TEM HEAT DISSIPATION SYSTEM

Increasing performance of a thermoelectrical integrated facade through the heat dissipation system

master thesis

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ABSTRACT

Recent studies show an increase in energy use on buildings due to higher cooling demands, constituting an increase of 17% of the global energy consumption by 2050. Tendencies also show that cooling degree days around the globe will also increase and this will display a greater impact on developing countries with warm climates. Subsequently, this gives interest in reducing energy demands on buildings through both innovative passive and active design strategies that can convert these buildings into energy efficient buildings whilst reaching their desired comfort values. The potential to integrate these strategies for cooling system into a building façade has been looked into by recent research. As is the case of the thermoelectric technology, which is a promising cooling technology that has gained interest from architects in the past few years, and it has a great potential for integration. This device has the advantage of generating a temperature difference between the device's two sides when direct current is applied it and so it has been widely studied and used as coolers at small scale. There are not enough studies and experimentation of integration at façade level has been conducted with this technology, and those that exists show that the system's performance is still much lower than traditional air-conditioning systems.

Thus, this graduation project focuses on a performance-based design, where the heat dissipation system's design and its integration with the TE is explored and investigated, what parameters affects its performance, and, subsequently, their effect on the façade and the architecture of the building within a hot-arid climate in Mexico.

For this, a combination of experiments and simulations were used to determine the effect certain design parameters have on the thermal performance of the heat dissipation system. Parallel to this, an office case study was selected, and simulations performed to determine the ideal passive strategies for reduction cooling load in a hot-arid climate. A stepped methodology was used for the experiments and simulations for the heat dissipation system and a comparative evaluation on different passive design strategies for the office design was applied. A simplified heat transfer model for the heat dissipation of the thermoelectrical technology was developed, where a series of design strategies were possible to be tested. Analysing the results determined which parameters had a greater impact on the design, for the heat dissipation system its performance was evaluated through its COP, and for the office design lower cooling loads were the defining parameter.

General trends were identified on both evaluated levels and each show their potential. These were then translated into design guidelines for the heat dissipation system and office building design and then visualized as a final thermoelectrical facade design. The final COP of the cooling system based on the heat dissipation designed was 1.40. An evaluation on the designed TE façade was done, its limitations and potentials stated, as well as future possibilities that be further developed with this technology.

Keywords: thermoelectric, façade design, climate design, passive design, integrated façade, hot-arid climate, heat dissipation

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A INTRODUCTION

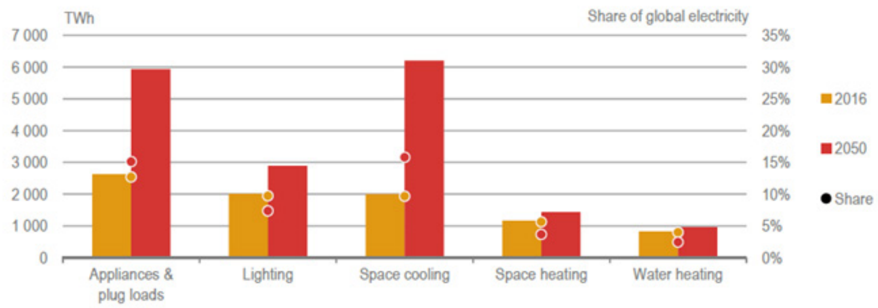
CHAPTER OVERVIEW

This chapter introduces the scope and background of this research project. The context is first described to highlight the motivations of this topic, followed by a brief overview of energy strategies in the built environment. The problems on the cooling performance of the Peltier modules are explained, forming the main problem statement of this research. The focus and restrictions for the case study reference will be identified. The research framework follows, showing the main aims, objectives, and research questions. Lastly, this chapter concludes with the research overview of the methodology phases.

A.1 CONTEXT

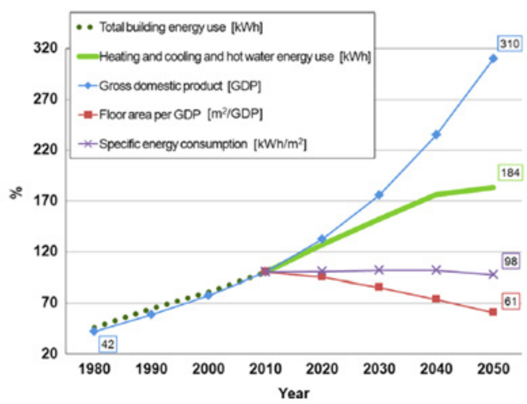
Worldwide, buildings and the activities that happen within them amount for a great impact in current environmental problems. As levels of wealth and lifestyle evolve around the world, the increase of electricity consumption also changes. Studies show that 85% of the increase in energy use of a building by 2050 will come from urban areas and 70% of this is from the developing cities. The main drivers for this trend in an increase in energy usage are gains in personal living space, population migrating to cities, an increase in types and number of electrical equipment needed for the everyday life, and climate change. (Ürge-Vorsatz, Cabeza, Serrano, Barreneche, & Petrichenko, 2015)

According to the International Energy Agency, cooling will account for 17% of the total increase in final electricity consumption between 2016 and 2050; by country, the range is from an increase of 8% in China to nearly 40% in Indonesia. The total increase in cooling demand is equivalent to more than 10% of total global electricity consumption in 2016. From the graph below the trend shows that the energy demand for space cooling by 2050 will increase to twice as much as it was demanded in 2016, becoming the largest user of electricity in buildings according to the IEA. (IEA, 2018)



Graph 1.1 Building electricity demand by end-use application. Source :(IEA, 2018)

In 2016, cooling made up about 10.5% of the total electricity use in buildings in the USA, followed by Mexico with a 9.8%, Japan, 9.5%, China 9.3% and Korea, 8.5%. Rising temperatures as a result of climate change will unquestionably lead to a significant increase in the global cooling degree days (Up to 25% globally), some regions amounting for bigger hikes than normal. These being in Africa, Latin America, southern and eastern Asia, and the Middle east. (IEA, 2018)
The research paper from Ürge-Vorsatz explains that since the increase in energy use on the commercial buildings is related to the economic activity, and this will increase more; a more dynamic increase is expected in the commercial sector when comparing it with the residential sector. Nonetheless, for both residential and commercial buildings the air conditioning use of energy is expected to increase in every region, but a major increase of almost triple, is seen in developing countries by 2050. (Ürge-Vorsatz et al., 2015)



Graph 2.Trends in energy consumption in commercial buildings in the world 1980-2050. Source : (Ürge-Vorsatz et al., 2015)

A.2 ENERGY STRATEGIES

At the moment, researchers and engineers are looking towards new technologies to implement in the built environment that could reduce its energy consumption. In addition, countries are encouraging the use of energy efficient codes, as is the case for developing countries, to change common practices and provide energy efficient buildings. (Luo et al., 2019 The initial measures taken should be passive strategies for the design of sustainable buildings that respond to their immediate context. This becomes very important for cases such as commercial and office buildings, where air conditioning systems are necessary to cope with the thermal comfort required by their occupants, especially in hot climates, and the amount of energy used by these systems could be up to 50% of the total energy consumption. (Prieto Hoces, 2018) Reaching the comfort conditions needed without the use of air-conditioning systems becomes an almost impossible task for warm countries. The increase in capacity for both heating and cooling for these systems could be complex and costly, since mechanical parts like pumps and compressors are needed in the scheme, not to mention the use of refrigerants that ultimately become hazardous to the environment. (Ibañez-Puy & Sacristán, 2014; Prieto Hoces, 2018)

For these reasons, new passive and active technologies that could boost the performance of façade systems and their energy usage is of great interest, since building envelopes impact more than half of typical usage in buildings, influencing its thermal performance, heating, cooling, ventilation and lighting. (Aksamija, 2013)The building envelope serves more than for its aesthetic values, it also regulates heat exchange between the inside and the outside of the building, however, even with proper design and optimization following passive design strategies, there still exists undesirable heat losses or gains, due to temperature differences from inside and outside. In consequence, there is heat conduction in the façades, radiative heat exchange in the surfaces that face outside and direct leakage from air.(Luo et al., 2019)

A.3 THERMOELECTRICAL INTEGRATED FAÇADES

The potential in strengthening building envelopes and technologies has been studied for bettering their thermal performance, such as: air layers in the envelope, Trombe walls, the use of phase-change materials (PCM), dynamic shading systems, among others. There are some that work passively, and others that are active systems, though it should be mentioned that for cases with extreme conditions, with very hot summers, a higher comfort is achieved with active systems . (Luo et al., 2017) As a response to the challenges mentioned, new approaches are now being explored and one of them is the integration of the building services with the traditional functions of the façade. In this case, the possibility of integrating active ventilation, heating, air-conditioning systems, among others is of special interest since these are the main sources of energy consumption for buildings. This integration of the façade with decentralised building services has several advantages such as its potential in saving costs, energy, and assembly time. In addition to this, flexibility is possible in several levels such as having prefabricated façade modules, using less space if the services are integrated in the façade or with the local control perceived by the users. (Prieto, Klein, Knaack, & Auer, 2017)

The integration of services into the façade has not been used often in the industry despite previous studies on its potential uses, so in most cases, they remain only as façade concepts, such is the case for the thermoelectrical integrated façade. (Prieto, Klein, et al., 2017) Previous research establish that thermoelectric system installed in the envelope has a potential to be further developed so they could ultimately fix the disadvantages of the typical air-conditioning systems since they can be directly powered from renewable sources, are lightweight and compact, and could function for both cooling and heating purposes without the use of refrigerants. This technology is already well developed for military and aerospace purposes, but is still on research and development stages for its functionality as an air-conditioning alternative in the built environment. (Ibañez-Puy & Sacristán, 2014)

As recently reviewed by Prieto et al. (Prieto, Knaack, Auer, & Klein, 2017) there is enough potential on the use of thermoelectric technology on the façade system to lower the energy consumption of the cooling demands, especially for warm climates. The main issue reported being the lower efficiency of the material, especially in the cooling mode, which is associated with its integration and operation with all the façade components needed.

A.4 PROBLEM STATEMENT

As it was previously mentioned there is potential in the integration of cooling systems into a building façade to mitigate the environmental impact of buildings by lowering its energy usage. The idea is to find a way to design an integrated façade system using TE technology that has enough cooling and heating capacity to achieve the thermal comfort of an office building in a hot arid climate of a developing country, in this case, Monterrey. Research has been conducted on the application of thermoelectrical systems, but not enough testing has been done for it to be commercially available. The performance is still below that of conventional air conditioning systems and most problems arise when integrating and connecting to the other elements needed in a façade system. The major issue that arises is when the system is working on cooling mode, as the excess heat generated by the structure on its hot side lowers its performance dramatically. There is extensive research on how to increase the performance of heat dissipation systems and these strategies have been widely studied, nonetheless, in isolation, and their application in combination with TE system is still lacking exploration and research. Other problems that need to be tackled in this graduation project are how the design of this new system could be physically integrated in the façade so that it does not become as complex and complicated as a typical air-conditioning system.

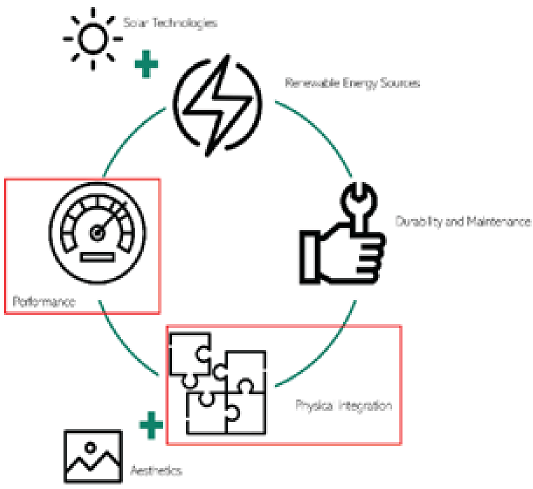


Figure 1. Main problems and drivers of this thesis

Thus, the problem focuses on performance-based design, where the heat dissipation system's design and integration with the TE needs to be explored and further investigated, what parameters affects its performance, and, subsequently, their effect on the façade and the architecture of the building. All these aspects need to work together so that the integrated façade can cope with the complete cooling power required for the office building. In consequence, another problem to tackle is the possibility of lowering the cooling loads of a typical office building in order to aid the design of the integrated façade and lower its complexity through the use of passive design strategies.

A.5 FOCUS AND RESTRICTIONS

There are several ways in which a façade can be designed within architecture, therefore a case study was selected as the focus of this investigation. Since this research is based on climate design and the integration of technological components and systems at façade level, a building typology selection and its context climate are also necessary to have boundaries and conditions for real life, so that several design variables can be frozen and further focus on this integration of the component is possible. This research will focus on the office typology where overheating is a problem, and air-conditioning is widely used. In addition to this, the occupancy schedules of this typology offer opportunities to manage the excess heat generated by the thermoelectric module when the building is unoccupied. The selected climate is hot-arid situated in Mexico (Monterrey).

Nonetheless, it should be noted that there are several boundary conditions in the following graduation project. In case of the Peltier modules, the commercially available will be used as reference when needed, although real condition prototyping will be out of the scope of this research. Finally, as the research evolves, possible conditions will be fixed when designing the heat dissipation systems and typologies, in order to do proper evaluations and comparisons.

A.6 RESEARCH QUESTION

This research takes into consideration two main hypothesis at different levels of the design. The hypothesis for the heat dissipation system is that with a proper heat sink shape design and manipulation, the performance of the TEM can increase. In the context of the office building, the hypothesis is that a proper passive design can reduce the annual cooling loads of the space. Thus, this graduation project aims to answer the following research question:

How could a heat dissipation system for an integrated façade with TE active cooling be designed, for it to cover the cooling loads of a typical office building?

A.7 SUB RESEARCH QUESTIONS

For this question to be answered, other sub-questions also need to be taken into account and will also be answered throughout this thesis project.
In the context of a Thermoelectric integrated façade in an office typology, situated in a specific climate, the following sub-research questions arise:

A. Which passive cooling strategies can be adopted to improve overall energy performance and lower cooling demands for hot arid climates?

The hypothesis focuses on the component level, but will be tested in different scales, thus:

B. What is the optimal heat sink design plus its complementary elements, if needed, for the heat dissipation of the active TE system?

a. What are the main design constraints for the development of heat dissipation system, including possible complementary elements? (plate thickness, shape, air flows, material) *b. What implications do these design constraints have on the performance of the TE façade system?*

Façade Level:

C. Which façade parameters and requirements need to be addressed in this design, for the TEM 's functionality, if situated in an office building, to be integrated?

A.8 AIMS AND OBJECTIVES

The aim of this project is to advance in the knowledge base of an existing cooling system concept with relatively new materials, an adapted heat sink design and integration methods for the façade. This research could offer an alternative method for the typical cooling system design and contribute to the efforts in sustainable design research. For this, develop and design of a heat dissipation system for an integrated façade with TE technology that provides enough cooling for an office building or serves as an aid, in a hot arid climate becomes the general objective. The research should explore the possibilities and constraints within heat dissipation and how this could be part of the TE system.
The objectives of this research are:

- Analysis and evaluation of various systems with an integration of TE modules and choose one to further design and develop.
- Analysis and evaluation of different heat dissipation technologies that could be applied on the TE system and boost its performance.
- Exploration of complementary strategies that can increase the heat dissipation system.
- Development and design of an office model as case study in Monterrey with the actual construction trends, contextual climate conditions, thermal comfort and government guidelines.
- Optimization of developed office model with passive strategies.

The expected main products of this work are:

- A design of a heat dissipation system within a TE façade integrated system chosen to develop, in the base-case scenario.
- An evaluation matrix of various integrated systems with the use of TE
- An evaluation matrix with design parameters that increase or decrease the performance of a heat dissipation system (in their order of retribution)
- An optimised base case designed office space with Monterrey's climate conditions, construction trends and thermal guidelines.
- Small experiments with the heat dissipation design in the integrated system

A.9 APPROACH AND METHODOLOGY

This graduation project starts with the research phase. Parameters for the research were established and it was conducted in four major blocks. One block was on the overall energy demands and trends currently found globally, another on everything related to the context such as the climate in Monterrey, the thermal comfort requirements of an office, etc, and the last one was the façade integration with thermoelectric cooling systems, going more in depth, the next step was on heat sinks and heat dissipation possibilities within the system (including material, composition, orientations, etc). The search was done on ScienceDirect database, ResearchGate

database, TU Delft repository and TU Delft campus library.
Search inputs:

- The articles/books had to be published recently, from 90's onwards. Because a lot of the sources found on Heat Sink dated before that, so an exception was made on that specific topic.

- Key words: 1) Energy trends, Building sector, future energy demands, cooling demands, heating demands 2) active façade system, integration, energy thermoelectric modules, thermoelectric systems, solar cooling façade, heat transfer, building envelope, photovoltaic, Peltier module, cooling and heating active system, Peltier effect 3) heat sink optimization, heat storage, PMCs for heat control, PCM, heat dissipation in electronics, heat sinks, thermoelectric modules**, performance*, evaluation*, façade** 4) passive strategies in office buildings, thermal comfort in office buildings, thermal comfort in warm semi-arid climates, Mexican energy trends, cooling and heating demand and Monterrey , energy demands, hvac demand, climate in Monterrey .

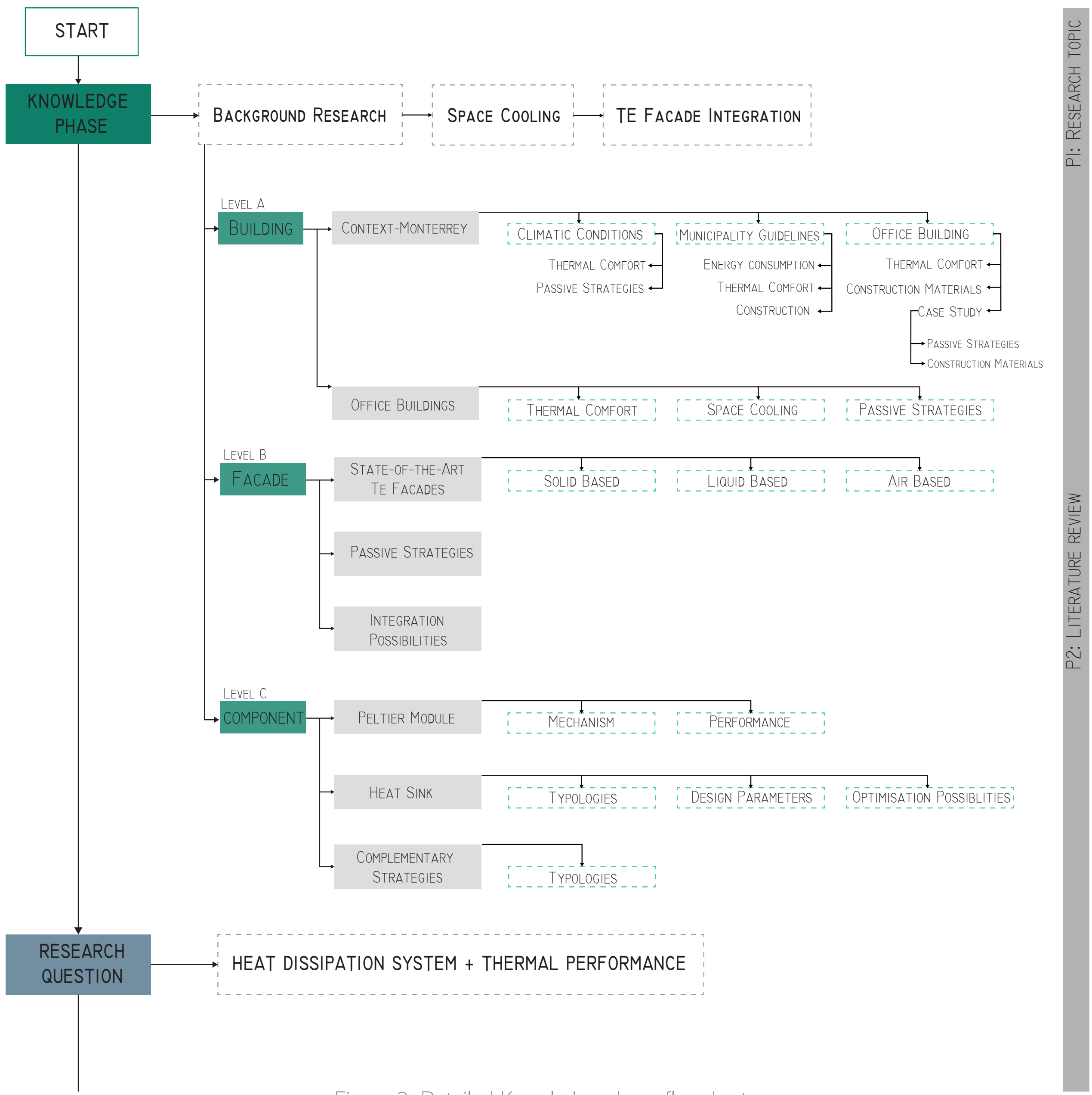


Figure 2. Detailed Knowledge phase flowchart

*evaluation and performance were added since a lot of results on heats sink were found.
**additional filters such as façade or thermoelectric modules was included to further limit the results on heat sink applications.

Expected results from this phase are the main hypothesis and design parameters for the design and experimentation phase. The second phase of the project is the conceptual design, where the design strategies to evaluate for each design level will be established based on the knowledge phase. At level A, the design strategies to diminish the base cooling load of the main case-study is assigned. Parallel to this, possible heat dissipation strategies will be explored according to the required needs and the found design constraints and parameters.

At the third stage, the methodology and evaluation of the conceptual design strategies are conducted. In the methodology, a detailed methodology on how each strategy is evaluated for each different level is explained. For the evaluation phase of the design, simulations with the appropriate software are applied (dependant on the scale to analyse) as well as a possible small-scale experiment of the heat dissipation system developed with a set of constraints to evaluate its potential. The idea is to be able to see where possible connection and integration problems could arise whilst using the system in real-life conditions. As for the simulations, for the building scale of the office space, DesignBuilder is used, as well as the basic elements of the façade. For the detailed performance of the heat dissipation system, experiments and simulations will be used for the analysis of the strategies applied, where the experiments are crucial for the validation of the simulation. The COMSOL software is used for these simulations plus hand calculations to evaluate its final performance.

Due to time constraints, a final design from the iteration process is selected and properly developed, this design will also go through a final assessment on the focus of the office building and type of climate condition selected, adding also qualitative evaluation focused on its feasibility and integration potential.

A.10 RELEVANCE

As it was mentioned before, the aim of this project is to substitute the use of air-conditioning systems with Thermoelectric technology, which could consequently lower the cooling loads needed in in an office building. Even though, the worst-case scenario is being used, at the end, this could also be applied for other commercial or residential buildings. The same happens with the case of cities which have a similar climate condition as that of Monterrey. The idea is that this research explores the potential of the system so that it can get closer to becoming commercially available for the built environment, and thus, aiding in the ultimate goal of lowering the energy consumption in the built environment.

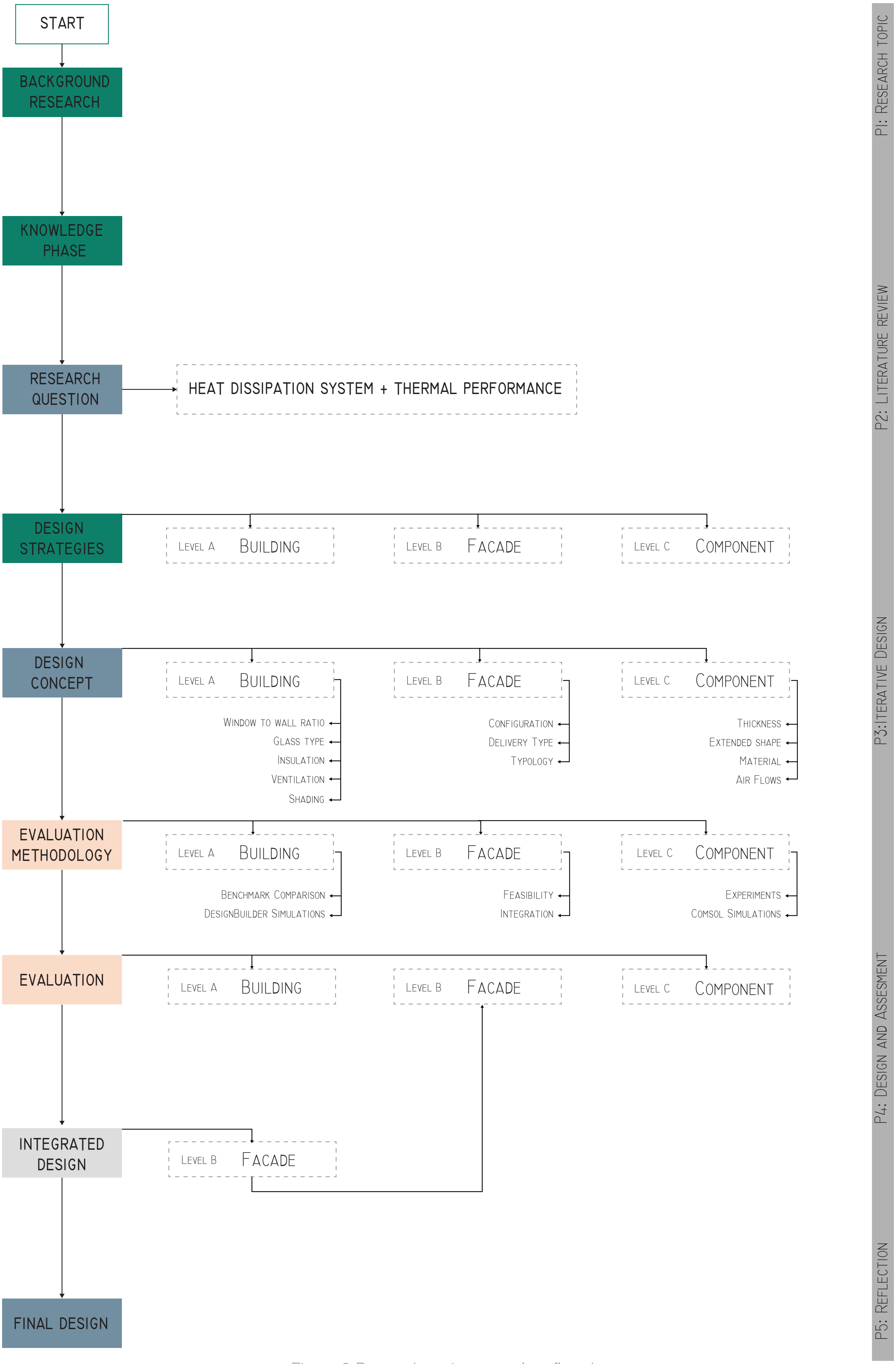


Figure 3.Research project complete flowchart

B KNOWLEDGE

CHAPTER OVERVIEW

This chapter of the project gives an overview of the different topics that are discussed throughout the research. The knowledge phase is divided into the three scale levels, going from component, to façade and finally with research at building level. The initial mechanics behind the thermoelectric technology, its advantages, and disadvantages will be discussed. A general analysis regarding heat dissipation systems, typologies, main constrains and complementary strategies, to pinpoint the parameters which need to be addressed for the design. Studies which have coupled TE technology in the façade system are analysed and classified by typology, discussing their current state, and identifying the main knowledge gaps for potential research. A brief investigation into the case-study selection is also be carried out, including municipality guidelines, thermal comfort, and context related information. Finally, a research on possible passive strategies to apply at building level is conducted.

