m^{2}K.

6.2.4 Rasmaska summer 2017 Weather

The weather station installed on site near the test cells in the northern town of Rasmaska recorded the following data seen in figure 6.5, whereas the hottest two months of August and July are detailed in these observations:

(a) Summer 2017 had a July hotter than August with mean temperatures of 28.1 and 27.7^{o}C respectively.
(b) Hottest mean days temperatures are 30.7 and 30.4^{o}C for July and August respectively.
(c) Coolest mean night temperatures are 25.1 and 24.4^{o}C for July and August respectively.
(d) Hottest recorded temperatures are 33.8 and 33.4^{o}C for July and August respectively.
(e) Hottest day temperature is usually in the afternoon between 4:00 and 5:00pm, well past the solar noon (around 12:40pm) and a couple of hours before sunset (6:50-7:15pm)
(f) Coolest night temperature is in the hour before or within day break (4:00 and 5:00am)
(g) Wind cycle kicks off in the late morning, around 9:00am, until late afternoon around 6:00pm. Day wind has a faster speed than night wind with a value of 3.66m/s during August.
(h) Night wind cycle starts between 9:00 and 10:00pm until the hour before day break 3:00am with a value of 1.02 m/s for August.
(i) The mean diurnal difference between day maximum and night minimum varies a little between 7.0; 5.6 and 5.9K for June, July, and August respectively.
(j) Relative humidity is high with a mean above 70%RH and low near 60 and high above 80.
(k) Hourly solar radiation varies between 193 and 235 W/m^2 for August and July.

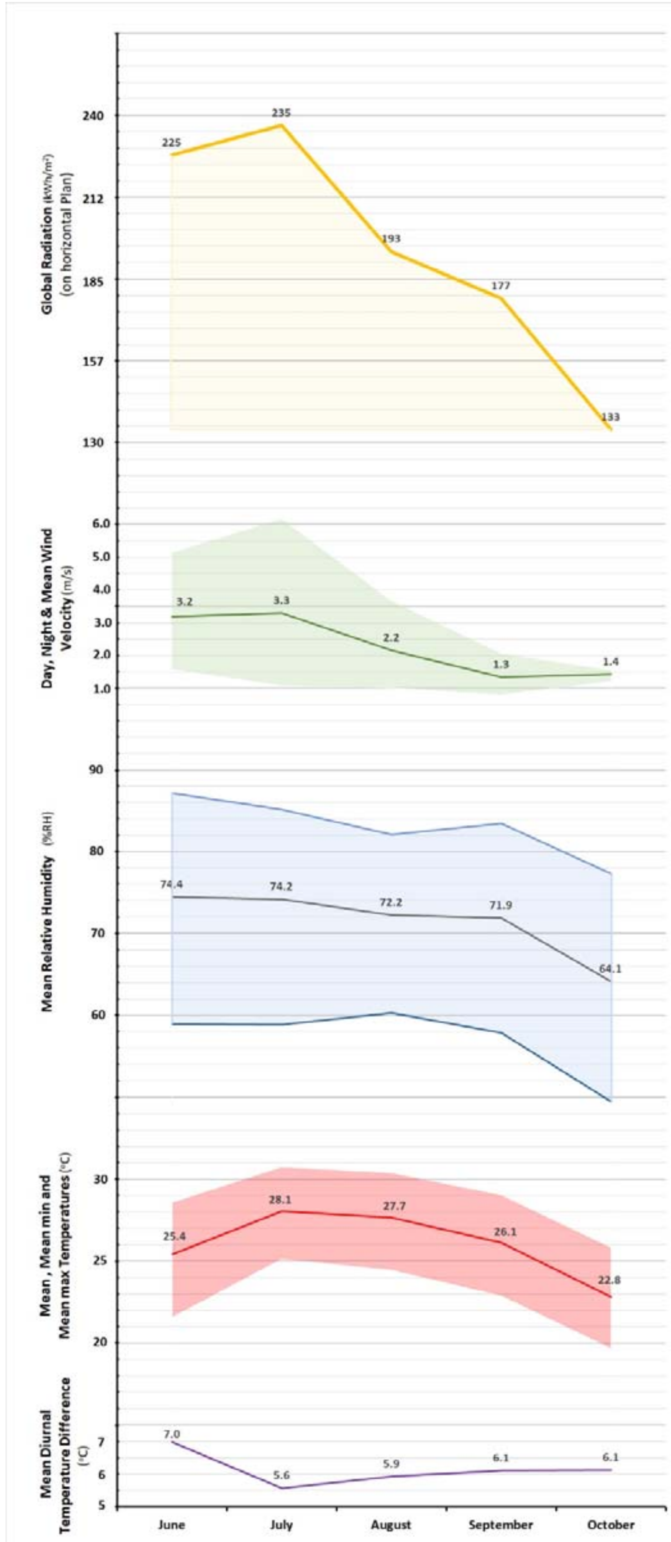


Figure 6.5 Overall recorded weather data from the Rasmaska weather station for summer 2017.

6.3 Non-Simultaneous performance assessment

Different assessment methods for non-simultaneous temperature performance are introduced in this section. The aim of this portion is to observe test cells with different parameters in parallel. The results for such a case is clear but can get complicated when additional variables are added such as white external painting, closing and opening glass windows and shutters, adding ventilation, and internal gains. The challenge becomes on how to assess these new non-simultaneous observations and reliably pinpoint the effect of individual parameters on keeping the internal temperature at its coolest. In other words, how to combine the continuously changing external weather data (ambient air temperature and solar radiation) with the measured internal temperature in order to find an adequate method of assessing which days and what specific parameter(s) had the best impact for a better internal temperature performance. The proposed methods that will be expanded are the following:

(a) Degree days calculation and ∆ degree hours

(b) Summation of hourly ∆t for entire day

(c) Summation of hourly ∆t for night and day

(d) Combined ∆t with day's min/max temperature

6.3.1 Degree hours

The first method consists of the degree hours (Dh) defined as the summation of the number of degrees on an hourly recording above or below a certain benchmark temperature (Szokolay 2008). In this case, the degree hours' calculation in the test cells is feasible, but with the change in day and night ambient air temperatures, the proposed method applied can be:

a- Calculate the $\mathbf{Dh_r}$ at a set temperature, for the different parameters under study.

b- Calculate the $\mathbf{Dh_a}$ at the same set temperature for the outdoors ambient air.

c- Calculate the ∆ $\mathbf{Dh_r\text{-}Dh_a}$ for the different parameters.

These values will show which of the un-simultaneous parameter has better effect on temperature performance. It is important here to note that the degree hours in this case is not a performance indication for overheating as what was used before. The flexibility of the degree hours is that it can be used for different outcomes and measurements. For example, in this case, using the 24°C as a benchmark only for comparative days might not show any temperatures above 30°C.

The second method is the summation of hourly ∆t by calculating the hourly ∆t between the test cell temperature and the recorded air temperature and compare the daily sum and mean values of these differences between the different parametric runs (the sum is the same as the (Dh_r-Dh_a) of previous method).

The third method is an upgraded version of the previous method where sums and means ∆t are now further divided into day and night performance; thus, taking into account that day and night temperature performances are different.

This last method, more complex than the previous ones, is the most accurate. It starts by looking at days with similar ambient air max-min Δt of not more than ±0.2°C difference. Then, the Δt max between the room and outdoors are compared. The lower values will show better performance. In addition to these numerical and calculated factors, the overall day temperature graph should be also compared to make sure that day peak time falls within the reasonably same time slot. Further comparisons can also include the overall daily solar radiation graph (that should also look similar) and wind patterns (direction and speed).

Good examples can be found on days 198 and 217 (July 17 and August 5) which show that the white-painted external walls have performed better.

Bad examples can be found on days 192 and 216 (July 12 and August 4) where with Δt values of 7.7 & 7.9K respectively, on day 192, the day's peak exceptionally occurred at 8:00am in the morning. In all these cases, the peak temperature did not exceed above 30°C which explains the reasoning behind keeping the Dh above 24°C to avoid compromising the results.

6.4 Results: Three Test Cells Simultaneous Monitoring

Both the Dry bulb temperature (DBT) and the globe temperature are monitored and recorded inside the test cells. 'internal temperatures' refer to the dry bulb air temperatures inside the test cell, and all 'outdoor' 'external, or ambient temperatures' refer to the dry bulb air temperature. unless otherwise specified. The first part of the following study is looking at weekly temperature graph of DBT. The second part looks at overall temperature performance of the entire monitored period using the Dry Resultant Temperature (DRT). This is the equivalent to the mean Dry Bulb and Globe Temperature recorded with the two-data logger installed in the test cells (The globe temperature data logger is enclosed in a black sphere).

6.4.1 Internal Dry Bulb Temperature (DBT) Results

During the first few weeks, different window and shutter schedules are implemented (always at the same time) in all three test cells. The early monitoring period showed that each test cell performed differently with significant day and night differences:

During the day, test cell #1 (outer insulation) had the lowest DBT peak, followed by test cell #2 (middle insulation), while test cell #3 (inner insulation) recorded the hottest peak. During the night, test cell #1 maintained the lowest DBT, but test cell # 2 recorded the warmest ones.

Initially, during days 172, 173 and 174 on June 21, 22 and 23 (fig. 6.6), before the installation of the shutters, the windows are kept closed for three full days; internal DBT trends with warmest and coolest temperature rose noticeably, and then dropped as soon as the windows are opened, and the shutters closed. Peak temperature of the coolest test cell #1 rose from 28.1°C on day 172 to 28.9°C on day 173 and reached above 29.7°C on day 174, whereas the hottest test cell #3 peak temperature starting at 29°C rose to 29.9°C and reached 31.4°C on day 174. Accordingly, the peak temperature difference between the hottest (test cell #3) and coolest (test cell #1) became larger, starting at 0.9K and reaching almost 1.7K. Furthermore, the day's ambient/outdoor DBT on day 174 (June 23) is 25.9°C whereas the previous day it was 27.1°C with similar solar radiation levels on both days. Hence the continuous window closure accompanied with a 1.2K drop in the day's ambient DBT resulted in a 1.5K rise of the internal temperature in the hottest test cell#3 and 0.8K in the coolest test cell #1. During night, the lowest ambient air temperature starting at 20.8 °C continued to drop further to 20.3°C and then increased back to 21°C. Internal night DBT rose continuously for the hottest test cell #2 from 23.8 to 25.7 and reached 26.6°C making a total increase of 2.8K.

During day 174 (June 23), the windows are kept closed for the entire day; they are only opened from 7:55pm to 8:55pm. Opening the windows was not apparent because the overall (internal) DBT was dropping by that time. However, the re-closure of the windows is clearly traced with a very small but sharp rise in temperature from 0.2 to 0.3K. Even though this is not perceivable in terms of human comfort, yet this shows specific temperature behaviour of the various wall configuration under study.

When the windows are installed, and the shutters are kept closed around early afternoon of day 175 (June 24), and before the day's peak, test cells' peak temperature dropped more than 1K from the previous day with values varying between 30 and high 28°C. The day's peak temperature (175 June 24) was actually 28°C, 2K warmer than the previous day.

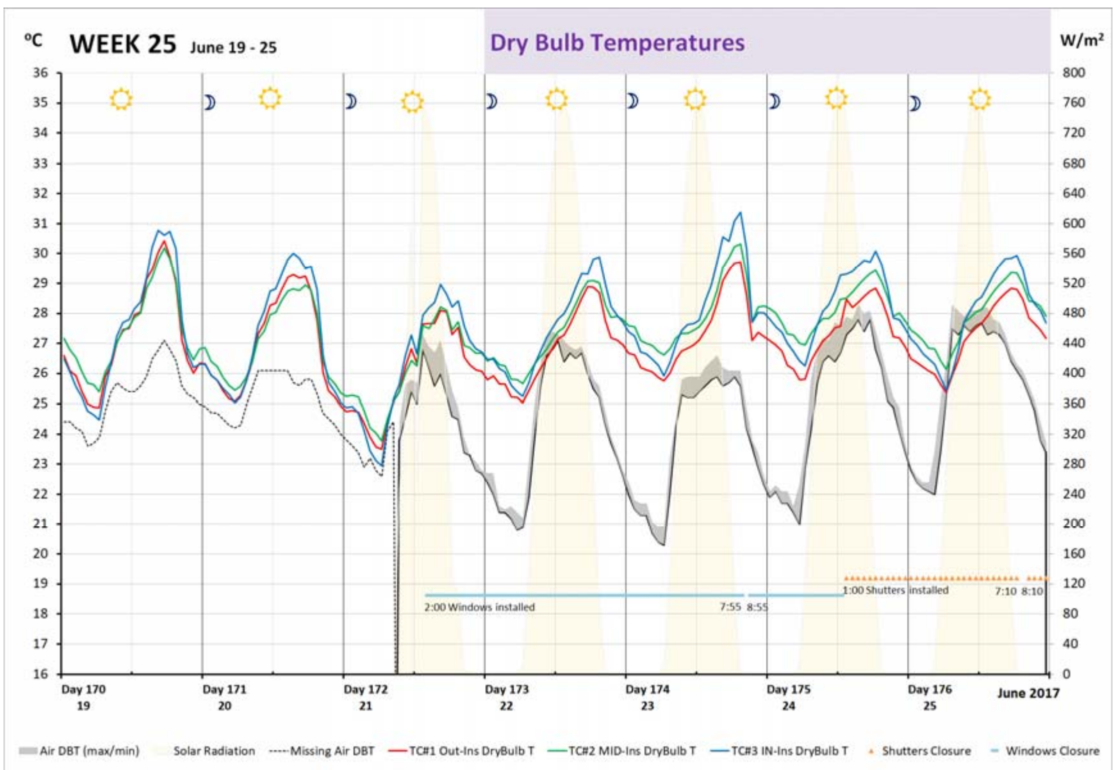


Figure 6.6 Internal DBT graphs for week 25 (June 19 to 25, 2017; days 170-176). Days 170 and 171 the weather station is not installed yet hence no weather data

It is interesting to point out a tipping time where one test cell with a period of cooler internal DBT than another test cell shifts to having a warmer temperature for another period. The temperatures of test cell #2 and #3 changed during the mornings (days 174,175 and 176), between 9:00 and 10:00am, and in the late evening and before midnight around 10:00 and 11:00pm. From morning until late evening (daytime), the internal DBT of test cell #3 (internal insulation) is the hottest, followed by test cell #2 with the middle insulation. After the tipping time (during the night), the DBT of test cell #2 becomes the warmest followed by test cell #3.

During week 26 (fig. 6.7), the windows are always open, and shutters are opened in a couple of mornings and closed later on. The days' DBT peaks sharply rise on day 179 (June 28) from 28.9 °C to 30.1°C and 29.4 to 32.2°C on day 183 (July 2). This abrupt rise resulted in a couple of morning hours where internal DBT is lower than the external in all three test cells. This difference reached up to 3K on day 183, yet the internal peak DBT only increased between 0.8 and 1K.

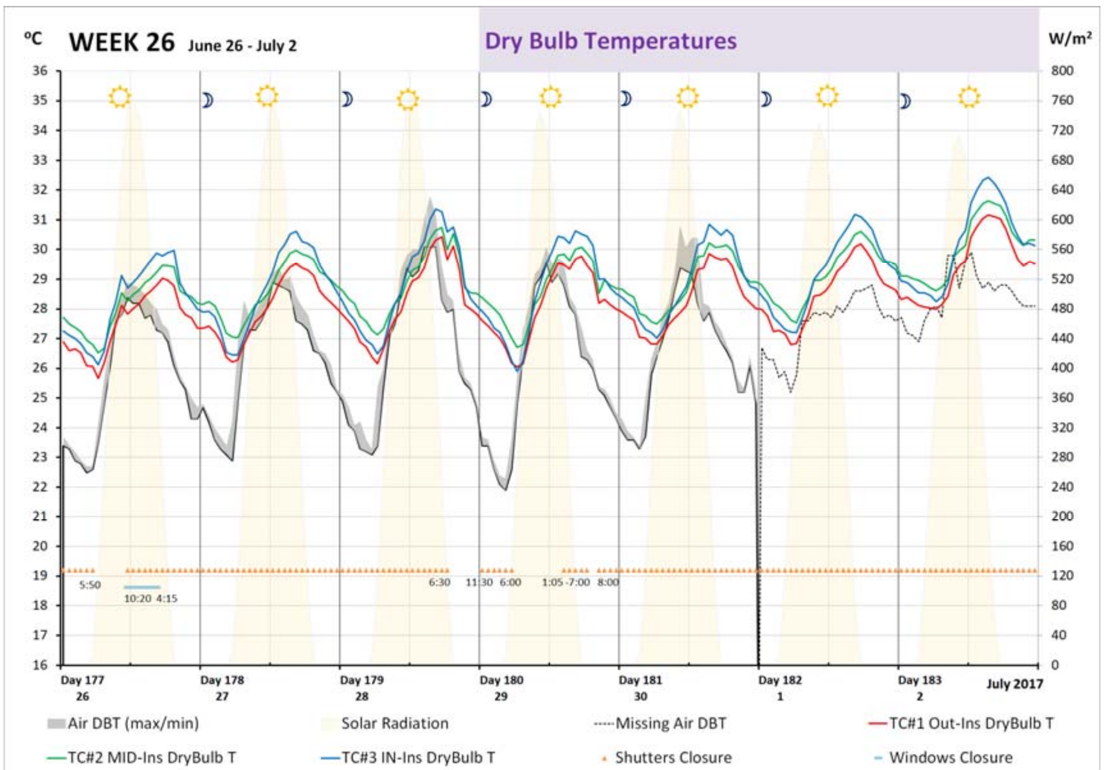


Figure 6.7 Internal DBT graphs for week 26 (June 26 - July 2, 2017; days 177-183).

During the night, drops in the nights DBT affect little internal temperatures. This is evident during the night of day 179-180 when lowest air temperature dropped from 23.1°C (previous night) to 21.9°C with a difference of 1.2K. Accordingly, lowest internal air temperature dropped from 26.2 to 26.1 (0.1K) for test cell #1; from 27.1°C to 26.7 °C (0.4K) for test cell #2; and from 26.5°C to 25.9°C (0.6K) for test cell #3.

Internal peaks and valleys always happen at various times; as a general trend they occur a few hours after the day's hottest or the night's coolest peak.

For a few nights, the night's lowest internal DBT was recorded in test cell #3 (internal) with only a 0.2- 0.6K difference than test cell #1 (external). As the monitoring progresses, these exceptions become more and more frequent, until it becomes the dominant behaviour from week 31 (August) onwards.

Closing the windows for an extended time have caused a gradual raise in internal DBT, but the daily short-term use of shutters and the closure and opening of windows was not evident to observe. During week 28, days 191-194 on July 10-13, (fig. 6.8), shutters and windows are closed from noon time until right after sunset in an attempt to see if this method has any impact on cooling day-time peaks or night-time temperature. No significant temperature behaviour is observed, or to be more accurate, it is not possible to quantify and compare the results of this modification to an open window scenario. Nonetheless, when both windows and shutters are closed for an extended time (over 6 days) from day 195 to 200 (July 14-19) (fig. 6.9), the overall internal DBT trend did not show any considerable differences as seen in the previous window only closed scenario.

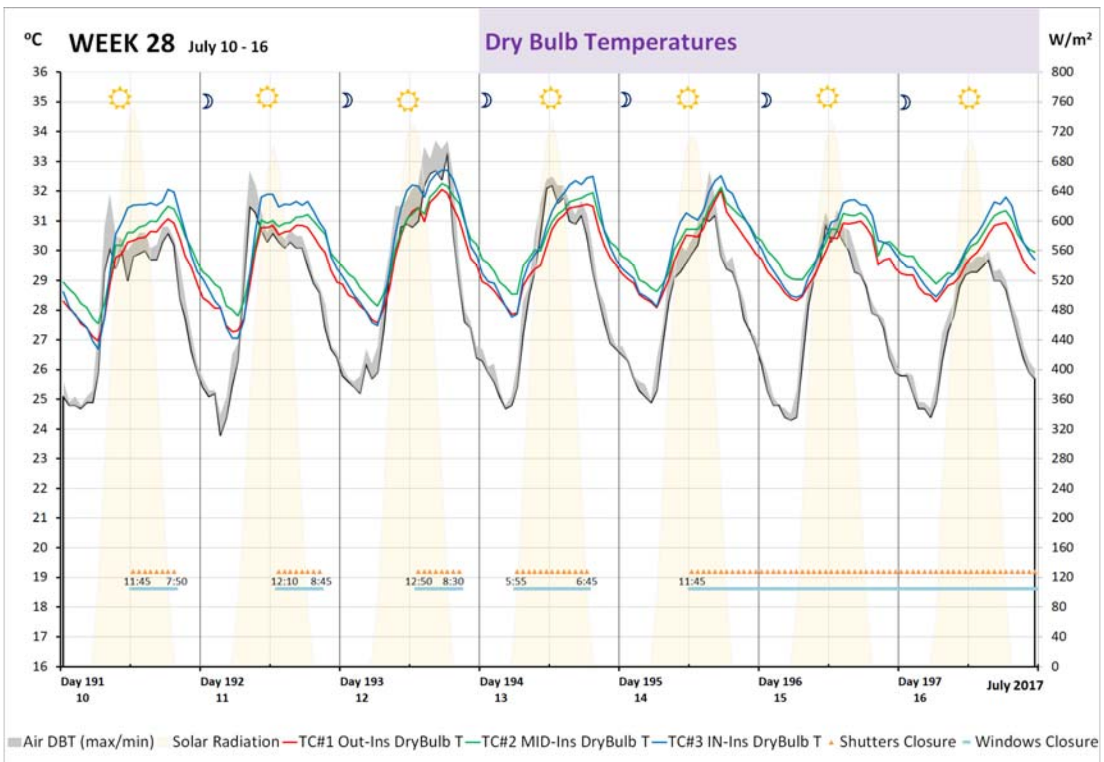


Figure 6.8 Internal DBT graphs for Week 28 July 10 till 16, 2017; days 191-197

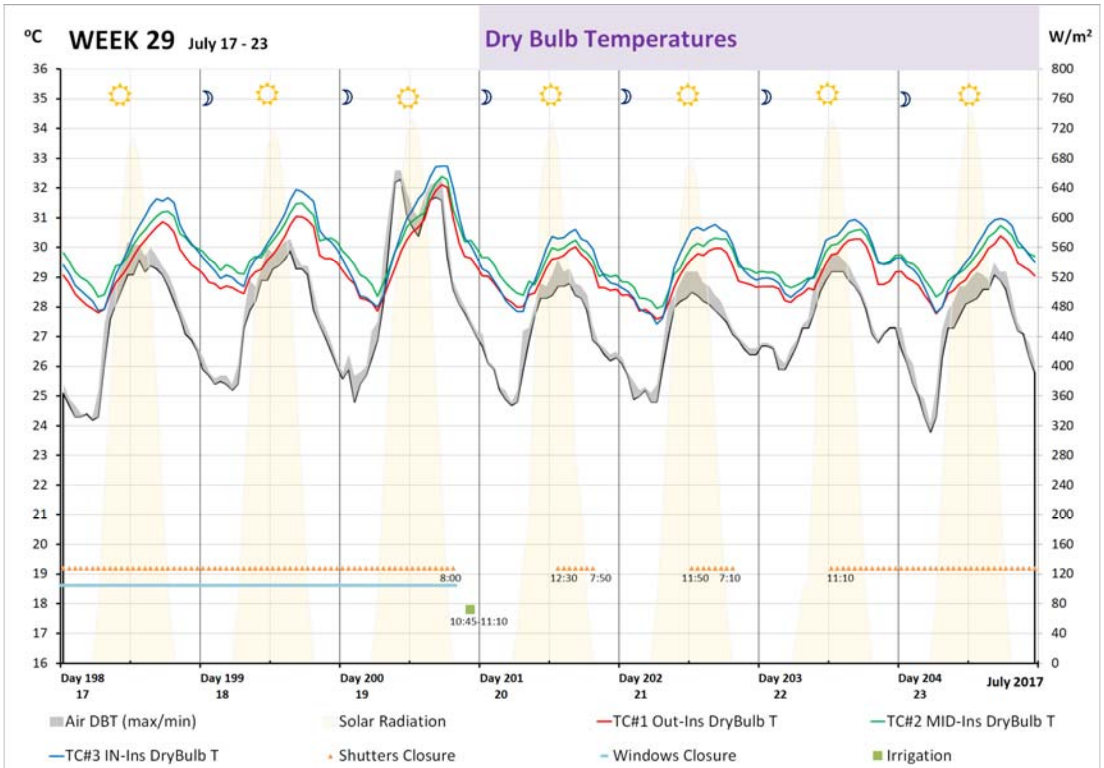


Figure 6.9 Internal DBT graphs for Week 29 (July 17-23, 2017; days 198-204).