B.1 PELTIER MODULES

Thermoelectric materials can be used for either cooling or power generation as it can be seen in the image below. Its construction consists of N and P semiconductor arrays, that, when applying heat source on one side and a cooler heat sink to the other side, electric power is produced, and vice versa. Electric power can be converted then to cooling or heating by reversing the current's direction. (Zheng, Liu, Yan, & Wang, 2014) In essence the Peltier modules work as heat pumps when a direct voltage is applied, where the cold side absorbs heat from media and remove the absorbed heat to the environment. In the past 15 years, a lot of research has been put into thermoelectric energy and for some time TEMs have been used for cooling and heating applications in military, aerospace and electronic instruments. (Aksamija, Aksamija, Counihan, Brown, & Upadhyaya, 2019)

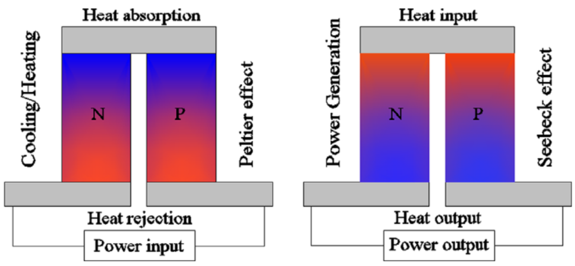


Figure 4. Cooling/Heating and power generation thermoelectric heat engines. Source: (Zheng et al., 2014)

In the analysis of the thermoelectric modules, four different heat effects happen: Peltier cooling, Peltier heating, Joule heat and Fourier heat. For the Peltier effects, they are defined by their cold (Tc) and hot(Th) surfaces. The Joule effect occurs when the electrical current is passed through an electrical resistance (R), and Fourier heat being the heat transfer from hot surface to cold surface by conduction. (Yilmazoglu, 2016)

$$Q_{pc} = \alpha I T_c \quad (1)$$
$$Q_{ph} = \alpha I T_h \quad (2)$$
$$Q_J = I^2 R \quad (3)$$
$$Q_{con} = k(T_h - T_c) \quad (4)$$

The Coefficient of Performance of the Peltier can be obtained from the Seebeck effect, the material conductivity, and the temperature difference from the hot and cold sides. This can be calculated with the following formulas: (Yilmazoglu, 2016)

$$Q_c = \alpha I T_c - \frac{1}{2} I^2 R - k(T_h - T_c) \quad (5)$$
$$Q_h = \alpha I T_h + \frac{1}{2} I^2 R - k(T_h - T_c) \quad (6)$$
$$P = \alpha(T_h - T_c) + I^2 R \quad (7)$$
$$COP_c = \frac{Q_c}{P} \quad (8)$$
$$COP_h = \frac{Q_h}{P} \quad (9)$$

k : thermal conductivity, $Wm^{-1}K^{-1}$
α: Seebeck coefficient, VK^{-1}
R: electrical resistance, ohm
I: current, A
P: electric power, W

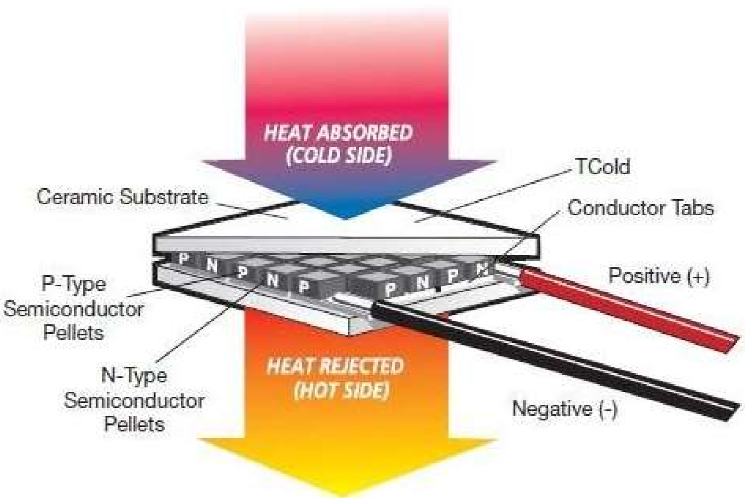


Figure 5.Peltier Module mechanism (source : https://www.researchgate.net/figure/Construction-of-thermoelectric-module-Peltier-162_fig2_308335959)

B.1.1 ADVANTAGES AND DISADVANTAGES OF PELTIER MODULES

Thermoelectric is a promising technology with potential architectural applications since TEMs do not contain any moving parts, they are very compact in size, while their operation is quite reliable and stable. This greatly reduces maintenance costs when compared to other types of air conditioning systems. (Prieto Hoces, 2018; Shen, Xiao, Chen, & Wang, 2013) Additionally, there is the possibility of using of renewable energy since it only requires direct current for the system to operate. Peltier modules are also scalable without releasing any pollutant to the environment during operations.

When considering only the Peltier module, the main disadvantage is their performance, when compared to that of conventional HVAC systems even when integrated in a system. As explained by Zhao and Tan, Peltier modules have a Coefficient of Performance (COP) of around 0.5 according to research and experiments, with temperature differences of 20-25 °C. The typical HVAC systems have a COP of 2.6-3.0. (as cited in Miryazdi, 2019)

The high heat flux generation from these electronic devices causes high operating temperatures which impact their performance and reliability. Either passive or active cooling technologies must be applied for the system to operate to its full advantage. Further discussion on their low performance once they are integrated will be discussed later in this chapter.

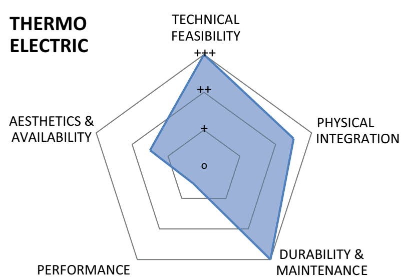


Figure 6.Qualitative assessment maps for the façade integration potential of selected solar cooling technologies. Source: (Prieto Hoces, 2018)

B.2 TE APPLIED IN FAÇADES SYSTEMS

Building envelopes act as a thermal interface between the indoor and the outdoor environments, and therefore have direct influence on the indoor thermal conditions and the energy consumption of air-conditioning systems within the building. Developing a high-performance envelope could guarantee both low energy consumption and high indoor comfort. A review on state-of-the-art research and developments of TE applied in façade systems is conducted, to find the major research gap.

A research conducted by Xu explains that their system is mainly affected by the heat sink resistance in real applications, especially in the hot side of the TE module. The experiment results show that the heat flux in the cooling mode is always smaller than in hot mode, indicating that the heating capacity of the TEM is higher than that of its cooling capacity.(Xu, Dessel, & Messac, 2007) On their evaluation of their developed prototype, Xu, Dessel & Messac, show that TE modules can affect indoor temperature from 2-6 °C in their tested room, nonetheless this was not enough for extreme hot or cold conditions. The suggestions on further research are on increasing the number of TE modules used, designing a more effective heat dissipation system and decreasing energy losses in the places with direct contact with the TE modules. (Xu & Van Dessel, 2008)

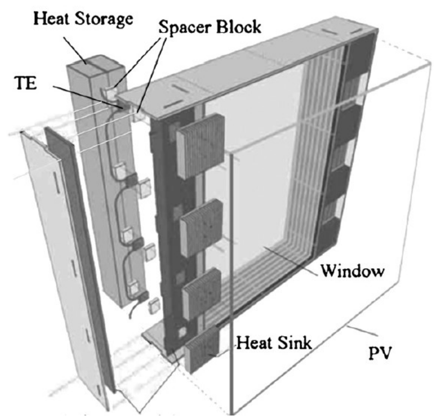


Figure 7. Active Envelope system proposed and tested. Source: (Xu et al., 2007)

Gibson developed an active manifold concept, where the double skin façade allows for the TE units to give heat in the thermal buffer and diminish solar gains. The main idea is for the system to control both internal heat and air exchange under some conditions. Experiments with cooling under real conditions, show that the interior partition effectively acted as a buffering for high temperatures (due to solar radiation) for the TE device. The main conclusions of this study were that the manifold geometry could eventually affect the way air is flowing within the cavity and more types should be explored, as well as the potential of experimenting with natural convection on both sides of the system to allow for better heat transfer. (Gibson, 2008)

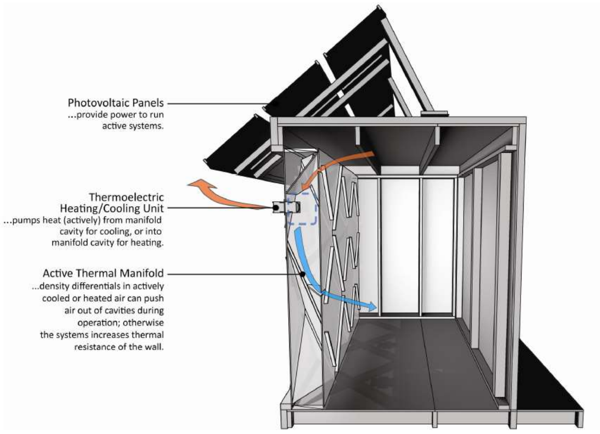


Figure 8.Schematic view of prototype showing PV system, TE units, and active thermal manifold. Source: (Gibson, 2008)

Ibañez-Puy et al. developed an active Peltier façade system with integrated ventilation which consists of ventilation dampers, at the bottom and at the top of the façade that allows the control of the air circulating the air cavity and the addition of the TE modular equipment. The figure below shows the expected behaviour per season, where the air cavity is opened during the hot seasons to allow proper heat dissipation within the façade.

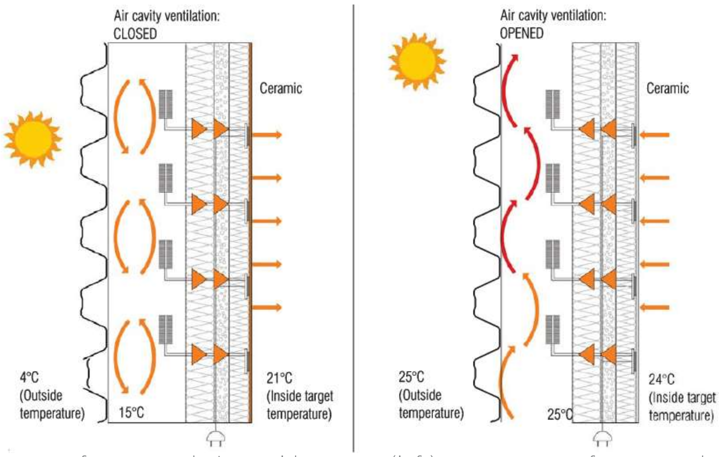


Figure 9.Figure 9. Energy performance during cold season (left) vs energy performance during hot seasons (right). Source: (Ibáñez-Puy, Sacristán Fernández, Martín-Gómez, & Vidaurre-Arbizu, 2015)

When considering cooling modes, the high radiation due to warm summers creates a high current in the modules, thus lowering the performance of the modules according to a study of TE integrated with Solar panels and another research on an integrated system with TE. (Cosnier, Fraisse, & Luo, 2008; Ibañez-Puy, Martín-Gómez, Bermejo-Busto, Sacristán, & Ibañez-Puy, 2018; Le Pierrès, Cosnier, Luo, & Fraisse, 2008) Other observations by Ibañez-Puy were that the module's performance is also affected by it integration to a system, and how all the parts eventually work together. When integrating the thermoelectric system into the façade, proper measures should be made as to avoid thermal bridges. Also, special notice on the materials could be considered, since the ones implemented in this experiment had low inertia and reacted to any disturbance in the ambient. Due to the Joule effect, it could be more efficient to apply more cells at lower voltages, and lower intensity, than the contrary, this when talking about cooling mode. (Ibañez-Puy, Martín-Gómez, Bermejo-Busto, Sacristán, & Ibañez-Puy, 2017)

On the other hand, a façade system with solar photovoltaic thermoelectric radiant wall in cooling dominant climates was developed by Luo et al. (Luo et al., 2017)Their simulation results show that for both cooling modes and heating modes the radiant wall performed much better than the typical concrete wall. Although, in heating it performed even up to 10 times better than the normal wall. The system worked with heat pipes to help heat dissipation of the TE modules in addition to the use of the natural convection of the air cavity within the façade.

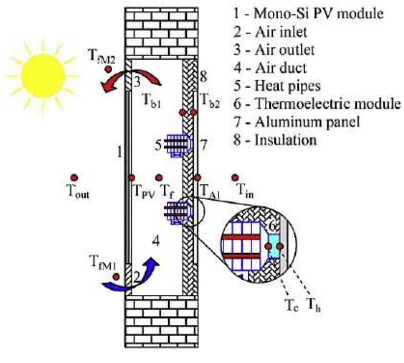


Figure 10. Luo et al, BIPVTE wall system. Source: (Luo et al., 2017)

An active thermoelectric ventilated system coupled with multiple thermoelectric coolers and heat sinks was proposed by Cai et al.(Cai, Wang, Ding, Liu, & Zhao, 2019) The experiments and simulations showed that when the number of coolers exceeded 8, the cooling capacity of this new system went down. When comparing the two types of heat exchange methods, counter flow showed higher performance values, with a cooling capacity of 9.06 W.

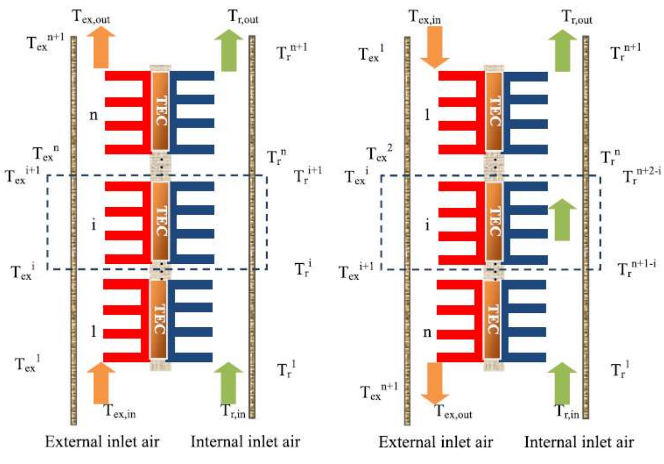


Figure 11. Schematic diagram of an active thermoelectric ventilated system a) parallel flow heat exchanger, b) counter flow heat exchanger. Source: (Cai et al., 2019)

Finally, Aksamija et al. (Aksamija et al., 2019) did a series of experiments to test the heating and cooling potential through an integrated façade, and results show that despite the TEM having a low efficiency in power generation mode, the COP in heating and cooling modes can easily exceed 1. Performance also showed better values under smaller temperature differences between the heat sink and the room, which was similarly found by Ibañez-Puy. This last note gives hints into the importance that an integral design based on the context and climate situations could represent for the overall system to perform accordingly.
A summary of the conclusions found in each research reviewed are addressed in Table 1.

#	Facade concept	Cooling distribution	Cooling delivery	Other facade function	Integration Approach	Peltier module used	Author	Main Conclusions
1	Thermoelectric modules for active building envelopes	Water-based transfer	Surface cooling (Mounted pipe)	Window Heating Heat storage	Modular	CP1.4-127-045L PT44-12-40	(Xu et al., 2007)	The system was affected by the heat sink resistance, especially in the hot side. Hot side shows better performance. PT-type modules worked better.
2	Active thermoelectric manifold double facade	Air-based transfer	Air cooling (diffusers)	Heating Visual Ventilation	Modular	Tellurex A22 TE coolers	(Gibson, 2008)	Modules in an array. Air cavity as buffer zone for Solar radiation. Manifold geometry impact
3	Active facade envelope with Peltier cells	Air-based transfer	Air cooling (diffusers)	Heating Ventilation Insulation	Integral	RC12-8	(Ibañez-Puy & Sacristán, 2014)	Three layers and 2 air cavities. Driven by PV panels. Ventilation and air moving are essential
4	ThEEn: Adaptive Thermoelectric vent. Facade	Solid-based transfer	Surface cooling (radiative wall)	Heating Ventilation Insulation	Integral		(Ibáñez-Puy et al., 2015)	Smaller Air cavity for natural ventilation, stack effect.
5	Active solar thermoelectric radiant wall	Solid-based transfer	Surface cooling (radiative wall)	Heating mode Insulation	Integral	9500/127/060 B	(Liu, Zhang, Gong, & Han, 2015)	Cooling efficiency was about 3.3% and 7.1% with PV at angles 90 and 60. Better heat dissipation needed.
6	Active thermal Wall based on TE	Solid-based transfer	Surface cooling (thermal mass)	Window	Integral		(Vázquez-Arias, et al., 2001)	COP values of 1.01-1.04 with 4 A for the balance of COP and cooling power. (for summer conditions)
7	ATW TE in windows	Air-based transfer	Air cooling (heat exchanger)	Heating Window Visual (80%)	Integral	Melcor CP1.0-63-05L	(Arenas-Alonso, et al. , 2008)	TE Units in window to transfer heat/cool to the room. The HEX and configuration used did not allow full power. Temp. At both sides keeps increasing.
8	PV + TE for pre-cooling and pre-heating	Air-based transfer	Air cooling (ventilation ducts)	Heating Ventilation	Integral	Melcor CP2-127-06	(Le Pierrès et al., 2008)	TE COP higher than 2 for low DC. Direct PV-TE coupling in summer is not sustainable. Indirect is suggested.
9	TE Heat Pump for ABE System	Solid-based transfer	Surface cooling (thermal mass)	Heating Insulation	Integral	Melcor CP1.0-N-08L CP1.0-N-06L CP1.0-N-05L	(Khire, Messac, & Van Dessel, 2005)	Total input of power required decreases as the distribution density of TE coolers increases. Plus, resistance of HS plays a key role.
10	Active Building PV + TE	Solid-based transfer	Surface cooling (thermal mass)	Insulation	Integral		(Luo et al., 2016)	Potential in cities with hot summers and warm winters show energy savings, Performance of the system vs typical wall showed better values.
11	TE Air ducts with PV in tropical climate	Air-based transfer	Air cooling (diffuser)		Integral	TEC 1-12730	(Irshad, Habib, Basrawi, & Saha, 2017)	At 6A, optimum ΔT of 6.8˚C with cooling capacity of 517.24 W and COP of 1.15. Suggest further study on heat dissipation, use of PCM.
12	VATE Ventilated Active Thermoelectric envelope	Air-based transfer	Air cooling (diffuser)		Integral		(Ibañez-Puy et al., 2017, 2018)	For cooling mode: better to work with low V. Optimum ΔT is important for the cooling mode. Thermal bridges affect the system
13	ATEV system Active thermoelectric ventilation system for cooling	Air-based transfer	Air cooling (diffuser)	Insulation	Integral	9500/127/060 B	(Cai et al., 2019)	With >8 TE coolers, cooling capacity decreased. HEX of counter flow more effective than parallel HEX
14	Integration of TE in facade systems	Air-based transfer	Air cooling (diffuser)	Insulation Heating	Integral		(Aksamija et al., 2019)	COP in heating and cooling modes exceeds 1. Smaller ΔT between elements, gives better results

Table 1. Reviewed papers with TE integrated façade systems.

B.2.1 CONCLUSIONS

From the studied TE systems applied in façades several conclusions can be drawn. There are some parameters that affect the performance of the TE integrated systems and those are: current intensity and voltage levels, heat dissipation, material development, integration with complete system, temperature difference and max heat transfer. Some of them have already been thoroughly investigated in the research studies shown above, and other are still lacking attention such as the improvement in the system performance by focusing on the heat dissipation and its integration to the façade. Thus, two additional columns were added to the reviewed papers on TE integrated in the façade to identify the type of heat control systems used by each concept.

As it can be seen in the table at the previous section, the results vary from using very simple types of heat dissipation, to a more complex typology with forced convection through mechanical fans and heat sinks. There is an almost unanimous opinion by researchers that a better heat dissipation system could ultimately be the catalyst for the TE integrated system to perform properly as an alternative for air conditioning systems. For this, an evaluation of the possible heat dissipation systems, heat transfer boost and heat storage possibilities will be addressed in the next chapter and their potential to be integrated in the façade. Another major conclusion from the TE systems evaluated is that there exists a greater potential for this system to work as an air-based transfer, that could serve as a ventilation system to cool the space inside.

B.3 HEAT DISSIPATION

As it can be concluded from the previous chapter, one of the main problems that the TE applied systems in the façade besides its integration prospect, is its overall performance, specifically the excess heat produced by the hot side of the TE modules, which then transfers to the cold side. For this reason, heat dissipation on the system becomes an important issue to solve for the complete integrated façade to be functional.

Heat dissipation in the façade system can be done through different ways such as passive, active or with complementary elements. These different strategies can be achieved with convection (either forced or natural), conduction (through solids or liquids) or radiation (through surfaces); although this last one is least common for electronic elements. For heat dissipation to occur, a proper heat sink with enough temperature difference must be present and an efficient thermal coupling between the two. The heat sink can be the ambient air, the water, the ground or the sky. (Santamouris & Kolokotsa, 2013)Among these, air-based heat dissipation in the envelope has the highest thermal resistance, although air facilitates the removal of excess thermal energy. Heat dissipation through air can be done naturally or forced. (Davies, 2004)For water-based systems, they are used for thermal storage and transfer. It should also be noted that since water has a higher thermal capacity, it can improve the system's efficiency considerably and a according to a literature survey conducted by Yongqiang, there are more studies on water-based active envelope systems, showing the preference for this method. (Luo et al., 2019)

As it was mentioned, heat dissipation is ruled by three heat-transfer fundamentals: conduction, convection, and radiation; and these affect in various degrees its performance depending on whether heat sink used relies on passive, active or hybrid methods to cool down the heat source. Conduction refers to the thermal transport through solids, and is governed by the materials thermal conductivity, k, which refers to the material's property of conducting heat, resulting in a temperature difference achieved at steady-state diffusion. (Kraus & Bar-Cohen, 1995)

$$Q_{cd} = k * A * \frac{dT}{dx} \ [W] \qquad (10)$$

Q_{cd} = heat flow in W

k= thermal conductivity of the material, W/mK

A = cross/sectional area for the heat flow

$\frac{dT}{dx}$ = temperature gradient in the direction of heat flow

Thus, thermal resistance due to conduction becomes:

$$R_{cd} = \frac{(T_1 - T_2)}{q} = \frac{L}{kA} \ [K/W] \qquad (11)$$

Convective heat transfer refers to the thermal transport from a surface to a fluid in motion, and is dependent on the heat transfer coefficient, h, the surface to fluid temperature difference and the surface area, S. The h value, ranges from 2 to 10 W/m2K for natural convection and from 20 to 100 W/m2K for forced convection.

$$Q_{cv} = h * S * (T_s - T_{fl}) \quad [W] \qquad (12)$$

S= surface area

h=heat transfer coefficient [W/m*K]

Thus, the thermal resistance due to convection becomes:

$$R_{cv} = \frac{1}{h*S} \quad [K/W] \qquad (13)$$

Lastly, radiation refers to the electromagnetic waves emitted from all surfaces with a temp erature above 0 Kelvin and is not linearly dependent on the temperature difference as the other two conditions.

$$Q_r = \sigma * S * \varepsilon * T^4 \qquad (14)$$

σ=Stefan-Boltzman constant, $5.67x10^{-8}$, W/m^2K^4

S = surface area

ε= element emissivity coefficient

The heat transfer coefficient for an ideal black surface in an absorbing environment is like that of natural convection of air, thus, the radiation thermal resistance becomes:

$$R_r = \frac{1}{h_r*S} \qquad (15)$$

Observing the convection, conduction and radiation formulas, radiation is heavily affected by the temperature of the surface, and so for lower surface temperatures the expected effect of radiation is lower than that of convection. Nonetheless, the effect of solar radiation should be managed carefully so that the element does not absorb any undesirable heat besides that generated.

In this section, the different possibilities for heat dissipation and their bases will be addressed and analysed. It should be noted that only elements that have potential to be integrated in the façade are studied. In cities like Monterrey, where there is high solar radiation throughout the year, the excess heat caused by this solar radiation could hinder further the efficiency of the system. Strategies such as PCMs or heat exchangers that act as heat storage so that this extra heat can be released when needed could be possible or that stabilize the temperature difference between two elements, though this will be addressed as complementary strategies that could aid the heat dissipation system.