Different attempts of irrigating the front side of the test cells with both windows and shutters open are done to see if such a practice has any impact on the internal rooms temperature. It should be noted that this practice used to be relatively common in contemporary houses built either of stones or plastered masonry block. This practice attempts to flood the concrete terrace/front yard with fresh water in the late afternoon or early evening in order to reduce the excess heat of the afternoon. The numerous attempts (days 200; 208; 213; 231; 234 and 237) did not show any clear impact in the temperature graphs except during two instances; the first consists of a two-day comparison and the second is based on observation:

(1) Day 179 (June 28) and day 231 (August 19) had a similar instantaneous surge in temperature of less than half Kelvin. This surge resulted in a marked rise in the internal temperature on day 179; whereas on day 231 (fig. 6.10), the surge (more prominent this time) although coincided with the irrigation time, resulted in only a minor rise in the test cells DBT.
(2) On day 234 (August 22), irrigation was done at noon time between 12:35 and 12:55pm. The internal DBT in the three test cells show (fig. 6.11):

A clear and sharp drop is recorded on the graph at 1:00pm. A drop of almost 1K in test cell #3 which rose back one hour later to a slightly less or equal temperature prior to the drop. The day's DBT did not have similar sharp drops and rises.

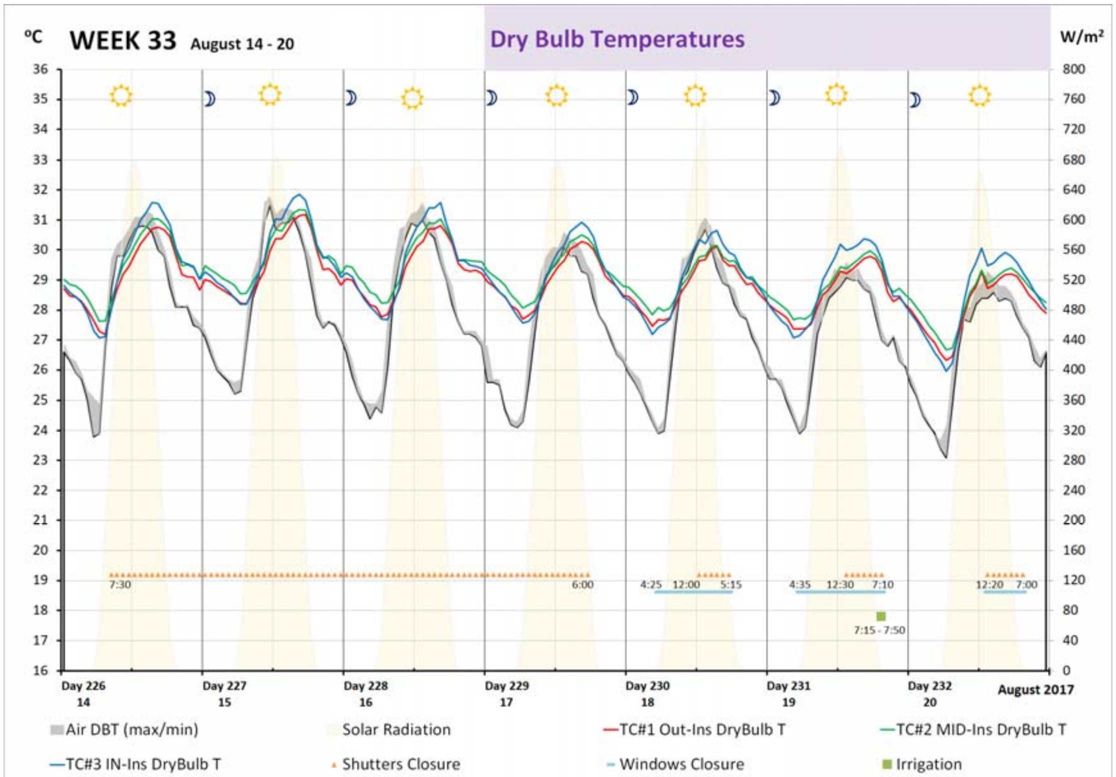


Figure 6.10 Internal DBT graphs for Week 33 (August 14-20, 2017; days 226-232).

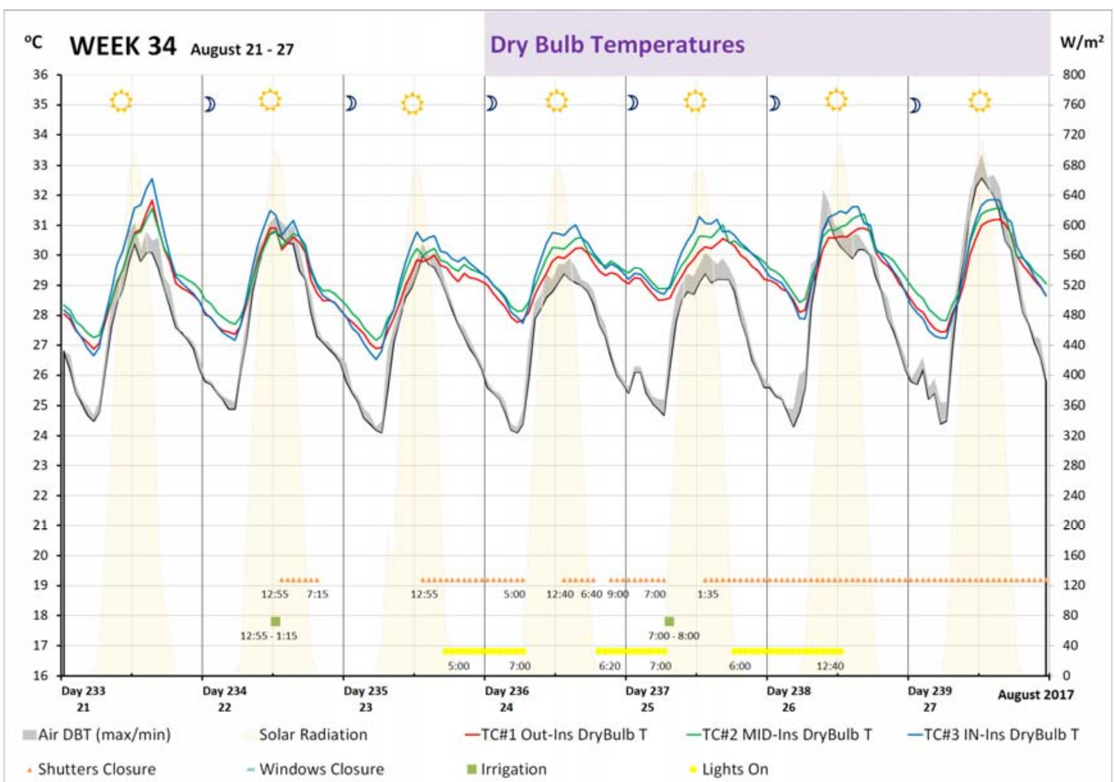


Figure 6.11 Internal DBT graphs for Week 34 (August 21-27, 2017; days 233-239).

On a single occasion during which the windows are closed, on day 209 (July 28; fig. 6.12), the impact of no ventilation is clearly evident by the sharp drop of day's ambient DBT from late afternoon to dawn, while the internal DBT drop is more gradual and slower.

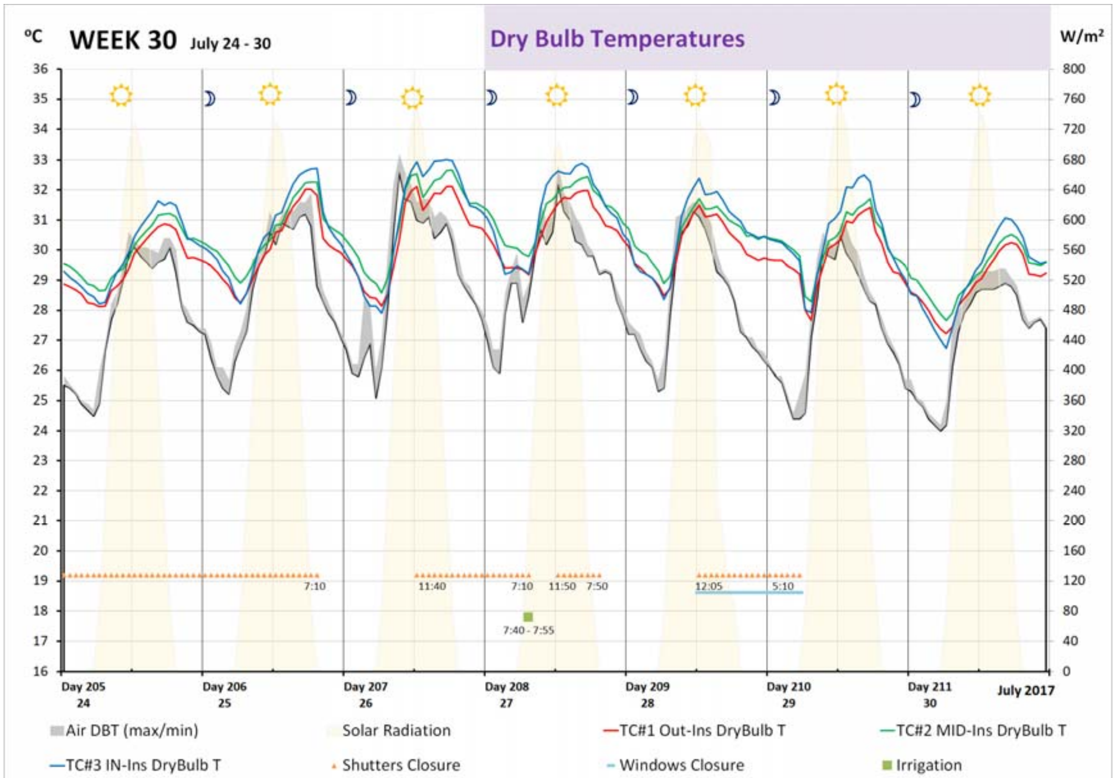


Figure 6.12 Internal DBT graphs for Week 30 (July 24- 30, 2017; days 205-211)

6.4.2 Impact of white paint

In order to assess the impact of the external white paint on the internal DBT in the three test cells, similar days' DBT (above 24ºC and not more than ±1ºC difference) are recorded before and after the white paint application:

(a) Days 217 and 218 (August 5 and 6), the effect of white paint addition was compared to day 202 (July 21) before white paint (fig. 6.13).
(b) Day 217 (August 5) for white paint to be compared to days 201 and 204 for July 20 and 23 without paint.

It should be noted that, on day 217, both windows and shutters are closed during day time from 4:30am until 6:00pm. On day 218, only the shutter is closed from 8:20am and not opened again for the next two days. And on day 202, the shutters were closed from 11:50am until 7:10pm. The entire day's Dh of outdoors DBT (above 24 ºC) is at 67 and 68 for the painted days (217 and 218 respectively) and 68 for the non-painted day (day 202). When the Degree hours are separated into day degree hours (DDh) and night degree hours (NDh), the DDh becomes 54 and 55 for days 217 and 218, and 51 for day 202. Days 217 and 218 had an NDh of 12 and 14, while day 202 had it at 16. All-inclusive variations are good for comparing the internal Dh among the three rooms:

The full day Dh of test cell #1 (the coolest) is at 104 and 105 for days 217 and 218, whereas it is at 117 on day 202. That is the first indication on the significant impact of white paint on internal temperature.

The full day Dh of test cell #3 (the warmest) is at 110 and 111 for days 217 and 218, whereas it is at 127 on day 202.

Similar observations applied when comparing DDh of test cell #1 at 70 and 71 for days 217 and 218 compared to 77 for day 202.

In line with the above, NDh for test cell #2 (warmest in this case) is at 38 and 39 for days but 43 for day 202.

This comparison highlights the fact that even with closed windows for an entire day, the white paint had a cooling effect on the internal DBT. Both these comparisons demonstrate that external white paint had a direct impact on the internal DBT of the three test cells. Furthermore, the combination of the external white paint with the lack of any internal gains allowed the internally insulated test cell #3 to have cooler night internal DBT (with a single night exception). The reason behind this is due to the fact that the heavyweight structure of the other test cell's internal walls stores some heat after sun exposure, while test cell #3 is not able to do so, consequently it stays warmer during the day, but cooler during the night.

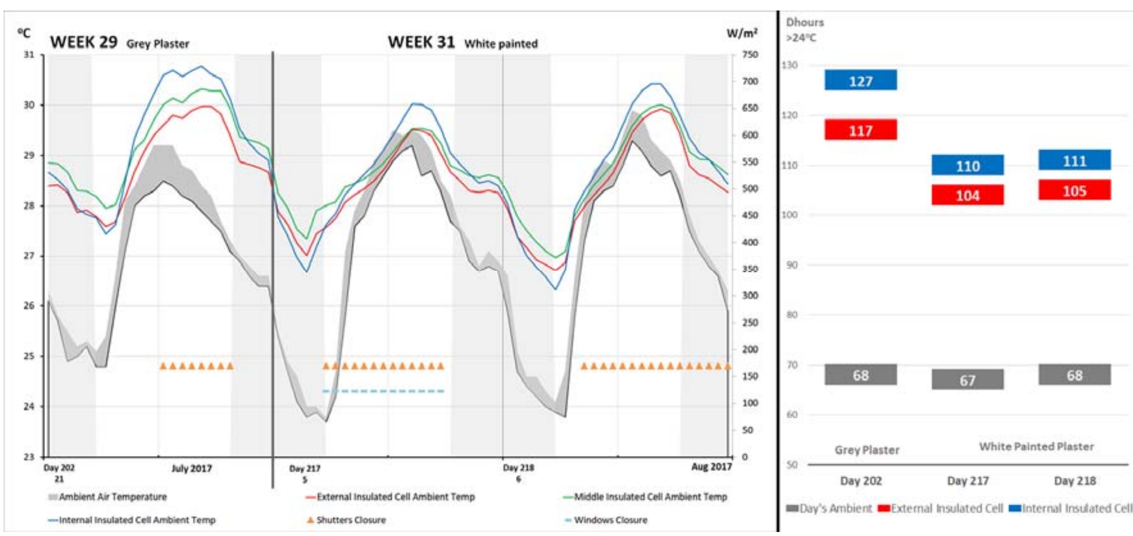


Figure 6.13 Temperature and Degree hours graph for an entire day; day and night graphs for comparative days 202, 217 and 218.

The second set looks at day 216 (70Dh) for painted cells in order to compare them to days 201 and 204 (71Dh) without paint. However, the difference becomes more pronounced when reviewing day and night performance: 61DDh for day 216 and 53DDh for both 201 and 204; as for the night, day 216 is at 8NDh compared to 23 & 20NDh for days 201 and 204 respectively.

In this case, performance comparison might not be relevant; nonetheless comparison yields an overall Dh of 110 for the coolest painted test cell #1 which is less than its previously non-painted version which was at 119 and 123Dh for days 201 and 204 respectively.

Similarly, the overall Dh of test cell #3 when painted is at 115Dh, lower than its unpainted version that recorded 128 and 134Dh for days 201 and 204 respectively.

So, based on these two comparisons, it is valid to conclude that external white paint has a direct cooling impact on the internal temperature of the three test cells.

In addition to the cooling effect of external white paint, another noticeable effect is shown in the internal DBT graphs by the fact that although test cell #3 with the internal insulation remained the warmest during the day, during the nights its temperature dropped to the lowest out of the other cells (with an exception of a single night) and before the introduction of lights or internal gains inside the test cells.

6.4.3 Internal Gains

The effect of the 300W internal gain produced by the three incandescent lamps is to check whether the ranking of the test cells will be altered following the excess of internal gains. No significant changes in ranking occurred, and the day's coolest peak remains in test cell #1 (external insulation) while the warmest in test cell#3 (internal insulation). The most easily recognizable impact of internal gain is on day 272 (September 29; fig. 6.14) when at 11:00am the windows are opened, and the lights are turned on, while the shutters are kept closed; a clear instantaneous rise in internal DBT occurs from 25.5 to 26.7 ^{o}C in test cell #1, and 26.0 to 27.0 ^{o}C in test cell #3. Although the difference between both cells is minimal (0.1K), this actually indicates the instantaneous ability of the exposed thermal mass in test cell #1 to store more heat compared to the missing thermal mass of test cell #3.

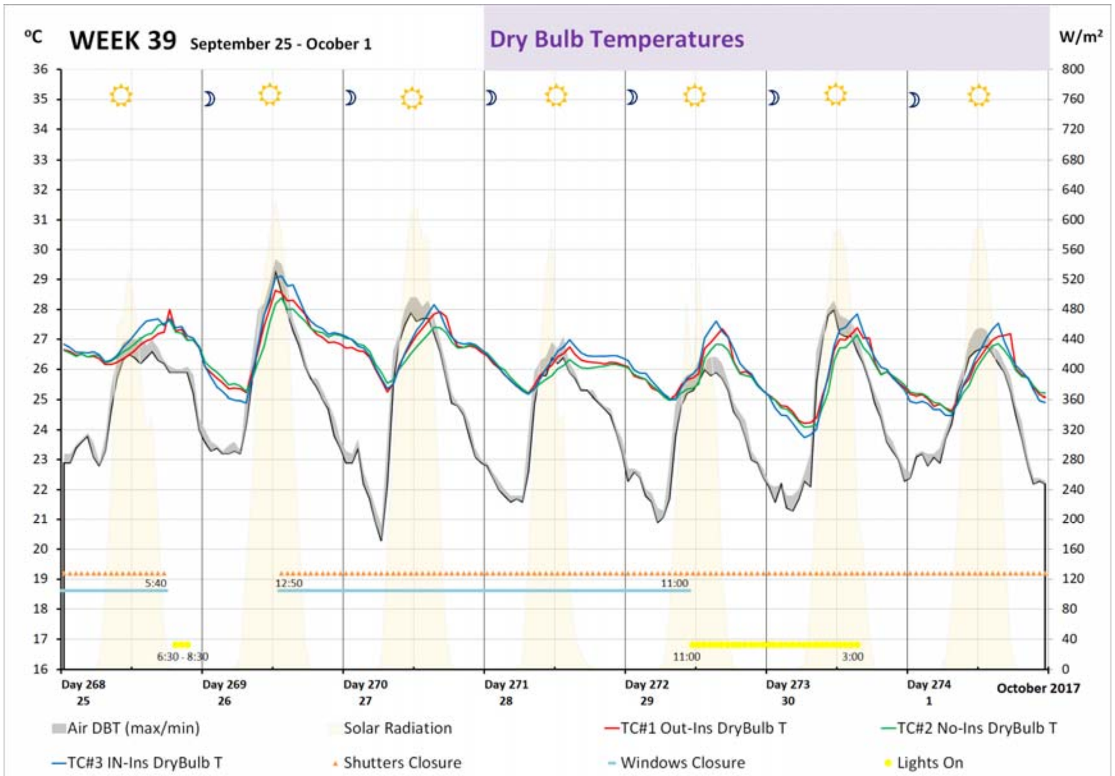


Figure 6.14 Internal temperature graphs for Week 39 (September 25-October 1, 2017; days 268-274). Clear indication of the impact of the added internal gain (on day 287 at 11:00am with the windows open, lights on, and shutters closed) to raise internal temperature from 24.5 to 26.7ºC in test cell #1 and 26.0 to 27.0ºC in test cell #3.

6.4.4 Surface Temperature Results

External and internal surface temperature of the west elevation are monitored starting with the plastered period until after the application of external white paint.

A west elevation induces peaks in external surface temperature in the late afternoon around sunset time (fig. 6.15) with temperatures ranging from highs of 40ºC and averaging in the 50ºC; with the hottest peak at 57ºC in the test cell #1 (internal insulation). The peaks of both the other test cells are almost 1K less (an exception where it reached to up to 2K).

Nightime coolest external surface temperature occurs during the night's coolest hour (usually on the hour before dawn). It drops to be cooler than the night ambient air by less than 1K for test cell #1, whereas the other test cells external surface temperatures are 1 to 2K warmer than the test cell #1 night surface.

Once the light grey plastered surface is painted white (fig. 6.16), the external surface peak significantly drops to a range between 40-45ºC; a reduction by 5-12K or 10-21%. These observations confirm the previously discussed cooling effect of white external paint's effect on internal temperature.

However, the night external surface temperature trend of all three test cells continues to behave as previously suggesting that it is not affected by the white paint. This is due to the fact that with no heat gains during the night, the white paint does not affect the heat release from the external surfaces. It does only reduce the solar heat gains into the surface during the day.

Day and night fluctuations of the internal surface temperature, much less than the external ones, vary between 3 - 5K; always showing warmer day and night temperatures than outside with limited exceptions during morning hours. External day temperatures are cooler than internal ones, but warmer during the night. They seem to follow the same order as the test cells internal temperature as: test cell #1 (outer insulation) is coolest and test cell #3 (inner insulation) warmest during the day, whereas during the night, test cell #3 becomes the coolest and test cell #2 (mid insulation) the warmest.

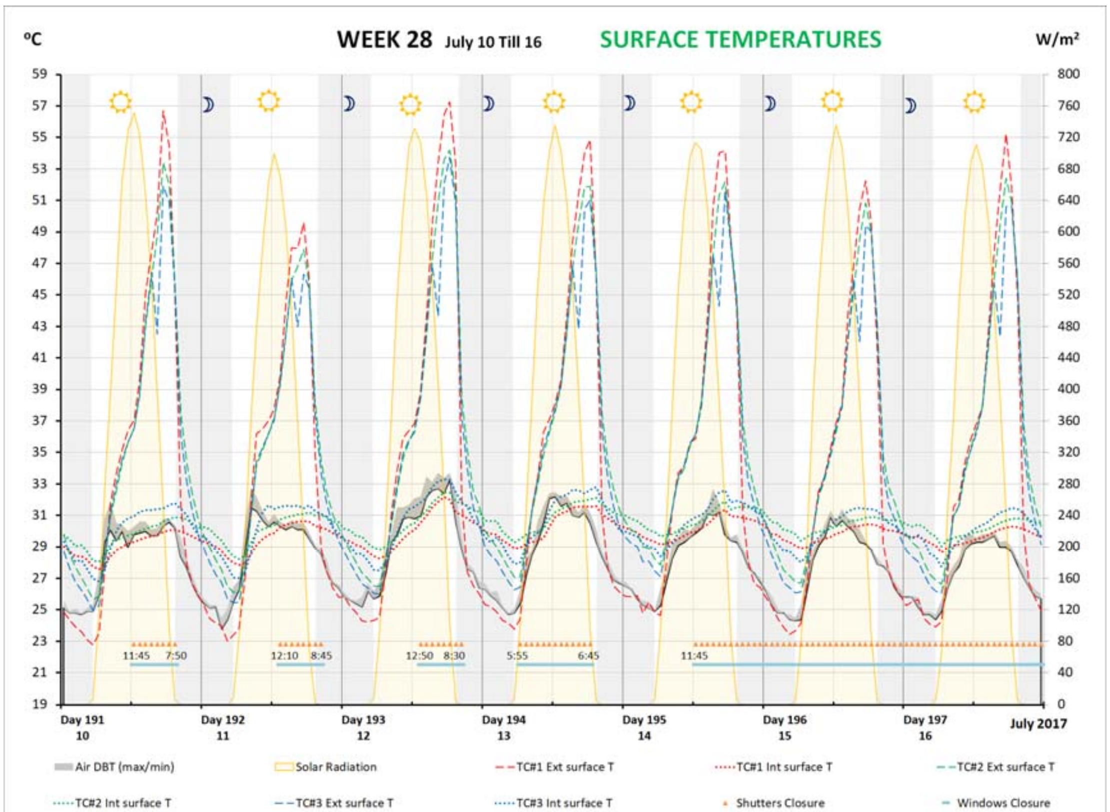


Figure 6.15 Surface temperature for week 28 (July 10-16, 2017; days 191-197) showing external peaks on the west-exposed surface well above 50^{o}C, before the external plastered walls are white painted.

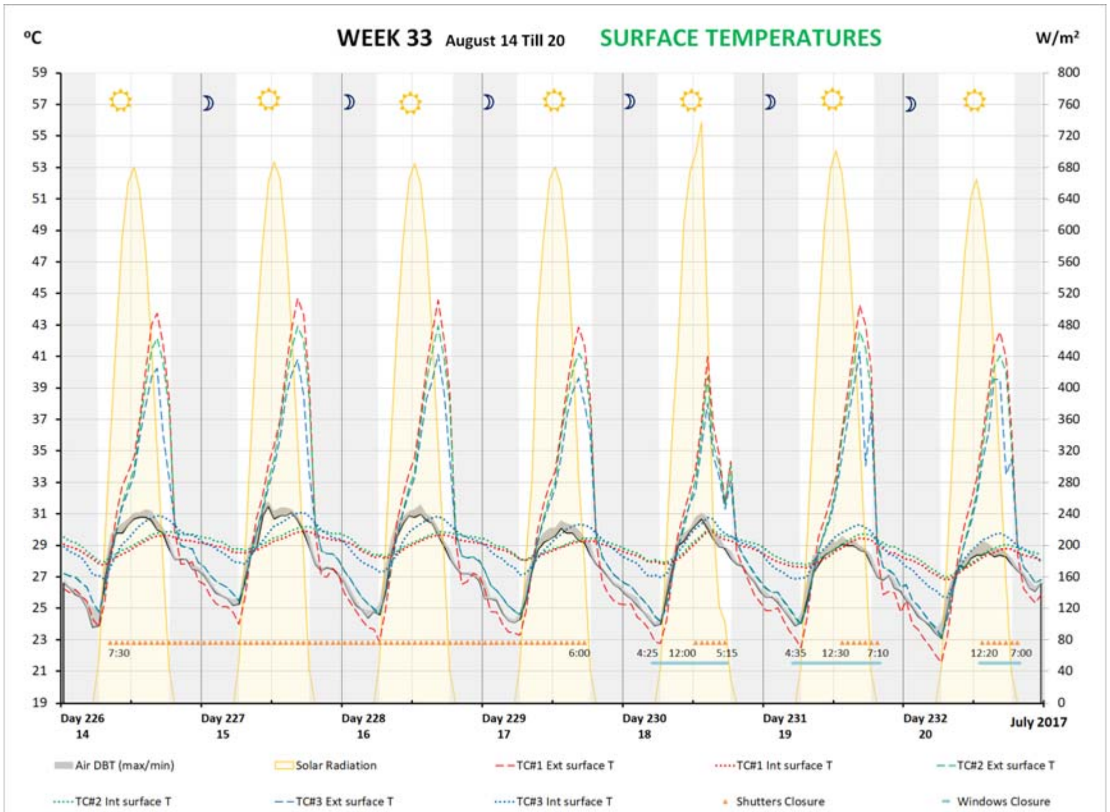


Figure 6.16 Surface temperature for week 33 (August 14 - 20, 2017; days 226-232), after the external white plastered walls are painted with external peaks within the low 40°C.

6.4.5 Removing the middle insulation

Once the middle insulation of test cell #2 is removed during week 35, the test cells' DBT performances start to show some changes: while test cell #3 remained the warmest during the daytime, test cell #1 came in second, and the un-insulated test cell (#2) is now showing slightly lower peaks (fig. 6.17).

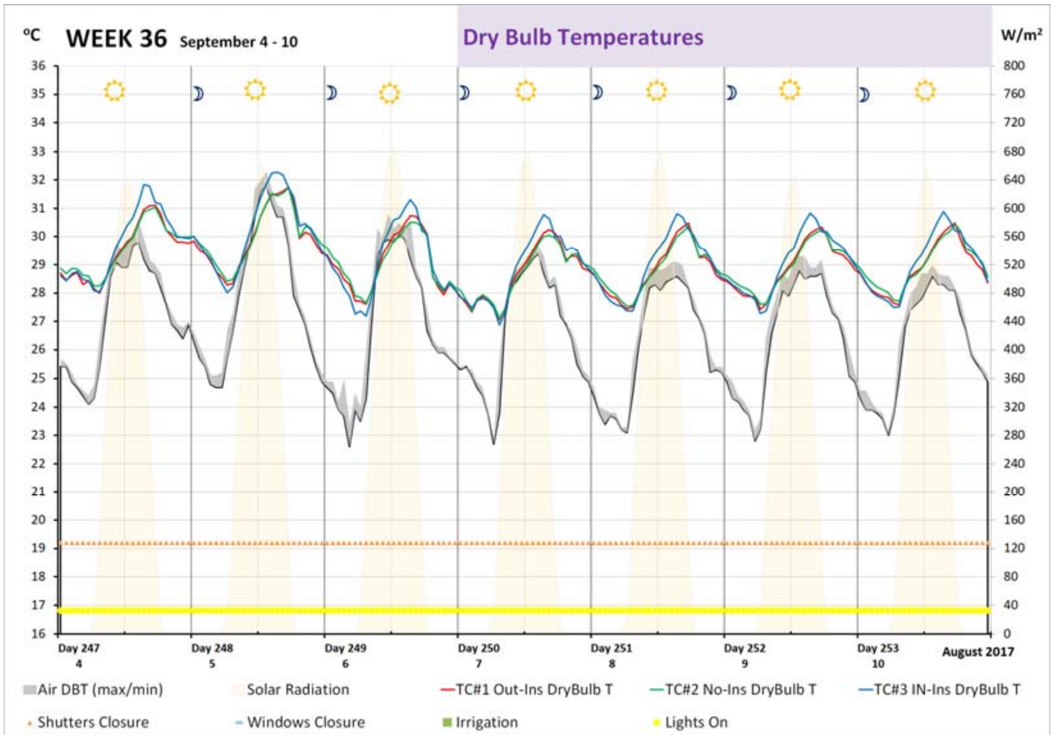


Figure 6.17 Internal DBT graphs for Week 36 (September 4-10, 2017; days 247-253).

6.4.6 Combined influence of internal gains and ventilation

In addition to the shifting in the internal DBT performance of the test cells, the gap between the peak temperatures is now much more prominent with high internal gains, by either solar or lighting gains. This was evident on Week 40 (days 276-278; October 3-5; fig. 6.18) when the shutters are kept open, but the windows closed (no ventilation) and on the same week 40 but on days 279-281 (October 6-8) when the lights are on and the windows and shutters closed (no ventilation). For the case of days 276-278, temperature difference (Δt) between the warmest and coolest peak is 1.8K and varies between 1.3- 1.7K for the coolest and intermediate peaks. Similarly, for days 279-281, the Δt between warmest and coolest is 1.3- 1.4K and between the coolest and intermediate Δt ranges between 0.7 and 0.8K.

In regard to other days with ventilation, a regularly occurring Δt between warmest and coolest peak is between 0.7- 0.8K with less occurrences of lower and higher values from 0.1 to 1.0K.

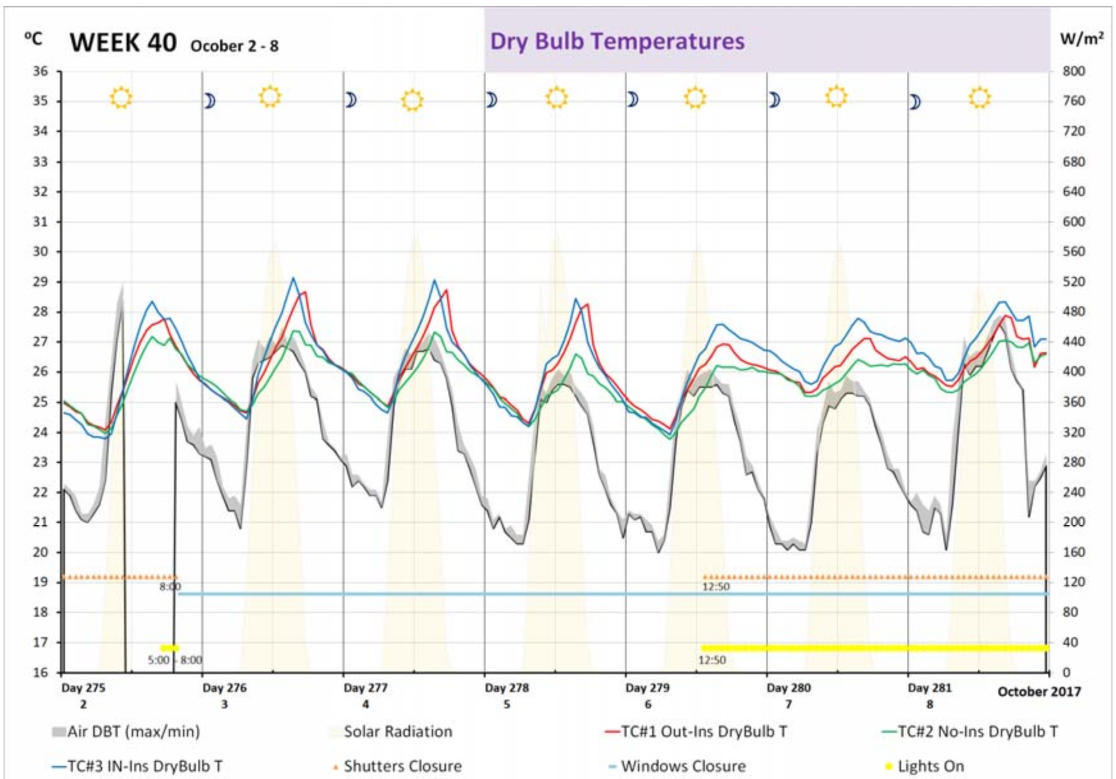


Figure 6.18 Internal DBT graphs for Week 40 (October 2-8, 2017; days 275-281)

6.4.7 Shifting the data loggers

Due to minor differences in the temperature behaviour of the different test cells, it was decided to shift the location of the data loggers to ensure whether these differences are due to calibration errors in the data loggers. Regardless of the shift (day 268; September 25), the results remained the same with similar minor differences in the night lowest temperatures, and similar more pronounced differences in the day's peak. similarly, the ranking of the test cells stayed the same, proving that the data loggers are working well, and the results reflect the correct temperature behaviour of the various test cells.

6.4.8 Thermal mass heat storing

It is typical for the local climate to have heat waves sometime between October and November, after a relatively cool period. This happened exceptionally for only one day this year (day 292; October 19) when the day's peak reached 29ºC compared to the 25.7ºC of the previous day (figure 6.19).

These are compared to similar days with day's DBT peaks near 29ºC. Although higher solar radiation peaks existed, the internal DBT of day 292 is drastically different from all previous similar hot days, with all three internal DBT considerably cooler than the day's DBT throughout the entire daytime; a behaviour never seen before in the test cells but observed numerous times with the apartment monitoring in summer 2015.

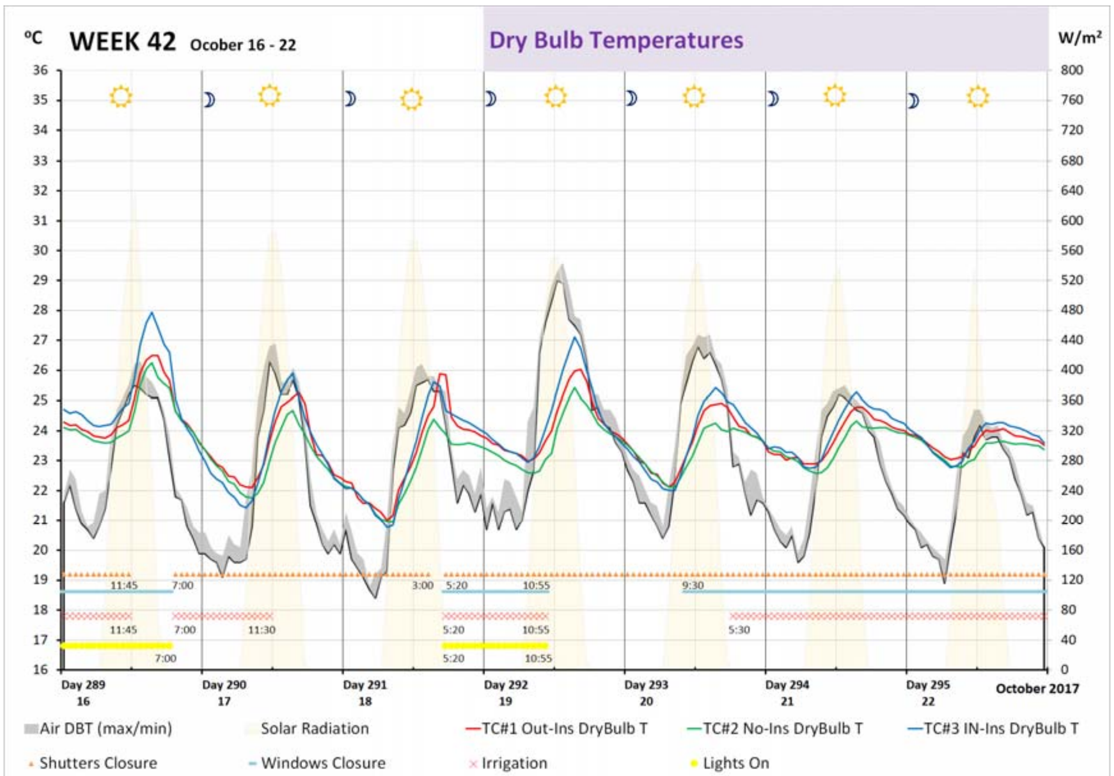


Figure 6.19 Internal DBT graph for week 42 (October 16-22, 2017; days 289-295).

6.4.9 Ventilation

Fan ventilation started by the end of week 41, when cooler day and night temperature started to be the norm. This made it difficult to assess if the ventilation had any direct influence on the internal test cells temperature. Similar temperature trends happen starting week 38 onwards, and accordingly, finding similar day's peaks and coolest temperature are possible for either the peak or the coolest, but not both. Furthermore, Δt between internal and external temperature is varying between less than 2K before the fans and up to 4K after the fans; making it difficult to be sure whether they had any impact in reducing the internal temperature as expected in the literature review.

6.5 Discussion

The most obvious observation is the ability of thermal mass in absorbing and storing heat resulting in many days with internal morning DBT lower than the outdoor. Examples observed in all cells including (days 182,184,194,270,273,290,291,292,293,294) suggesting that even the thin layer of 11mm internal cement plaster is playing some role in storing heat in the internally insulated test cell.

Similarly, the same effect of storing the heat during the day and releasing it during the night is clear in the night internal DBT which is always warmer than the outdoors (observed in all test cells). Especially when combined with a relatively low wind velocity during the night not enough to flush out the heat outside of the test cells.

The slow response to the daily changes in the day's DBT is visible when external day temperature rises sharply compared to the previous day. The internal DBT shows minimally warmer temperature compared to the previous days. Similarly, when the night's DBT sharply drops, the internal DBT remains as warm as the previous night. This is not necessarily due to the effect of insulation slowing the external day time heat from entering and the accumulated daytime heat from escaping at night-time; this effect is also observed in the test cell without insulation. Furthermore, the different locations of the insulation in the walls should have resulted in different behaviours, which was not the case in the experiment.

A sudden and limited temperature change (rise or drop) in the external air temperature of 2-3K might affect the internal temperature by not more than 0.5K.

Comparing the previously monitored apartment during summer 2015, an interesting observation is noted: the apartments showed numerous days when internal DBT was continuously lower than the daytime external air DBT. The test cells did show something similar only in October, (day 293, October 20) only after one day was considerably hotter than the previous. The reason behind this is that the monitored apartments were all intermediate floors, whereas the test cells have an exposed roof with no consideration given to enhance its thermal performance (by adding insulation or an air gap).

Taking the different wall configurations tested in this study, two roofs can be proposed with an expected improved performance: (1) concrete slab with external insulation, protected by some tiles (concrete or stone), or (2) concrete slab above which is a raised floor made out of concrete tiles, thus mimicking the double masonry wall with the air gap in the middle.

The effect of changing the external colour from medium grey to white is well observed and quantified in the 10- 20% reduction of the external surface temperature. It was further confirmed by using the degree hours method that showed this colour change had an impact on reducing the internal temperature as well.

The added impact of the test cells' construction and monitoring gave an accurate insight into the temperature behaviour resulting from different positions of insulation within double cavity masonry walls. Even with same calculated thermal parameter, each test cell performed differently when exposed to the following heat gain factors:

(a) Conductive heat transfer from walls and roof
(b) Radiative heat gains from sun rays through the window
(c) Convective heat gains from ventilation (through the shutters or the open windows)
(d) direct gains from the three heat sources emitting 300W

The wall U-value which does not vary considerably between the different test cells is only affecting point (a). Thermal mass property is responsible for acting on the remaining factors (b, c and d).

The externally insulated test cell presented the lowest internal DBT peaks during the day, but it alternated during the night with only few nights as the coolest but more nights as the intermediate night DBT. Based on the literature review about thermal mass (ref chapter 3.2), it is said that (a) 50-120mm of thermal mass is enough to provide improved temperature performance, and (b) both the k-Value or heat capacity calculation method applies to the calculation of the admittance or Y-value is based on whatever is reached first from (1) half the wall; (2) 100mm of depth from the internal space; and (3) until the insulation layer.

Based on the above, test cells #1 (external) and #2 (mid insulated) will have the same effect by their thermal mass made from 100mm internal masonry block and 11mm internal plaster, and accordingly, are expected to have similar internal temperature performance. But practically, that was not the case.

Within the same line of reasoning, the air gap in test cell #1 extends the depth of thermal mass (100mm masonry) into the external 200mm masonry wall by convective heat transfer promotes further heat storage during the day. Similarly, during the night, the 100mm masonry wall will continue to release heat into the air gap as well as into the internal room resulting in the coolest day's peak; thus, having more day storage should result in more heat release during the night. This phenomenon cannot be blamed on faulty construction where the roof might not seal the air gap properly; the 49mm timber roof planks cross the 40mm air gap to rest on the outer 200mm walls, and a 160mm loose gravel bed covers those planks.

This middle-insulated test cell has the intermediate day's peak DBT and the night's warmest compared to the other test cells, this is due to the limited heat storage within the 100mm masonry wall during the day and similarly this limited and one-way diurnal storage will result in heat release only into the internal room during the night. When compared to the internally-insulated test cell, it has limited heat storage, and hence shows cooler night DBT. Meanwhile the outer insulated, as explained above, allows heat storage in both masonry walls.

The internally insulated test cell has the hottest internal DBT peaks during the day, but also becomes the coolest during the night after a few weeks of running the experiment. The reason behind this behaviour is the minimal heat storage in the 11mm internal plaster which makes the test cell the most vulnerable to direct gains (b, c and d) during daytime with little storage for excess heat thus hotter during the day, but consequently less heat to release at night. As for conductive heat transfer through walls and roof (a) a similar behaviour between the inner and outer insulated cells is to be expected since they share the same U-values.

When insulation is removed from test cell #2, daytime peak becomes the lowest among the others test cells. Additionally, less ventilation and more internal gains result in larger temperature difference between the lowest and warmest peak of the other test cells.

The difference is much less marked for the night lowest temperature varying between 0-0.6K. It is not clear which test cells has the lowest night DBT since it tends to alter frequently. Nonetheless, test cell #3 (internal insulation) shows to be lowest for most nights.

Thermal mass saturation is related to the already mentioned fact that heat is being stored and released within the thermal mass. This would lead to a **saturated and un-saturated mass**. This was shown during the experiment at two different instances. Although this notion is seldom referred to in the literature, **it is a common seasonal term used in Lebanon to describe the perceivable internal coolness of a given place, in the early hot season or whenever a sudden and few day-long heat wave happens** (usually during the months of May). It is referred to as the ***Khamasseen*** (the eastern hot and dry wind) and October referred to as the second summer between October and November. During these sudden and short heat waves, or within the early hot season, the internal temperature remains considerably cooler for a few days due to the construction's thermal mass, and it is expressed as **"the thermal mass has not saturated yet".**

During the first weeks of observation (week 25 onwards) when the construction had just been completed, the night temperature of test cell #1 is the coolest until week 29 when internal night temperature of test cell #3 becomes the coolest. This is a clear observation of the saturation of both 100mm and 200mm masonry walls of test cell #1 no longer able to store any further heat during the day to release it back during the night.

When October temperature rises above the previous day's peak (day 292), the internal temperature remains much cooler for the entire day time. This is another temperature behaviour that illustrates the de-saturation of the thermal mass. After many days of cooler temperature, the thermal mass is slowly releasing the extra stored heat. In this example, when a sudden rise in temperature occurs, the internal temperature remains cooler for a much longer time span for the entire day time.

Although internal gains affected the temperature, they did not change the ranking of temperature performances between the different test cells.

6.5.1 Performance indicators

Performance indicators take into consideration the Dry Resultant Temperature (DRT) equivalent to the mean temperature of the Dry Bulb Temperature (DBT) and the Globe Temperature monitored with the two data logger types installed in the test cells. The globe temperature data logger is enclosed with a black sphere (fig. 6.14).

Following the results and discussion of the temperature performance of the test cells, this section introduces different performance indicators: temperature difference, amount of degree hours, and energy values for cooling.

Since the research is based on simultaneous observations within two periods, it is easy to compare each of the performance of the three different constructions within each of these periods. Figure 6.20 shows all the DRT graphs of the three test cells for the entire period of observation including the various phases.