B.3.1 HEAT SINKS

A heat sink is a device to effectively absorb or dissipate heat (thermal energy) from the surroundings using extended surfaces such as fins or plates. Heat sinks have been used in a wide range of applications where efficient heat dissipation is needed; some of this include refrigeration, heat engines, and cooling electronic devices. Although a heat sink could adopt various forms, the most common one is a metal device with fins. The performance of the heat sink can be improved by increasing the thermal conductivity of the fins, increasing the surface area of the fins, or increasing the heat transfer coefficient. (H. Lee, 2011)

Heat dissipation with heat sinks is usually performed through four different ways: natural convection, forced convection, through liquid cooling, although this last one is the least recommended by the authors studied. When reliability is a major aspect, liquid cooling heat sink is generally avoided, since fluid circulation requires regular maintenance. (Castelan, Cougo, Dutour, & Meynard, 2019)

B.3.1.1 Passive heat sinks

Natural convection or passive heat sinks are applied when the system does not rely on air supply for the heat dissipation to be conducted and uses the free buoyant flow of air surrounding the heat sink. On the other hand, forced convection could work as a semi-active or active sink, depending on whether the leverage is obtained from an existing fan in the system or if the employment of designated fans for this particular use are needed, respectively. In this last case, as it was mentioned, the reliability of the system depends on the reliability of the moving parts. In liquid cold plates, the use of tubes in block designs or milled passaged in assemblies are used for pumping water, oil or other liquids.(S. Lee, 1995)

In a research on optimization of a passive heat sink by Baldry et al. 2019 for TEC applied in cryotherapy, several conclusions were found by exploring several design parameters such as plate thickness, fin array and fin profiles. Tapered cross sections showed an enhancement in the convection created in the heat sink. Furthermore, the increase in sectional area also increased the conduction through the pins. Although different explorations were conducted with the height of the pins, and their diameter, the increase in the base plate thickness showed a decrease of up to 1.5 C for the same quantity of pins. (Baldry, Timchenko, & Menictas, 2019)

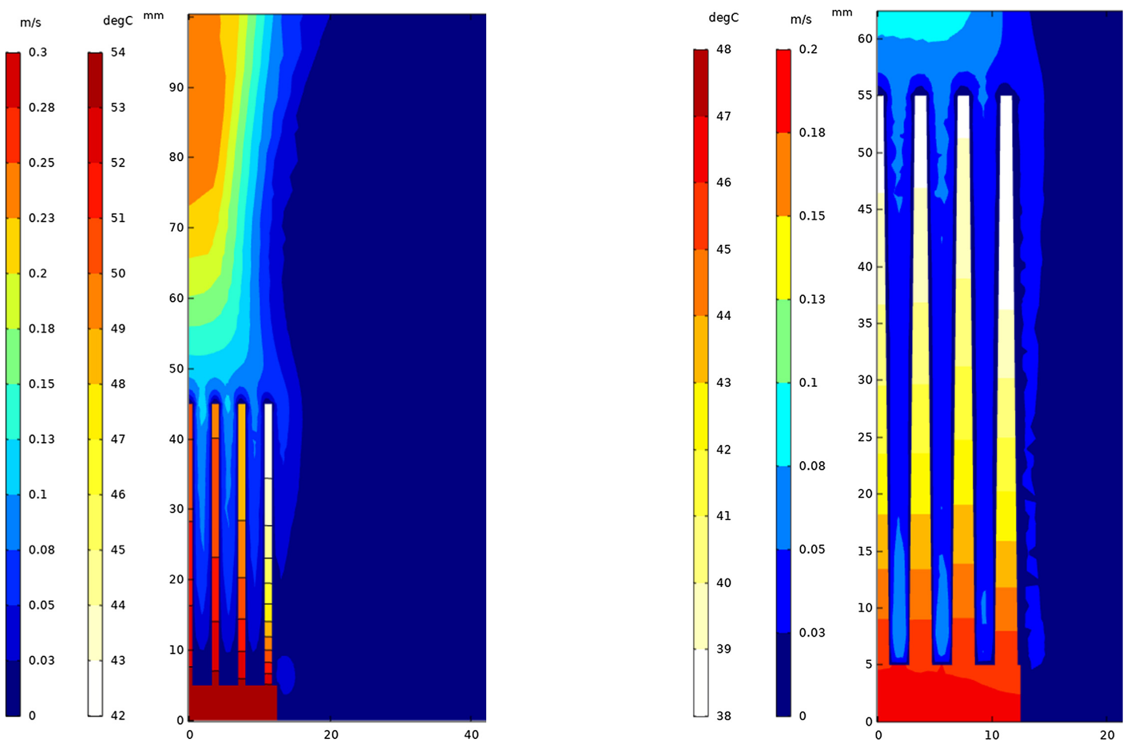


Figure 12.Symmetry plan temperature and velocity; left: straight fins; right: tapered fins.

In most of the articles studied that explored optimization options with natural convection stressed the importance the orientation of the fins or the channels have on their performance, such as it was for Baldry et al. 2019 and Elshafei et al. 2010, where a parallel orientation with the natural flow served to enhance the overall results. A summary of the conclusions found in each research reviewed are addressed in Table 2.

PASSIVE HEAT SINKS								
Common name	Heat Sink Type	Heat dissipation/ storage/transfer through	Tested parameter	Applications	Experiment	Numerical Analysis	Author, Reference	Conclusions
Plate- Fin	Natural Convection	air	Type of HS				(Joo & Kim, 2015)	Performs better when using heat total heat dissipation
Parallel Plates	Natural convection	air	Fin spacing Material	Electronics		X	(Kraus & Bar-Cohen, 1995)	Shows the least-material approach also as the superior thermal design. Magnesium proved to be the most efficient
Pin- Fin	Natural Convection	air	Type of HS		X		(Joo & Kim, 2015)	Performs better when using heat dissipation per unit mass
Pin-fin Heat Sink	Natural Convection	air	shape/profile Fin number Pin array		X	X	(Baldry et al., 2019)	Tapered fin showed lower thermal resistance with a specific fin quantity
Tapered Pin Heat Sink	Natural Convection	air	shape/profile Fin number Pin array	Cryotherapy	X	X	(Baldry et al., 2019)	
Hollow Pin Fins	Natural Convection	air	shape/profile orientation		X	x	(Elshafei, 2010)	Sideward hollow performed better than solid upward
Hybrid Pin Fins	Natural Convection	air	shape/profile		X	X	(Effendi & Kim, 2017)	Solid Hybrid PF showed lower Rth values than conventional PFHS
Pin-Fin	Natural Convection	air	Fin spacing number of fins Fin length		X	X	(Sparrow & Vemuri, 1985)	When fin number increased, Heat transfer also increase, got a max, then decreased. Radiation affected more the more populated arrays- Base Plate affected more than fin diameter

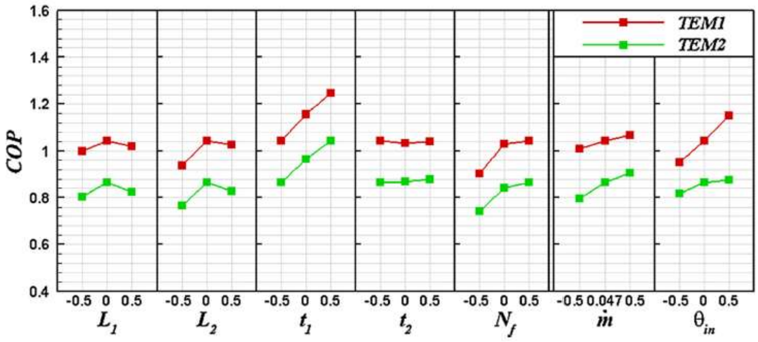
Table 2. Summary of reviewed papers on passive heat sinks

B.3.1.2 Active heat sinks

Active heat sinks refer to those with forced convection, and usually requires the aid of extra elements such as fans, and although in most cases this allows for an increase in heat dissipation, it adds to the system's complexity and diminishes its portability, whereas with natural convection no additional elements are needed. (Baldry et al., 2019) It should be noted, that similarly to heat sinks under natural convection, the parameters explored by the researchers in order to increase its efficiency were the same, with the added parameter of flow velocity in some cases. The orientation and the heat sink shape were the most predominate features discussed. In a study on 3D- printed air-cooled heat sinks, the tapered heat sink performed the best when compared with cylindrical fins, which is in accordance with conclusions drawn from the passive heat sink review. In the case of a thermal analysis of solid fins versus perforated fins under forced convection, perforated fins showed an increase of 1-4% in the thermal efficiency. (Tijani & Jaffri, 2018a)

A recent numerical study done on the performance of the TE modules with different heat sink shapes, showed that the parameters in order of strength in their effect on the TE modules were: fin thickness, fin number, mass flow rate, hot side fin length, cold side fin length, and base thickness; inlet temperature having no influence even though the system was applied as in an air duct with inlet air coming in. Another important conclusion is that the temperature of the cold and hot sides of the TEM2 heat sinks are respectively lower and higher than those of TEM1 because the temperature of TEM1 quickly reaches steady state due to the flow direction. (Seo et al., 2018)

A summary of the conclusions found in each research reviewed are addressed in the following table.



Graph 3.Coefficient of performance on each TEM for various parameters. TEM 1: at the inlet; TEM 2: at outlet ; L1: Hot side fin length; L2: Cold side fin length; t1: fin thickness hot; t2: fin thickness cold; Nf: fin number ; m: base thickness; teta: temperature. Source: (Seo et al., 2018)

ACTIVE HEAT SINKS									
Common name	Heat Sink Type	Heat dissipation/ storage/transfer through	Added element	Tested parameter	Applications	Experiment	Numerical Analysis	Author, Reference	Conclusions
Parallel Plates	Forced convection	air	fans + air duct	Fin length Fin thickness Base Thickness Fin number	TE	X	X	(Seo et al., 2018)	Concludes in the order of strength each parameter has under FC in PFHS
Perforated plate fin	Forced convection	air	fans	shape/profile		X	X	(Tijani & Jaffri, 2018b)	1-4% improve in thermal perf. Compared to solid counterpart
Hollow Tapered Pin Fins	Forced Convection	air	fans	shape/profile material		X	X	(See & Leong, 2017)	HTPF was better compared to SPF in heat transfer per unit cell. But contrary SPF had higher Nu
Nozzle-shaped Pin Fin	Forced Convection	air	fans	shape/profile material				(See & Leong, 2017)	Nozzle behaved better than SPF and HPF, but worse than HTPF
Perforated pin-fin	Forced convection	air	fans	shape/profile	Electronics	X	X	(Al-Damook, Kapur, Summers, & Thompson, 2015)	5 perforations showed 11% increase in Nu when facing air flow compared to SFP
Perforated pin fin	Forced convection	air	fans	shape/profile		X	X	(Tijani & Jaffri, 2018b)	1-4% improve in thermal perf. Compared to solid counterpart
Bar Plate	NC vs FC	air	fans	orientation	Electronics	X	X	(Pua, Ong, Lai, & Naghavi, 2019)	PFHS are better when compared under NC and vertical orientation
Parallel Fin Plates	NC vs FC	air	fans	orientation	Electronics	X	X		
Cilindrical Fin Plates	NC vs FC	air	fans	orientation	Electronics	X	X		

Table 3. Summary of reviewed papers on active heat sinks

B.3.1.3 Heat sink material

A material exploration on possible alternatives for the heat sink composition was done with the aid of CES EDU software. The aim of this first approach was to get a list of materials that could also be suitable for façade components, have a high thermal conductivity and a low price per unit volume. A research on which of these materials could be applied to façade components was conducted.

Further limitations were done pricewise to make it feasible for production and application on the façade. Comparisons with thermal conductivity versus density also showed the best options for a light-weight system. Although graphite has a high thermal conduction, it has a poor thermal radiation , thus serving poorly as a heat sink.(Fan, Jin, Wang, Liu, & Li, 2020)Graphite has a high emission coefficient, of up to 0.98, whereas materials like aluminium have a emission coefficient of around 0.07. This means that if the element is exposed to solar radiation, a material with high emission coefficient would also absorb this heat, compromising the system's functionality.

Material	Thermal Conductivity	Price per unit volume	Density	Production Technique	Building Industry	Recycle	Notes
Aluminium	205 - 213 W/m.°C	*5.03e3 - 5.97e3 EUR/m^3	2.69e3 - 2.73e3 kg/m^3	Cold Forming, Hot forming, Press forming	X	X	Typicaly Aluminium Alloys are used, such as 6060
Aluminium Honey comb	9.48 - 10.5 W/m.°C	*2.8e3 - 4.86e3 EUR/m^3	194 - 202 kg/m^3	Band saw, circular saw, laser cutting and milling	X	X	Although price and density are the lowest, it would need custom areas to ensure the most contact surface with the TEM
Aluminium Foam	28 - 46 W/m.°C	*6.88e3 - 9.16e3 EUR/m^3	970-1.03e3 kg/m^3	Band saw, circular saw, electro-chemical machining, laser cutting and milling	X	X	Although is less dense than the commercial aluminium, the price is much higher
Graphite	192 - 208 W/m.°C	1.44e4 - 2.77e4 EUR/m^3	1.5e3 - 1.9e3 kg/m^3	Wide range of production techniques			Although graphite has a high thermal conduction, it has a poor thermal radiation, thus serving poorly as a heat sink. (Fan et al. 2020)
Copper	207 - 248 W/m.°C	*4.61e4 - 5.58e4 EUR/m^3	8.94e3 - 8.95e3 kg/m^3	Cold Forming, Hot forming, Press forming	X	X	Although copper has the highest thermal conductivity, it is still comperable with Aluminium and much more expensive

Table 4. Summary of material properties

B.3.2 COMPLEMENTARY STRATEGIES

From the TE integrated systems studied, some of them use help of complementary elements besides their main heat sink or dissipation element, such as heat storage systems, mechanical fans, among others. For this reason, some these will also be reviewed for their potential to aid the complete system. The following table shows a summary of the articles reviewed on complementary strategies for heat dissipation.

Common name	Heat Sink Type	Heat dissipation /storage/transfer through	Added element	Tested parameter	Applications	Experiment	Numerical Analysis	Author	Conclusions
Micro Pin Fins	Liquid cooled	water	water	Fin thickness Fin spacing/array	Electronics	X	X	(Chiu, Hsieh, Wang, Jang, & Yu, 2017)	Heat Transfer perf dependant on porosity of arrays and pin diameter. ANSYS-Fluent was used for the numerical simulations
S-shaped channel Heat Sink	Liquid cooled	water	water	cross-cut pattern	Electronics	X	X	(Li, Ding, Jing, Xiong, & Meng, 2019)	Both topographic optimized HS showed better performance than typical S-shaped channel HS
Topographic optimized	Liquid cooled	water	water	cross-cut pattern	Electronics	X	X		
VPC NC PWC	Phase change Natural Convection Liquid cooled	various	PCM NA Water	heat transfer type	TE	X	X	(El-Adl, Mousa, & Hegazi, 2018)	Vapour Phase Change showed better performance than the other two
Micro Channel HS - PCM	Liquid cooled	water + PCM encapsulation	HEX	heat flux Reynolds number PCM concentration	Electronics	X	X	(Ho, Hsu, Rashidi, & Yan, 2019)	Small Re: Ra decreases with higher concentration of PCM. Ra reduces when increasing Re Most effective: Re of 100, heat flux 3.21 W/cm2, and max value of latent-sensible ratio
TE Heating system with PCM	Phase change	water + PCM		thermal efficiency	TE	X	X	(Sun, Lin, Lin, & Zhu, 2019)	TE had a COP of 1.7 when being an auxiliary heat source. Lower when operating alone. TE unit had a higher COP for heating in combo with PCM
Heat Pump improvement	Phase change	PCM	Cold and hot tank Fans	Energy storage	Heat Pump		X	(Real et al., 2014)	Simulated energy savings of around 19%.
Space cooling TE + PCM	Phase change	PCM	HEX	Heat sink properties	TE		X	(Tan & Zhao, 2015)	System cooling improved by 56% due to PCM integration. The accumulated heat dissipation needed determines de volume of PCM. Local climate influences a lot.
Thermosyphon HEX	Natural Convection Heat Exchanger	Isobutane	Heat Pipes	cross-cut pattern	Electronics	X	X	(Nikolaenko, Alekseik, Kozak, & Nikolaienko, 2018)	The heat pipe with threaded capillary structure show lower thermal resistance than the smooth surface aluminium thermosyphon
Loop heat pipe with fan	Forced convection Heat Exchanger	air	Heat Pipes Fans Condenser Evaporator	Impeller blades	Electronics	X	X	(Allison et al., 2011)	Using impeller blades integrated in the HEX increased the performance by a factor of 2 to traditional approaches, makes it compact and efficient

Table 5. Summary of reviewed papers on complementary strategies

B.3.2.1 Phase Change Materials

An excess of energy is often stored in thermal energy storage facilities since it has the advantage of grid peak shifting and conserving this energy, as well as improving the thermal mass. Phase change materials are of great potential since it absorbs/releases large amounts of latent heat during its phase transition, in a small temperature range. There is also the added value of high energy density allowing for a large heat storage with small volume. (Hu, Heiselberg, Johra, & Guo, 2020) Phase change materials belong in the physical storage classification. Within this, there are two categories: sensible heat storage and latent heat storage. The first one stores heat via its heat capacities, such as water; the second one, stores heat through phase transitions and can outperform the best heat storage materials. PCMs can use any phase change transition, but solid-liquids are the most common, since this requires the least volume change in the material and has a high enthalpy change. (Kumar & Banerjee, 2018) There are different ways to incorporate PCMs in the envelopes: direct incorporation, mixed with the construction material; immersion, where liquid PCM is impregnated in the material; encapsulation, where small particles are enclosed in thin shells or litres of PCM are packed in containers before introducing them in the material. (Noël, Kahwaji, Desgrosseilliers, Groulx, & White, 2016)

The PCM has some main constraints. PCM main constraints:

- Thermal conductivity of material
- Material's latent heat
- Material should not degrade
- Daily temperature profile (and TE modules temperature at each side)

PCM main design parameters that could be controllable:

- Container characteristics (non-degradable, compact, etc.)
- PCM concentration
- PCM location
- Temperature distribution (material of the envelope)

Performance criteria:

- amount of stored heat
- time needed to charge/discharge
- overall energy density of the device

A study on increasing the efficiency of a heat pump through the use of PCMs, works with two tanks, a cold one that provided possibility to store energy at night, and a warm one, that can dissipate the heat in this PCM tank can later in the night reject it outside when the temperature drops at a certain limit. (Real et al., 2014) Although it should be mentioned that the concept is more feasible in climates with large temperature differences between day and night (higher than 15 C). Mainly since the intense impact of summer weather conditions could hinder the PCM performance during the night, if the temperature does not change a lot during the night. (Souayfane, Fardoun, & Biwole, 2016) Another drawback is that further investigation is still needed for the heat transfer within the PCM to reduce the required air flow so that the phase change is present, and it works properly as a heat storage. This could be a liability if this is further combined with the problems the TE system still needs to solve for it to be a proper cooling system through the façade.

B.3.3 CONCLUSIONS

Based on the information reviewed in this section, the main design constrains that a heat dissipation system should consider are:

- Induced approach flow velocity
- Available pressure drops
- Cross sectional geometry of incoming flow
- Amount of required heat dissipation
- Maximum heat sink temperature
- Ambient fluid temperature
- Maximum size of the heat sink
- Orientation with respect to the gravity
- Appearance and cost

Once these design constraints are determined, the performance of the heat sink can be controlled by the optimization of certain shape conditions:

- Fin height
- Fin length
- Fin thickness/ spacing
- Number/density of fins
- Fin shape/profile
- Base plate thickness
- Cross-cut patterns
- Heat sink material, etc

B.4 CONTEXT

As it was mentioned previously, tendencies show a major increase in the energy consumption of buildings by 2050, according to Urge-Vorsatz et al. 85% of this growth will be attributed to urban areas, and from this, 70% corresponds to developing countries. (Ürge-Vorsatz et al., 2015) For this reason, one of the main focus in this research project is the adaptation of the system so that it can operate in contexts such as Mexico. In addition to this, taking into consideration that thermoelectrical modules can operate both for cooling and heating, a hot-arid climate becomes ideal since this brings out the potential of the system to use both operation possibilities. In this case, the hot-arid city of Monterrey in Mexico was chosen for the development and focus of this research.

B.4.1 HOT ARID STEPPE CLIMATE

The Mexican state Nuevo León has many different types of climates, ranging from cold climates to semi-arid ones. The predominant is hot arid steppes, BSh, as per the Köppen and Geiger classification, with average precipitation of 606 mm. (Climate-Data.org, n.d.) Though it must be mentioned that in Steppe climates vegetation is different to that found in Mexico, so this areas are typically known as hot dry or arid climates. (García, 1964)

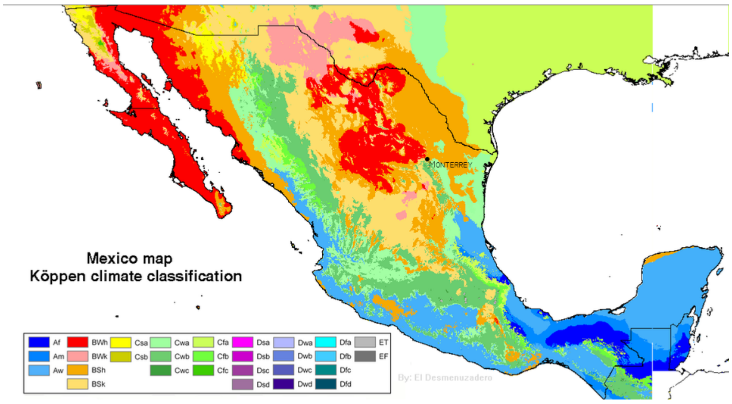


Figure 13.Mexican map: Köppen climate classification. Source: Wikipedia, edited by author

B.4.2 MAIN DATA OF THE CITY

Nuevo León had a population of 5.12 as of 2015, from which 4.68 live in the metropolitan city of Monterrey, in a surface of 6357 km2. (Inegi.org, 2015) The metropolitan area consists of 13 municipalities that can be seen in the figure, and around 88% of the population of the whole regional state lives there, having around 736 habitants per km2. Trends studied by INEGI also show that this number will continue to increase in the upcoming years, as a result of migration to the main cities.

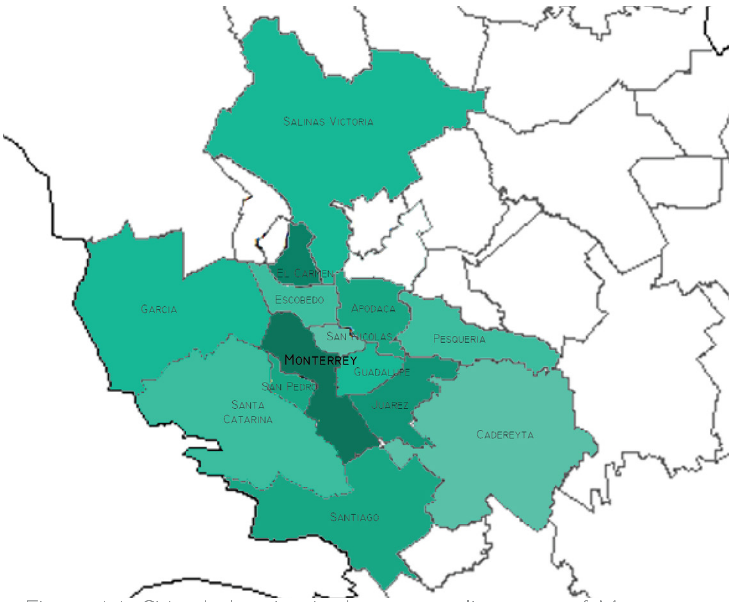


Figure 14. Cities belonging in the metropolitan area of Monterrey.

The average yearly temperature is 20 °C, and the maximum average is 32°C from May to August, and the minimum average is 5°C, in January. Rainfall is present mostly at the end of the summer period, in September.
It should be noted that the temperature is above 20 °C most of the days of the year, and even though the highest average temperatures amount to 32°C, some days in the summer temperatures reach higher values, with extremes of 45°C and average values above of 22°C in the urban areas. (Secretaría de Energía, 2015) Throughout the year it is mostly sunny or partly cloudy as it can be seen from the graphs below.

Predominant winds come from the East, but since Monterrey is located between various mountains (Sierra de las Mitras, Cerro de la Silla, Cerro del Topo Chico, Sierra Madre Oriental, Cerro de la Loma Larga and Cerro del Obispado), micro currents and climates, could account for a change in the wind direction and on the thermal conditions within the city.

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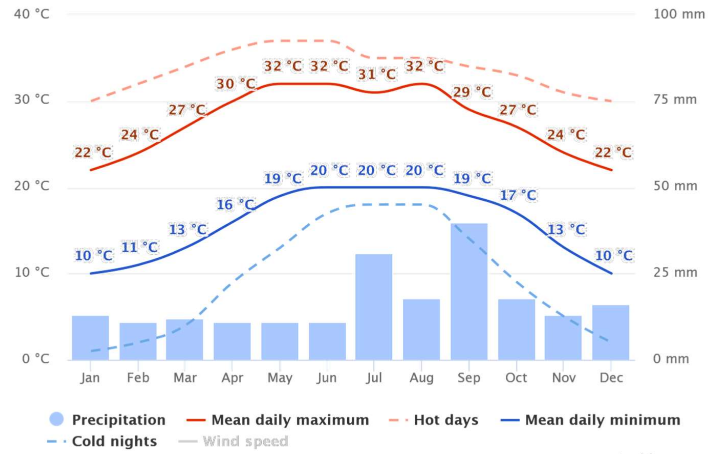


Figure 15. Average temperature and precipitation in Monterrey (Meteoblue.com, 2019)

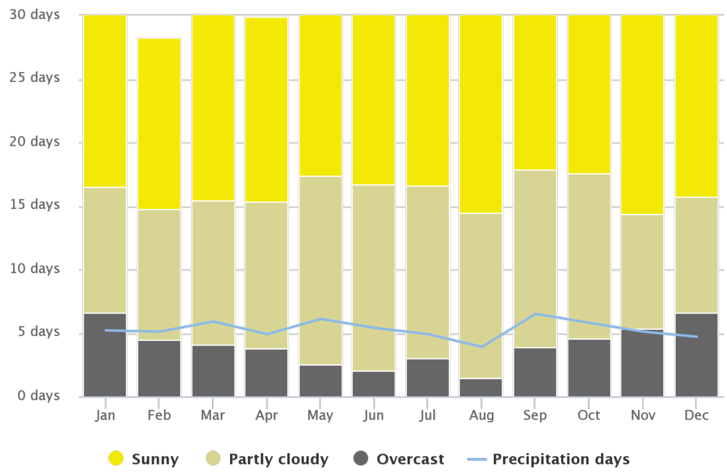


Figure 16. Sunny days (Meteoblue.com, 2019)

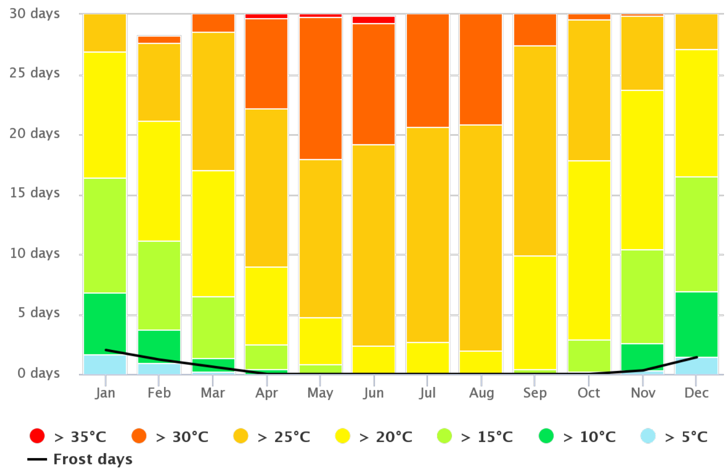


Figure 17. Maximum Temperatures in days (Meteoblue.com, 2019)

B.4.3 ENERGY CONSUMPTION IN MONTERREY

According to an Evaluation on the use of energy in the city of Monterrey, buildings contribute to around 12.4% of the total energy consumption. Within this percentage, the main consumption was distributed between the Air conditioning systems and the illumination of the building. (Secretaría de Energía, 2015)

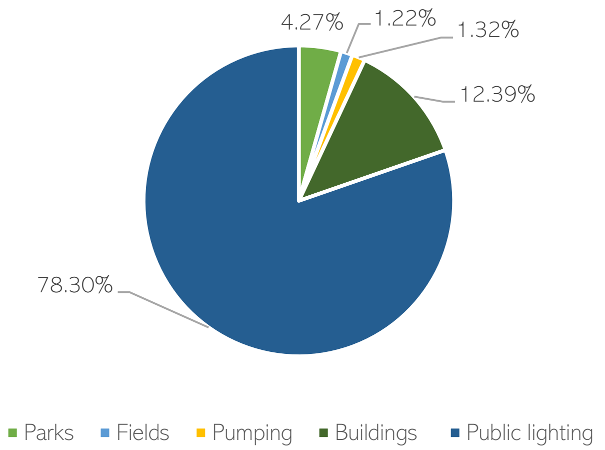


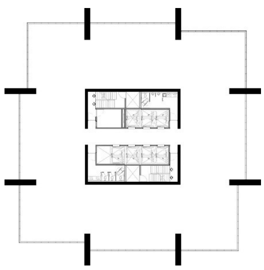
Figure 18. Distribution of total energy consumption on services in Monterrey. Source: (Secretaría de Energía, 2015)

It should be noted that even though Mexico City has almost double the number of inhabitants, Nuevo León is up to par in total energy consumption. This can be due to the region and average temperatures that can reach both cities, Monterrey reaching more extreme temperatures. Although an analysis by Morales Ramírez shows that the increment in economic activity in the region has a higher impact on the total energy consumption, as their income for such services increases, rather than the type of climate the Northeast region has. (Morales & Luyando, 2014)

B.5 CASE STUDY

For the implementation of the integral system a case-study will be developed so that this system can respond accordingly to some fixed parameters in terms of thermal comfort needed, surrounding climate, and building typology.