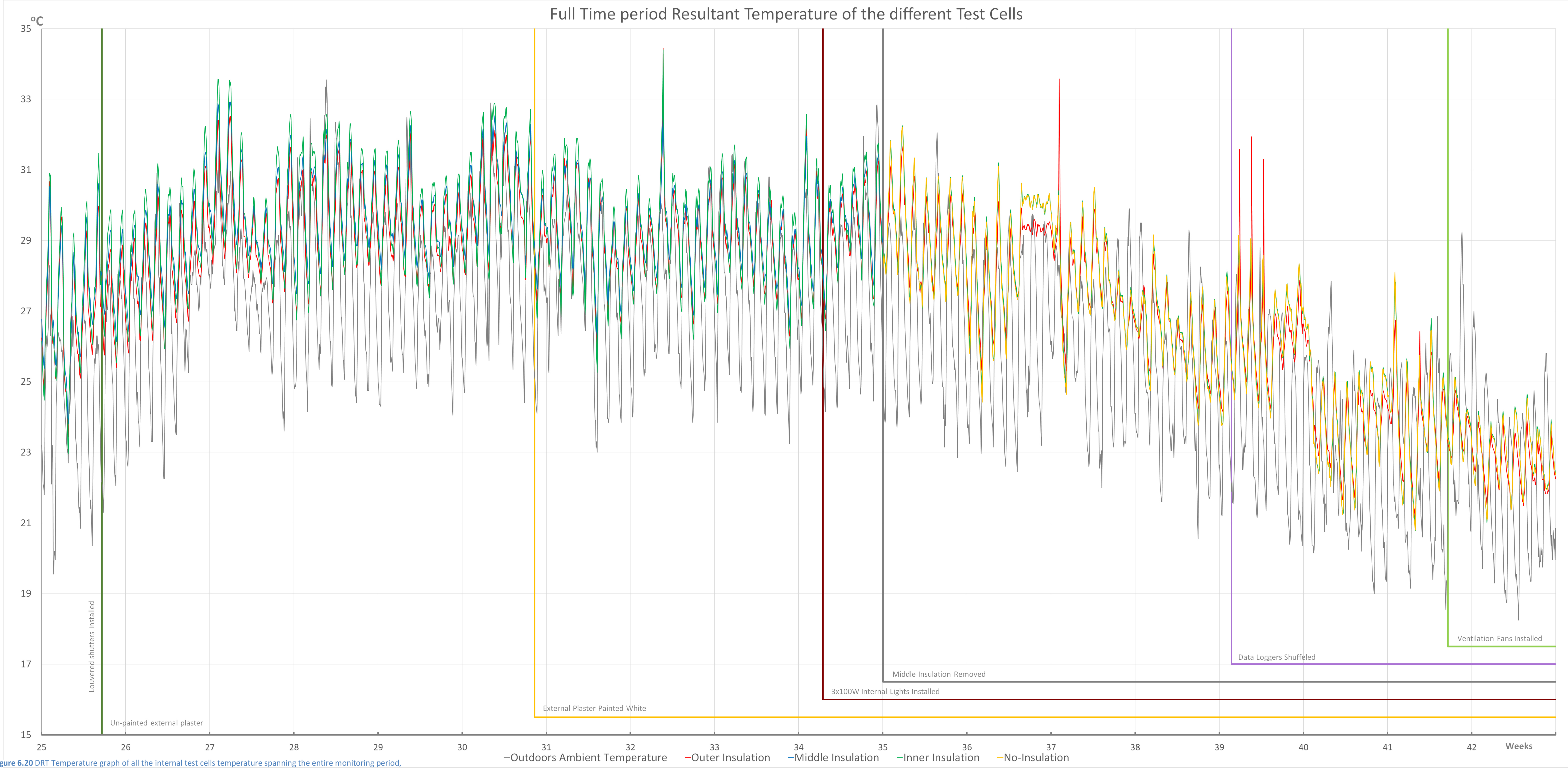


Figure 6.20 DRT Temperature graph of all the internal test cells temperature spanning the entire monitoring period, with the different intervention applied

In order to compare all four of them (including un-insulated cell) at the same time, a small regression application is applied (appendix 6), (results in fig. 6.21) in terms of degree hours of overheating above 30°C DRT.

The base case with the least degree hours stands for the non-insulated walls, followed by the outer insulation with a difference of 40%. The middle insulation follows it with an almost 90% difference. The inner insulation has the most degree hours of overheating at almost 180% more than the non-insulated one.

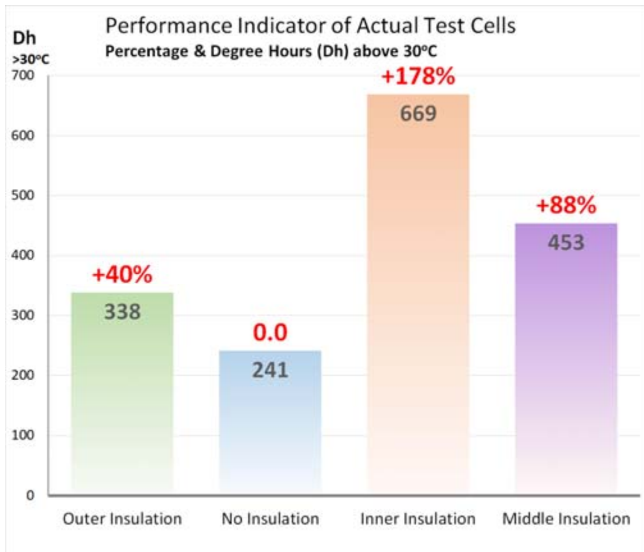


Figure 6.21 The final performance indicator based on degree hours of overheating above 30°C DRT for the test cells.

While analysing the daytimes' peak recorded DRT within each of the different test cells, tables 6.2 and 6.3 show that for the first period the coolest peak temperature is for the externally insulated test cell, followed by the middle and internally insulated which are warmer by 0.86% and 2.64% respectively. For the second period, the coolest peak is for the non-insulated test cell followed by the externally and then internally insulated test cells which are respectively 1.53% and 3.33% warmer.

Table 6.2 Mean daily/daytime peak DRT temperatures and differences (all values in °C).

	Weeks 25-34		**Weeks 36-43**	
	Mean Peak Temperature	Mean Δt (Ambient-Inside)	Mean Peak Temperature	Mean Δt (Ambient-Inside)
Outdoor DBT	28.82		27.02	
No insulation DRT			27.01	**-0.02**
External insulation DRT	30.61	**2.60**	27.42	**0.40**
Middle insulation DRT	30.88	**2.05**		
Internal insulation DRT	31.42	**1.79**	27.90	**0.88**

Table 6.3 Mean days' peak temperature percentage differences.

	Weeks 25-34		**Weeks 36-43**	
	Mean Peak Temperature	% difference (Best/other)	Mean Peak Temperature	% difference (Best/other)
Outdoor DBT	28.82		27.02	
No insulation DRT			**27.01**	**0.00**
External insulation DRT	**30.61**	**0.00**	27.42	**1.53**
Middle insulation DRT	30.88	**0.86**		
Internal insulation DRT	31.42	**2.64**	27.91	**3.33**

Regarding the coolest recorded night DRT within each of the different test cells, tables 6.4 and 6.5 show that for the first period the coolest night temperature is for the externally insulated test cell, followed by the internally and middle insulated, 0.14% and 2.05% warmer respectively. For the second period, the coolest peak is for the internally insulated test cell followed by the non-insulated and the externally insulated warmer by 0.34% and 0.58%.

Table 6.4 Night-time lowest mean temperature and differences (all values in °C).

	Weeks 25-34		**Weeks 36-43**	
	Mean Temperature	Mean Δt (Ambient-Inside)	Mean Temperature	Mean Δt (Ambient-Inside)
Outdoor DBT	23.6		20.9	
No Insulation DRT			24.7	**3.8**
External Insulation DRT	27.3	**3.6**	24.7	**3.9**
Middle insulation DRT	27.8	**4.2**		
Internal DRT	27.3	**3.7**	24.6	**3.7**

Table 6.5 Nights' coolest mean temperature and percentage differences.

	Weeks 25-34		Weeks 36-43	
	Mean Peak Temperature	% Difference (Best/other)	Mean Peak Temperature	% Difference (Best/other)
Outdoor DBT	23.64		20.9	
No Insulation DRT			24.67	**0.34**
External insulation DRT	**27.27**	**0.00**	24.73	**0.58**
Middle insulation DRT	27.83	**2.05**		
Internal insulation DRT	27.31	**0.14**	**24.59**	**0.00**

The mean days' temperatures of both periods (tables 6.6 and 6.7) show that for the first period the coolest mean DRT is for the externally insulated test cell; followed by the middle and internally insulated which are 1.56% and 1.70% warmer. For the second period, the coolest peak is for the non-insulated test cell followed by the externally and then internally insulated test cells 0.60% and 1.29% warmer.

Table 6.6 Overall periods mean temperature performance indicators (all values in ^{o}C).

	Weeks 25-34		Weeks 36-43	
	Mean Temperature	Mean Δt (Ambient-Inside)	Mean Peak Temperature	Mean Δt (Ambient-Inside)
Outdoor DBT	27.31		24.19	
No insulation DRT			25.84	**1.66**
External insulation DRT	28.94	**1.63**	26.00	**1.81**
Middle insulation DRT	29.39	**2.08**		
Internal insulation DRT	29.44	**2.13**	26.18	**1.99**

Table 6.7 Percentage differences based on all periods

	Weeks 25-34		Weeks 36-43	
	Mean Peak Temperature	% difference (Best/other)	Mean Peak Temperature	% difference (Best/other)
Outdoor DBT	27.31		24.19	
No insulation DRT			**25.84**	**0.00**
External insulation DRT	**28.94**	**0.00**	26.00	**0.60**
Middle insulation DRT	29.39	**1.56**		
Internal insulation DRT	29.44	**1.70**	26.18	**1.29**

6.6 Conclusion

The main purpose of this chapter was to significantly reduce the uncertainties found in the previous apartments monitoring experiment and to study the effect of different variables simultaneously in a controlled environment. Hence three heavyweight test cells with different insulation configurations within their double masonry walls are built. These are monitored for a full summer season with various variable manipulations always happening at the same time in all the three test cells. Their double masonry walls have different insulation positions: outside, middle, or inside of the cavity of the walls. At a later stage, the middle insulation is completely removed. In addition to parallel observations, non-simultaneous changes are studied as well. The variables include: external white paint, windows, shutters, added light bulbs, and mechanical fan ventilation. Results show that there is a clear differentiation between day and night dry resultant temperature behaviour: the day's coolest peak is always well defined for the externally insulated test cell when compared to the other two insulated ones. Although the night coolest is not as clear as the day's, nevertheless, the night coolest tends to be within the internally insulated cell. Once the middle insulation is removed, the coolest day's peak shifts into the un-insulated test cell and is significantly distinguished from the others. The night coolest is still slightly unstable switching between the internally insulated and the non-insulated ones. With the 4 months period of observation, it was possible to clearly show the heat storage effect of thermal mass during a full day where internal dry bulb temperatures are cooler than the outdoor's. This is observed to be a common behaviour that occurred frequently during the apartment monitoring but only for short morning periods during similar days in summer. The un-insulated test cell with the highest U-value scored the least overheating in terms of Degree hours above 30^{o}C DRT whereas the inner insulation scored the most (in line with hypothesis) with 178% more overheating than the best performing test cell (i.e. un-insulated cell). The outer insulation performed second best presenting 40% more overheating than the best performing (un-insulated). Finally, the middle insulated is at 88% more than the best performing cell. When it comes to comparing the three cells based on their percentage temperature differences; the lowest DRT peak temperature is for the externally insulated test cell, followed by the middle and internally insulated (respectively 0.86% and 2.64% warmer). Once the middle insulation is removed, the lowest DRT peak is for the non-insulated test cell followed by the externally and then the internally insulated test cells (respectively 1.53% and 3.33% warmer).

The method of purposely building three full-scale test cells combined with simultaneous testing proved to be the best methodology for studying the temperature performance of heavyweight constructions in Beirut's hot summer. **It significantly reduced the uncertainties through the long-term observation and allowed to clearly conclude that un-insulated double masonry walls will have the least overheating.**

7 Test Cells Software-Based Studies

7.1 Introduction

The previous chapter of monitoring full-scale built test cells over a full summer season showed that uninsulated double masonry walls provide the least internal overheating. This chapter takes the same test cells data for software studies, with both un-calibrated and calibrated models, to check to what extent such simulation results are in correlation with the results. This step is crucial and different from the apartment monitoring. The difference lies by the fact that in this case the uncertainties are considerably reduced, along with the added advantage and importance of simultaneous observations happening at the same time in three different test cells. The comparative details are expanded in table 7.1.

Table 7.1 Comparative difference of the uncertainties between the apartment monitoring and the full-scale test cells

Case	Apartment Monitoring	Full Scale Test Cell
Wall construction	estimated; based on expected construction typology	accurately known; based on simultaneous construction, material choice, construction techniques
Infiltration rates	estimated	estimated, but same in all cases due to same fixation conditions
Slabs and Roofs	estimated	accurately known; based on simultaneous construction, material choice, construction technique
living patterns	based on occupant feedback*; generalized	NONE
Lighting power & schedule	based on occupant feedback* and observation; generalized,	accurate with 2 x 100W light bulbs; same scheduled lighting in the three test cells
Equipment power & Schedule	based on occupant feedback* and observation; generalized,	NONE; until the fans are put on with an accurate schedule
Windows & shutters	based on occupant feedback*	accurately noted and always done at the same time in the three test cells
Orientation	each room in the apartment has a different orientation	All three rooms have the same orientation

*Occupant feedback is done at the beginning of the observation, once in an intermediate phase, and at the end.

The chapter runs temperature simulations based on the same characteristics of the four test cells from the previous chapter; checking for overheating degree hours above 30°C using the same physical and weather data. A calibration model is then carried out to compare if it will require less modifications than the adjustments done for the apartment calibrated model.

The modelled four test cells share the same internal area of 10m^2 with double masonry walls of 200mm external and 100mm internal, separated by a 40mm air gap. Both external and internal surfaces are cement plastered. The difference lies in the location of the 25mm XPS insulation:

1- On the outer side of the 200mm masonry block, beneath the plaster;
2- Within the air gap, which is hence reduced to 15mm;
3- On the inner side of the 100mm masonry blocks, beneath the plastering;
4- One with no insulation.

In the last round, further calibration is completed under a more controlled environment (compared to the previous monitored and calibrated apartment). This time both the internal gains and their relative schedules are controlled.

These runs are a further attempt to check whether smaller sized test cells in a controlled environment would show better correlations between the actual and simulated results. Additionally, the runs would allow to see if calibration will still require the same level of modifications as seen before.

7.2 Thermal Software Simulation Runs for Test Cells

One simple room is modelled using EDSL TAS thermal software with 3450 x 2900mm internal dimensions; 10m^2 surface and 3000mm internal height. A window/door of 1200 x 2000mm is positioned in the middle of the west-oriented 3450 mm long side. Within the different sets, the walls will be changing based on a double cavity wall of 200mm outside wall and 100mm inside wall. The roof is the same for all rooms; made of a 70mm timber planks above which 160mm of gravel is deposited, the calculated U-value is 1.5 W/m^{2}K, and the windows are single pane with a U-value of 5.7 W/m^{2}K. The rooms with the different walls and insulation configurations are simulated and compared for least overheating in terms of Degree hours above 30^{o}C. Simulations are run from June 1 to October 31. The variables consist of applying the following percentages: 20% for no internal gains, 65% with medium internal gains at 8W/m^2, and 15% with high internal gains at 25W/m^2. These were applied in a similar random order within the actual test cells.

Simulated results (fig. 7.1) do not correspond to the observed results nor to the ranking. The middle insulation has the least summer overheating, followed almost similarly by both the outer insulation (27%) and non-insulated and (30%). Unlike the others, only the inner insulation with the highest overheating (51%) coincides with the literature; where the outer insulation should have had the least overheating.

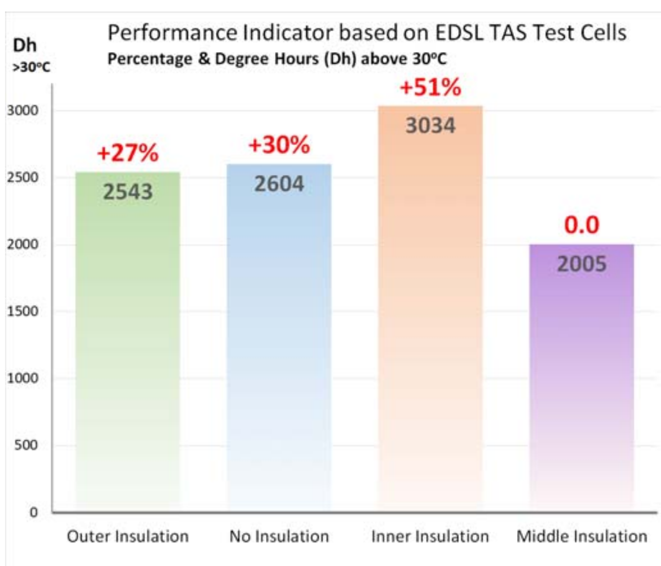


Figure 7.1 All combined tests for free-running mode with different internal gains

7.3 Thermal Software Calibration Runs for Test Cells

This study carries on with the calibration process by calibrating the actual full-scale test cells specially built for the study (chapter 6). This is based on all the physical and thermal properties of the constructed test cells, as well as all the weather data collected from the weather station on site. The simulation is then compared to the actual recorded data.

Three sets of random three consecutive days are chosen and simulated:

(a) Week 29 (days 198-200; July 17-19): windows and shutters are always closed, with no internal gains;
(b) Week 34 (days 235-237; August 23-25): windows are always open, but shutters and internal gains undergo different schedules;
(c) Week 40 (days 278-280; October 5-7): windows are always closed; shutters and internal lights are continuously on from mid-day 279.

Three consecutive days are chosen for the simulation in order to use the different schedules allowed by TAS for the weekdays Saturdays, and Sundays. Even if the choices are not within these days, minor modifications of the imbedded calendar can solve this issue. As seen in chapter 3.7, the three days hourly range sum up to 72 hours/points, hence they fit within the available calibration protocols since there is no mention of a specific time frame. More importantly even with the short period of observation, noise-induced errors are negligible since the three test cells are simultaneously monitored closely with the same lighting patterns, same window and shutter closures. Furthermore, the calibration is done for all three eliminates any potential noise-induced errors. Similar to the previous calibration process, both values of the CVRMSE and NMBE are calculated. In this simulation, walls and roof U-values are not changed. They are based on inputted construction details (table 7.2).

Table 7.2 TAS calculated and used U-values for walls and roof for the different simulated test cells.

	Non-Insulated	Outer Insulated	Middle Insulated	Inner Insulated	Roof
U-value (W/m^2K)	1.1	0.6	0.7	0.6	1.2

7.3.1 Week 34 Simulation: Lights on/Internal Gains on

The first round of simulation for week 34 (fig. 7.2) has the same U-values for the different constructions, as well as the same schedule for shutters and internal gains from lights at $30W/m^2$ to sum up to a 300W total. Results show that the three simulated test cells have very close temperature behaviours; differences are barely noticeable on the graph. The coolest night temperature occurs in test cell #3 (internal) but with a difference of no more than 0.2K. Similarly, the hottest day temperature is also for test cell# 3 with a Δt of not more than 0.4K.

During the day and with the windows open, all simulated internal temperatures follow closely the ambient air temperature; they are cooler than the actual recorded values.

As soon as the lights are turned on, a sudden rise in temperature is well observed in the simulated graph, which was not clear in the recorded ones. Similarly, sudden changes in the night temperature are well marked on the simulated graphs but barely visible on the recorded ones.

Both day and night simulated temperatures are lower than the recorded ones with a more prominent gap during the night.

In the second run, internal gains from the lights are raised from 30 to 50W/ m^2 on schedule, but another 10W/m^2 is continuously added. This is the only observation where the combined simulated temperatures have the closest similarities with the recorded ones, still, with a clear sharp increase at the beginning of the lighting schedule and when external temperature fluctuates.

To reach similar outcomes, the internal gains are raised to 60W/m^2 including the continuous 10W/m^2 (mounting to 200% rise) or doubling the internal gains to have better similarities.

It should be noted for this first period of calibration that windows are always open, and the infiltration rate input is kept null.

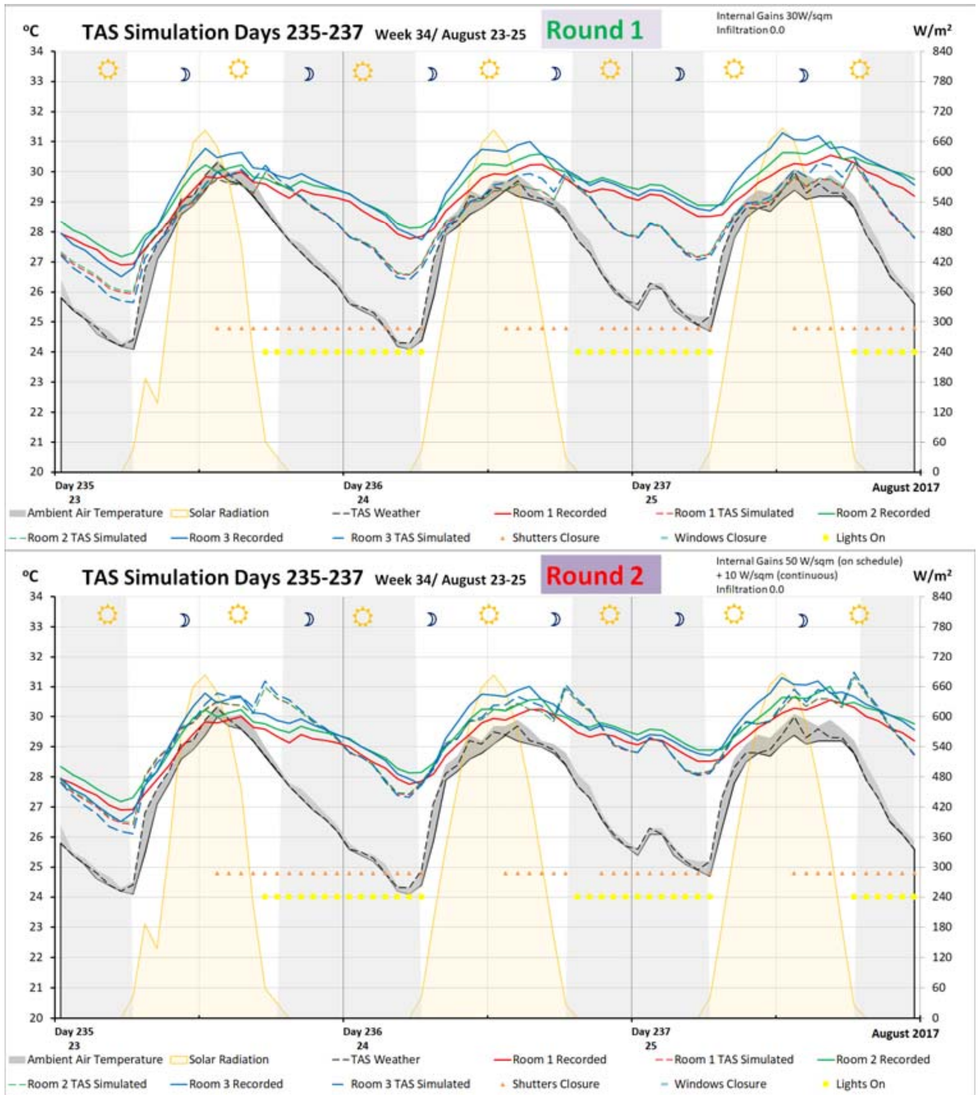


Figure 7.2 Two rounds/steps of calibration for days 235-237 that included 150% increase in internal gains from 30 to 50W/sqm (scheduled), in addition to continuous 10W/sqm increase, to reach better similarities.

7.3.2 Week 29 Simulation: No Internal Gains

The simulation for week 29 (fig. 7.3) has no internal gains and the windows and shutters are closed for the entire three days except for the last afternoon/night of the last day. Also, ambient air day peak temperature of that last day (July 19; day 200) rose more than 2.4K from the previous day's peak; recorded internal temperatures were all cooler than the outdoors.

Only one run is done with no internal gains. Results show warmer night temperatures than the recorded, but cooler days. Moreover, the gap between the simulated rooms is more prominent than in the previous run, but still not similar to the recorded data. The simulated test cell with the internal insulation recorded the coolest night and the hottest day temperature, with a clear and continuous rise in the day's peak of up to 1K sustained for 8 hours warmer than the other simulated rooms.

When ambient temperature rose more than the previous day, the simulated rooms' temperature showed cooler temperature that remained lower than the outdoors for the entire daytime, unlike the recorded ones that showed this behaviour for only the morning.

Finally, once the windows and shutters are open, a clear decrease in the simulated temperature is noted.

With no internal gains and closed windows, the different simulated rooms start to show minor differences in their temperature performance. The night's lowest and the day's peak are cooler than the recorded, thus the day/night fluctuation is less prominent than the existing ones.