Most of the office tower examples found were for the tallest buildings of the city, and they represent the current construction trend within the city. The next table shows nine representative buildings with their main function and façade material and type. The buildings found had the same type of façade typology and material, and a look into their floor plan showed that most of them had a centralized core that allowed for open floor office configuration. From the nine specimens studied, only one had a lateral core, "Torre Dataflux" from Landa Arquitectos. Thus, for the selection of the building to use as the case study was based on the amount of information found. A summary of the office buildings studied can be found in appendix I.1.



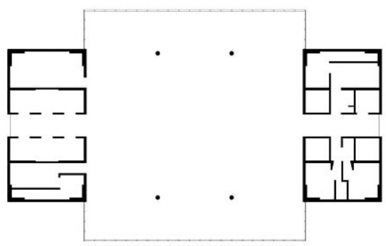


Figure 19. Left: Typical floor plan with central core, Torre Pabellón M; right: Typical floor plan with lateral core, Torre Dataflux from Landa Arquitectos. Source: https://www.floornature.com/landa-arquitectos-pabellon-m-in-monterrey-mexico-11834/

B.5.1 CHOSEN CASE-STUDY: TORRE KOI

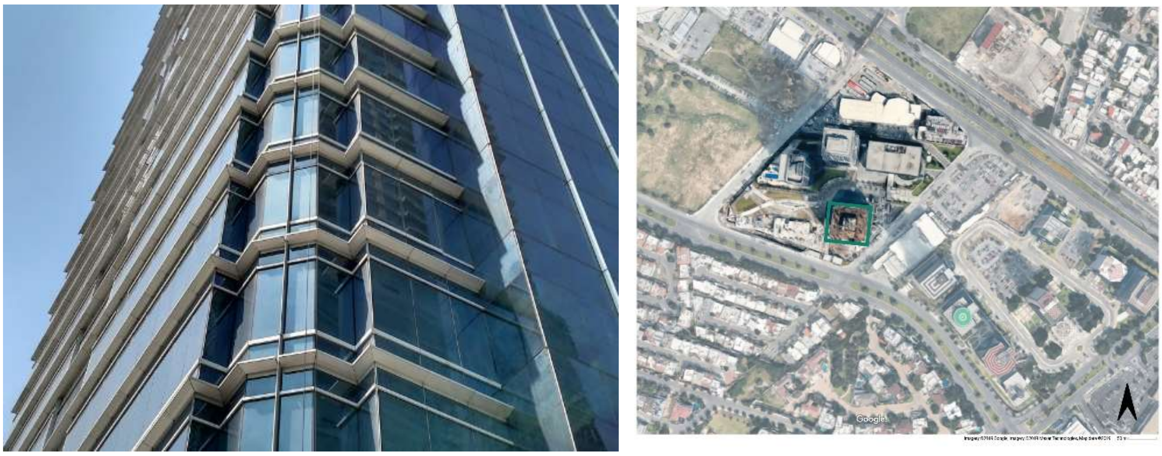


Figure 20. Left: Koi Tower façade focus. Right: Complex Location. Source: Google Maps edited by author

Architectural Firm: VFO Arquitectos
Date: 2012-2017
Built area: 183,866.04 m2

The Koi tower is a mixed used building composed of offices, residential apartments and commercial space designed by VFO Arquitectos. It is also one of the tallest buildings in Mexico, with 279.1 meters high and 65 floors above ground.

The Koi tower's façade is a double-glazed integral façade and has a total of 30,000 m2 of transparent glass,10,000 m2 of spandrel and a total of 500 tons of aluminium. The offices have a total of 3,500 façade modules. (VFO Arquitectos, 2016) As it was mentioned, the vertical circulations are at the centre of the floor plan, allowing a free configuration for the offices.

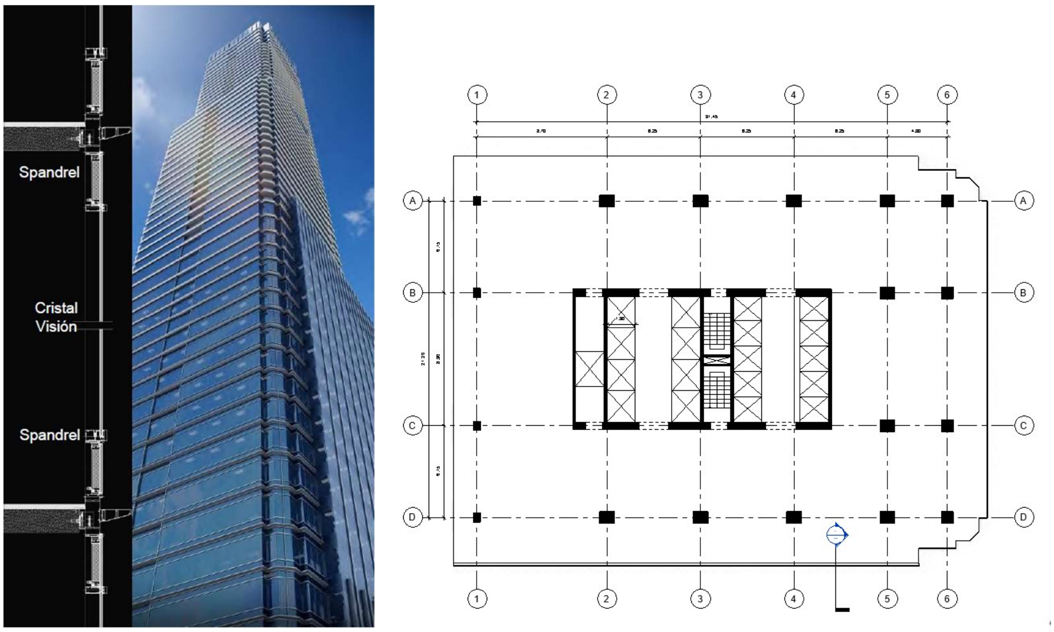


Figure 21. Façade section, mullion detail and main floor plan. Source: https://v-fo.com/projects/koi-tower/

B.5.2 MUNICIPALITY GUIDELINES

NOM-008-ENER-2001 is a normative conducted by the Mexican government to limit a building's thermal gains through its façade for non-residential buildings. It should be noted that this normative has not been updated since 2001. Another important normative is NOM-024-ENER-2012, on thermal and optical characteristics of glass and glazed systems for buildings. This last one only gives information on how to calculate the R value and the Light transmittance of a glass façade but does not give any further restrictions or norms on the required values for a glazed façade system.

As it should be expected, the allowable U value in Monterrey is one of the lowest when compared to other cities such as Mexico City. Monterrey has a hot-arid climate, where building need to be more protected from the extreme weather in comparison to Mexico City, which has a temperate climate, and temperatures do not reach the extremes. Monterrey requires an average U value of 0.768 W/m2k, compared to a 2.200 needed in Mexico city, according to NOM-008 . (Secretaria de Energía, 2001) This norm also gives information on overhangs for sun protection depending on the climatic zone and the orientation the window is facing.

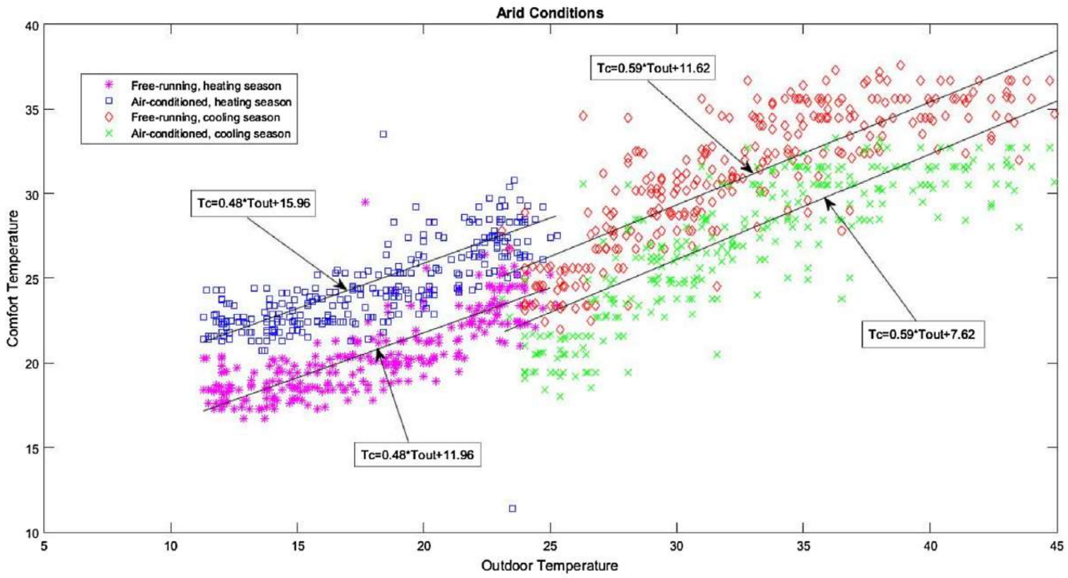
B.6 THERMAL COMFORT

There is an increasing need on saving energy, considering the high energy consumption in buildings, but proper levels of indoor environment are necessary to allow for the health and wellbeing of the occupants. For this, thermal comfort, acoustical comfort, light comfort, and indoor air quality are all indoor environment elements that need consideration when designing a building. In this research, a focus on the thermal comfort will be done and will be one of the ruling parameters when designing the base office space. Thermal comfort defined as "that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation" (ASHRAE, 2004)The ASHRAE standard also mentions that 6 primary factors must be addressed when referencing thermal comfort: metabolic rate, clothing insulation, air temperature, radiant temperature, air speed and humidity.

Thus, the thermal comfort criteria for hot arid climates found by various research papers will be discussed, and the guidelines established by the municipality in the context to design will also be consulted. Furthermore, a dive into office buildings and their usual comfort parameters will also be researched. The final product of this chapter is to have a proper list of limits and boundary conditions for the base case.

B.6.1 GENERAL THERMAL COMFORT CRITERIA FOR HOT ARID CLIMATES

Thermal comfort becomes particularly important when facing extreme weather conditions such as in northern Mexico, where to achieve proper indoor temperatures the use of AC systems is needed. (Oropeza-Perez, Petzold-Rodriguez, & Bonilla-Lopez, 2017) The survey conducted by Universidad de las Americas Puebla took into consideration the 4 different climatic regions found in Mexico, and human factors such as the long-term adaptation of the occupants. The adaptive model from arid conditions, as can be seen in the next figure, showed that people are cable of standing high temperatures, even more than 35 °C if they don't have an AC system, in the cooling season. There was a higher tolerance from respondents, especially in warm conditions, when comparing with the AHRAE standards, for high temperatures and contrary to that, low tolerance when facing low temperatures. (Oropeza-Perez et al., 2017)
The usual AC set point was 19.5 °C for answers in air conditions, cooling season, but because of the long-term adaptiveness form the occupants, this set-point could be increased to lower the



Graph 4. Adaptive thermal comfort model for arid conditions in Mexico. Source: (Oropeza-Perez et al., 2017)

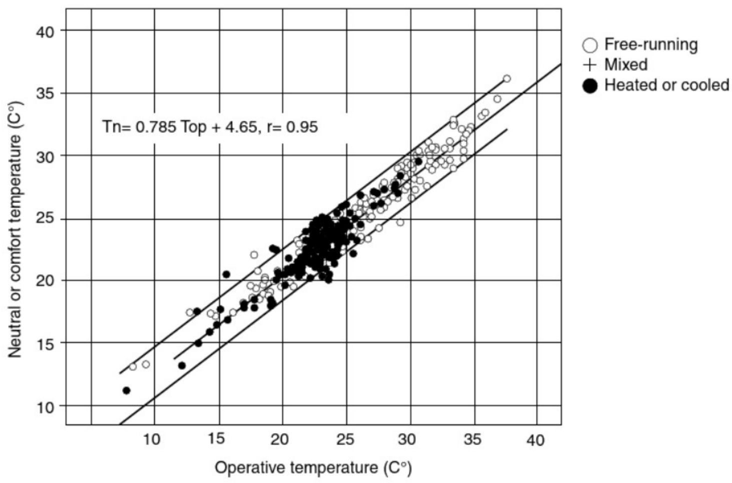
cooling demand of buildings. Though it must be mentioned that this survey was mostly conducted for residential buildings, which might offer different activities when compared to an office building. Another survey in Mexicali and Hermosillo, both with similar climate characteristics to Monterrey, also had comparable profiles of thermal comfort. Mexicali had a lower limit of 26.5°C and upper limit of 42.1°C, and Hermosillo 28.6°C and 35.7°C. Despite the high neutral temperature obtained by the field study, the high expectations for cooler conditions, and the low level of tolerance showed from the survey, the respondents still declared the building they were in was generally acceptable. (Gómez-Azpeitia et al., 2012)

B.6.2 GUIDELINES ON OFFICE BUILDINGS FOR THERMAL COMFORT

Although some models for finding the comfort temperature in hot dry climates were identified, a further research on how this applies in offices is also addressed. Similar results were also found by another research on adaptive thermal comfort but for offices. The surveys were conducted on hot summer and warm winter climate zone of China, like Monterrey's climate conditions. The results show that considering the local people's thermal adaptation in hot climates, the temperature of air conditioning in office buildings can be set to a higher level than it usually is to save energy without sacrificing the occupants' comfort. (Wu, Cao, & Zhu, 2018)

The acceptable range differs when focusing in heated or cooled buildings, where the range of comfort temperature is smaller than the free-running buildings, according to a meta-analysis of field study results conducted by Humphreys. (Nicol, Humphreys, & Roaf, 2012) In heated or cooled buildings, the situation becomes more complex and less stable, since other factors come into practice such as the custom of the occupants, the expected thermal conditions based on past experiences and the building's typology. (Brager & De Dear, 1998) Some surveys in Singapore show a difference of up to 4°C when comparing office buildings naturally ventilated versus air conditioned ones, where the lowest tolerance refers to air conditioned buildings. (Mahdavi & Kumar, 1996) The question of whether a specific indoor climate should be stablished throughout the whole year should be considered, since the natural outdoor climate variation should also be accepted inside the building as it was proven by the previous surveys discussed in free-running buildings.

B.6.3 MUNICIPALITY GUIDELINES ON AIR CONDITIONING SYSTEMS



Graph 5. The variation of comfort or neutral temperature with the mean operative temperature in a large number of survey populations. Source: (Nicol et al., 2012)

On the other hand, Mexico has its own air conditioning guidelines for the proper indoor temperature depending on the city. For the calculation of the comfort temperature needed, the exterior temperature must be first identified. In the metropolitan area of Monterrey, first the extreme maximum temperature must be identified and from there the design exterior temperature can be obtained, the resulting values from this method will be shown in the conclusions. The Mexican guideline also suggest that no air condition is required for cities outside extreme or tropical climates. (INIFED, 2014)

B.6.4 CONCLUSIONS

The comfort temperature for the interior of the case study was calculated as per the models studied in this chapter and their values and differences can be observed in the table below. For some only the permissible temperature during summer season was calculated. As one of the aims of this project is to focus on reducing the energy loads of the air conditioning needed in office buildings, an adaptive model will be chosen, so that there is possibility of shutting down the system if the temperature outside is comfortable enough to open windows and allow natural ventilation.
Although, studies in cities with Monterrey's climate show great potential of accepting higher

THERMAL COMFORT			
Standard	Model	Tc (comfort)	Source
Arid Mex- Heating (Adaptive)	Tc = 0.48*Tout +13.9	18.7 °C	(Oropeza-Perez et al., 2017)
Arid Mex- Cooling (Adaptive)	Tc = 0.59*Tout + 9.6	32 °C	(Oropeza-Perez et al., 2017)
Mexican AC Guideline (Cooling)	Tc = 18 + 0.2*Tcalc	25.6 °C	(INIFED, 2014)
ASHRAE 55	Tc = 0.31*Tout + 17.8	29.6 °C	(ASHRAE, 2011)
EN 15251	Tc = 0.33*Tout +18.8	31.3 °C	EN 15251
Adaptive Model (Cooling)	Tc = 0.09*Tout + 24.6	28 °C	(Nicol et al., 2012)
Adaptive Model (Heating)	Tc = 0.09*Tout + 20.6	21.5 °C	(Nicol et al., 2012)
Min temperature outside used: 10 °C			
Max temperature outside used: 38 °C			

Table 6. Thermal comfort variations based on method.

temperatures in the case of summer season, it should be noted that perceived thermal satisfaction of occupants is reflected in a boost in workplace productivity. (Tanabe, Haneda, & Nishihara, 2015) This means that, even though Oropeza-Perez's model for arid cities in Mexico has a lot of potential, since it was focussed mostly for residential buildings, and people tend to have a higher threshold of adaptability and acceptance in their own homes even if they stay there for longer periods of times, this model was discarded for the purposes of this thesis. For these reasons, a more conservative approach through Nicol & Humphrey's adaptive thermal comfort model was chosen for the proper design of the office building, and to set the boundaries that will affect the final design of the TE system.

B.7 PASSIVE STRATEGIES

The articles and benchmarks considered for the research were focused on BSh type climate (Koppen's classification), hot arid climate, with focus on passive cooling. The strategies for the evaluation were those widely found on the literature phase, as well as the initial recommendations from institutions such as the ASHREA. These are: window to wall ratio, shading, glass type, insulation, and ventilation. The general recommendations are those given by the ASHRAE and the specific recommendations will be addressed with other research found that focus on passive strategies used in office buildings with similar climatic situation as that of Monterrey. For the complete summary of these finding refer to chapter B.7.5.

For referential purposes, the comparison will be done in terms of cooling demands with respect to the base case scenario after the application of each strategy.

B.7.1 GENERAL RECOMMENDATIONS

When talking about hot dry climates, according to the ASHRAE, the main source of heat gains comes from conduction and solar loads that come through the windows and lack of proper ventilation. (ASHRAE, 2011) Strategies suggested by the ASHRAE to reduce energy loads are as follow:

Envelope
- Proper glass size (recommended 20 to 40 %)
- Well-placed shading (blinds or similar on W, E and S façades)
- Increased insulation (total U-value of 0.60 W/m2K)
- Solar-reflective roofs and walls
- Glass type (double glazed low-e)

Lighting
- Window size
- Window position
- External shading

HVAC
- Free night cooling
- Natural ventilation during winter and off-peak seasons
- Air-sized economizers
- Indirect evaporative cooling
- Radiant floors or ceilings
- Near façade: fan-coil unit
- Near façade: dedicated perimeter air-conditioning system (if heavily glazed)

- Water-based cooling towers

One of the main recommendations for office buildings trying to achieve energy savings is that WWR should not exceed 40%, which is rarely seen in modern office buildings. (ASHRAE, 2011)

B.7.2 INSULATION

Research on the impact of insulation material on hot dry climates suggests that thicknesses of above 50 mm and its location (towards the inside or the outside) should benefit more the energy and thermal performance of the building. (Saleh, 1990) Thus, the application of the insulation with two different thicknesses besides the original were tested, 75 mm and 100 mm of rigid extruded polystyrene foam which is common in Mexico.

B.7.3 SHADING

Fixed External Shading is the most effective way for the solar heat gain to be controlled, though it has the disadvantage of having less accessibility for maintenance. They also work well on peak hours but perform poorly the rest of the time or become a hindrance for natural daylight and views. They can be horizontal or vertical devices. Another option is the dynamic shading system or operable, which makes possible to adjust depending on the necessity, but this are less common on the exterior.

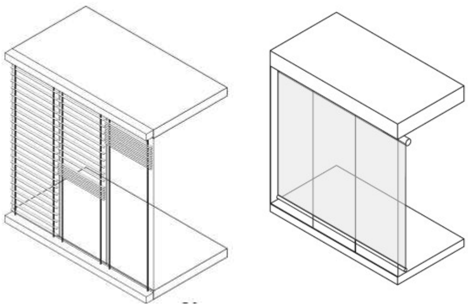


Figure 22. Shading typologies. Source: (Knaack, Klein, Bilow, & Auer, 2007)

The possibility of having an interstitial system is also there, where the operable louvers are located between the insulated glazing unit, making it easier to access for maintenance and protects it from the wind. Interior shading is not recommended for energy savings since it serves more for glare.

B.7.4 VENTILATION

In terms of ventilation, studies show that there is a higher temperature threshold when having control over ventilation. When the user has the possibility of opening the windows, and changing his working space, this results in a higher tolerance. This is in accordance to the adaptive model mentioned in the previous chapter. For the interior temperature of the building to fluctuate similarly to the outside temperature the possibility of natural ventilation is desired.

There are several options to reduce energy usage on the building through proper ventilation systems. In a study by Ben-David et al., natural ventilation in combination with mechanical systems show good results in lowering an office energy consumption but require well scheduled and controlled systems for it not to be contra effective. On the other hand, the application of economizer system to both mechanical and natural ventilation, as to have free cooling also amounts to energy savings of around 35% for both of these cases. (Ben-David & Waring, 2016)

Another study for a hot dry climate by Friess, Wilhelm showed energy saving from 35% to 63% when applying mixed mode ventilation, this increased to 56% to 70% when adding night ventilation with the mixed mode ventilation system. (Friess & Rakhshan, 2017)

In a similar regard, ventilation strategies tested for warm-dry climates by Prieto et al. also show the best results when applying ventilation strategies, up to 50%. It is also mentioned, that the best results were obtained by also allowing a wider range on the comfort temperatures, which is in accordance with what was found through the adaptive model, and other studies on ventilation as an energy saving method. (Prieto, Knaack, Auer, & Klein, 2018)

B.7.5 CONCLUSIONS

In general, most of the cases studied show that the highest impact is achieved through ventilation and window size, especially when talking about hot arid climates such as Monterrey. A summary of the conclusions found in the research studied can be seen in the following table.

Type of study	Author	Location	Climate	Parameters tested	Results	General Notes	Detailed notes
Guidelines	(ASHRAE, 2011)		hot-arid	Envelope HVAC	up to 50% savings if well designed	Suggests window size and ventilation as major strategies to consider	Specific recommendations per topic apply
Research	(Ben-David & Waring, 2016)	Phoenix, AZ, USA	hot-arid	Natural Ventilation Mechanical Ventilation	Nat econ: Up to 35% when Nat hybrid: 84%	Natural economiser with a wider setpoint range	Hybrid situations also showed good results, though requires well controlled systems
Research	(Assem & Al-Mumin, 2010)	Kuwait	hot-arid	Glazing Type HVAC Type	GT: 27.5% with reflective low e AC COP: above 2.2 for air-cooled 4.7 for water-cooled	Heat recovery: 18% lower in air-cooled 15% in water-cooled	GT: achieved lower than 70 W/m2 SHGC: lower than 0.4 should be used
Research	(Gómez-Azpeitia et al., 2012)	Monterrey Hermosillo	hot-arid	Overall Energy Savings			M: Base Case- 390 MWh annual cooling energy consumption H: 460 MWh
Research	(Friess & Rakhshan, 2017)	Abu Dhabi	hot-arid	Insulation Nat Vent: Mix Mode	I: 2.6 % cooling energy reduction NV: up to 35-73% if night ventilation is applied		The building envelope has potential to lower energy cooling loads. Louvres also lower this, in combination with interior light control
Research	(Prieto et al., 2018).	various	warm-dry	Shading Glazing Size Glazing Type Ventilation	S: 25% avg GS: 34% avg GT: 22% avg V: 50% avg	Ventilation has the greatest impact followed by Window to wall ratio	S: louvres and screens + impact than overhangs GS: 20% WTW ratio already results in important savings

Table 7. Summary of passive strategies employed by reviewed research. (Hot-dry climate oriented)

C CONCEPT DESIGN

CHAPTER OVERVIEW

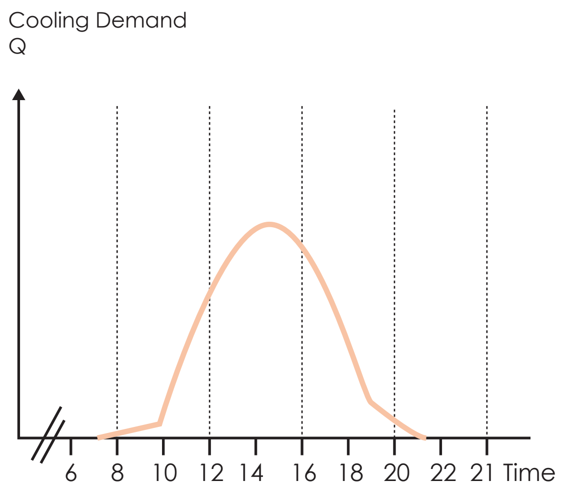
This chapter will summarize the conclusions found in the literature review, focusing on the design parameters and strategies required. These strategies will serve as the starting point for the method of evaluation and consequently the assessment of each strategy and their impact on the thermal performance of the design. First, the focus of study will be established, such as the technology, context, and climate where the design will be settled. Secondly, the design levels that will be addressed for the design will also be shown and explained and the main design parameters will be highlighted per level. Lastly the concept design strategies will be selected based on previous research for their evaluation. This chapter will answer to specific sub questions. At façade level: What are the main design constraints for the development of heat dissipation system, including possible complementary elements? (plate thickness, shape, air flows, material); and secondly: Which façade parameters and requirements need to be addressed in the design, in the context of an office typology?

C.1 FOCUS PARAMETERS

This research will focus on a final façade design. There are three main groups of requirement that will be addressed during the project, which are the building typology, the typo of technology used and the climate context where the design will be applied.

C.1.1 BUILDING TYPOLOGY

As it was mentioned, this research will focus on the office typology were overheating is a problem, and air-conditioning is widely used. In addition to this, the occupancy schedules of this typology offer opportunities to manage the excess heat generated by the thermoelectric module when the building is unoccupied. The office building to use as the base case for the TEC system to be applied is the Koi Tower (refer to chapter B.5.1).



Graph 6.Histogram for office air-conditioning (summer), redrawn from:(Daniels, 2002)

C.1.2 PELTIER MODULES

Another important focus on the design is at system component level, were the heat dissipation system will be developed for the Peltier Module to operate on the façade system. The tests and simulations will be conducted with the Peltier element as the source of cooling and heating power. The main idea is to test the potential of this technology for space cooling.

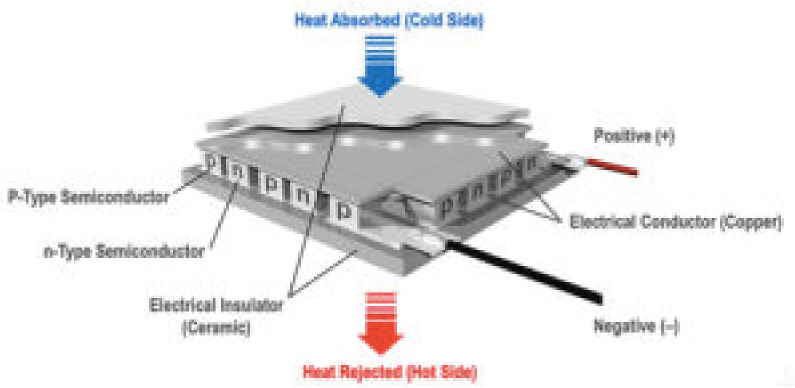


Figure 23.Peltier Module Mechanism (source: https://www.medicaldesignandoutsourcing.com/thermoelectric-cooler-solutions-for-medical-applications/)

C.1.3 CLIMATE CONTEXT

The hot arid climate was selected for this study and its main conditions are outlined on chapter B.5. The parameters of this climate will be used for the improvement of the office building design with passive strategies and for the assessment of the façade system once the TEC composition is developed.

Figure 24.Location of city of Monterrey in México

C.2 DESIGN LEVELS

The in-depth literature research on the existing projects and case studies which explored the use of thermoelectrical systems on the façade showed the scale of effect on the overall performance of the system. The design was divided onto three main scales: Level A, B and C. Level A is the building level, were the design of the office building will be optimised passively. At level B, the façade's cross section will be analysed and designed and at level C, the component system consisting of the TE plus its dissipation system will be designed.

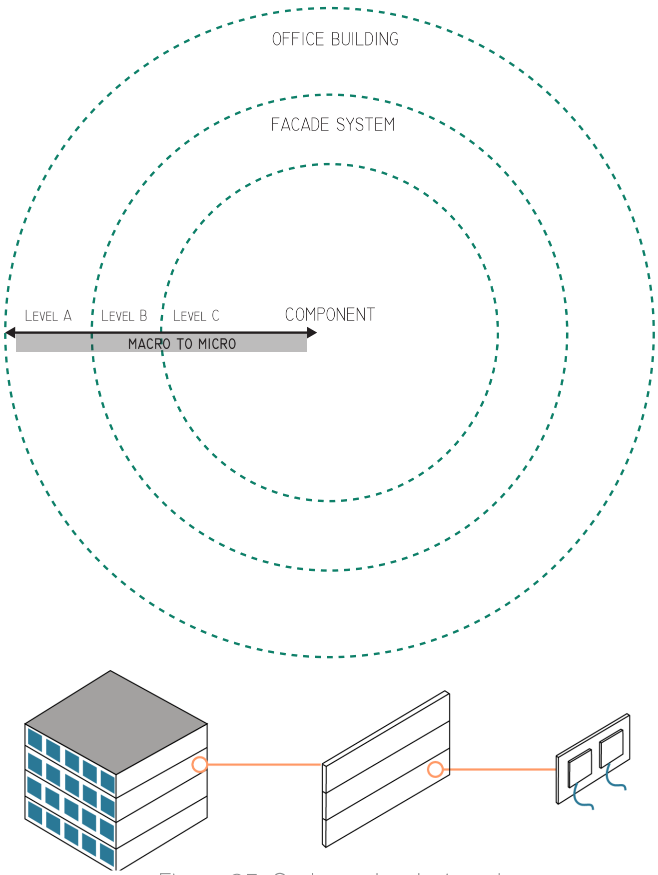


Figure 25. Scales to be designed

C.3 DESIGN PARAMETERS

The main objective of the research is for the cooling system with TE to provide enough cooling power for the office building at the aforementioned climate, and for this to be achieved, each level to be designed needs to reach certain standards. Thus, each level has its own objectives, aims and hypothesis.
Design Aims:

Level A: minimize peak cooling loads through passive strategies.

Level B: maximum integration potential with level C through proper configuration for increased performance.

Level C: maximize heat transfer of the heat sink through shape transfer typology to increase the system's performance.

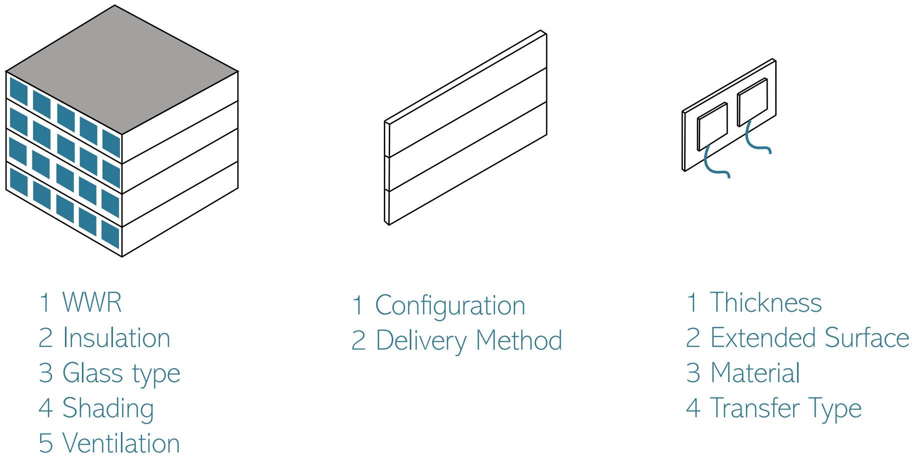


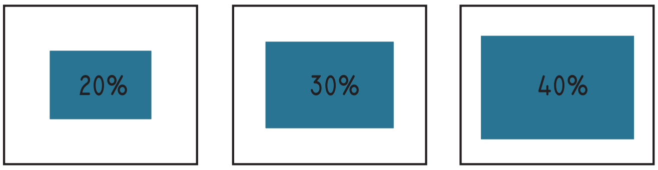
Figure 26. Overall design Parameters per level

C.4 DESIGN STRATEGIES

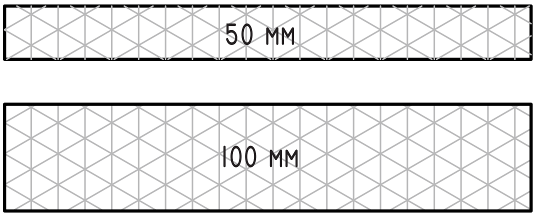
The design parameters established previously served as the base for the design strategies that is tested in the evaluation section of the research. The strategies for building and component levels are addressed in a similar way, where the strategies mentioned will be evaluated and analysed. In the case of the façade level, although there are some strategies that can already be implemented and analysed, these depend on the results obtained at level A and C, so the real strategy will be the integration of these two.

C.4.1 LEVEL A

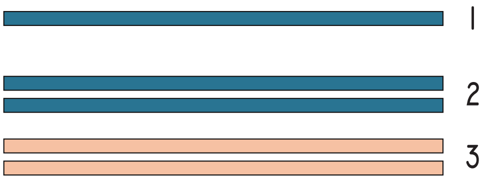
For the building level the following design strategies will be tested in order to minimize the cooling loads during summer peak time for the case study. Ideally for such a type of climate, below 40% of glazing is suggested, so reasonable decrease in the cooling load should come from this particular strategy. In addition, the studies found explain that the use of natural ventilation also adds to the energy performance of the building. The times of the year where the outside temperature is within the comfortable levels during the day or at night, natural ventilation can be used to save energy. Nonetheless, it is expected that the combination of all these strategies should diminish the total cooling loads that the base case currently requires to reach the thermal comfort of its occupants.



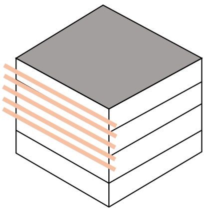
1 WWR Variations
- 20 %
- 30 %
- 40 %



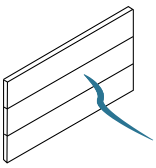
2 Insulation
- 50 mm
- 100 mm



3 Glass Type
- Double, Low-E coating, Air
- Double, Low-E reflective, Argon
- Double, Low E coating, Argon



4 Shading Type
- External Blinds
- Internal Blinds



5 Ventilation
- Natural Ventilation
- Night Ventilation

Figure 27. Level A design strategies

C4.3 LEVEL C

Design will have to start with level C to raise the system's performance from the smallest level. The underlying hypothesis is that with a proper heat sink shape design and manipulation, the performance of the TEM can increase. For this reason, certain design strategies found in the knowledge phase will be tested so that their impact on the performance of the TEM can be evaluated. The first strategy will be the thickness since the contact between the module and the heat sink can be critical for the heat transfer of the system. In consequence, a proper thickness that responds to this and does not exceed affordable material quantities should be found. The material of the heat sink and their combination can also affect both positively and negatively, thus, testing at material level will also be conducted. As most of the reviewed papers show, there is great potential on shape manipulation of the heat sink to increase its final performance, and these are sometimes coupled with experimenting with different types of cooling (natural or forced). Though most of these where tested at low scales, so it is in order to adapt these strategies for a TEM façade scale.

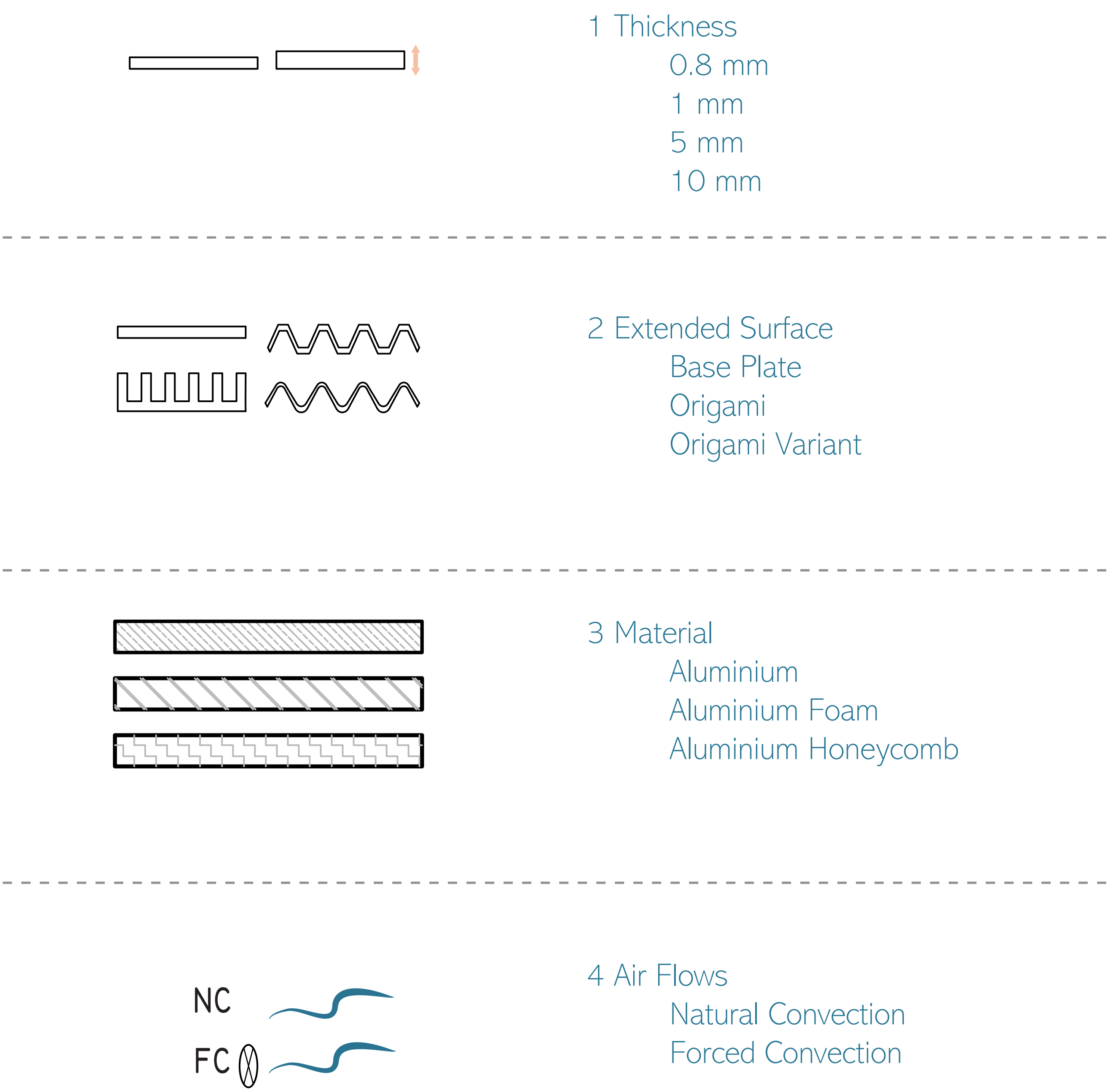


Figure 28. Level C design strategies

C.4.2 LEVEL B

For the façade level, the design of level C and A are required to analyse and evaluate the possible configurations that can be achieved with this result. In this case, the design strategy that applies to the façade level is the integration of both these parts. The final configuration and the delivery method of the cooling system will be a result of the design guidelines found for level A and C. Further information on the façade design will be addressed in chapter F.

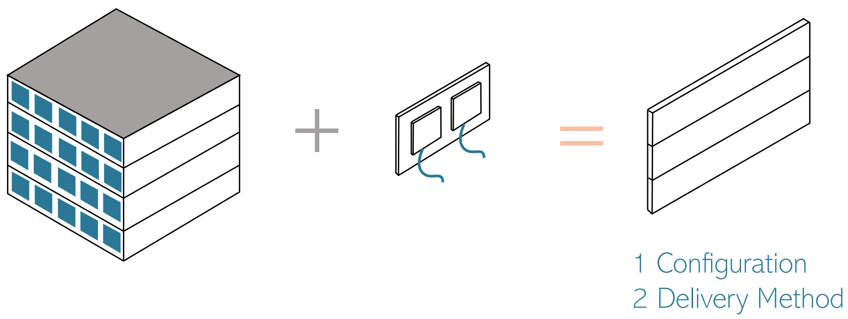


Figure 29. Level B design strategies

C.5 DESIGN METHODOLOGY OVERVIEW

An important task was to create a design methodology that could answer the main research question and the sub-questions. For this reason, the following diagram and table show the process followed and overall methodology applied for the upcoming evaluation phases.

Graph 7. Summary of design methodology

Level Area	Concept Design	Tools	Evaluation	Concept Design	Tools	Evaluation	Final Design	Tools	Evaluation
Level A: Context and Building Level	Optimised Office Building	Drawings Revit Research Other studies	Lowest Cooling Load (energy consumption) Feasability (Mex) Comparison with other studies				Facade Integrated in Building	Drawings Revit Design Builder Simulation	Performance Energy Usage Feasability Integration
Level B: Façade Level	TE facade system	Drawings Research	NA	Integrated Facade System	Drawings COMSOL Simulation	Performance Feasability Integration			
Level C: Component Level	Heat Dissipation System	Drawings Hand Calculations (EES) Research Experiments COMSOL Simulation	Performance Feasability COP Heat Transfer (flux)						

Table 8. Assessment type per level

D EVALUATION AT LEVEL C

CHAPTER OVERVIEW

This phase includes the experimental and computational process used to determine the effect of each design strategy on its performance (increase system performance at level b and C). The process is based on a stepped design methodology, in which each strategy is assessed and then the best result from each set of evaluations is further developed and tested. Experiments and Multiphysics simulation software and were used to establish the different effects at this scale. The methodology is divided into four studies. Limitations at each one will be addressed. Each study will be described in detail, including simplification process, and main boundaries. Lastly, the design process will start from Level C, since designs at Level B required data from C. In the evaluation phase, the design strategies defined on the previous chapters were analysed and their impact on the thermal performance of the system assessed. At level C, the results from the experimental set-up will be presented here and discussed. The simulations will be possible with the comparison with the results obtained from the experiments, to corroborate that the baseline is proper for the assessment of the all the design strategies discussed. The best option within each strategy will be selected and a new simulation conducted with the new strategy applied. Finally, a comparison on the impact of each strategy will be done to provide the answer to the question: What implications do these design constraints have on the performance of the TE façade system? This phase will end with the design options for level B, based on findings from level C. These options will be evaluated as it was previously mentioned.

D.1 METHODOLOGY

Before officially beginning with conceptual design, first an understanding of the type or research that would be used will be explained. Since the focus of this research is finding the optimal heat dissipation design for a thermoelectrical module to have a comparable cooling performance of that of a typical air-conditioning system some experimental studies were done, followed by the proper simulations to continue testing the design strategies.

D.1.1 STEPPED METHODOLOGY

The effects of the heat sink shape over the performance of the system were observed through a stepped methodology. The strategies to be tested were based on those found in the knowledge phase. One of the advantages of the stepped methodology is that it makes possible the assessment of one strategy at a time (making logistics easier to handle) and thus easier to evaluate the obtained results. Although the stepped methodology might be useful in terms of these small experiments, when going into more complex shapes with the digital software, some strategies might not work ideally together. Furthermore, there can be an infinite amount of design options, and could be much time consuming to reach the optimal design. Thus, further tests in COMSOL, though simulations might be necessary for some final decisions, thought he same limitations of the stepped methodology apply. Although a possible matrix with the combination of different strategies could be an alternative for this limitation, the computational cost could be too high, and since this research's aim is to find the effects of the heat dissipation design over the performance of the cooling system, the final optimal design is not required in its totality.

D.1.2 EXPERIMENTS

The goal of these initial experiments was to understand the technology at hand and how some variations in the heat sink geometry could affect its performance. For this, a stepped methodology for the first design phase was taken for the shape of the heat sink

D.1.2.1 Variables tested

For the variables tested, temperature played a major role. The following variables were recorded: ambient temperature (Tamb), hot box temperature (Thb), heat sink hot side (Th) and heat sink cold side (Tc), air velocity (when forced convection was applied). Infrared photographs were also taken to see the changes in temperature with time. These are all physical variables.

D.1.2.2 Equipment and techniques

To be able to measure the temperature, Dataloggers (HOBO), Figure 31, with an external probe were used for the experiment. The air velocity when fans were used was measured with an air velocimeter. I-buttons were also explored as a possibility, but since they can only record data each minute as the minimum time rate, the Dataloggers were selected since they have a wider range. The Dataloggers allow data record every 5 or 1 second, making them ideal for TE modules which react immediately as you connect them to a power supply (this was found out after some trial an error).

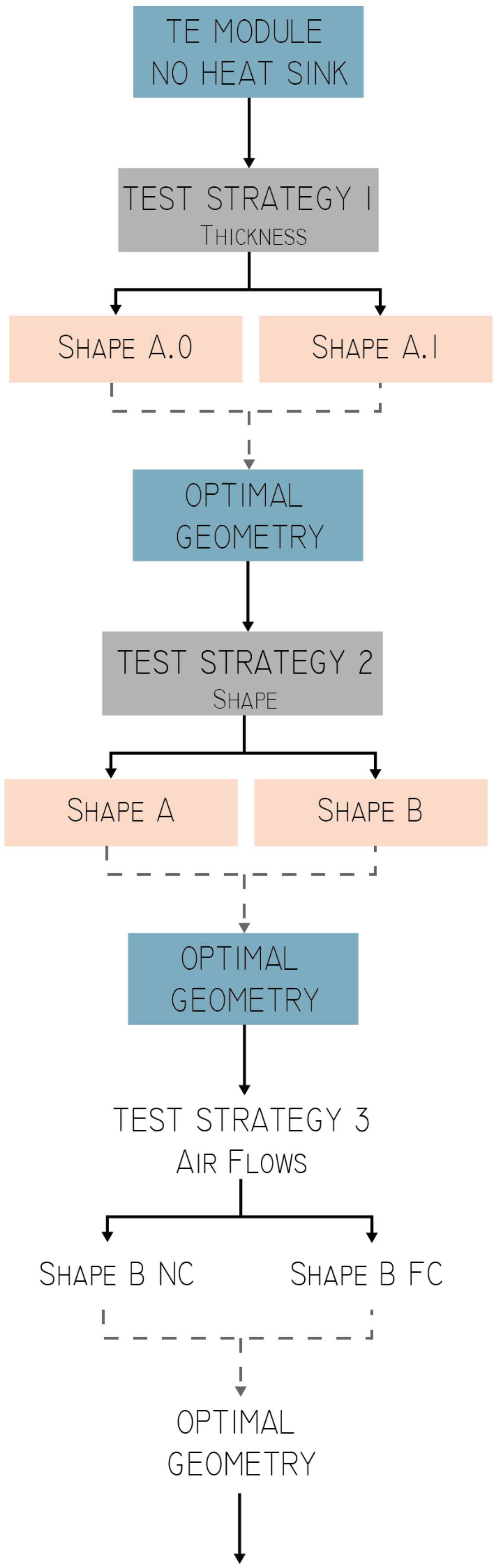


Figure 30.Stepped Methodology diagram

As for the TEMs, cheap and available Peltier Modules were used, TEC1-12706. The module is 40x40x3.8 mm and its performance indicators are as shown in Table 9. For information on the validation of the three modules used refer to annex B. For the TEMs to be powered a Minleaf DC Power Supply was used, model NPS3010W. (Figure 31) It can provide a range from 0 – 30 Volts. Although for this test, experiments above 6 volts will not be conducted, this power supply was chosen since it shows the current applied to the module at different values of Voltage. (this will be useful when conducting numerical validations).

For simulation of forced convection, a computer fan, patented NB-Multiframe-Low Noise technology, S-series, with direct current of 12 Volts, was used.
The experiments were conducted on a small hot box built out of extruded polystyrene foam.

a b c d

Figure 31. a: Datalogger (HOBO), b: air velocimeter, c: infrared camera, d: power suppy

The dimensions of the box were 345X307X311 mm, with a thickness of 40 mm. The expected U Value calculated for the box was 0.67 W/m2.K, but after some calibration tests with a heat source, the real U Value of the box found was around 1.00 W/m2.K, and it takes around one hour to reach steady state. This information is valuable if longer tests on the cooling performance of the system want to be done later. For more information on the hot box calibration refer to appendix I.3.

TEC1 - 12706 MODULE

I max	6.4	6.4
V max	14.4	16.4
ΔT	66	75
T hot	25	50
Q max	50	57
AC resistance	1.98	2.3
Number of couples	127	
Dimensions	40*40*3.8	

Table 9. TEC1-12706 Datasheet specifications

D.1.2.3 Execution Plan

The temperature is measured by the Dataloggers from the locations shown in the schematic diagram of the hot box, shown in the figure below. Datalogger 4 is located inside and measures the temperature inside the box, its external probe measures the surface temperature of the cold side of the heat sink, whilst Datalogger 2 measures the ambient temperature and its external probe measures the surface temperature of the hot side of the heat sink . To generate the temperature difference in the TE modules, they are connected to a power supply. Air velocity of the computer fan will be fixed and measured before each test that requires it.

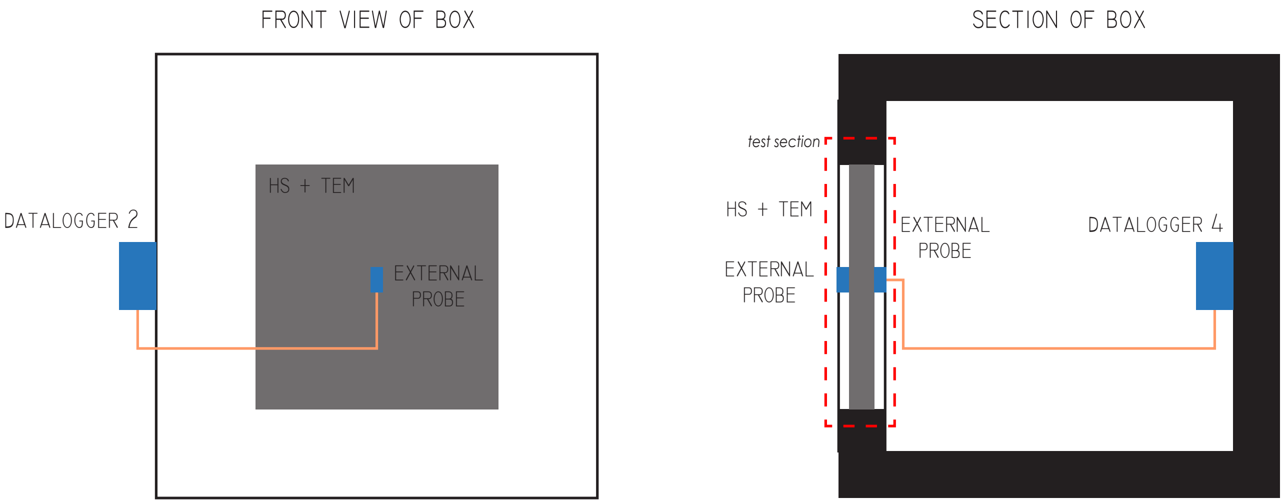


Figure 32. Schematic diagram of hot box configuration

The heat sinks tested were all aluminium, the base length is L, base width W, base thickness is t1 and fin height h (see table of experiments for exact dimensions). Information about the TEM was obtained from the commercial datasheet shown before. The test was developed to see the variation in the temperature of the TEM over time inside and outside the hot box, comparing its performance with the small changes on the heat sink parameters. Since the TEM starts operating immediately to its full performance after it is turned on, tests of only 2 minutes each were done to see the effect of each heat sink.

A schematic diagram of how the system was assembled is shown on figure 37. When required, the heat sink was replaced for the new experiment to be performed. The TEM 1 was attached to the plates with thermal paste and removed with isopropyl alcohol (99% alcohol) with a coffee filter (which leaves minimal residual) to be reused again in the next test. The thermal paste used was V1, IC value thermal compound, non- corrosive, with a thermal conductivity above 1.85 W/m-K. The isopropyl alcohol was also used to properly clean the heat sinks before their use.

The insulation material used between the two heat sinks was cotton balls since they were easier and cheaper to get for the scale of this experiment. As it can be seen in figure 36, the heat sink plus TEM component was placed in the opening of the box and the measurement devices attached as shown. The thermoelectric module with the heat sink is installed in the test section and then connected to the power supply for the voltage control and the camera placed in front of the whole system to visualize and record the process.