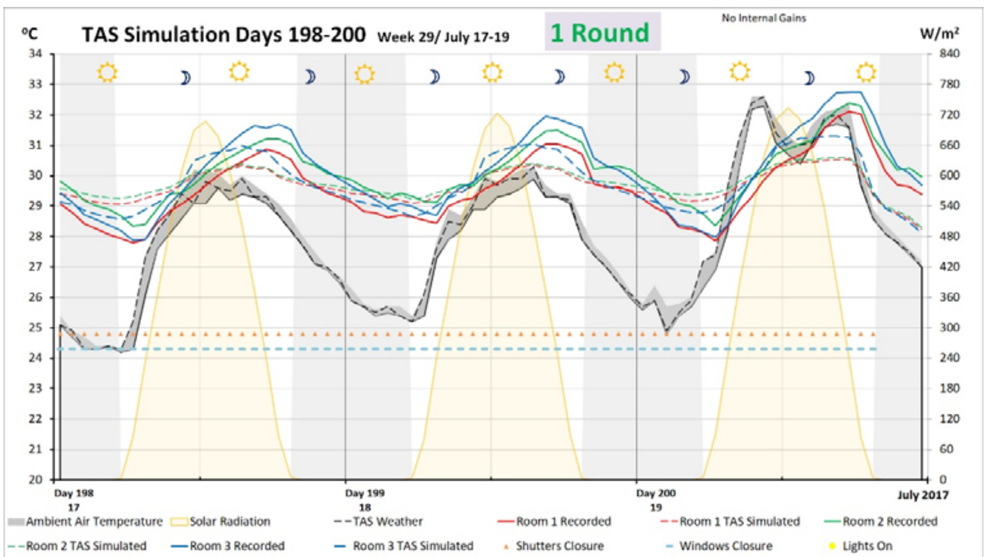


Figure 7.3 The one-run simulation for days 198-200 with no internal gains showing a fair similitude between recorded and simulated.

7.3.3 Week 40 Simulation: Internal Gains On

During Week 40 (day 278-280; October 5-7), the windows are closed during the three days while the lights are on from mid-day 279 and the shutter closed at the same time (fig. 7.4).

The first run shows that the simulated rooms did not get influenced by the solar internal gains on day 278, and accordingly the simulated day's peak is much less than the actual recorded one.

On day 279, early afternoon, following turning on the lights at an internal gain of 30W/sqm and an infiltration rate of 0.2ach, a sharp rise of 2-3K is observed with the temperature remaining consistently high.

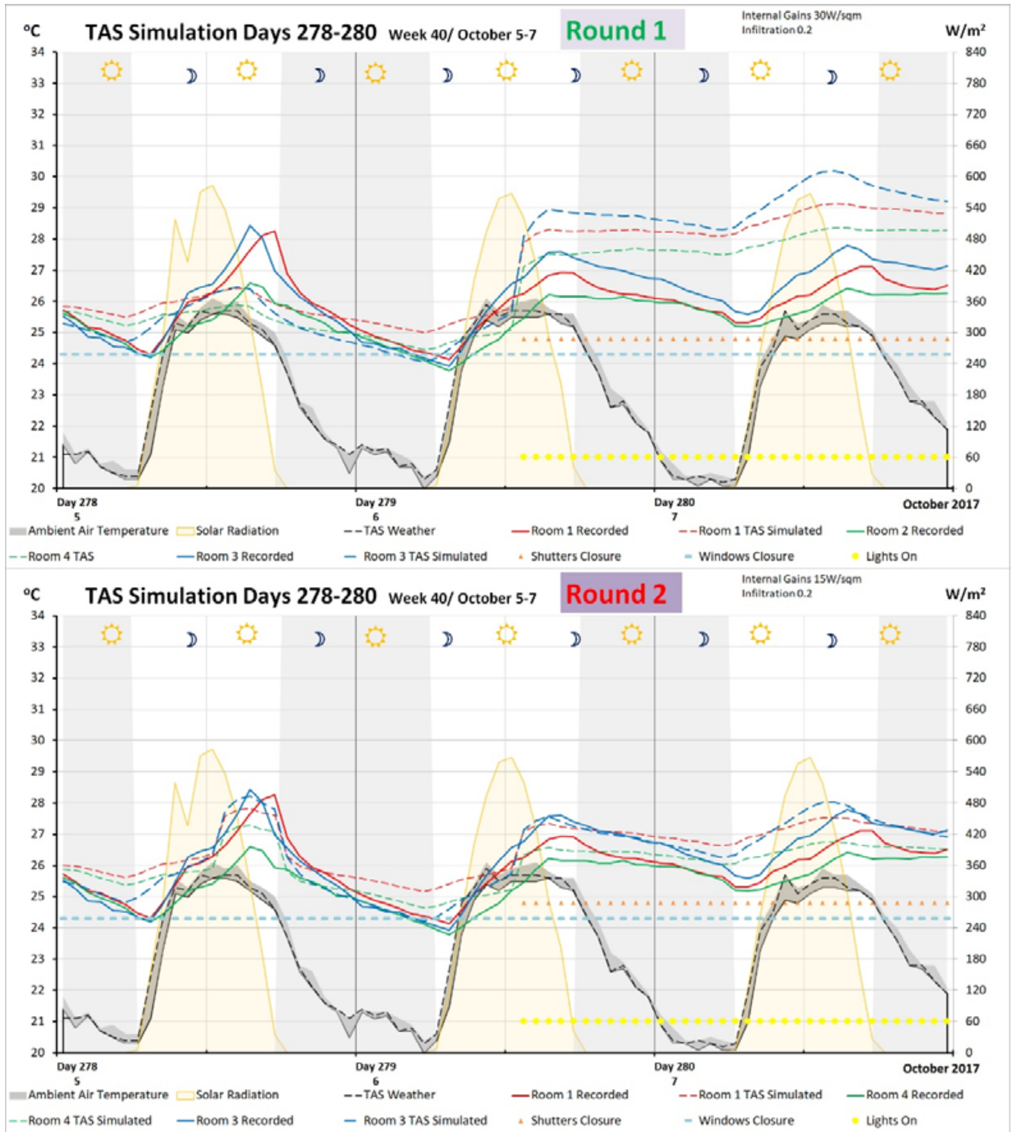


Figure 7.4 Temperature graphs of both runs for days 278-279 showing (a) large gap when the actual internal gains of 30W/m² are inputted, and (b) the impact of halving the internal gains to only 15W/m². Also seen in (b) the compensation through internal gains for day 278 afternoon peak.

Similarly, as stated previously when there are internal gains, a clear differentiation is shown between the different simulated rooms. This time the coolest simulated room is the one with no insulation, and the warmest is the internally insulated. Nonetheless, the gap between the simulated and recorded is considerable with up to 2K for the day's peak and 3K for the night coolest.

With the considerable gap between simulated and recorded, another run is done with reduced internal gains (30 to 15W/m²) on schedule, in addition to an added time when the recorded temperature peaked in the afternoon of day 278 without any actual internal gains from lighting.

This second run reduced the gap between the recorded and simulated, especially during day 279, whereas, on day 280, the early day temperature is warmer than the recorded temperature and peaks before them as well. Only the night temperature of that day shows very similar values.

The basic internal gains of 30W/m^2 did not provide good similarities with the recorded ones. Instead, they are reduced by half to 15W/m^2 in this run. Also, the day peak from the combined afternoon solar and external heat transfer was not achieved until the same 15W/m^2 was added to this time period.

It should be noted here that since windows are closed, the infiltration rate is kept at 0.2.

Table 7.3 shows the CVRMSE and NMBE values for the different runs and weeks of calibration; reaching good values of 5 and -0.2% with the only change in the internal gains. When re-tested for another week, values remained within the acceptable range, but were higher by 15 and 1.8% respectively.

Table 7.3 Calculated correlation indices of CVRMSE and NMBE weighted from the three rooms, in the different rounds and weeks, along with the initial internal gains (I.G.) and the values used in the calibration process.

	Week 34		**Week 29**	**Week 40**	
	Round 1	Round 2	Round 1	Round 1	Round 2
CVRMSE	26	5	7	34	15
NMBE	-3.1	-0.2	-0.7	4.1	1.8
Internal Gains (W/m^2)	30	60	Nil	30	15

7.4 Conclusion

This chapter completed software-based simulations based on individual smaller test cells where the testing environment is more controlled than the previous inhabited apartment observation. Through two complementary rounds of simulation, the goal of the chapter is to check whether the reduced uncertainties within the smaller test cells (both in real observation and software simulated environment) will provide better correlation between the simulated results and the actual observation, at least for establishing a ranking of better performance in terms of least overheating degree hours above 30^{o}C. It consisted of simulating similar four test cells as the constructed ones with basic double masonry walls and insulation positioned (1) on the outer side, (2) in the middle within the air gap, (3) on the inner side, and (4) with no insulation. They are simulated for least overheating outcomes during 22 weeks of summer (from early June to late October). Results show that the middle insulation has the least overheating, followed by both the outer and the non-insulated with little differences between both at 27% and 30% respectively. The most overheating occurred in the inner insulated cell. Other than the result of the inner cell with the most overheating, the other results did not correspond to the observed results where the non-insulated had the least overheating, followed by the outer insulated with a difference of 40%. The middle insulated had an extra difference of 88% more than the non-insulated and the inner insulated reached a 178% difference. Furthermore, calibration only required modification of the internal gains and not the envelope properties as done for the apartment calibration. This informs the research that the first software study of this chapter can be considered calibrated, and there is no need for post-calibration runs. Figure 7.5 compares both calibrations of the apartment and the test cells and shows the elements that have been modified.

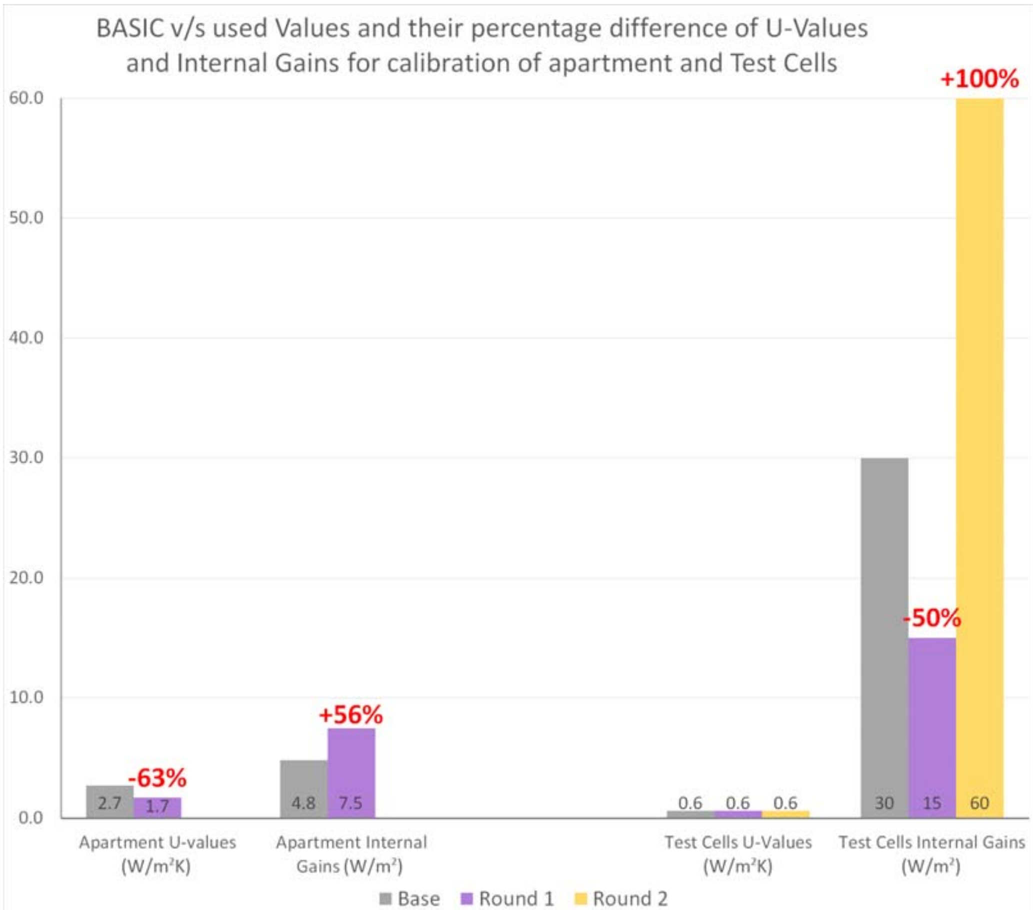


Figure 7.5 Base U-values, internal gains and percentage differences with the values used for calibration in both apartment and test cells.

When it comes to this method of assessment, the chapter tried to re-assess the software method by working on a smaller and a more controlled environment. Results did not show any improvements from what was observed in the apartment software simulation. Thus, the concluding remark is that **software simulation of heavyweight constructions within Beirut's summers is not accurately representing or reflecting temperature behaviours**.

8 Discussion and Conclusion

The main research question ***is to find the best wall construction composition and materiality that will have minimal internal overheating, and thus reduce or eliminate cooling energy loads*** within Lebanon's geographical context composed of: a warm temperate climate; hot summers; and a built environment largely made of heavyweight construction. All these factors lead to overreliance on air-conditioning to achieve summer internal comfort exacerbating Lebanon's chronic power supply shortage.

The research reviewed Lebanon's geographic, climatic, institutional, and constructional context as well as the terms, definitions and previous research required to understand this problem. The research then focused on experiments that spanned from apartment monitoring for summer temperatures to purpose-built test cells. In both cases, extensive software simulations were carried out. Results show that un-insulated double masonry walls produce least overheating, followed by an externally insulated wall with a 40% difference in overheating Degree-hours. This result has not been mentioned in any previous studies in contrast with the frequent citations that the outer-insulated wall is the best construction to limit overheating.

During the process of answering the main question, the following four related conclusions are reached as well:

1- Improve the understanding of heavyweight construction temperature performance of local constructions in Lebanon's summers:

The monitoring showed temperature behaviour in terms of day internal temperature to be cooler than outside, even with the windows open, but night internal temperature to be always warmer than the outside. Both effects are due to the combined effect of thermal mass storing heat during the day and the lack of high wind velocity in Beirut to help flush out the excess heat.

Similarly, the slow response of internal temperature to sudden excess heat or temperature fluctuation is highlighted as well.

Two instances of internally-located and naturally low ventilated spaces (not on the main façade and with no direct solar gains) showed minimal temperature fluctuations with average temperature almost equal to the day's mean temperature.

Outer and inner surface temperatures trends vary considerably; both peak with a time lag varying between one to four hours. Direct solar gains are not the only parameters affecting external surface temperature, both the colour of the external façade's finishing and its constitution (type) also play an important role. Internal surface temperatures are influenced by the walls' thermal properties in terms of time for the external heat to reach the inner surface. More so, the internal ambient room temperature affects the internal surface temperatures especially when the cooling is on.

2-*Show the expectations and limitations of thermal software when simulating heavyweight constructions in hot climates.*

Software simulation showed that EDSL TAS does provide a fair overall temperature behaviour representation for heavyweight construction, in climates with hot summers. When looking at single cases alone, it is clear that the higher the internal gains, the more overheating is shown, similarly, the effect of extended night time window opening in considerably reducing the overheating is clear. Nevertheless, when comparing different constructions at the same time, the issue of accuracy in temperature behaviour becomes a problem. The study has showed too many exceptions within the different runs. Ranking is constantly being shuffled. Lowest overheating is shared by two constructions with low and high U-values, similarly highest overheating is shared by three constructions with various U-values. This is happening due to the software's simplification of the complex temperature behaviour of heavyweight material. This becomes particularly obvious when various constructions are compared.

The purpose built full-scale test cells did show, showed that the structure with the least degree hours of overheating is with the non-insulated walls, followed by the outer insulation with a difference of 40%, then the middle insulation with almost a 90% difference. The internal insulation has the most degree hours of overheating at almost 180% more than the non-insulated one. Chapter 6.4 explains the reason behind this performance which is due to the capacity of both the heavy weight walls to store and release heat into the room and the outdoors, unobstructed by any insulation. Figure 8.1 combines the results of the three methods and shows both the absolute values and the variable percentage difference results reached through each method.

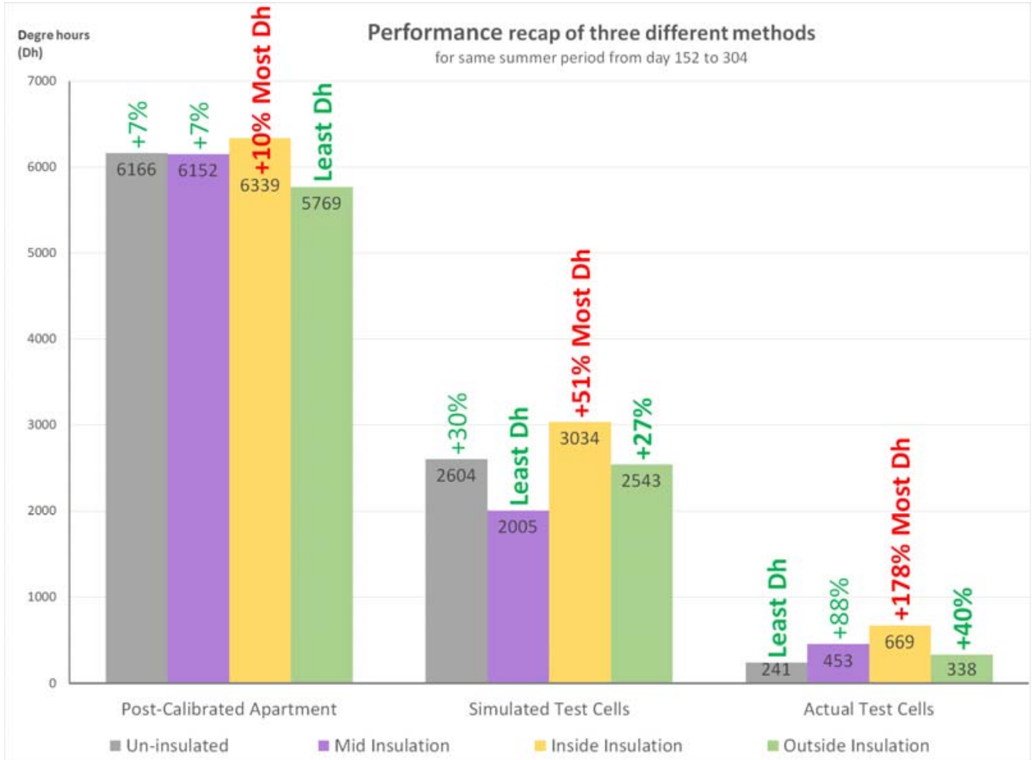


Figure 8.1 Absolute values in terms of degree hours above 30^oC and percentage differences of the four walls typologies, based on the three different methods: the post calibrated apartment; test cell software simulation; and the actual measured built test cells.

It is important to note here that each method was used with different variables (such as length of observation/simulation and different year) as expanded in table 8.2 for summer 2015 and table 8.3 for summer 2017. The study emphasizes that comparative ranking (and not individual results which are bound to be different) of similar construction tested within the different periods should have a minimum of similarities: The best, second and least performing constructions should remain the same, (with a possible modified percentage difference) within the different observable periods. Ranking observed were not similar.

Table 8.1 Basic variables included in the different methods used for the apartment studies.

	Method		Orientation	Cooling Mode	Occupancy	Observation /simulation period	Note
1	Direct observation of existing buildings	Apartment #2	South/West	Mixed Mode	Occupied	1 Aug- 30 Oct	
2	Software simulation	Apartment #2	South/West	Free Running	Occupied	1 June- 31 Oct	Same historical weather file (Aug-Oct 2015)
3	Software calibrated simulation	Apartment #2	South/West	Free Running	Occupied	1 June- 31 Oct	
4	Construction and monitoring of physical models	Test Cells x3	West	Free Running	Un-Occupied	19 June- 29 Oct	

Table 8.2 Basic variables included in the different methods used for the test cells studies.

	Method	Orientation	Cooling Mode	Occupancy	Observation /simulation period	Note	
1	Direct observation of existing buildings						
2	Software simulation	West	Free Running	Un-Occupied	1 June- 31 Oct	Same historical weather file (Mid-June Oct 2017)	
3	software calibrated simulation	West	Free Running	Un-Occupied	1 June- 31 Oct		Random Schedule of Variables
4	construction and monitoring of physical models	West	Free Running	Un-Occupied	19 June- 29 Oct		Random Schedule of Variables

8.1 Contribution to Knowledge

The different methods followed within the study allowed for three novel knowledge contributions:

1- A thorough understanding of the summer temperature behaviour of various heavyweight constructions is reached. This understanding helps to produce valid expectations of how internal summer temperature of heavyweight structures will perform, as well as what are the factors that influence them to become cooler or warmer. This contribution to knowledge is specific to Lebanon and is already an important asset. Yet, furthermore it can be applied in similar zones such a Mediterranean /south European climate.

2- Next, a detailed assessment of heavyweight temperature software simulations reveals well defined expectations and limitations. This also is applicable to any study where heavyweight is included. This can be achieved by numerous runs, comparisons under various conditions, but also by the calibration exercises.

3- Finally, the purpose-built test cells and their summer long monitoring proved that an un-insulated double masonry wall will provide least summer overheating when compared to other insulated double masonry walls. This is a major breakthrough, specifically for similar climatic zones, and in particular for Mediterranean south Europe regions, where energy reduction studies focus on adding insulation on walls rather than decreasing it.

8.2 Limitations and Future Research

The observed and recorded temperature differences between the different purpose-built test cells are relatively small; furthermore, dimensional similarities and occupation (as relationship between size of test cells and internal gains) do not necessarily reflect real buildings. Additionally, the study mainly focused on only summer temperature performance. No winter data were collected or included to check whether the gained benefits of lower summer overheating will be lost during intentional winter heating.

Further research should focus on a year-long study where the expected increase in winter heating is compared to the reduced summer cooling. The comparison will start by comparing the net energy consumed for both in terms of kWh; it is also vital to compare the reduced actual budget of the electric power for cooling and the increase in fuel budget for heating. Both are then compared to the cost of the added wall insulation. It is only once all these steps are completed that a final verdict and consensus of the benefits of insulation can be reached.

8.3 Budget and Further Recommendations

It is worth noting that the achievements of this research are based on the construction of the three-test cell. The overall budget was 15,000GBP which includes 11,000GBP for construction, 3,000GBP for equipment, and 1,000GBP for subsistence. It is highly recommended that any large-scale future project does consider such experimental settings. With an estimated budget of not less than 15Million GBP, purposely building test cells for temperature monitoring would sum up to only 0.1% of the overall budget. The experiment should start in parallel with the design phase and implemented on/near site while site mobilization is ongoing. A practical idea would be to turn the test cells into construction site offices, where all on-site consultants and contractor personnel are stationed; precluding any issues of time or location. The impact of such a study will inform and considerably influence the cooling strategy to be implemented within the project. Thus, the minimal budget for a needed site requirement (site offices) would have a major impact on return investments by reducing cooling load. One could argue that the time frame might not allow the on-going construction to fully benefit from the experiment; in that case the results could be used by the consultants for their next project.