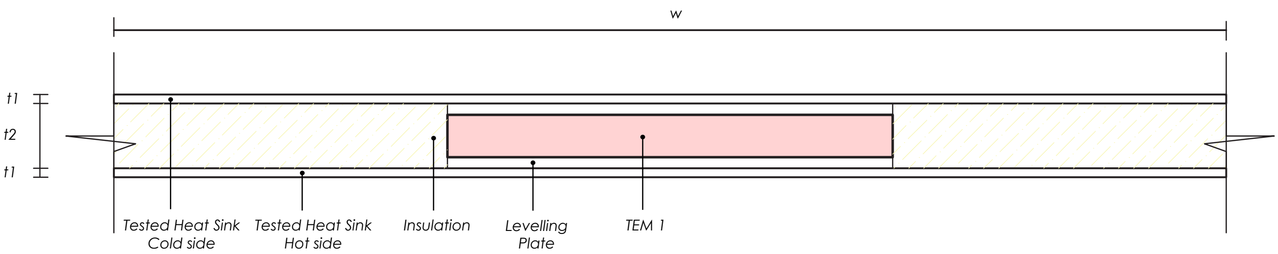


Figure 33. Schematic diagram of system configuration for testing

D.1.2.4 Execution Reality

The first tests had to be redone several times due to some minor setbacks. When taking pictures with the infrared camera, the aluminium showed temperature values that were not real, due to it reflection of the light. To correct this, the plates were painted with mate black. Another problem during execution with the camera was that it sometimes froze in the middle of the experiment and pictures could not be taken. In those cases, the experiment had to be redone since not enough data was obtained.
Another element noticed during the experiments was that the temperature differences weren't that high on tests conducted below 4 Volts, for this reason, the tests to analyse and compare were the ones with 5 Volts. Additional tests with 6 Volts of input were also done.

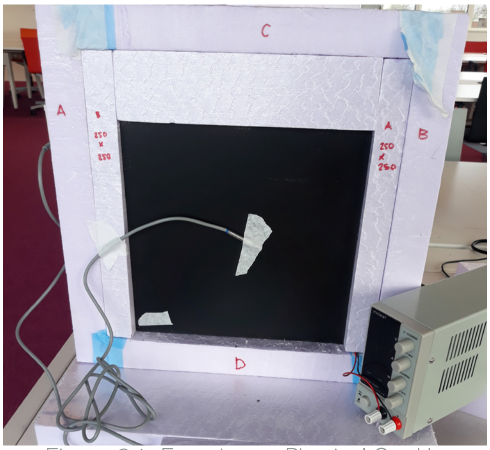


Figure 34. Experiment Physical Set Up

D.1.2.5 Experiment limitations

Although the stepped methodology might serve in terms of these small experiments, when going into more complex shapes with the digital software, some strategies might not work ideally together. A matrix of which strategies could work together could be done, and then further tested in COMSOL, though simulations might take longer time.

The experiments were done in a normal room, so the ambient temperature could not be controlled, and the initial state of each experiment varied a range of about 4 degrees. Another limitation in the experiment was the production of the tested shapes for the heat sink. The 0.8 mm aluminium plates were ordered online, and this thickness was not available in the student shop for the other tests. For this reason, the thickness comparison might not be completely reliable since the dimensions of the plate are different. (200 vs 250mm and 300 vs 250 mm) On that matter, a base thickness above 3 mm would be advisable for electronic components according to the knowledge phase, but this thickness would not be possible to shape around manually nor with the machinery available at the Architecture Faculty. The comparison was then done for slight changes in thickness below 1 mm, although this will probably show that it is insufficient for the TEMs, the idea of those tests was to check if the strategy had significant impact on the temperature difference even with a slight change in plate thickness.

D.1.2.6 Scientific reliability

As it was mentioned, the ambient temperature could not be controlled, thus the initial state of the experiments was different, this affected its reliability to be recreated in the future. Nonetheless, the test was conducted several times to evaluate the result and simultaneously recorded with the infrared camera to compare results obtained from the Dataloggers. I-buttons could additionally be used during testing, but they record each passing minute and the rapid temperature change in the thermoelectric modules would be missed.

D.1.2.7 Accuracy

The accuracy of the devices discussed previously is listed in the table below. This information was important to determine how accurate the data to collect in the experiments would be. Since human error and poor data processing could also diminish the data's overall accuracy, a starting point was needed. In addition, when handling the data provided for tests, calculations and presentation of it, the proper significant numbers to use is dependent on each device, its resolution and accuracy.

Accuracy of measuring devices			
Device	Temperature Accuracy	Temperature Range	Temperature Resolution
Datalogger	±0.7°C at +20°C	-20°C to +50°C	0.4°C at +20°C
Device	Velocity Accuracy	Velocity Range	Velocity Resolution
Velocicalc air velocity meter 9515	±5% of reading or (±0.025 m/s), whichever is greater	0 to 20 m/s	0.01 m/s

Table 10. Accuracy of measuring devices

D.1.3 SIMULATIONS

The experimental set up would give certain parameters and results for the design at component level, nonetheless there were limitations explained with regards to the construction of the specimens and tools required for certain tests. For these reasons, it was decided to use a simulation software to complement the experiments conducted. Simulations enable innovation, conception and understanding, and experiment validation in a more controlled environment. They allow for the optimized design by checking its performance, testing and verifying results faster and less costly than with individual prototypes. For the selection of the simulation software there were various options found from the research phase such as COMSOL Multiphysics and ANSYS Fluent. The software should be able to accept complex geometry, simulate heat transfer and air flows in detail, plus be user friendly enough to learn in the corresponding timeframe.

The COMSOL Multiphysics (version 5.4 and 5.5) is a cross-platform finite element analysis software allows multiple effects simultaneously plus complex geometries in different scales. The software allows for all the steps on the modelling flow to be defines such as the geometry, material, and physics that want to be solved to produce accurate results. (COMSOL Multiphysics®, n.d.) COMSOL also has the added advantage of being visual enough to read the results easier and enough freedom of modelling to test different hypothesis within the same setting.

D.1.3.1 Multiphysics software

The software has many possibilities and as it was mentioned, allows for a combination of physics parameters to be tested simultaneously on an element, such as electrical and heat transfer combinations. This makes the simulation time much higher and the results more complex to read, so for this reason only the two main physics within the studied research will be used for the tests. These two coupled together were able to simulate accurately the situation and show the effects on performance of the heat sink.
The two main physics modules used for the simulations:

1) Heat transfer Module (HT): contains tools to study mechanisms of heat transfer, conduction, convection, and radiation.

2) Laminar Flow Module: which simulates devices and systems were fluid flow is incorporated, in this study natural or forced air flows will correspond to this module
(COMSOL Multiphysics®, 2020)

The expected methodology was to be able to do a 3D model and simulate the Peltier module, since the software is known to have the thermoelectric physics module to test, plus the heat dissipation system with both air flows and heat transfer. Then, each strategy would be applied on the heat sink and simulated to observe their impact on the performance on the complete system. Nonetheless, the first trials with the software showed that this was not going to be completely possible. The modelling of the Peltier module proved to be too complex since it required to have knowledge beyond the scope of Building Technology. Even with a base, running the simulation for a test module took around 12 hours for simulation, without heat sink or laminar flows tested. On the other hand, adding laminar flow to the simulation also contributed to an increase in complexity of the tests, and also made simulations as long as 12 hours for simple elements and in some cases an error on lack of enough disk memory had the simulation collapse and end before any result was found. As it was expected, the mesh size of the model and type of solving system also contribute to the time cost of the simulations. For this reason, several alternatives were tested to decrease the complexity and the simulation cost:

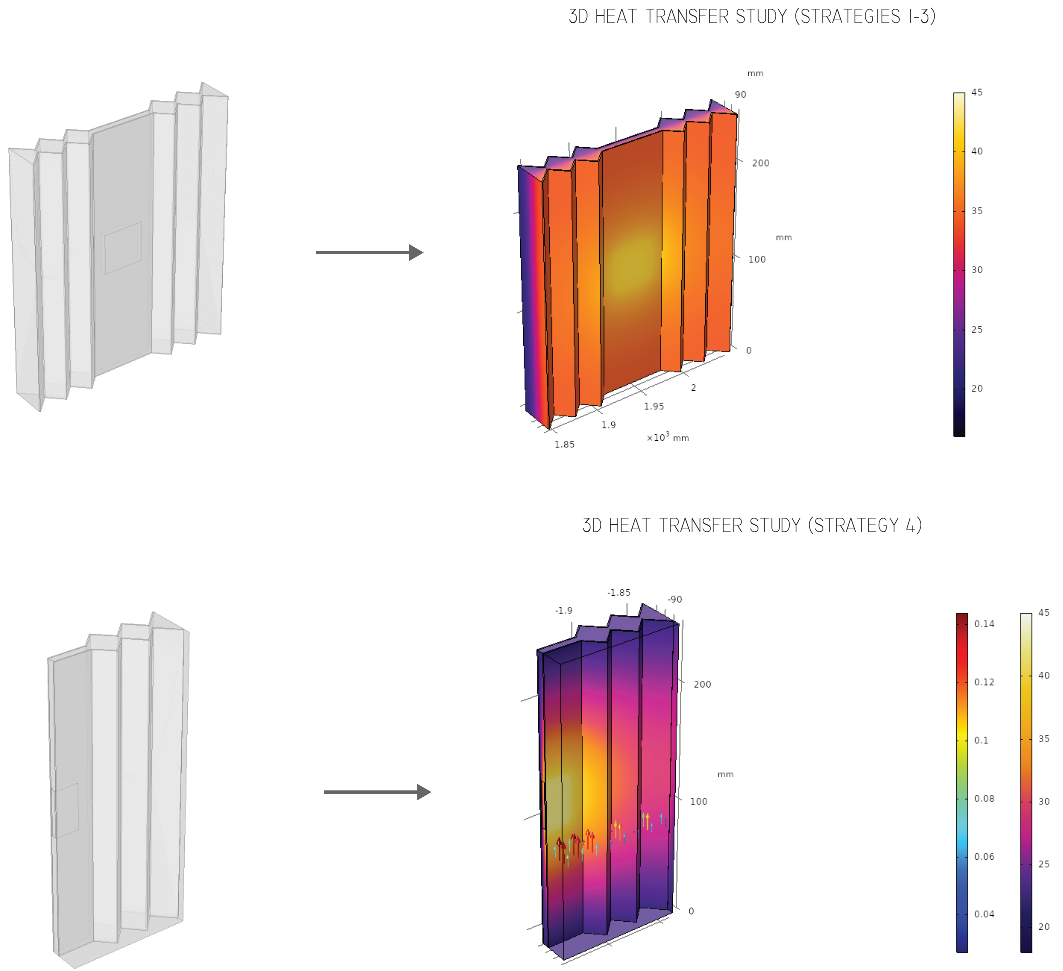


Figure 35. Simulation types for the different design strategies

- Using two boundary heat sources as the two sides of the Peltier module with predefined values.

- As mentioned, the h value of the heat sink contributes to its overall performance, and ideally the air flows would determine this value and give a proper result. The initial tests were done without the air flows and an empirical h value, found on literature, was used for these simulations.

- When applying the airflow channels, the heat sink was modelled in half and a boundary of symmetry defined at the middle to lower the computational time . An example is seen in Figure 35.

- Only simulations with the TEC1-12706 used for the experiment were done to have a direct comparison with the results found on that level of assessment.

- Simulations were done in a steady state environment setting.

D.1.3.2 COMSOL Set-Up

The methodology, as it was mentioned, was a stepped strategy, in order to obtain the effect of each design strategy on the heat dissipation system.

D.1.3.3 Assumptions

The simulations were done to asses which design strategies had a major impact on the heat dissipation system, and thus aid in the façade design. As mentioned, since the model was simplified, the simulations were conducted once they reach steady state and using the TEC1-12706 as base for the heat source values. The simulations were performed assuming the system is in cooling mode, since from the research it is known that the heating performs much better than the cooling, once the cooling is solved, it is assumed that the heating would be sufficient. Though further research on this could be possible. Once the baseline is simulated, based on the best result found from the experimental results, the different strategies will be applied and analysed. Since the final design will be placed in a specific context, once the baseline is established, based on real life conditions, the proper ambient conditions were applied on the model to respond to this context. In this case, an extreme day of summer (12th of July) was selected for the simulations, selected from DesignBuilder.

00 Baseline (Strategies 1-3)

In the baseline model, the main reference to find if the simulation results were accurate was to compare these results with the experiments conducted. Thus, the first model had the same conditions as those used during the experiment with the best results, this means the main constraints, limitations, initial values were defined. Starting with the heat sources, one was defined as heat absorption (cold side) and the other defined as heat rejection (hot side), the average air temperature of the room where the experiment was conducted was defined and the air temperature inside the thermal box as well, to simulate the different conditions. The heat sources were defined as global parameters in the model as Qc and Qh, in W. The heat flux conditions used were based on heat transfer coefficient, obtained from literature review since is it varies for corrugated surfaces and depends on a wide range of variables. A reverse calculation was done from the data obtained by the experiments to find the h-value to use as input for the software. The equation of the resistance required for the heat sink and the heat transfer coefficient formula from Bar-Cohen's equations on heat sinks. (Kraus & Bar-Cohen, 1995)

$$R_{req} = \Delta T/q \qquad (16)$$

$$h = 1/(R_{req} * S) \qquad (17)$$

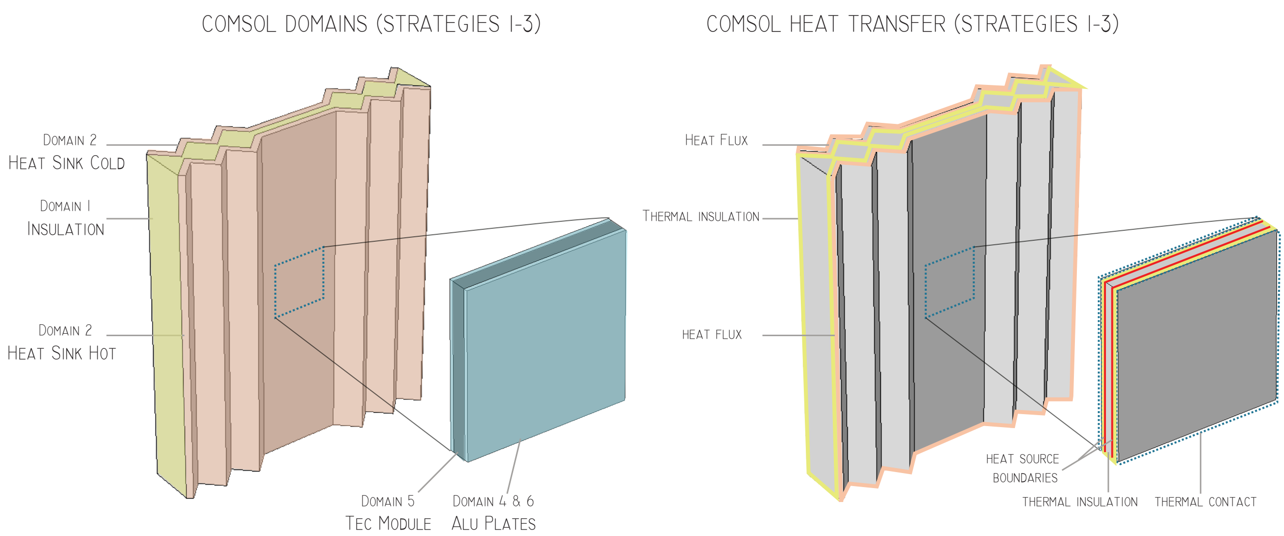


Figure 36.Domains and Boundary conditions for the COMSOL model (strategies 1-3)

The q being the heating power of the element, and the S responds to the surface area of the heat sink. In this case, the h-value obtained was 11.75 W/m^2 K, and this was the value used as input for the simplified baseline simulation. Once the base model was compared with the experiment and find matching, the next step was to adapt this model with the appropriate context. In this case, the ambient temperature was modified from 22.2 °C (from experiment) to 37.8 °C for Monterrey city.

The results given were found by locating several probes in the simulation model, and with the values obtained the COPc of the system was hand-calculated with an automated excel sheet. Through the simulation it is also possible to find the average temperature of the heat sink and how the heat actually distributes throughout the component, aiding the final analysis.

00 Baseline (Strategy 4)

In the baseline model when applying air flows the same initial values as for Baseline (strategies 1-3) were used. The difference on this model were the addition of the physics module Laminar Flow, which allows the simulation heat transfer through any fluid. In this case, the air was modelled as this fluid, thus there was no need to input a heat flux condition, since this is properly solved by the laminar flow module. Nonetheless, when modelling static air, certain boundaries had to be established. After some exploration and understanding of the software, it was found that the two fluid areas require a temperature reference, inlet and outlet of air for the simulation to search for a solution. With very little constraints the software finds convergence error, where it never reaches a solution since the number or iterations could be almost endless. Once the base model was compared with the experiment and find matching, the next step was to adapt this model with the appropriate context. In this case, the ambient temperature was modified from 22.2 °C (from experiment) to 37.8 °C, for Monterrey city and 22.7 °C (inside thermal box in experiment) 30.1°C for the inside in Mexican context (were the inside of the office can reach 30.1 if not properly cooled).

Similarly, to the first baseline model, the results given are found by locating several probes in the simulation model, and with the values obtained the COPc of the system was hand-calculated with an automated excel sheet. Through the simulation it is also possible to find the average temperature of the heat sink and how the heat actually distributes throughout the component, aiding the final analysis. In addition to this, with the laminar flows, it is possible to plot air velocity through the air fluid passing through the heat sink and analyse how the different strategies contribute to the effect on the air.

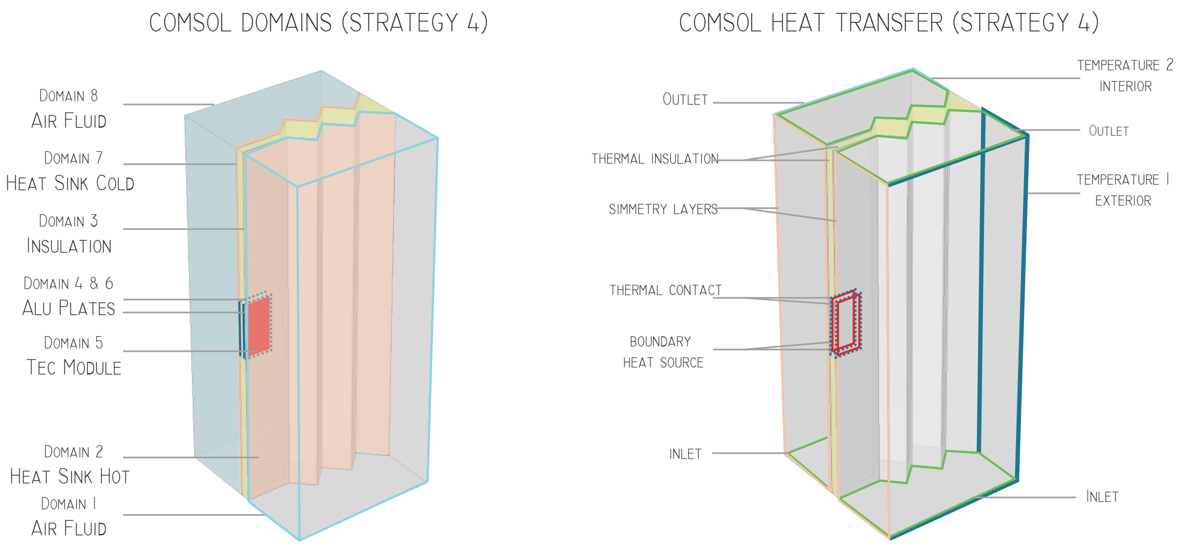


Figure 37.Domains and boundary conditions for the COMSOL model (strategy 4)

01 Thickness

For the simulations on the impact of thickness on the heat sink design, four different thicknesses were tested. (Base, 5 mm, 10 mm, and 1 mm in cold and 5 mm on hot for the last one).

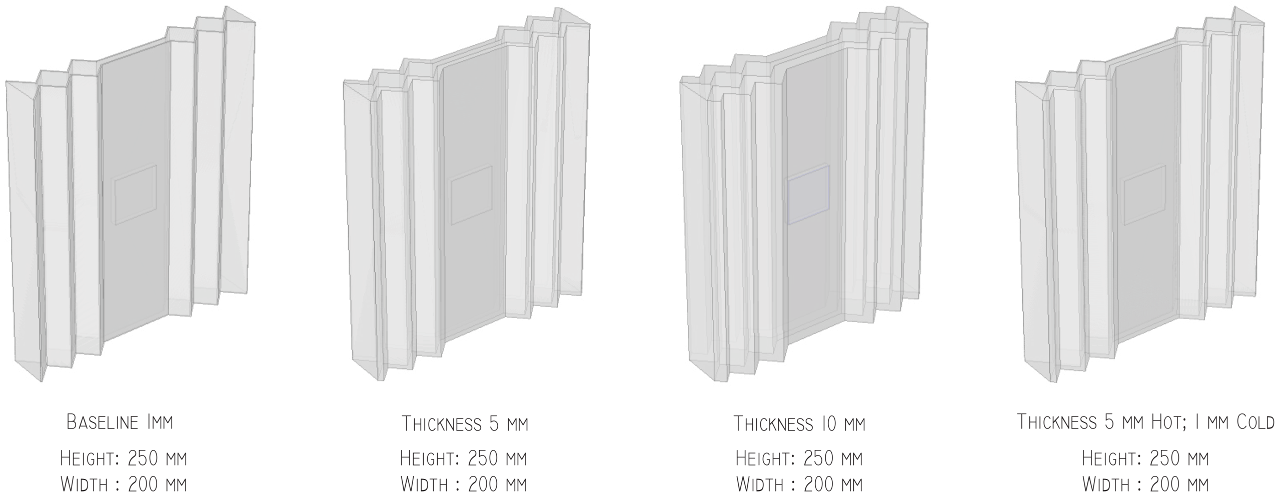


Figure 38.Variation in thickness simulated

02 Extended Surface

For the simulation on the impact of extended surface, four different shapes were tested. Shape B, obtained from simulation result 01, 200 mm x250 mm; shape C, to check how much the shape of the channels contributed to the performance, same 200 mm x 250 mm; shape D, were the surface area was doubled by the size of the channels, 200 mm x 250 mm; and shape E, a previous studied shape was sized as typical cladding system of 450 mmx450mm. The effect of the extended surface has an important impact on the design of the heat sink, as it was previously studied, and results vary if air flows are taken into consideration (their ease in between the channels, for instance) so not only the surface area but also the shape can contribute to the results in this strategy. Nonetheless, since the shape of the channels could be morphed an n amount of times until the most optimal is found, this would take to much time if a computational parametrized script is not used, so for this reason, only these 4 shapes were simulated to obtained the effect on the design.

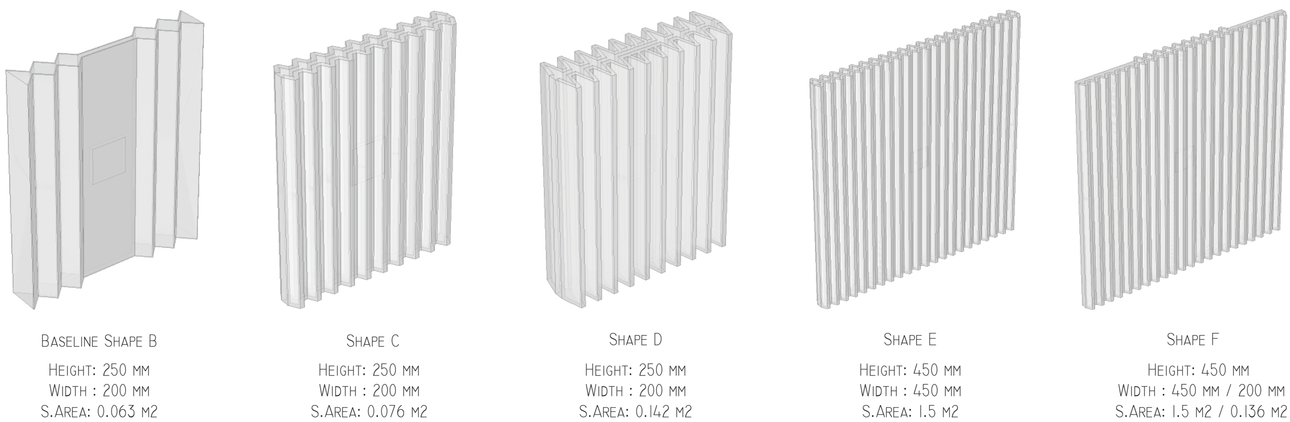


Figure 39. Variations in Shapes simulated

03 Material

In the third strategy simulated was the exploration with different materials, although from the research it was found that although the best in terms of thermal conductivity, aluminium is the best alternative since its cheaper and available. It is was still desired to find other options were the heat dissipation component could also work as the façade cladding. The different materials tested were: Aluminium, which is commonly used for such purposes; and aluminium foam, which could be a lighter alternative that could also serve as cladding. A last exploration was also necessary to check the impact of merging two materials together. For this, two simulations were done, one combining aluminium plus a layer of aluminium foam, an another of aluminium plus a layer of typical Mexican cladding material such as terracotta.