Published Papers

Peer reviewed Journal

Saleh, P.; Schiano-Phan, R.; Gleeson, C. **"The Rasmaska project: temperature behaviour of three, full scale test cells in hot Mediterranean summer: non-insulated double masonry wall and different insulation locations".** Energy and Buildings, Volume 178; Accepted August 15, 2018, pp 304-317

Conference Proceeding

Saleh, P.; Schiano-Phan, R.; Gleeson, C. "**Heavy Weight Thermal Calibration and Validation Methodologies: from Modelling to Full Scale Built Test Cells in Lebanon".** Building simulation and optimization 2018, University of Cambridge 11-12 September 2018

Saleh, P.; Schiano-Phan, R.; Gleeson, C. "**What heavy weight buildings in hot climates can tell us about their thermal performance".** PLEA 2017 Proceedings- Design to Thrive, Edinburgh, Scotland, July 2-5, 2017, Volume III, pp 4299-4306

Saleh, P.; Schiano-Phan, R.; Gleeson, C. "**Review of minimum U-Values for Lebanon and the associated effect of internal gains".** PLEA 2017 Proceedings- Design to Thrive, Edinburgh, Scotland, July 2-5, 2017, Volume III, pp 4307-4314

Saleh, P.; "**Re-assessing the numerous proposed and existing U-values for Lebanon".** The 2nd International ASHRAE conference on efficient building design, materials and HVAC technologies. Beirut, Lebanon, Sept 22-23, 2016. Paper no 19251

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Appendix 1 The monitored apartments

Apartment #1: Full time cooling

In brief: East orientation; full time cooling mode; family of three; monitored for 7 weeks from September 15 (week 37) to October 30 (week 43)

This 1960's east-facing apartment building has six floors with 4 apartments per floor (fig. A1.1). The slabs and the vertical structures are all reinforced concrete, whereas the partition walls are hollow concrete blocks. In each apartment, the floors are stone tiled while the walls and ceilings are plaster-painted. Windows are single glazed panes with steel frames, which are, (according to the occupants) permeable to wind suggesting high infiltration. The apartment is on the 4th floor (intermediate floor). The occupants are a family of three, spending much of their day at home, with continuous cooling in the living/dining area from an old individual window-type A/C. Three data loggers are monitoring the entrance, the dining area and the shaded balcony for dry bulb temperature and relative humidity for a total of 7 weeks (September 15 (week 37) to October 30 (week 43)).

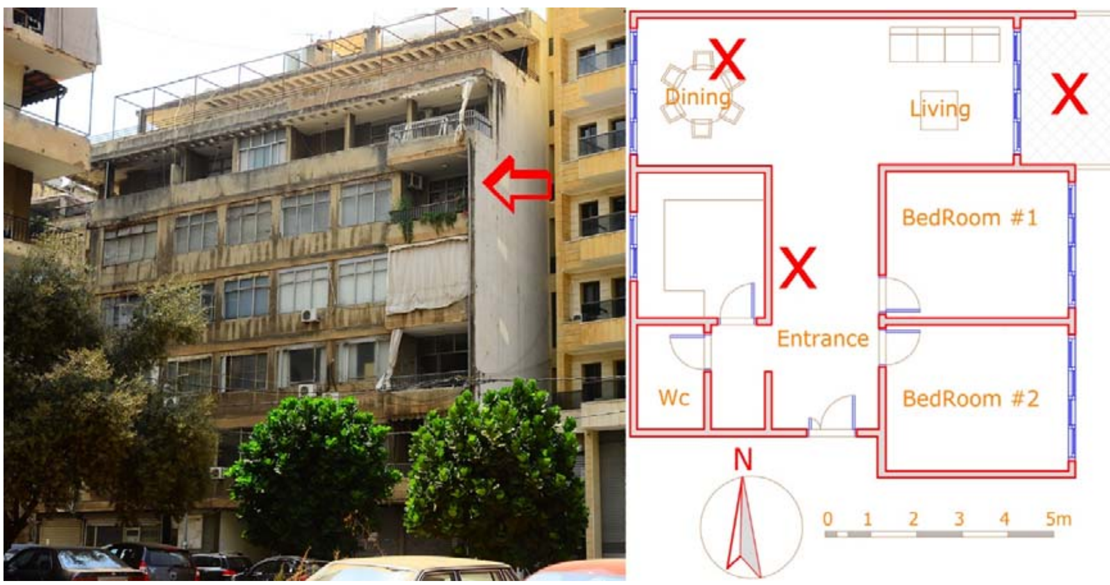


Figure 0.1 The building and the corresponding monitored apartment

Apartment #2: Mixed-mode cooling

In brief: South-West orientation; mixed mode cooling; family of four; monitored for 9 weeks from August 1(week 31) to October 2 (week 39)

Figure A1.2 The building and the corresponding plan of half the floor.

This apartment (fig. A1.2) is located in one of the oldest buildings in the area, dating to the late 1960's according to the occupants' description. The building has 5 floors, with two apartments on each, and a commercial ground floor. The living areas with their balconies have a south-west orientation, and the eastern façade is blank (continuous opaque wall with no windows). The building's structure is reinforced concrete for slabs and vertical structures whereas the external and partition walls are hollow concrete plastered and painted block walls., All the windows are single glazed with timber frames. The monitored floor is also an intermediate floor (4th floor). The apartment is occupied by a family of four (parents and two young adult children); it is composed of two bedrooms, one main living area, a dining area, and a kitchen. The father and one of the children is at work all day whereas the other attends university but is more often at home. The mother is mainly at home. Data loggers for dry bulb temperature and surface temperature are monitoring both the living area and the bedroom, as well as the semi outdoor space with perforated lightweight bricks (clostra) from August until early October (figure 4.8).

The apartment has individual A/C units one in each bedroom and one in the living/dining area. The latter is seldom used, whereas the bedroom A/Cs are used during the night, when the main EDL power is available (hence not when the neighbourhood generator is on). A fan and the open windows in the living area provide some comfort from the heat and humidity. When the A/C is used in whatever room, its internal timber door is closed to keep the coolness contained within and not to dissipate outside.

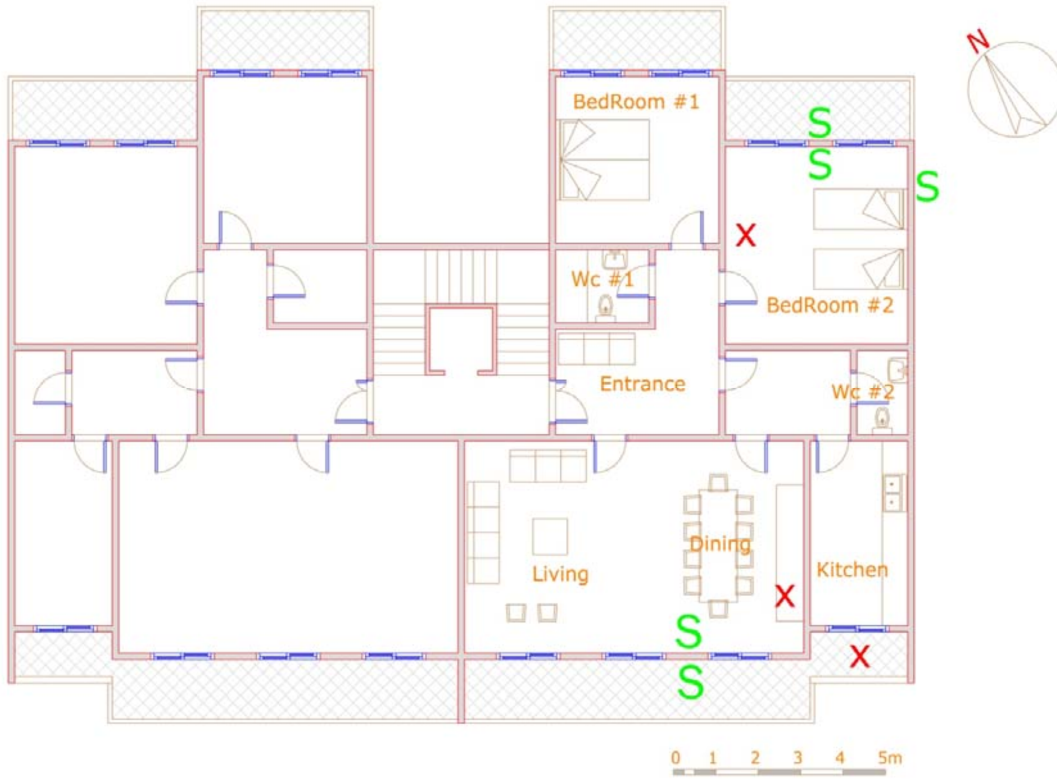


Figure 0.3 The full floor plan showing two adjacent apartments with the temperature and relative humidity data loggers (X) and the wall surface temperature data loggers (S).

Apartment # 3: Mixed-mode cooling

In brief: south orientation; mixed-mode cooling; family of five; monitored for 13 weeks from August 1 (week 31) to October 30 (week 43)

This apartment has a south orientation for the living areas; it is located on the same street as the previous building #2. Although dates back to the early 1990's, it has the same construction material except for the window frames which are aluminium. The monitored apartment is the 9th (last) floor with just a small roof construction over a small part above it (fig. A1.4). The apartment has two bedrooms, two living areas, and one dining room, for a family of five: working father, household mother and three university kids. Data loggers for dry bulb temperature and relative humidity are located in the living room, the dining area with an adjacent glazed balcony (fig. A1.5), and the entrance hall (added in mid-September). One surface temperature is located on the kitchen's ceiling. The monitoring started in August throughout the end of October. The apartment has individual A/C units, yet as in the previous building's case, the one in the living area is seldom used, instead an even larger fan is used when needed, with open windows.

Figure 0.4 Back (north) facade of the Ghanimeh Building; the monitored apartment is on the last floor (left).

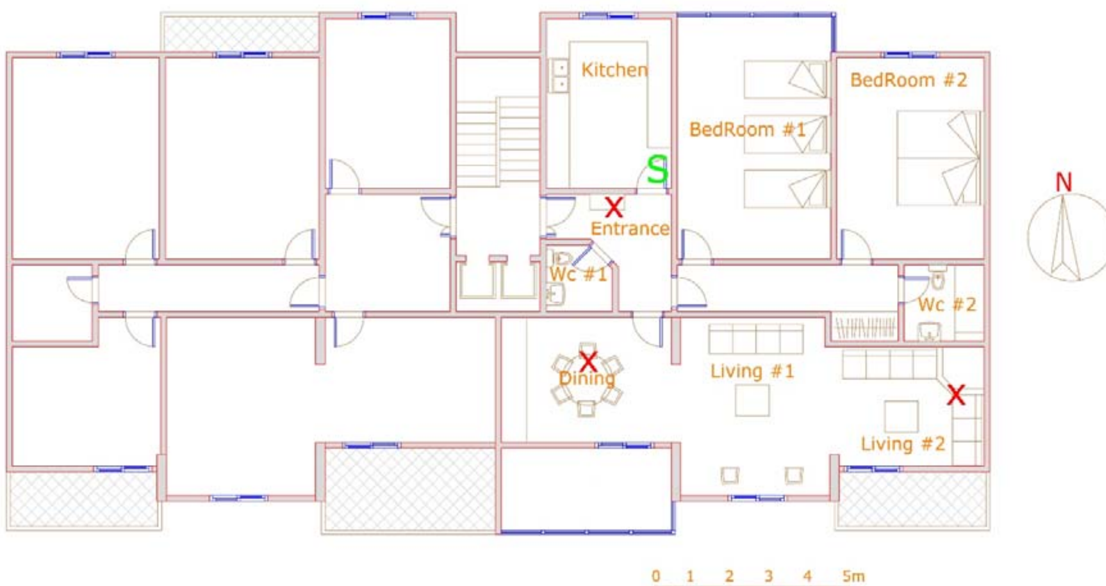


Figure 0.5 The full floor plan showing two adjacent apartments; the temperature and relative humidity data loggers (X) and the ceiling surface temperature data logger (S).

Apartment #4: Free running mode/ Unoccupied

In brief: east orientation; free running mode; unoccupied; monitored for 13 weeks from August 1 (week 31) to l October 30 (week 43)

Figure 0.6 Front (east) main façade with the North side façade. The monitored apartment is on the 7th floor.

The fourth monitored apartment is newly constructed and still empty. The building has an east orientation for the living areas, and is made out of concrete slabs, double cavity hollow concrete block walls cladded with natural white and yellow stones for the east main façade (fig. A1.6). The west façade is painted plastered double cavity hollow concrete. Data loggers for dry bulb temperature are placed in the main living area on the east side, as well as in one room on the west part, same goes for the surface temperature loggers placed on both sides of one east wall and one west wall. Since the east wall had two types of stones, the surface temperature data loggers are placed on both the yellow and white stone surfaces (fig. A1.7). The monitored phase spanned from August until the end of October. This apartment was on the 7th floor of a 9-story building, hence it is assigned as an intermediate location, and since it is not inhabited, neither A/C nor any other power or heat sources are activated. Furthermore, based on the recommendation of the building owner, one data logger is placed in the staircase leading to the underground basement; an area that is never used by any of the building's inhabitants. Also, that area is ventilated through the main gate and the entrance hall of the building but does not receive direct solar gains.

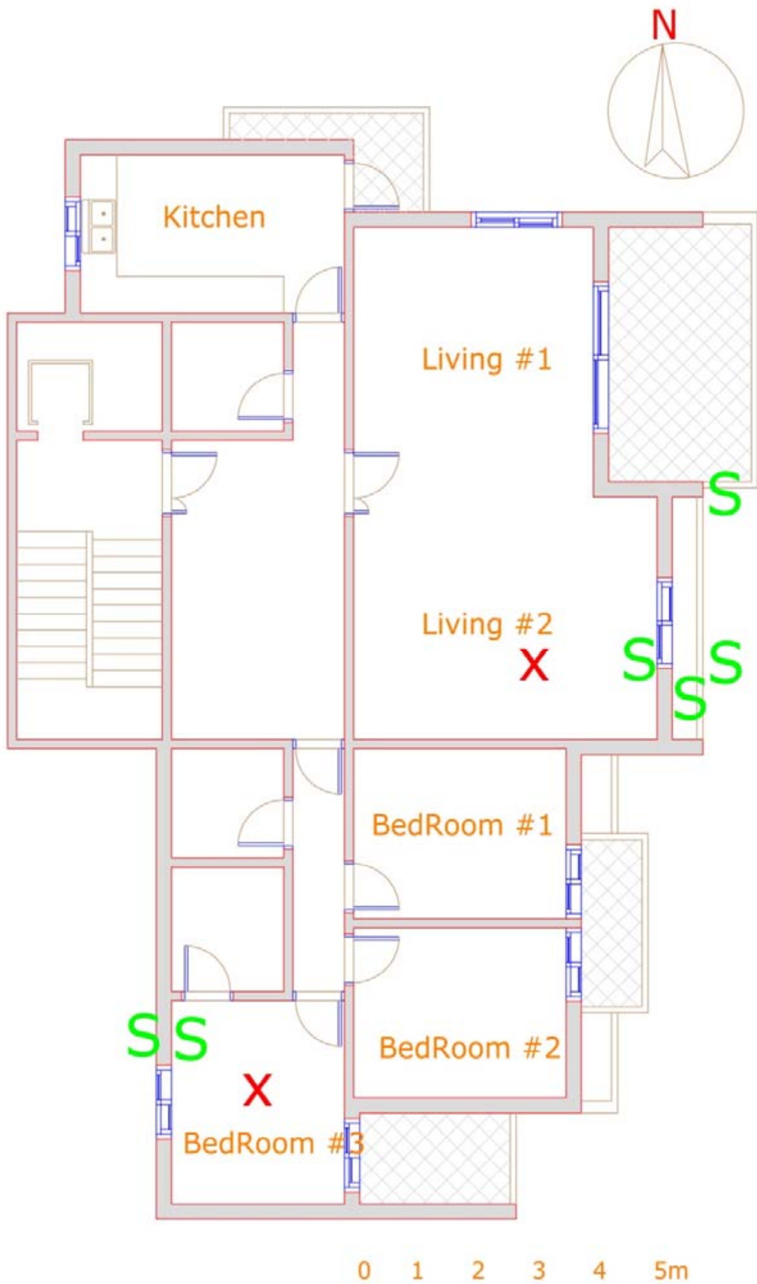


Figure A1.7 The full floor plan of the apartment; temperature and relative humidity data loggers (X) and wall surface temperature data loggers (S).

Appendix 2: Internal gains Calculation

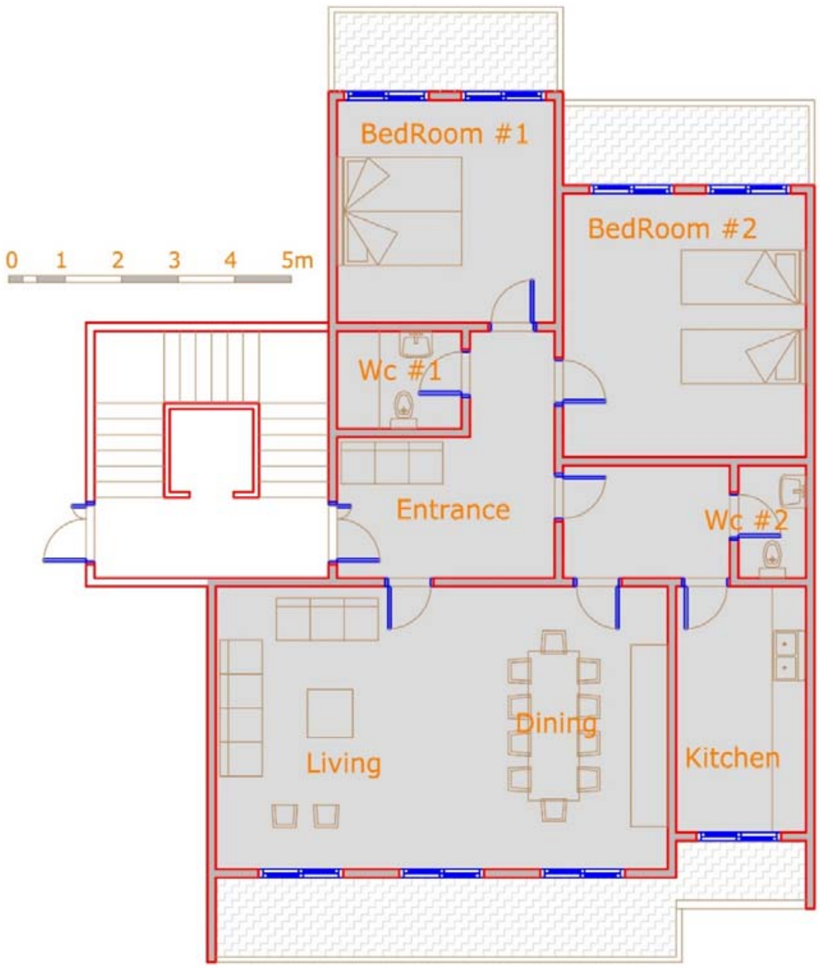


Figure A2.1 Plan of the apartment with the different rooms

Internal gains combine heat gains from lighting, users and equipment in each of the different rooms (fig. A2.1). They require the combination of both the Wattage of each and every element, along with the specific usage schedule (fig. A2.2). The uncertainties in this operation lies in establishing one typical week and extrapolating for the entire year.

Bedroom #1 the parents' bedroom, has one incandescent lamp of 80W and a TV set, electric mosquito repellent used with no specific schedule. Estimated heat is 90W from each.

The bedroom# 2 is the bedroom for two young brothers. It has one incandescent lamp of 80W. It also has a laptop, radio, electric mosquito repellent used with no specific schedule. Each brother heat is estimated at 100W.

Combined living and dining area has two chandeliers one with two sets of 4 incandescent lights each of 40W, totalling 8x40W = 320W. the other chandelier has four incandescent lights of 40W each in addition to one larger bulb of 100W. The total wattage of both chandeliers is 560W. It is used by the family, or to receive guests, up to 7 hours a day with an average of two to three people.

The entrance is more commonly used by the family, it has one incandescent light bulb of 80W in addition to the TV set. It is used for up to 5 hours with at least one to two persons.

Kitchen has low power lamp of 15W, in addition to the continuous running fridge, and the cooking.

Calculations are done for weekday (Table A2.1) and weekend schedule (Table A2.2), and later combined. To get the value is W/m^2 the overall yearly value of Wh is divided by the apartment area (109m^2) and the total hours in a year (8760), as shown in table A2.3.

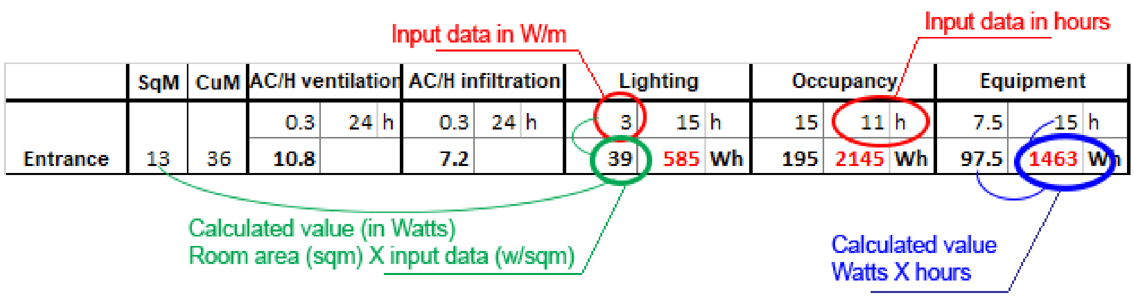


Figure 0.2 method of inputting values, and calculations

Table 0.1 Input and calculation process of weekday internal gains based on available and collected data.

Internal Gains WeekDAYS

	SqM	CuM	AC/H ventilation		AC/H infiltration		Lighting		Occupancy		Equipment	
			0.3	24 h	0.3	24 h	6	4 h	11	4 h	7.5	4 h
Entrance	13	36	**10.8**		**7.2**		**78**	**312 Wh**	**143**	**572 Wh**	**97.5**	**390 Wh**
			1.5	24 h	0.1	24 h	15	2 h	1	1 h	1	1 h
Service	5	15	**22.5**		**2.4**		**75**	**150 Wh**	**5**	**5 Wh**	**5**	**5 Wh**
			2	24 h	0.3	24 h	4	2 h	10	11 h	3	2 h
BedRoom 1	20	56	**112**		**7.2**		**80**	**160 Wh**	**200**	**2200 Wh**	**60**	**120 Wh**
			2	24 h	0.3	24 h	5.5	2 h	12	11 h	3	2 h
BedRoom 2	15	42	**84**		**7.2**		**83**	**165 Wh**	**180**	**1980 Wh**	**45**	**90 Wh**
			3	24 h	0.3	24 h	1.5	3 h	12	3 h	3	24 h
Kitchen	10	28	**84**		**7.2**		**15**	**45 Wh**	**120**	**360 Wh**	**30**	**720 Wh**
			2.5	24 h	0.3	24 h	14	5 h	6.5	7 h	2.5	7 h
Living	40	112	**280**		**7.2**		**560**	**2800 Wh**	**260**	**1820 Wh**	**100**	**700 Wh**
			1.5	24 h	0.1	24 h	4	1 h	1	1 h	1	1 h
WC 1	2	6	**9**		**2.4**		**8**	**8 Wh**	**2**	**2 Wh**	**2**	**2 Wh**
			1.5	24 h	0.1	24 h	2	1 h	1	1 h	1	1 h
WC 2	4	11	**16.5**		**2.4**		**8**	**8 Wh**	**4**	**4 Wh**	**4**	**4 Wh**
Total	109	**306**					**3,648**		**6,943**		**2,031**	
Total							**12,622**				**Wh/day**	
							3,294				**kW.h/year**	

Table 0.2 Input and calculation process of weekends internal gains based on available and collected data.

Internal Gains WeekEnds

	SqM	CuM	AC/H ventilation		AC/H infiltration		Lighting		Occupancy		Equipment	
			0.3	24 h	0.3	24 h	6	5 h	11	4 h	7.5	4 h
Entrance	13	36	**10.8**		**7.2**		**78**	**390 Wh**	**143**	**572 Wh**	**97.5**	**390 Wh**
			1.5	24 h	0.1	24 h	15	2 h	1	1 h	1	1 h
Service	5	15	**22.5**		**2.4**		**75**	**150 Wh**	**5**	**5 Wh**	**5**	**5 Wh**
			2	24 h	0.3	24 h	4	3 h	10	11 h	3	1 h
BedRoom 1	20	56	**112**		**7.2**		**80**	**240 Wh**	**200**	**2200 Wh**	**60**	**60 Wh**
			2	24 h	0.3	24 h	5.5	3 h	12	11 h	3	1 h
BedRoom 2	15	42	**84**		**7.2**		**83**	**247.5 Wh**	**180**	**1980 Wh**	**45**	**45 Wh**
			3	24 h	0.3	24 h	1.5	3 h	12	3 h	3	24 h
Kitchen	10	28	**84**		**7.2**		**15**	**45 Wh**	**120**	**360 Wh**	**30**	**720 Wh**
			2.5	24 h	0.3	24 h	14	5 h	6.5	6 h	2.5	6 h
Living	40	112	**280**		**7.2**		**560**	**2800 Wh**	**260**	**1560 Wh**	**100**	**600 Wh**
			1.5	24 h	0.1	24 h	4	1 h	1	1 h	1	1 h
WC 1	2	6	**9**		**2.4**		**8**	**8 Wh**	**2**	**2 Wh**	**2**	**2 Wh**
			1.5	24 h	0.1	24 h	2	1 h	1	1 h	1	1 h
WC 2	4	11	**16.5**		**2.4**		**8**	**8 Wh**	**4**	**4 Wh**	**4**	**4 Wh**
Total	109	**306**					**3,889**		**6,683**		**1,826**	
Total							**12,398**				**Wh/day**	
							1,289				**kW.h/year**	

Table A2.3 Calculation process of overall (yearly) internal gains expressed in kWh and Final figure expressed in W/m^2

Total Wh per WeekDays	**3,648**	**6,943**	**2,031**
Total Wh per WeekEnds	**3,889**	**6,683**	**1,826**
Total (Weekday x 261 + Weekend x 104)	**1,356,773**	**2,506,895**	**719,790**
Total Wh	**4,583,458**		**Wh/day**
Total kWh	**4,583**		**kW.h/year**
Total W/m^2	**4.80**		**W/m^2**

Appendix 3: Air exchange calculation

The calculation below and table A3.1, are based on Szkoloay (p.113; 2008) formula for air exchange calculation. These are done assuming the average wind speed is 2 m/s in a south/west direction.

Wind pressure (Pw) 0.6 x V^2

Pressure Coefficient Cp

Windward side 0.5< Cpw < 0.8

Leeward side -0.5< Cpl < -0.3

ΔPw Pw x (Cpw+Cpl)

Volume Flow rate 0.827 x A x Ce x $\sqrt{\Delta \mathrm{Pw}}$

Ce = 0.1 one window

Ce = 1 Full cross ventilation

A area of opening

Table A3.1 Calculation notes for the air exchange in the various apartments monitored during summer 2015

Apartment #1	Room 1		
	Floor Area	27	sqm
	Volume	76	cum
	Cpw	0.5	
	Cpl	-0.3	
	Window opening Area	1.2	sqm
	Ce	1	
	Volume Rate	0.69	cu.m/s
		2475	cu.m/h
	Air Exchange	33	ach
		0.8	

Apartment #3	Room 1		
	Floor Area	17	sqm
	Volume	48	cum
	Cpw	0.5	
	Cpl	-0.49	
	Window opening Area	0.6	sqm
	Ce	0.2	
	Volume Rate	0.02	cu.m/s
		55.3	cu.m/h
	Air Exchange	1.2	ach
		0.8	

Apartment #2	Room 1 Bedroom		
	Floor Area	20	sqm
	Volume	56	cum
	Cpw	0.5	
	Cpl	-0.49	
	Window opening Area	1.2	sqm
	Ce	0.8	
	Volume Rate	0.05	cu.m/s
		177	cu.m/h
	Air Exchange	3.2	ach
		2	

Apartment #4	Room 1 Bedroom		
	Floor Area	10	sqm
	Volume	28	cum
	Cpw	0.5	
	Cpl	-0.49	
	Window opening Area	0.4	sqm
	Ce	0.9	
	Volume Rate	0.02	cu.m/s
		66.4	cu.m/h
	Air Exchange	2.4	ach
		2	

Apartment #2	Room 2 Living		
	Floor Area	26	sqm
	Volume	73	cum
	Cpw	0.5	
	Cpl	-0.49	
	Window opening Area	2.6	sqm
	Ce	0.8	
	Volume Rate	0.27	cu.m/s
		959	cu.m/h
	Air Exchange	13	ach

Apartment #4	Room 2 Living		
	Floor Area	20	sqm
	Volume	56	cum
	Cpw	0.5	
	Cpl	-0.49	
	Window opening Area	0.6	sqm
	Ce	0.2	
	Volume Rate	0.02	cu.m/s
		55.3	cu.m/h
	Air Exchange	1.0	ach

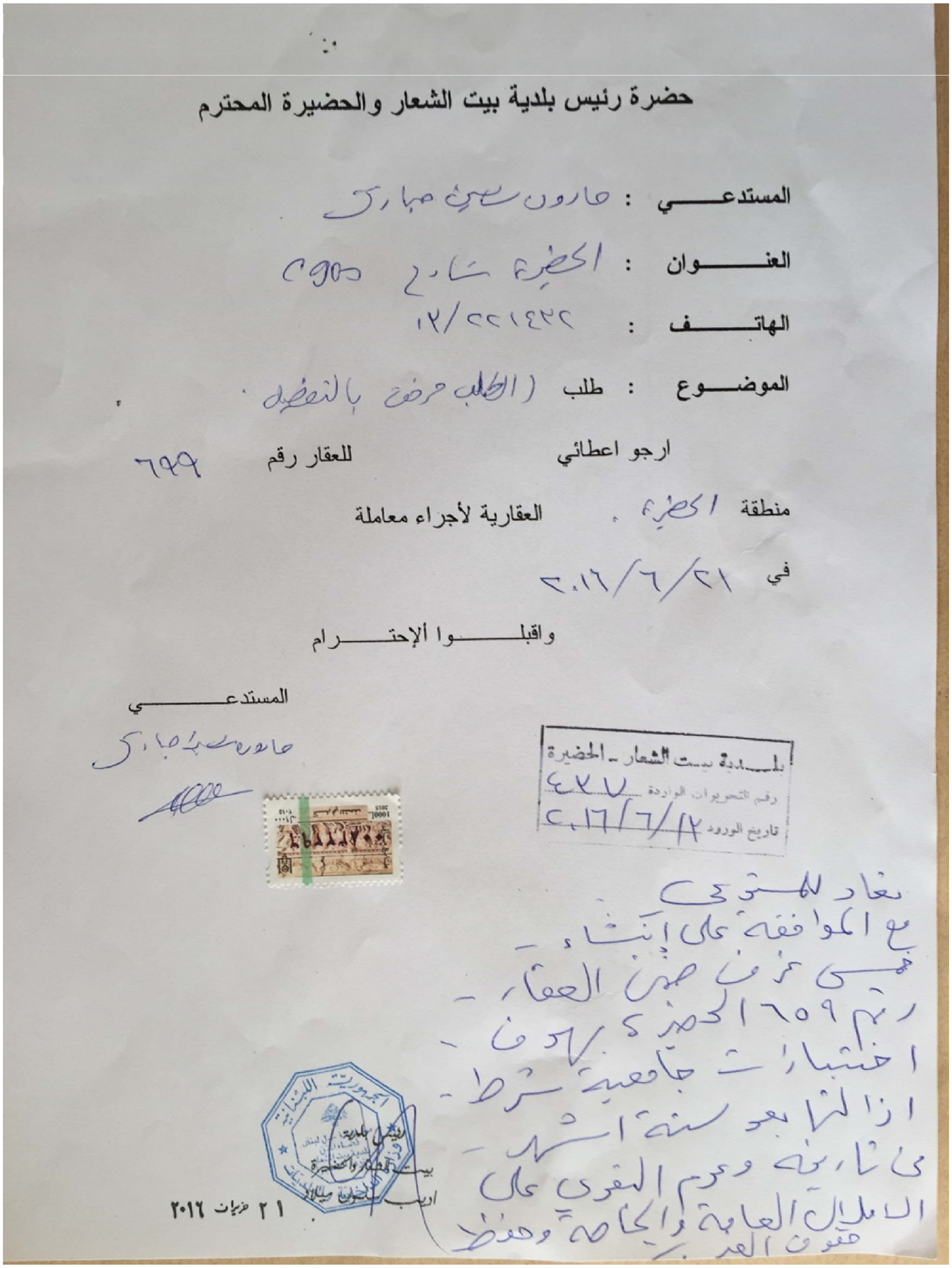
Appendix 4: The search for the land

The land search started in spring 2016 and considered as a simple uncomplicated process. The criteria are that it is needed for at least one full hot season, and thereafter for a whole year. The land should be located within the coastal zone of Lebanon, hence up to 400m above sea level as a maximum elevation. Once the experiments are done, the land owner will keep the test cells and could use them in whatever way he/she sees fit.

This first land located 15-20 minutes' drive from the researcher's residence, seems to be perfect, the owner Mr. Maroun Moubarak, was quite enthusiastic about the project, and fully supportive. He assisted in getting the municipality permit as shown in the figure A4.1 below which reads in the lower right corner, hand written part:

> *Return to the applicant with the approval to construct five rooms on Lot # 699 al-Hazira, for the purpose of university experiments, on the condition that they be removed after a year from this date (21 June 2016), and not to trespass on public and private properties and respect the rights of others.*

Thereafter site mobilization started. The period of late June 2016 is near the end of Ramadan and the feast of Eid el Fitr, accordingly it is common to have scarcity of man power and construction labours. Nevertheless, slow progress is made: the land is levelled and the steel reinforcement for the clean concrete/blinding are ready for a July 9 concrete pouring. Just a few minutes before the ready-mix concrete trucks reached the site, the police, locally called "darak" literally invaded the site, asked to check the permit, which they considered not valid for such a type of construction, and consequently forbid us to carry on any further. To make sure works will not resume, they purposely damaged the steel reinforcement beyond repair (figure A4.2). Consequently, putting a final stop to the construction on that site.



حضرة رئيس بلدية بيت الشعار والحضيرة المحترم

المستدعـــــي : هارون سليم مبارك

العنـــــوان : الحضيرة شارع ٥٩٠٥

الهاتـــــف : ١٢/٢٢١٤٣٢

الموضـــوع : طلب (الطلب مرفق بالتفصيل)

ارجو اعطائي للعقار رقم ٦٥٩

منطقة الحضيرة العقارية لأجراء معاملة

في ٢١/٦/٢٠١٦

واقبلــــوا الإحتـــرام

المستدعـــــي

هارون مبارك

بلدية بيت الشعار - الحضيرة

رقم التحريرات الواردة ٤٧٧

تاريخ الورود ٢٠١٦/٦/١٢

٢١ حزيران ٢٠١٦

Figure 0.1 The official municipality permit to build 5 rooms, signed and dated June 21 2016

Figure 0.2 The 6mm steel mesh reinforcements torn by the law reinforcement as a statement not to even think of carrying on with the works.

Acting as fast as possible and reducing the five planned test cells to only two for faster and easier land search the researcher got in touch with a friendly monastery in the northern part of Lebanon and a friend from the southern part of Lebanon in Houmine, Tyr.

The monastery's head nun was fast to be inspired by the Patron saint to tell us that such a decision is not within her jurisdiction but falls under the Bishop's authority. It was a polite way to tell us it can't be done.

Whereas the friend who actually is a construction manager within a major constructing company, did not have any objection to build the two test cells on his own secondary residence rural land. Furthermore, his own team of workers will carry on the construction; hence no need to supervise the process directly. The land is some 120Km away from the researcher residence and taking not less than an hour and a half drive to reach. In any case, construction started by end of July. By mid-august progress was not fast enough, and remote progress monitoring was not working properly. Reassessing the situation, with the added note that the research is aiming at studying the summer/hot season's temperature behaviour of the various construction methods, it was decided to stop the construction or, postpone everything till spring 2017.

In early spring 2017 a visit to the site (figure A4.3) is done to reassess how practical the driving distance is and to check the status of the built-up test cells. Turned out distance and driving are far and long for eventual couple of visits per week. Most surprisingly the rooms have construction errors: (a) two lateral openings un-planed and unwanted are added symmetrically on facing walls. (b) double cavity walls are not consistent in the construction with the external 150mm wall becoming 100mm.

So, all issues combined, these two test cells are no longer an option to use for the research.

Figure 0.3 The hastily built between late July and mid-August 2016 two test cells in the middle of the secondary residence field in the southern town of Houmine, Tyr.

The land search restarted by October 2016 and the goal was to find a land and get all necessary permits ready by early spring 2017. The maps on figures A4.4; A4.5; A4.6 give an idea of only the different institutions and organizations that were contacted. The individuals and private land owners contacted are not shown.

Hence several local municipalities, monasteries and private land owners were contacted in person and presented with a clear proposal of what is the research about, and how the land will be used and for how long. We got numerous good wishes from monasteries similar to: “how ambitious the researcher is, and how interesting the research is… but we can’t grant you any land”. Whereas the typical municipalities’ reply would be that had they have any available lots, or if we could find a lot they would fully support the project.

Finding the plot was only made possible by the support of **Mrs. Rima Sourour** who is among the first generation of local sustainable researcher. She introduced the researcher to the Municipality of **RasMaska**’s president **Mr. Simon Makhoul**, who was excited about the project and granted us a plot and full logistics support.

Figure 0.4 Overall map of Lebanon with all the different location of institutions and organizations contacted for land search

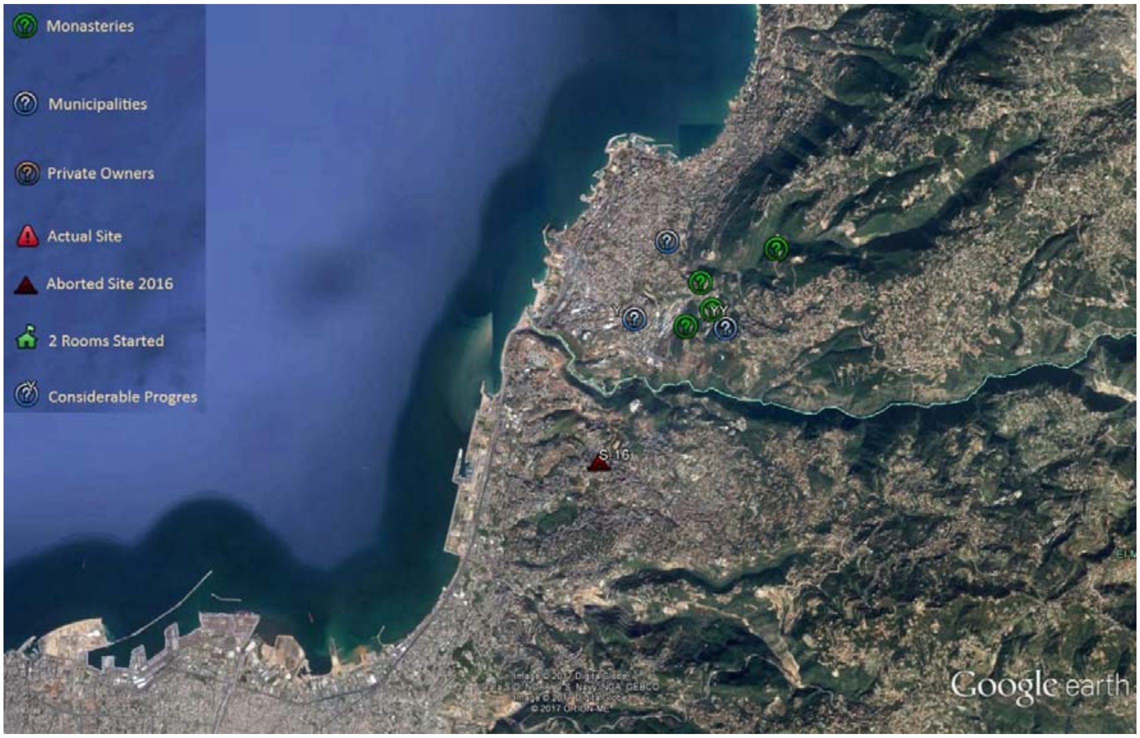


Figure A4.5 A closer view of the central area of Lebanon, north of Beirut, with the numerous contacts, as well as the location of the previous summer 2016 site

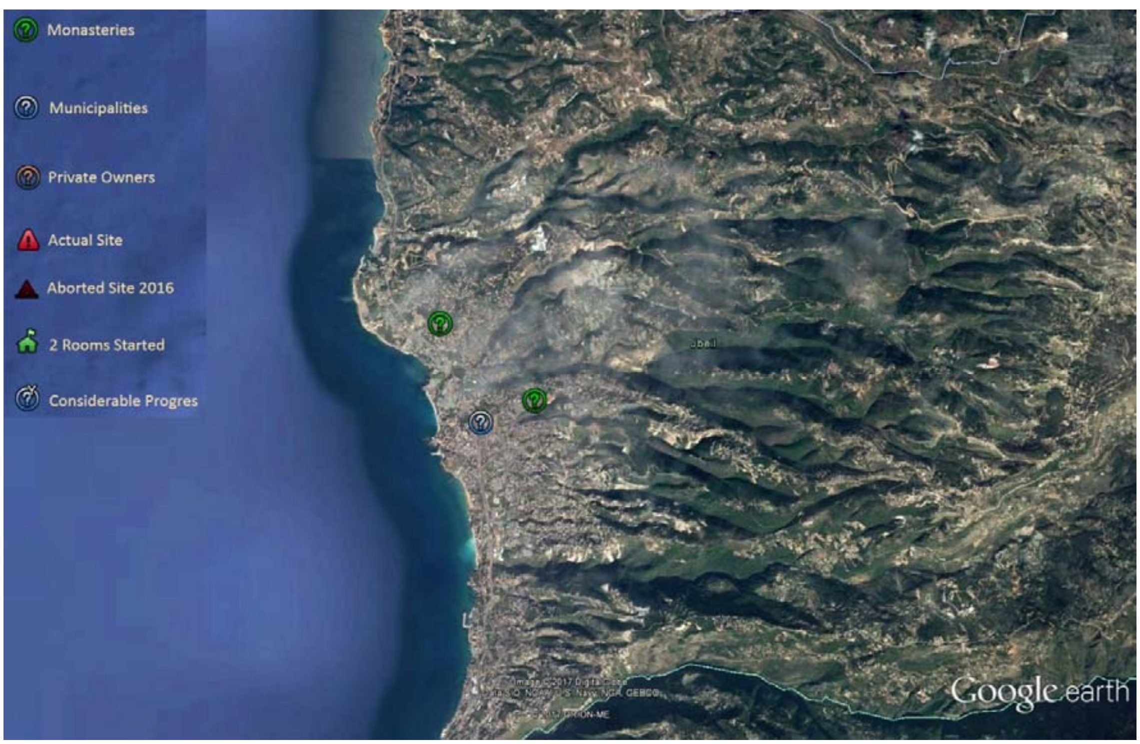


Figure 0.6 Further north of Beirut with more land search

Appendix 5: The Construction

Figure 0.1 Still further up north near the city of Tripoli and the location of the actual site

The land used for the construction is located a small town near the city of Tripoli is North Lebanon. Rasmaska is a large municipality in North Lebanon adjacent to the south of the coastal city of Tripoli; it expands onto the slightly elevated plateau of al-Koura (to its South and East) (fig. A5.1). It has a long sea front exposure as well as inland limits with elevations reaching around 200m. Furthermore, the newly elected municipality is working hard on improving the status and image of the town.

The land is at the entrance of a disaffected stone quarry. The entrance is marked by a monumental arched gate within a three-story structure. The land can fit up to four test cells with a west main exposure. On the east limit of the site are some vertical concrete structures linked by concrete tie-beams (fig. A5.2).

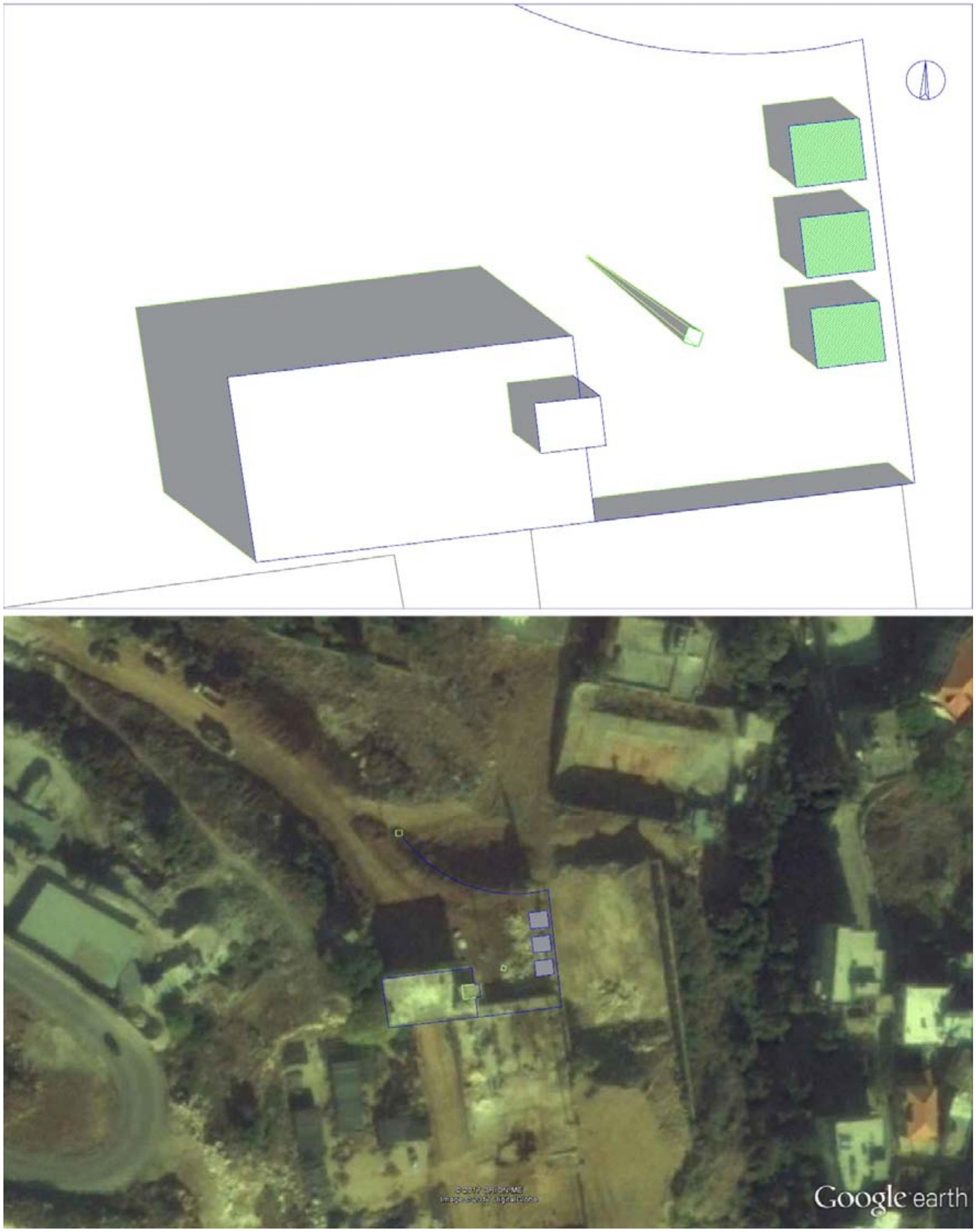


Figure 0.2 Site map and overlaid on Google map showing the three story structure at the end of the road (middle of the map) and the location of the 3 test cells to its right.