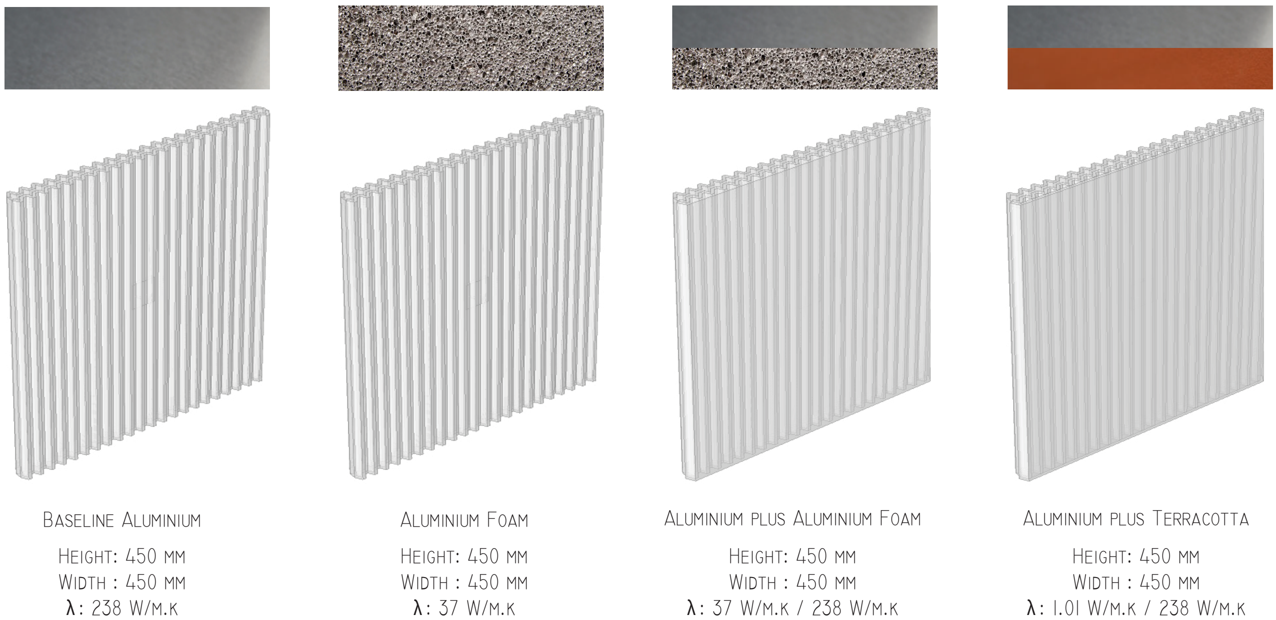


Figure 40.Variations in material for the heat sink

04 Airflows

The last strategy simulated was the effect of the type of air flow on the component. This strategy was conducted in two different phases. The first phase was done on the original shape to evaluate the difference in performance when applying natural convection and forced convection and variations of the same. Once the best result was found, the second phase consisted of simulating this air flow method on the best heat sink design found from previous strategies. In the first phase the variations were: natural convection on both sides, natural convection on one side and forced on the other (a minimal 1.1 m/s, to see the effect), and finally only airflow on one side (both natural and forced). The specific test conducted on the second phase of strategy 4 will be explained in detail on the results chapter, since they vary on previous remarks found on the study of the simulations.

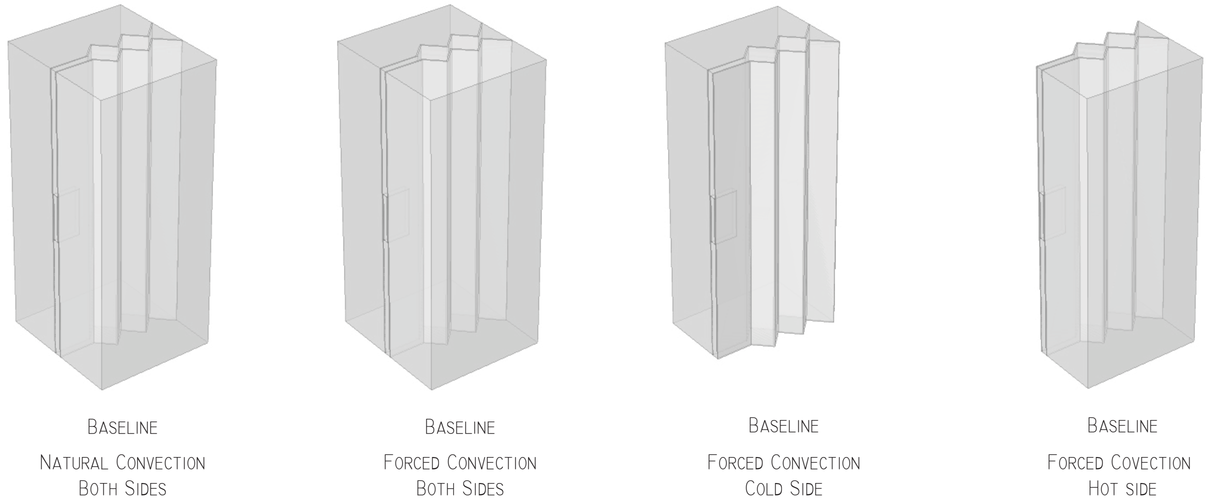


Figure 41.Main Variations on air flows to be simulated

D.1.3.4 Limitations

Some of the limitations were already addressed throughout the chapter, but the most important will be highlighted here. All the simulations would have been ideally with laminar flow, but computational cost was too high, so the initial strategies were tested on a reference heat transfer coefficient, and only the last strategy was tested with proper laminar flows, as mentioned. The porosity of the material was not tested on simulations, since this also made the model much more complex to handle, so in the case of aluminium foam, only the thermal conductivity served as statement for the effect on the performance. Some assumptions had to be made, such as with the boundary conditions of the laminar flow model, where the inlet and outlets were positioned on opposite ends.

D.2 EVALUATION

In this section of the research the application of the methodology previously explained was done in order to assess each design strategy at level C, component. For this, the evaluation is divided in two main sections: experimental results and simulation results, followed by an analysis of these results.

D.2.1 EXPERIMENT RESULTS

As it was mentioned, the first approach to the design at component level was done with a more hand on approach by conducting a few experiments.

D.2.1.1 Baseline experiments

The first experiments were done to calculate the thermal transmission of the thermal box where the experiments were going to take place. The U-value of the thermal box with the heat sink was 1.03 W/(m^2 K) and without the heat sink 1.02 W/(m^2 K). (for more information on how this was calculated refer to annex H.1)

For the validation on the TE modules, some tests were done to test their performance. Three modules from the same manufacturer were tested and they all had slight variations on their results. In this case, TEM1 showed the best performance of the three with a maximum ΔT of around 8 ˚C. Since TEM 1 showed a more stable increase in temperature and a lower ΔT, this Peltier module was used to conduct the rest of the tests. (for more information on how this was conducted, refer to annex H.2)

D.2.1.2 Strategy 1: Thickness

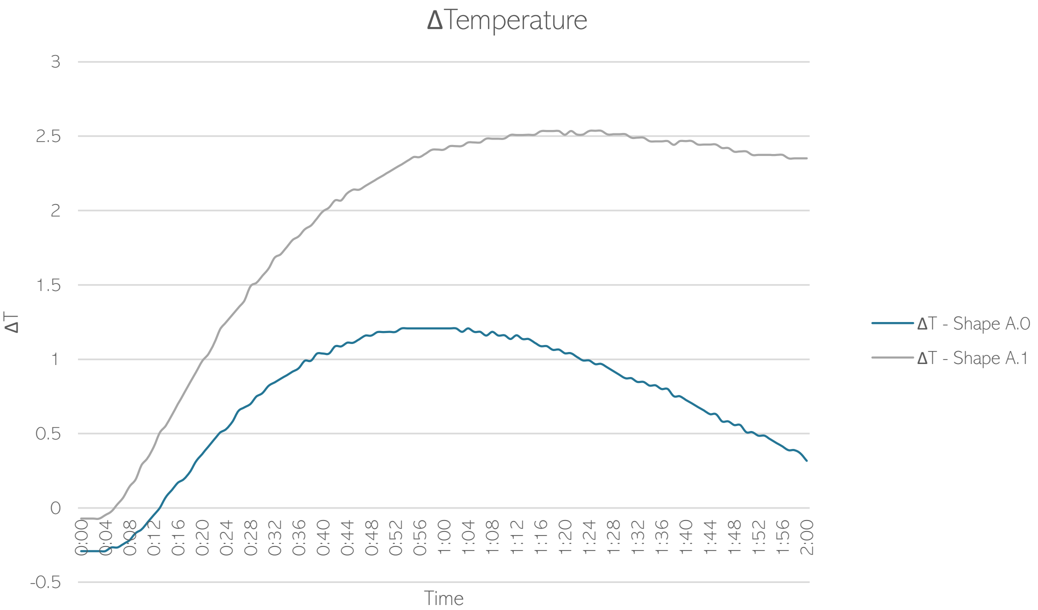
In the first strategy applied at component level was the variation on thickness.

Experiment Set-Up: Strategy 1									
num	TE module	TE quantity	Voltage (V)	Current (amps)	Power (W)	HS shape	Physical Parameter tested	Dimensions(mm)	Volume (mm3)
1	TEM1	1	5	1.23	6.1	Aluminium Plate	thickness	250x250x0.8	50000
2	TEM1	1	6	1.37	8.16	Aluminium Plate	thickness	250x250x0.8	50000
3	TEM1	1	5	1.22	6.05	Aluminium Plate	thickness	250x250x1.0	62500
4	TEM1	1	6	1.41	8.4	Aluminium Plate	thickness	250x250x1.0	62500

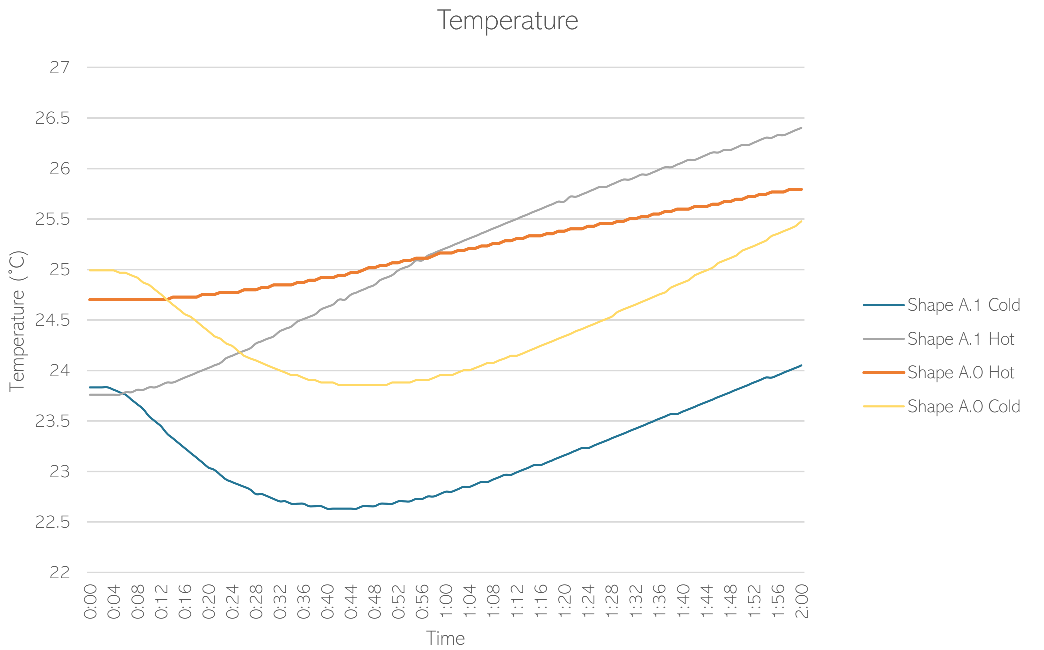
Table 11.Experimental set up for strategy 1

Checking the ΔT on the graph, the best performance is shown by the thinner plate. Although the difference is not much since the Surface area of the plates differ. A more compact element is desired, and the ΔT was not too high on 1 mm, the next experiments were done on Shape A.1.

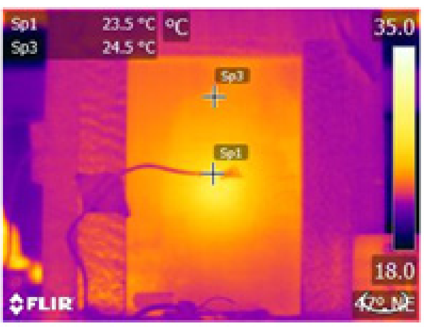
There were several limitations on these first experiments since both shapes did not have the same dimensions, due to availability of material. From literature review, it is known that a higher extended surface would result in a better performance, it makes sense that Shape A.0 performed better. Nonetheless, this was a first glance on the impact the shape has on the heat dissipation performance.



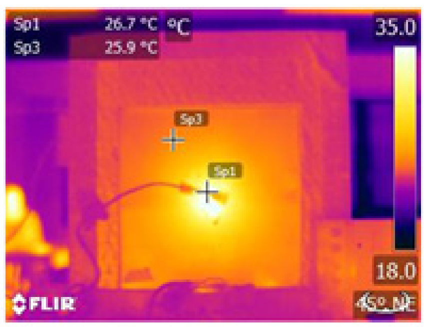
Graph 8.Temperature difference on Shape A.0 and A.1



Graph 9.Temperature at each side of the Heat Sink per thickness



0.8 mm
ΔT: 1.2 ˚C
HS Hot side: 25.04 ˚C
HS Cold side: 23.84 ˚C



1.0 mm
ΔT: 2.5 ˚C
HS Hot side: 26.54˚C
HS Cold side: 24.04 ˚C

Figure 42.Infrared image taken for both tests.

D.2.1.3 Strategy 2: Extended surface

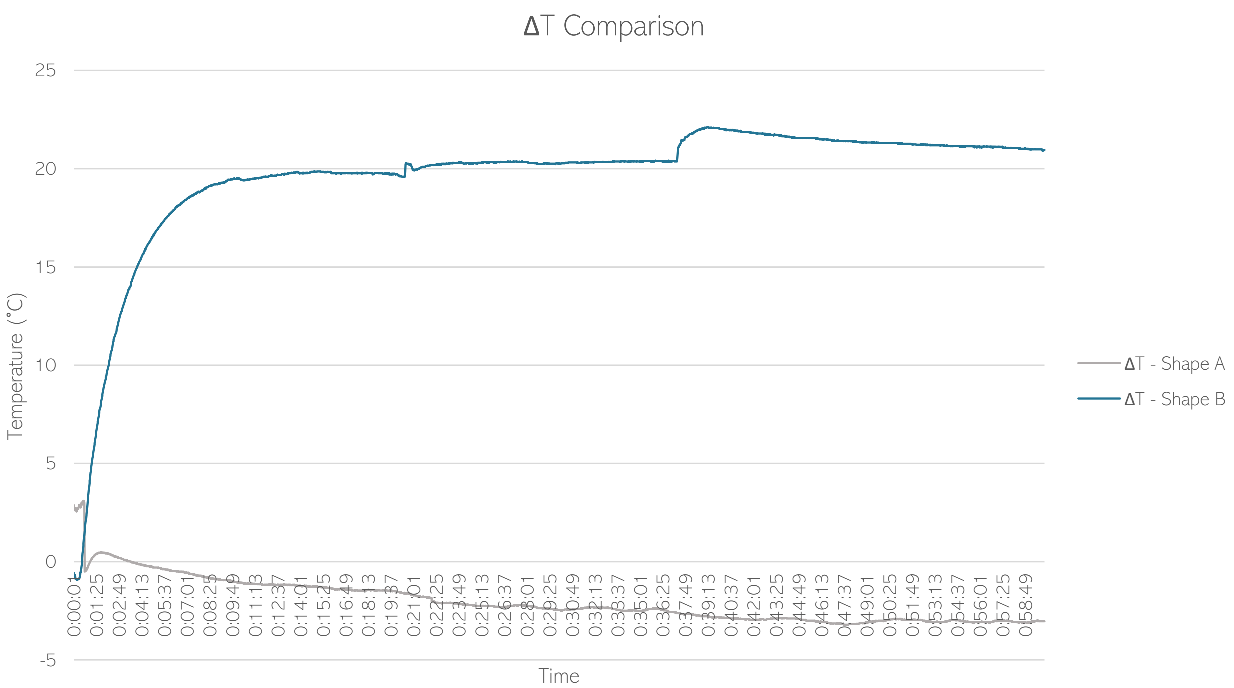
The second strategy tested was the impact of the shape, particularly in an extended corrugated plate compared a typical flat aluminium plate. Both specimens tested had 1mm diameter and were originally 250x250 mm.

Experiment Set-Up : Strategy 2									
num	TE module	TE quantity	Voltage (V)	Current (amps)	Power (W)	HS shape	Physical Parameter tested	Dimensions (mm)	Volume (mm3)
3	TEM1	1	5	1.22	6.05	A: Aluminium Plate	thickness	250x250x1.0	62500
4	TEM1	1	6	1.41	8.4	A: Aluminium Plate	thickness	250x250x1.0	62500
5	TEM1	1	5	1.51	7.55	B: Origami	Shape	250x250x1.0	62500
6	TEM1	1	6	1.77	10.6	B: Origami	Shape	250x250x1.0	62500

Table 12.Experimental set up for strategy 2

Checking the ΔT on the graph, Shape A took longer to reach steady state, and there was almost no temperature difference from one side and the other. Shape B was able to reach a ΔT of around 20 ˚C, which is within the desired values. On the other hand, at some point during the experiment, the temperature of the heat sink on the cold side of the component reached a higher temperature than that of the hot side. This made evident the importance of the complete integration of all the system. The major difference on both specimens was the amount of insulation applied, since the origami shape had a channel type space in between the two sides, this allowed for a thicker insulation on that specimen of around 30.0 mm on those areas and 3.0 mm on the back areas of the channel, compared to the uniform 5.8 mm thickness on Shape A (plates).

Looking at the infrared photos, it also shows the potential of the channels within the system. They seem to have lower temperature on the pockets, possibly due to the aid on the natural air flow going through. The selected shape for comparing performance with and without forced convection was Shape B origami.



Graph 10.Temperature difference on Shape A and B.

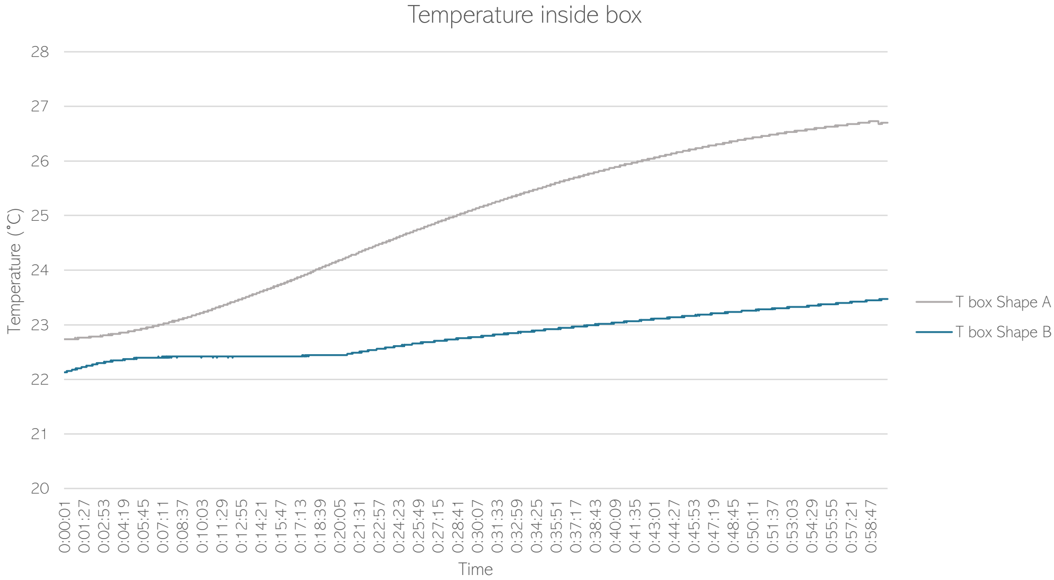
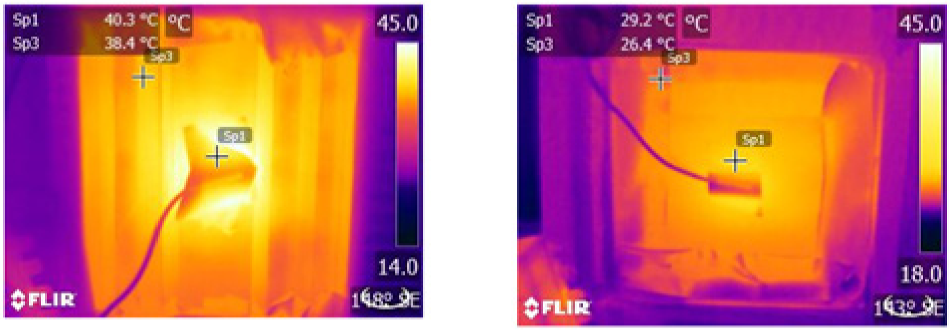


Figure 44. Temperature insde box



SHAPE B - ORIGAMI
ΔT: 20.25 °C
HS Hot side: 39.37 °C
HS Cold side: 19.13 °C

SHAPE A - PLATE
ΔT: 2.47 °C
HS Hot side: 28.90 °C
HS Cold side: 31.46 °C

Figure 43.Infrared image taken for both tests.

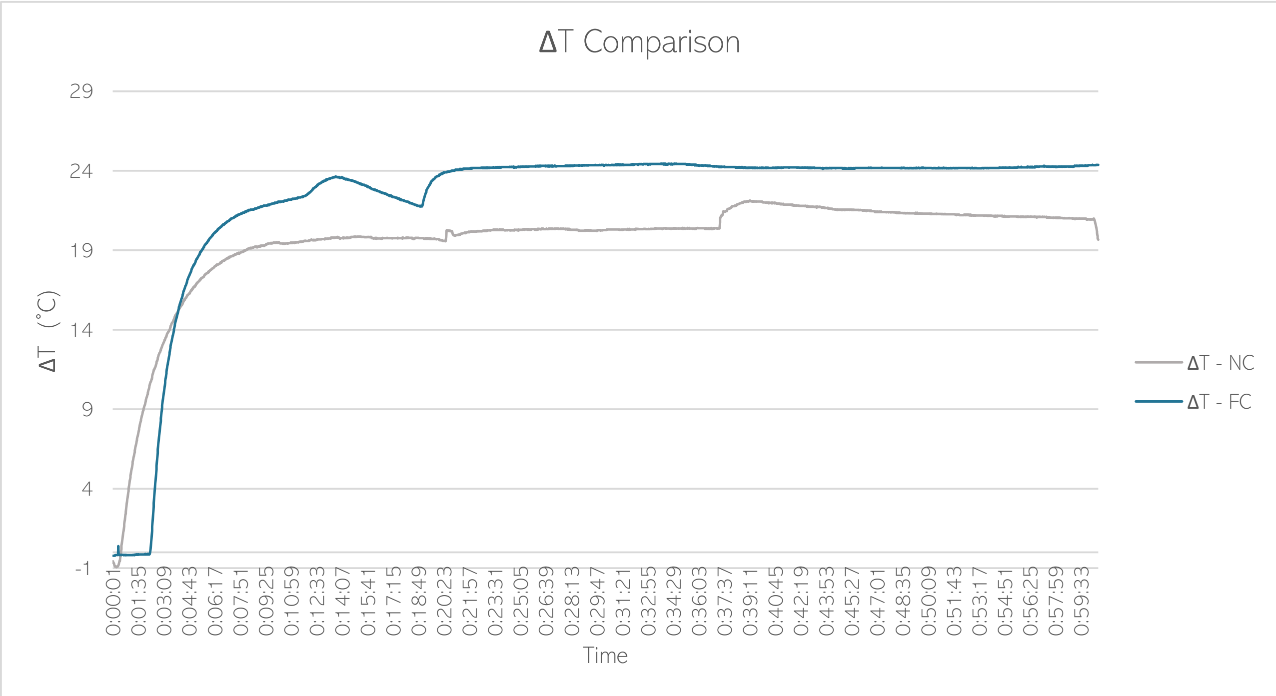
D.2.1.4 Strategy 3: Air flows

The last experiment conducted was comparing natural convection with forced convection. For this a computer fan with an outlet air flow velocity of 1.1-1.3 m/s was used. The test was conducted for one hour, to see the effect it had inside the thermal box once the system reached steady state.

Experiment Set-Up: Strategy 3											
num	TE module	TE quantity	Voltage (V)	Current (amps)	Power (W)	HS shape	Parameter tested	Dimensions (mm)	Volume (mm3)	Air Flow	Velocity m/s
5	TEM1	1	5	1.51	7.55	Origami	Shape	250x250x 1.0	62500	NC	NA
6	TEM1	1	6	1.77	10.6	Origami	Shape	250x250x 1.0	62500	NC	NA
7	TEM1	1	5	1.49	7.45	Origami	Shape	250x250x 1.0	62500	FC	1.10-1.30
8	TEM1	1	6	1.75	10.2	Origami	Shape	250x250x 1.0	62500	FC	1.10-1.30

Table 13.Experimental set up for strategy 3

Observing the ΔT for both experiments, the lowest temperature difference is seen in the natural convection test. In the forced convection test, the temperature difference reaches 24 ˚C, around 4 ˚C higher than with natural convection. Looking at the infrared photos, the specimen with forced convection shows a more uniform temperature throughout the whole heat sink, whereas the one with natural convection has a more defined temperature difference

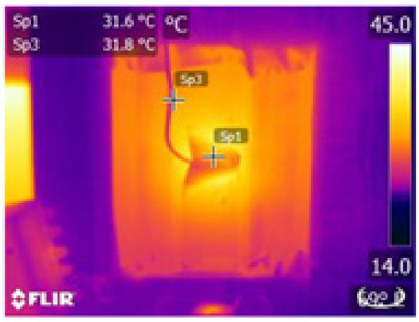


Graph 11.Temperature difference with natural and forced convection

between the channels.

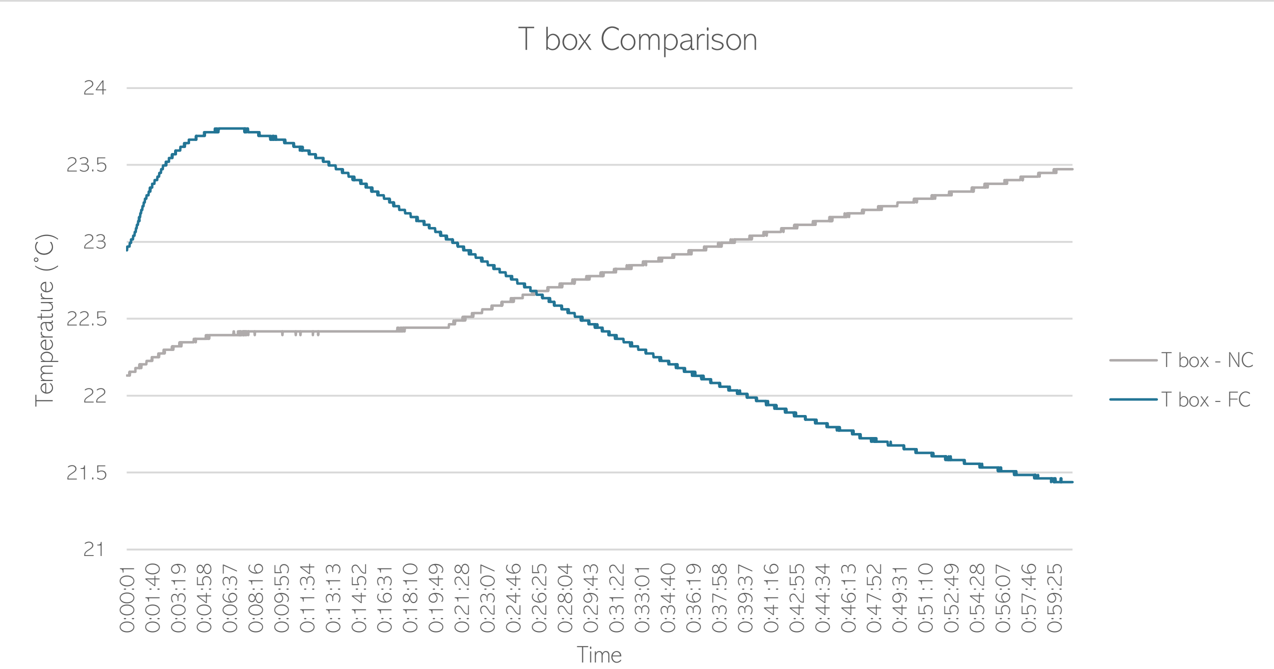
Nonetheless, a better performance was observed on the forced convection experiment when comparing the inside temperature of the thermal box. Even after one hour of the system being turned on, the temperature inside kept on either dropping, in the case of the forced convection or increasing in the case of the natural convection. The temperature on the natural convection test

NATURAL CONVECTION
ΔT: 20.13 °C
HS Hot side: 38.95 °C
HS Cold side: 18.82 °C



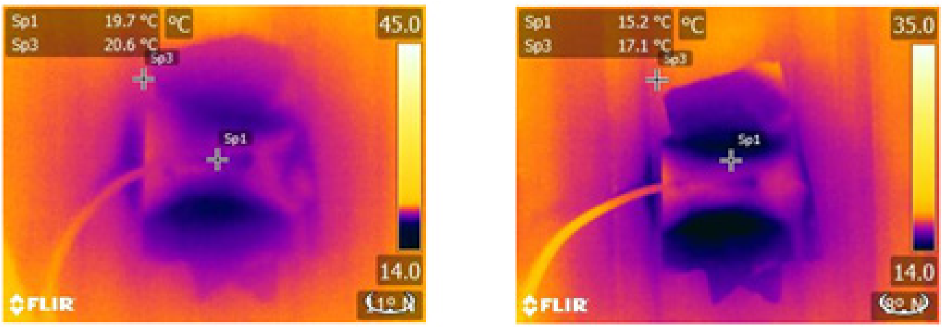
FORCED CONVECTION
ΔT: 24.13 °C
HS Hot side: 39.72 °C
HS Cold side: 15.58 °C

Figure 45.Infrared image taken for both tests.