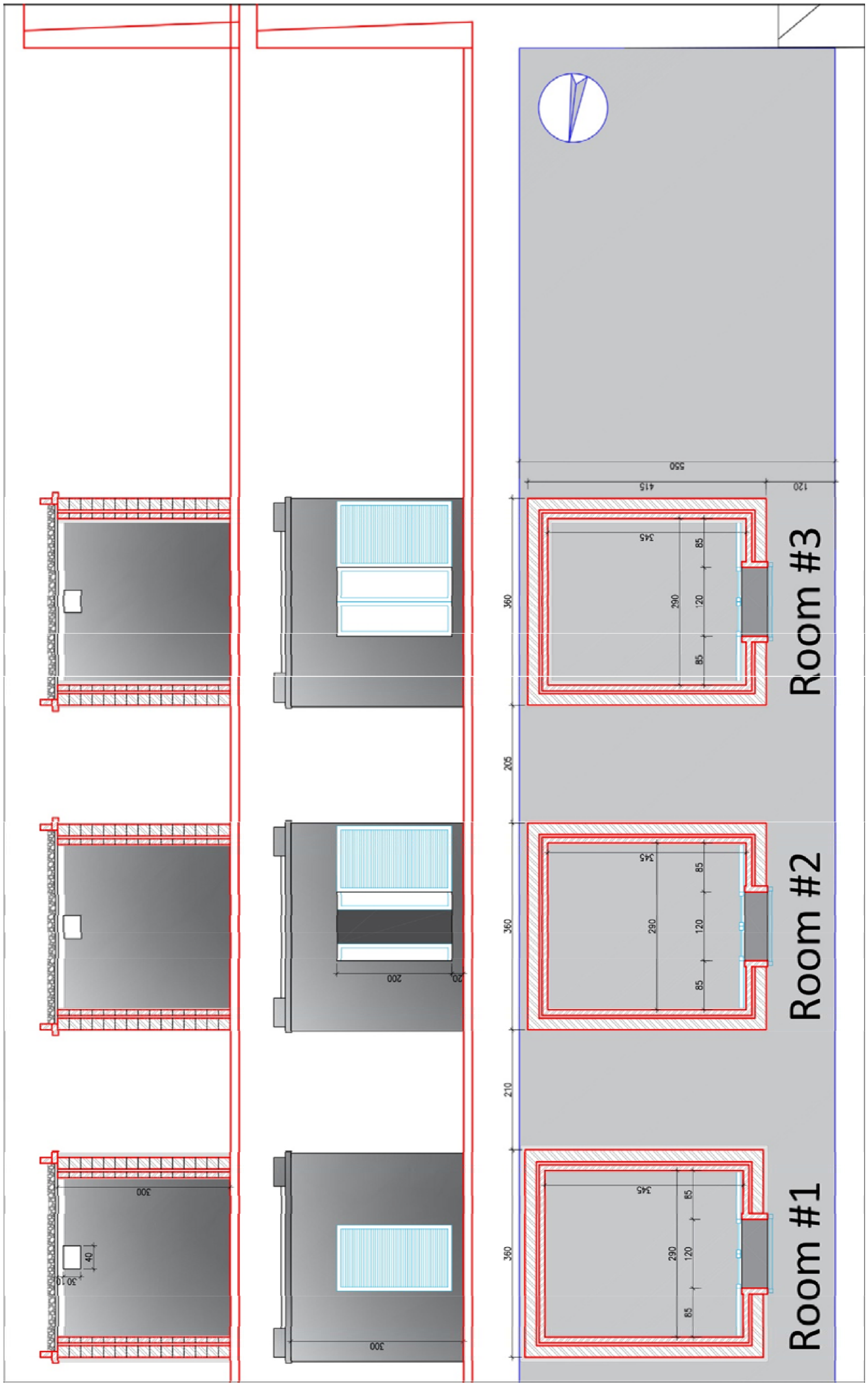


Figure 0.3 The technical maps, plans, sections and elevations of the three rooms.

Construction started by mid-May, under the direct and continuous supervision of the researcher. The technical maps of the three rooms on site and with all relevant details and dimension are shown in figure A5.3 and construction progress is shown in figure A5.4. The workers were from neighbouring city of Tripoli.

The first step consisted of pouring a concrete mat of 120mm in thickness with a mesh of 6mm steel reinforcement at every 200mm, in each direction. Concrete was delivered by two trucks from a neighbouring batching plant. The poured area was approximately 23m x 8m and took about 15 cubic meters. The surface was hand levelled and smoothened.

Once the clean concrete is finished, CMU (Concrete Masonry Units), also from a neighbouring factory, are brought on site along with cement, sand and water to provide the raw materials for the construction. Builders were specifically requested to fill the lower horizontal part of the CMU blocks as well as both its lateral sides with mortar. CMU blocks are laid by horizontal layers and the three test cells were built almost simultaneously and at the same pace to maintain as much as possible similar construction conditions and materials (mortar hand preparation and mixing).

Three walls are built to their full height of 3000mm whereas the front or main wall with its opening is put on hold at 2200mm for the lintel to be casted at a later stage.

The internal 100mm walls follow the same method of construction with the addition of a 40mm gap between both walls. Builders were requested to be very careful in limiting the mortar drops between the walls. A make shift wooden tool of 40mm width including a handle is used on each and every block to maintain same 40mm gap. Similarly, for the 200mm wall, the main west wall is stopped at the lintel level to be poured in-situ onto both the 100 and 200mm walls. Both walls are completed a couple of days later to allow the lintel's concrete to settle.

Decisions regarding the external and internal plastering over the extruded polystyrene insulation were given extra vigilance in order to keep similar construction conditions in the three cells. A nearby concrete retaining wall was used for numerous trials and samplings over extruded polystyrene fixation as well as plastering over them (fig. A5.5) before their actual application. The best method consisted of:

a- fastening the insulation boards by screws and anchors into the wall
b- scratching the insulation surface to make it unsmooth
c- adding a fibre lath over the insulation board joints

Figure 0.4 Work progress from the clean concrete to the finished 200mm external and 100mm internal concrete masonry walls.

Figure 0.5 Plastering sampling over insulation boards with the surface made rough, and fibre mesh added.

Expanded insulation of 25mm is fixed on the external wall for test cell #1, and on the internal wall of test cell #3. Whereas for test cell #2, insulation boards are pre-fixed by tape into long strips of 3000mm and manually inserted into the 40mm cavity (figure A5.6). This approach would allow for the easy removal of insulation at a later stage in the experiment. It should be noted here that test cell #2 thus has a reduced air gap of 15mm.

Figure A5.6 Insulation boards fixation, left column externally, right column internally, with screws and wire mesh shown.

Finally, all external and internal walls are plastered with an almost same 11mm thickness by a pre-layer of what is referred to as splatter dash where very liquid plaster is sprayed on the surface to create a new rough texture for better adhesion of the main plaster layer. Extra care is given to the test cell with external insulation where special angular metal laths are added onto the corners to provide further protection (fig. A5.7).

Figure A5.7 Plastering process, showing the first rough surface layer, the splatter dash, followed by the final thicker and smoother later. The angular metal lath is shown as well.

The roof is made of wood planks of 49mm thickness and 300mm width, laid over the full 100mm wall and partially over the 200mm. In addition, two 110mm square timber beams are employed to support the load. A nylon layer is placed over these wood planks above which an average of 160mm gravel is spread (fig. A5.8).

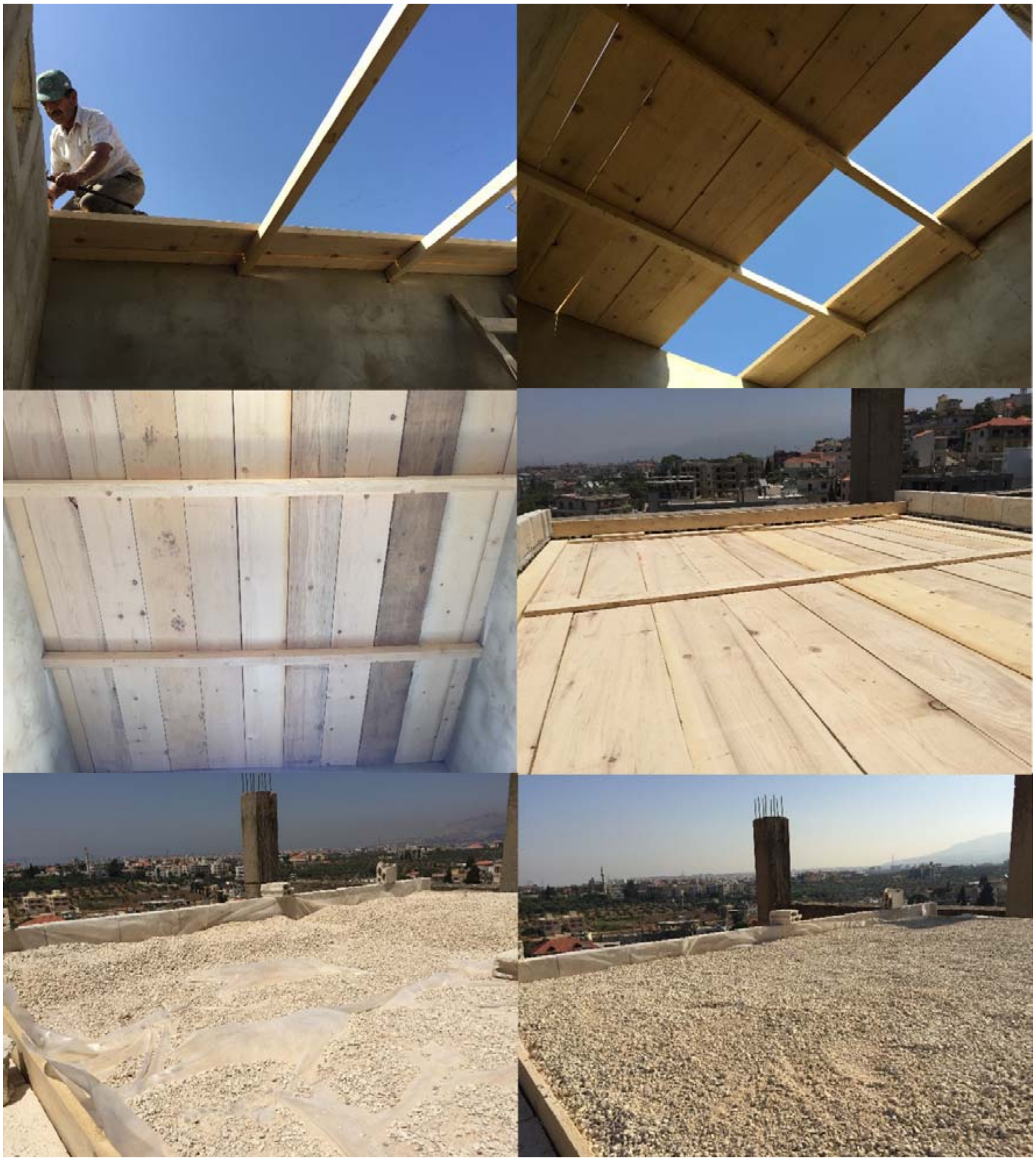


Figure A5.8 Roof progress with the 49mm wood planks above which a thin layer of nylon and 160mm of fine gravel.

Before installing the windows, a threshold is casted in-situ over which two sliding single glazed aluminium panels are installed on the rails inside the test cells and one sliding louvered white painted aluminium panel is installed on the outside (fig. A5.9).

Figure 0.9 The external louvered shutters with their railing frames and the internal two panel single windows sliding on their internal rails.

After 6 weeks of observation with the un-painted plastered finish walls they are painted white during week 30 (July 29-30; days 210-211; figure A5.10).

Figure 0.10 White painting the three test cells between July 29 and 30, 2017.

On August (day 235), three 100W incandescent light bulbs are added in each of the test cells. They are positioned at a height of 25cm from the floor, in a radial pattern of 120º angle, and at 900mm from the centre of the room. The light bulbs pointing towards the walls, with one perpendicular to the window (fig. A5.11).

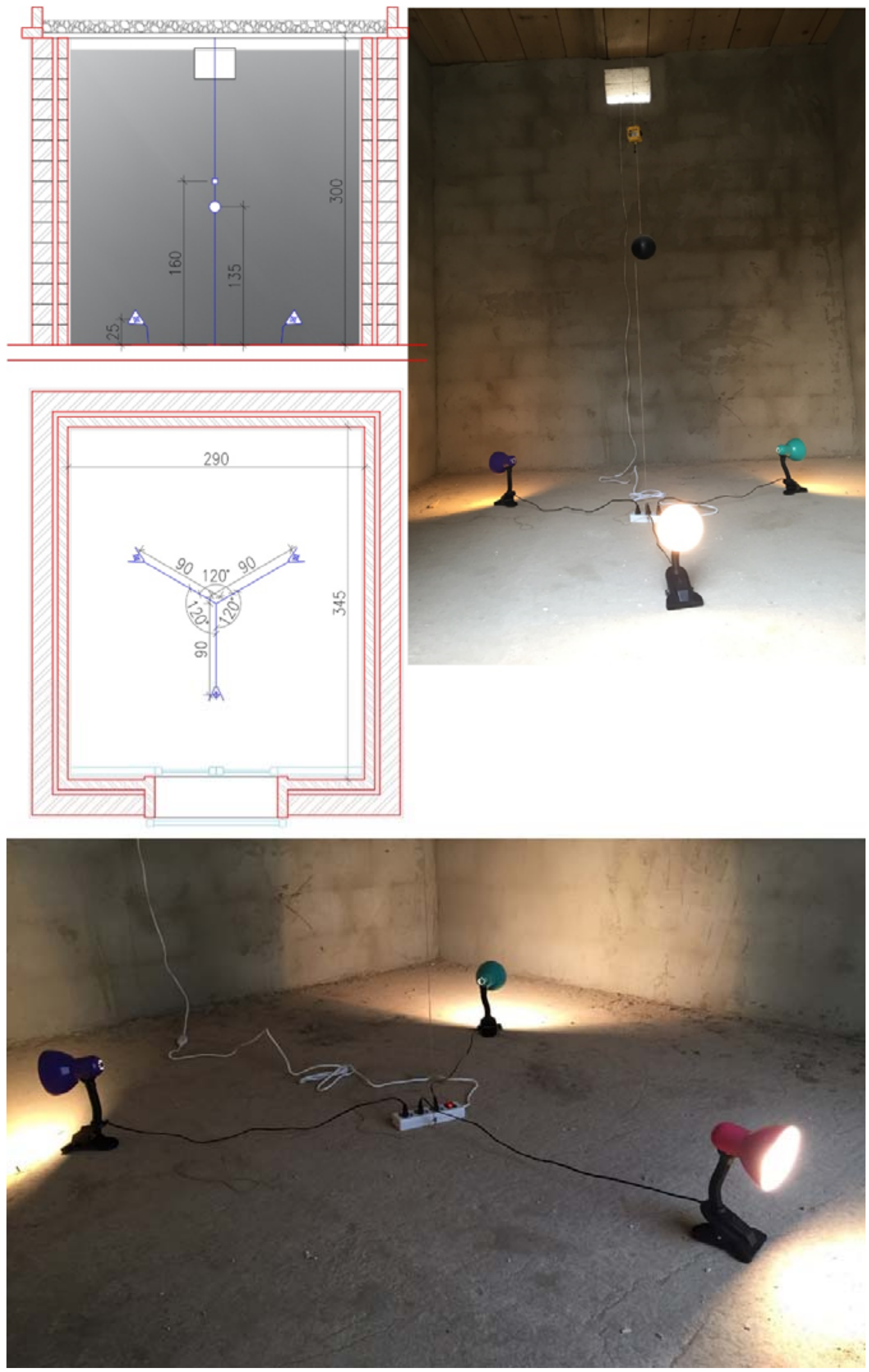


Figure A5.11 Technical drawings and photos of 3x 100W incandescent electrical bulbs layout within the test cells.

During week 34 between August 29 and 31 (days 241, 242 and 243), the insulation of the test cell #2 is removed from the middle of the double cavity wall. On the afternoon of August 29, a make shift scaffolding is installed between test cell #2 and #3, and the gravel is moved over this new location, exposing the timber roof. On the following day, August 30, the timber logs are moved to allow reaching to the insulation boards. The insulation in test cell #2 is loosely fitted in the 40mm cavity; they are also made into long strips of 600mm width and 3000mm length by using tape to stick two and one-half boards together.

Once all the insulations boards are removed, the initial wood planks are repositioned into their location. On August 31, all the initial gravel is returned into its initial location and the make shift scaffolds are removed (fig. A5.12).

All data loggers and lighting fixture are checked for good operation and repositioned into their original positions.

Figure 0.12 Sequence of insulation removal: from the scaffold installation to the gravel transfer, the insulation boards removal, and finally the re-transfer of the gravel and removal of scaffold.

Appendix 6: Regression method of calculation

In order to find the value of degree hours of overheating above 30^{o}C for the entire observed period, the following regressions are done. They take into account all the different variables.

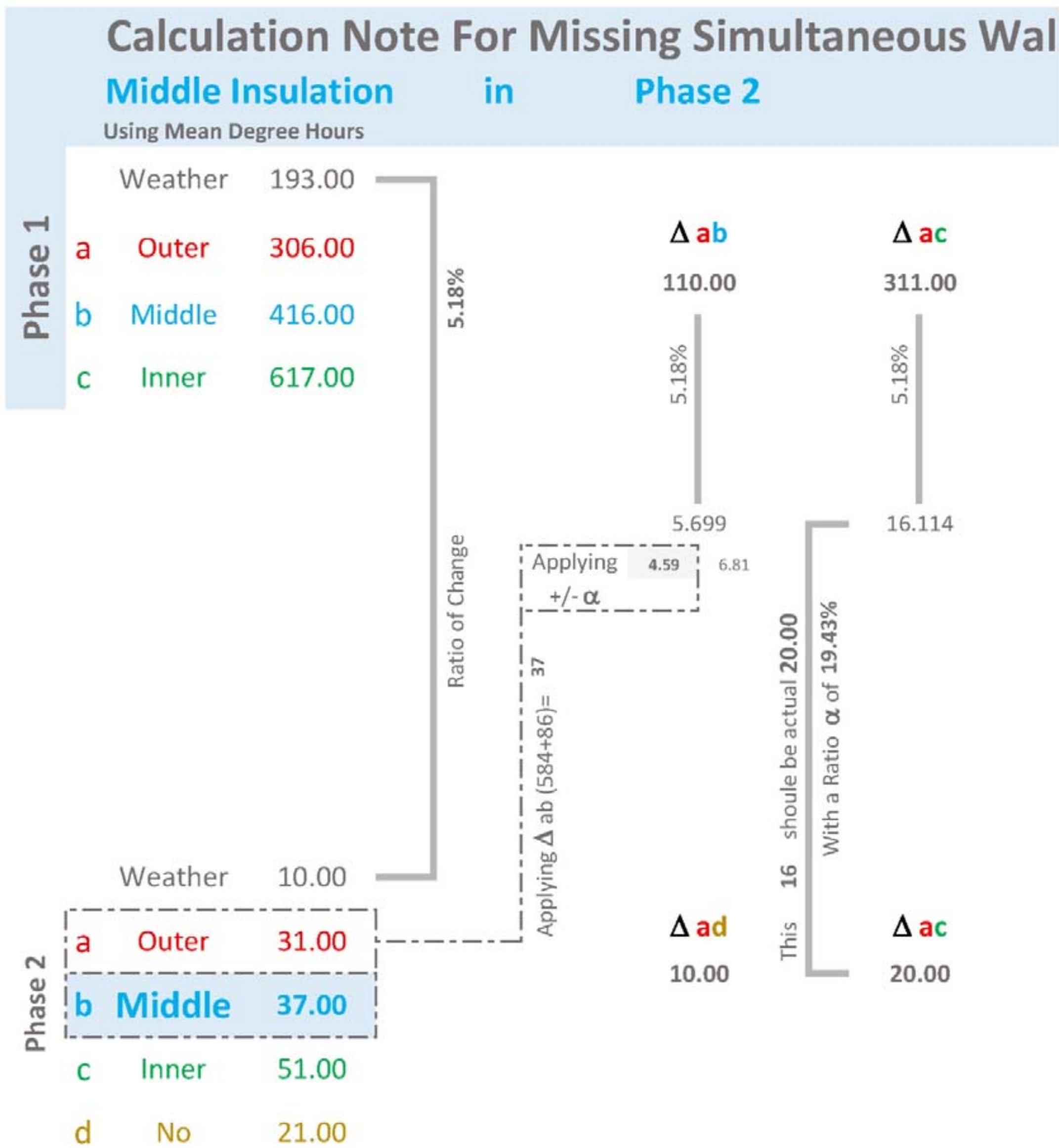


Figure A6.1 Regression calculation note to find the degree hours of Overheating for the no-insulated wall for the first period

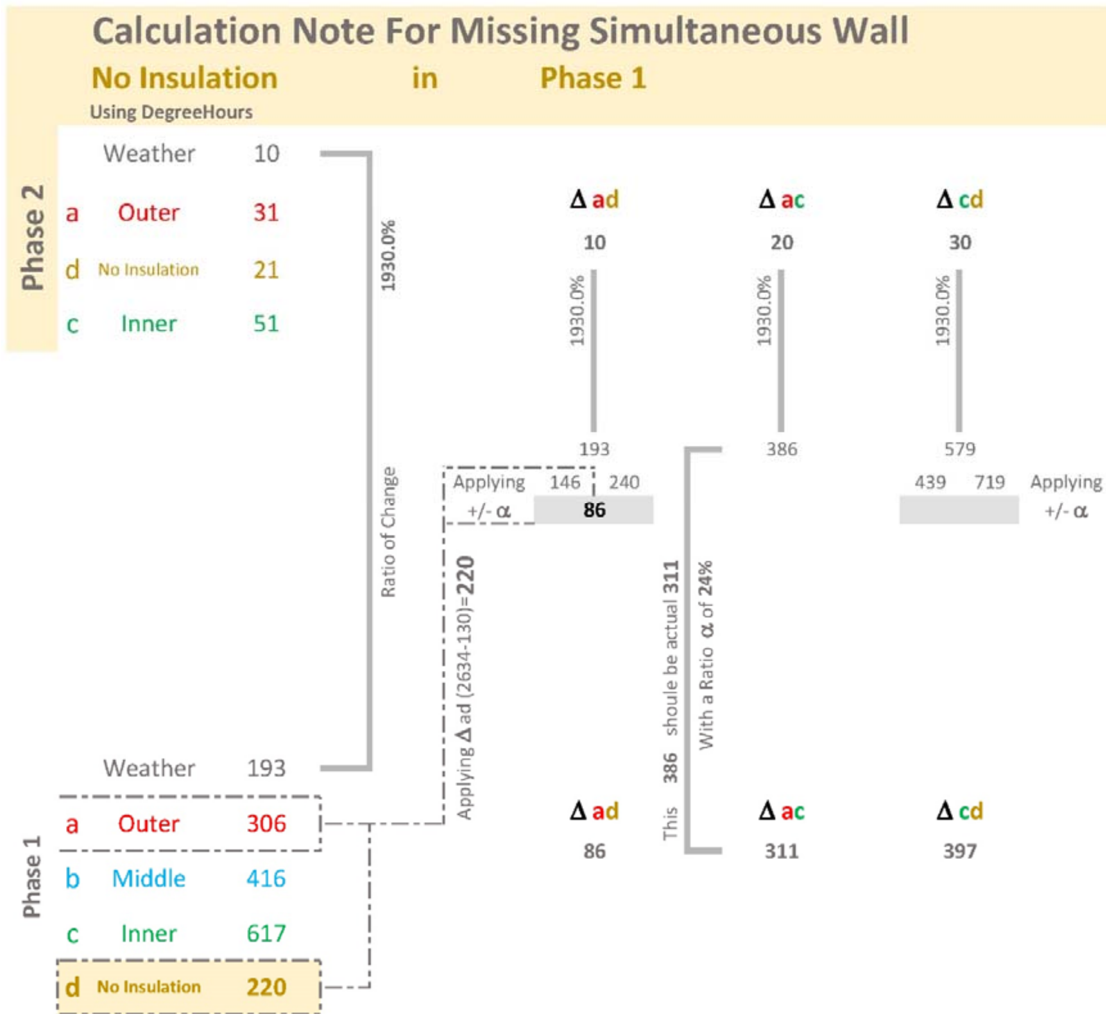


Figure 0.2 Regression calculation note to find the degree hours of Overheating for the middle insulated wall for the second period