Graph 12.Temperature inside the thermal box with natural and forced convection

reached around 22 ˚C and 21 ˚C in the forced one.
It is also important to note that the infrared camera shows the area where the Peltier module was reaching 15 ˚C and only around 19 ˚C on the natural convection. The natural convection test also showed a tendency of its temperature gradually increasing which could mean that the heat



NATURAL CONVECTION
Min T box: 22.13 °C

FORCED CONVECTION
Min T box: 21.44 °C

Figure 46.Infrared image taken for both tests.

dissipation is not enough on the hot side for the cold side not to absorb this excess heat.

D.2.1.5 Conclusions

Several conclusions could be drawn from the experiments aforementioned. When testing the thickness for the Heat Sinks, a small difference in thickness resulted in a difference of around 1.2 ˚C . This means that thickness indeed contributes to the performance of the system. Nonetheless, since the thickness still resulted not sufficient for the desired heat sink resistance, further testing was done in the simulation software.
The total surface has an effect on the Heat Sink as well, but is not completely conclusive on the experiment since only a variation of two shapes was explored, so further shapes are tested on the simulations software to see the real impact of this strategy on the heat sink performance.

D.2.2 SIMULATION RESULTS

The following subsections will show and discussed in depth the results of the design strategies tested on the Mexican context. In each section, observation on the behaviour of the system will be presented to aid on the final design.

D.2.2.1 Baseline

The best scenario from the experiments was then replicated on simulation level in the Multiphysics software COMSOL. A simplified version was simulated as to lower the computation cost of the tests to be performed, this means that the Peltier Module was simulated as a boundary heat source instead of modelling the complete thermoelectric effect, as mentioned on the methodology chapter.

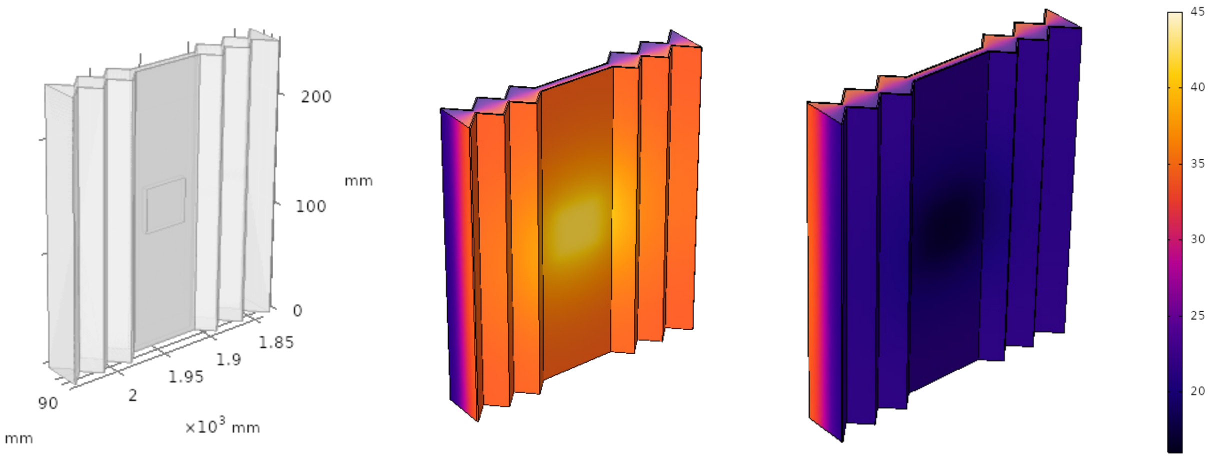
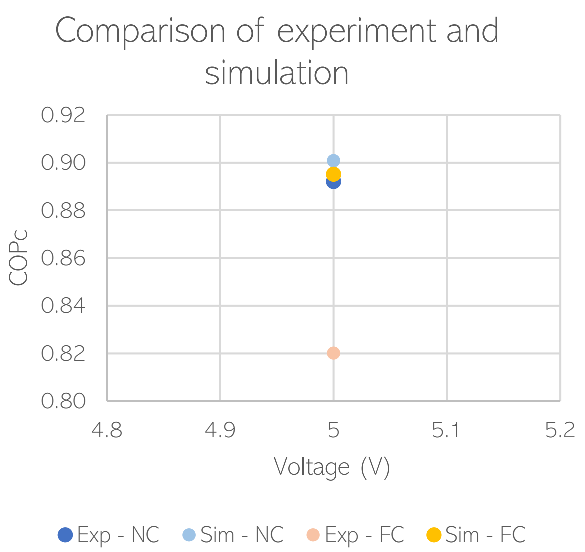
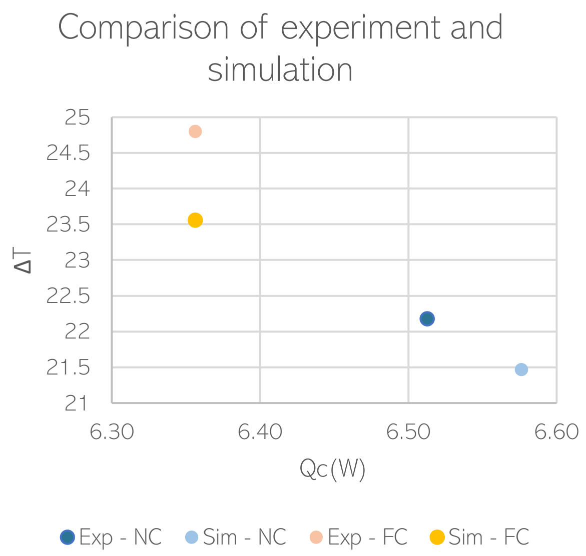


Figure 47.FigureLeft to right: modelled component, hot side, cold side

Comparing the simplified simulation 1 (with no laminar flow) with the values obtained on the experiment, the results have around 20% of difference, and it becomes very evident when analysing the COPc of 0.69 versus the 0.89 obtained on the experiments. Doing the simulation with the same parameters but applying a more realistic environment with laminar flows in the system, the results are in good accordance with the experimental values. Comparing the Qc of 13.88 W at the simulations versus the 13.81 W calculated from the experimental values, the same with the COPc, of 0.90 versus 0.89. It should be noted that the simulation values with laminar flow show a better performance than the actual situation, so this should be taken into consideration when the final assessment of the system. Although the simplified simulation has an acceptable difference from that of the experiment, it will still be used as the base to make the initial design strategy simulations, and the best result of these will have its assessment with laminar flow, to make computational costs lower.





Graph 13.Comparison of experiment values versus simulations values (left: voltage versus COPc; right: temperature difference versus cooling capacity)

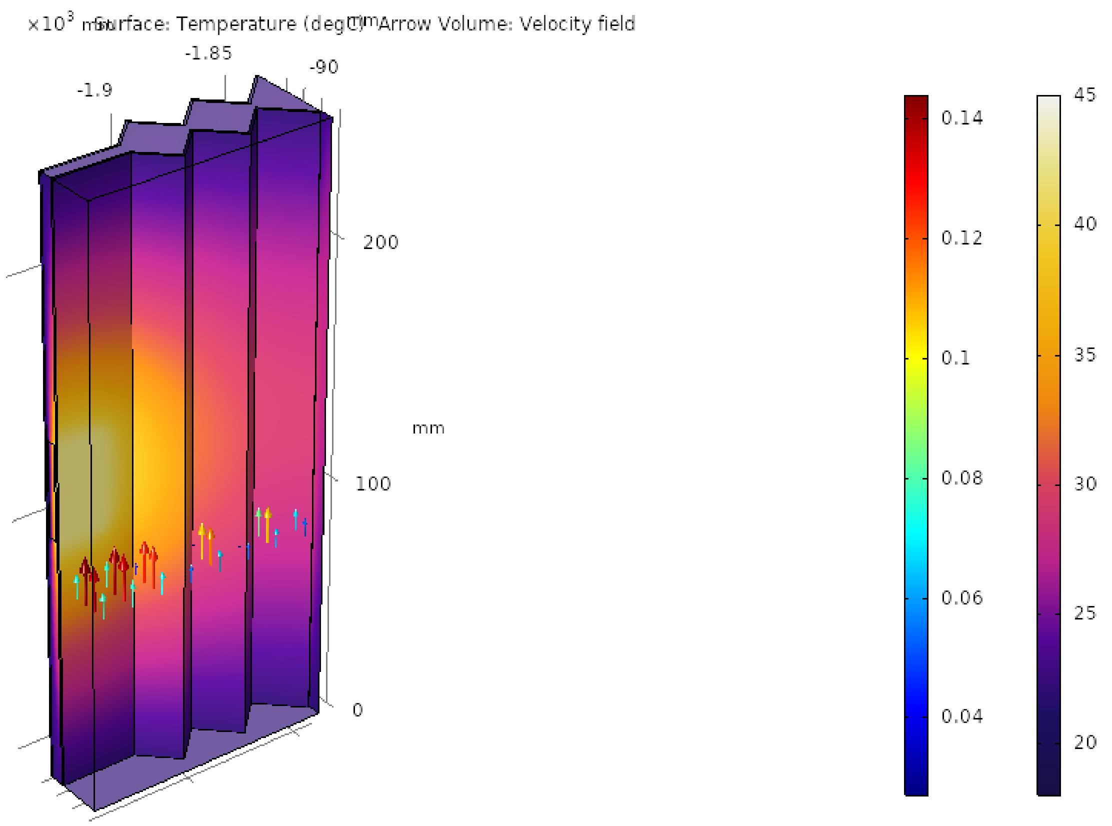


Figure 48.Basemodel for airflow simulations

D.2.2.2 Strategy 1: Thickness

Once the baseline simulation was finalized, the first design strategy was applied in the Mexican context. The simulations show that the cooling capacity is much higher with 10 mm, but not by much when compared with the thickness of 5mm. This shows that although there is an important impact of the thickness on the heat sink design, there is a point where this impact is lower, and it does not affect as much as initially. This factor was not visible on experiments (0.8 to 1mm), probably due to the small jump in the thickness applied. On the other hand, the last iteration, where a different thickness was used on the cold side, showed a COPc of 0.90, not higher than that with 5mm or 10 mm, but this was mostly due to the increase on the temperature difference between one side and the other, the cold side of the TEM reached 26 ˚C, whereas the hot side 49 ˚C, in comparison with 29.37 ˚C and 49.1 ˚C for the 5mm simulation. Even though, the 5 mm simulation model was chosen for the application of the following design strategies, the 1 & 5 mm will be kept as an alternative, since it shows desired TEM cold side temperatures.

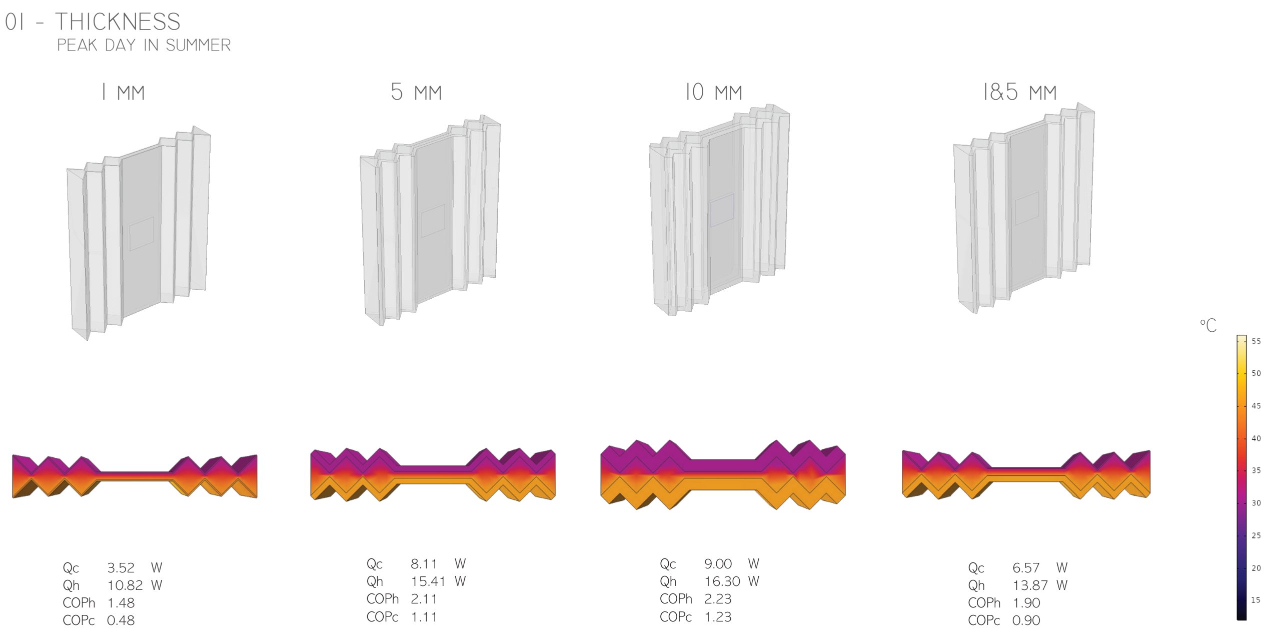


Figure 49.Strategy 1 thickness, simulation results

D.2.2.3 Strategy 2: Extended surface

The second strategy to implement in the heat dissipation design is surface augmentation through extended surface. This can be normally achieved through the addition of appendages to the prime surface such as fins, finned arrays or by the creation of channels, as it was mentioned in chapter B2. Taking a quick look into the heat transfer-rate equation explained by Bar-Cohen:

$$q = hS\theta \qquad (18)$$

The formula shows that for a specific rate of heat dissipation, q, the temperature difference is followed by the product of hS. This last product becomes increasingly important when designing a proper heat sink component, since normally the electronic element, in this case the TEM, is usually small, there is not much surface for heat dissipation. Increasing this product by increasing the heat transfer coefficient is not that easy, and a more practical way is by the extension of the surface.(Kraus & Bar-Cohen, 1995) Whilst the use of fins and channels does aid in the total heat dissipated, since they are not in direct contact to the prime surface, they do not perform as well, so this should still be taken into consideration for the analysis of the results in this strategy. The required thermal resistance between the ambient temperature and the component is calculated at 0.24 K/W, when the TEM temperature is 49.1˚C (from the results of strategy 1), this means that the product hS required so that the heat sink can at least have a similar temperature that of ambient, is around 4.16 W/K. When the simplified formula of the heat resistance a heat sink is one divided by the product of hS.

$$Rreq = 1/hS \qquad (19)$$

Following this simplified calculation shows that indeed, the actual heat sink surface is not enough for such a component, thus the results on the five simulations on the different shapes show how the overall performance of the system did increase when the surface area also increased. It should be noted still, that for a more accurate evaluation on the actual performance, a simulation with laminar flows will be conducted on the best result from this phase.

The COPc for Shape C is higher when compared to Shape B, and continues to increase until shape F, where it is slightly lower than that of shape E, since the cold side heat sink has a smaller size to that of the hot side of the system. On the cold side a better balance needs to be achieved, since shape D, with a smaller surface area reached a lower temperature, even thought it had a better COPc. Nonetheless, the temperature difference in all the tested shapes is still below the desired 20 ˚C, so this variation in size has the potential of being further studied.

On the other hand, there is also a limit in how much the surface can be increased and actually aid the system further, as it was mentioned, the prime surface area of contact impacts more the system, the farther away the channels, the less impact it has on the surface. Results from shape D, E and F gave major insights on how to proceed when doing the final simulations with laminar flow.

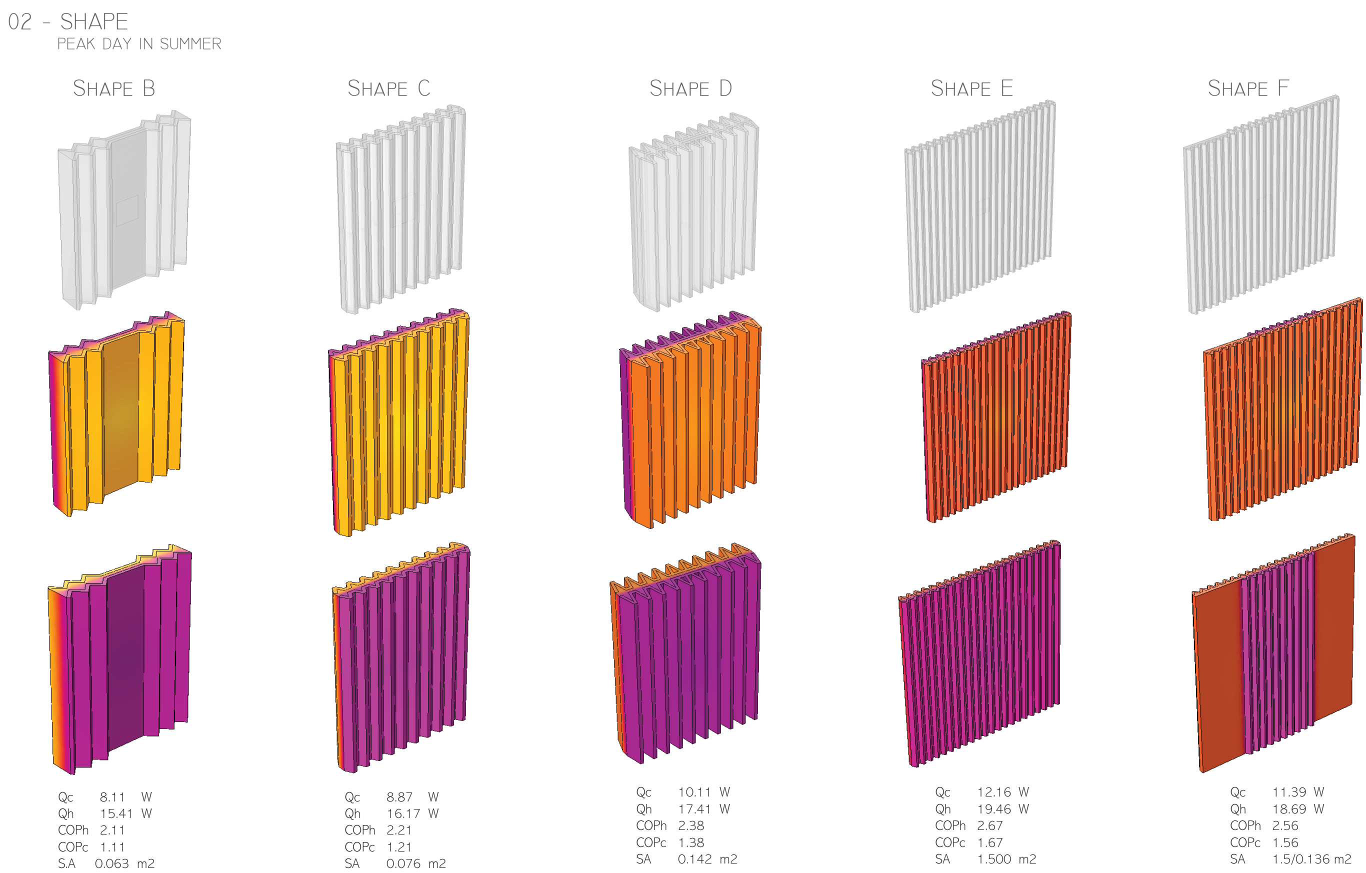


Figure 50.Strategy 2 extended surface, simulation results

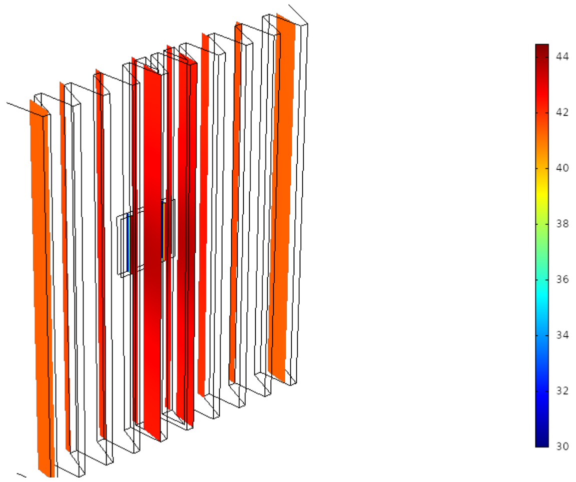


Figure 51.Shape D, temperature slices through the shape

D.2.2.4 Strategy 3: Material Exploration

The experiments and the first simulations conducted were done with aluminium as the component material, which is the most common material used for heat sinks. As it was found on the knowledge phase, cooper represents the optimum material, although aluminium still performs worse than the copper in terms of the area specific heat transfer at contact area, it works better when comparing their mass specific heat transfer, where material is "better" used when the heat sink channels are from aluminium. So, in terms of mass utilization, aluminium works much better. (Bar-Cohen & Rohsenow, 1984) Different configurations were tested, as it was mentioned on the methodology phase, to explore how the combination of different materials contributes to the performance of the component.

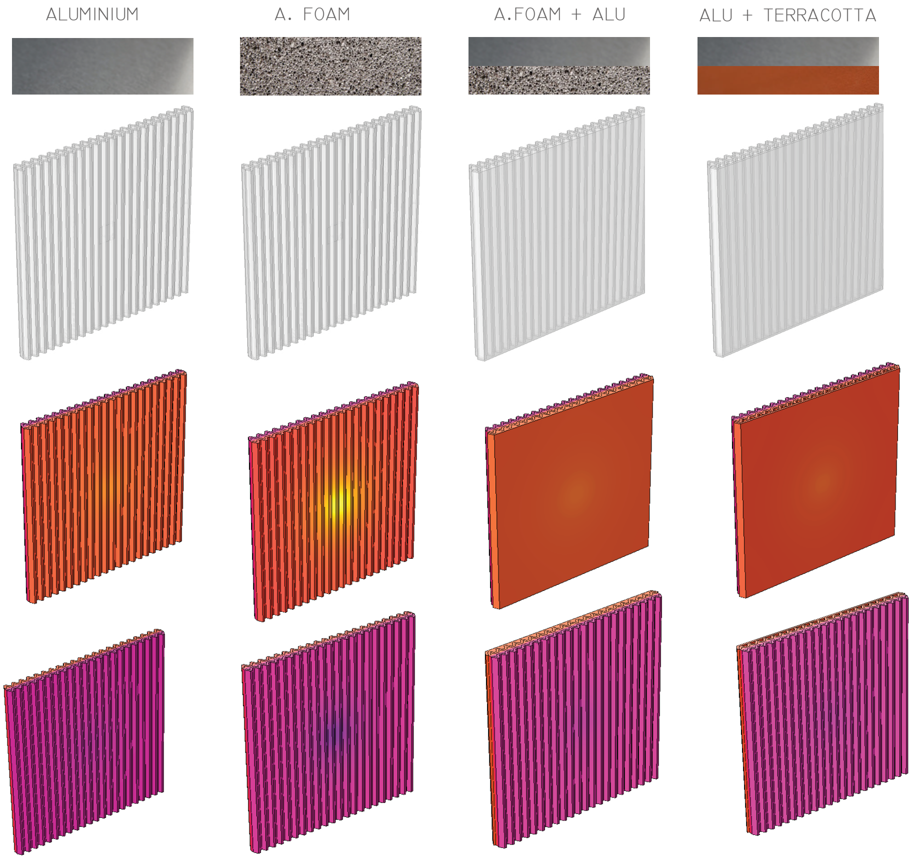
When exploring with aluminium foam as the heat sink material, the performance drops around 50%, the heat sink in the hot side reached up to 51.2 ˚C and the cold side a temperature of 26.8 ˚C. The thermal conductivity of Aluminium Foam is around 36 W/m2K and the COPc dropped around 0.9. Although this material is lighter, which could be an area of opportunity. Although its porosity is not tested here. It should be noted though, that the cold side did drop much more than with aluminium. When combining aluminium with aluminium foam as external cladding, the values remained almost the same, similarly with the addition of terracotta as exterior cladding in the last material iteration. Thus, when adding the Terracotta there was almost no change as with the values obtained in Aluminium. This suggests that since the Terracotta has almost no thermal conductivity it does not affect much on the heat transfer of the element, so long as there is some breathing space.

D.2.2.5 Strategy 4: Airflows

In the case of testing airflows, there were some differences when comparing results obtained when both are natural convection, versus both sides with upward forced convection of 3.0 m/s. With forced convection on both sides was applied, it showed the best COPc. Although, the results are slightly better for the cold side when there is forced convection there, and natural convection on the hot side since it reaches a lower temperature. From literature on façade concepts with this system it was expected that the variation in the air flows would have a stronger impact on the system component. The difference may be on that these simulations conducted on a relatively low capacity module, compared to some test done on elements that could reach higher values on the research papers. Even so, the maximum COP difference found by Cai et.al when comparing counter flow and parallel flow was that of 0.07, compared to the 0.03 found in this research.(Cai et al., 2019) In the diagram the direction of the flows and their velocity are evident, though the

03 - MATERIAL EXPLORATION

PEAK DAY IN SUMMER

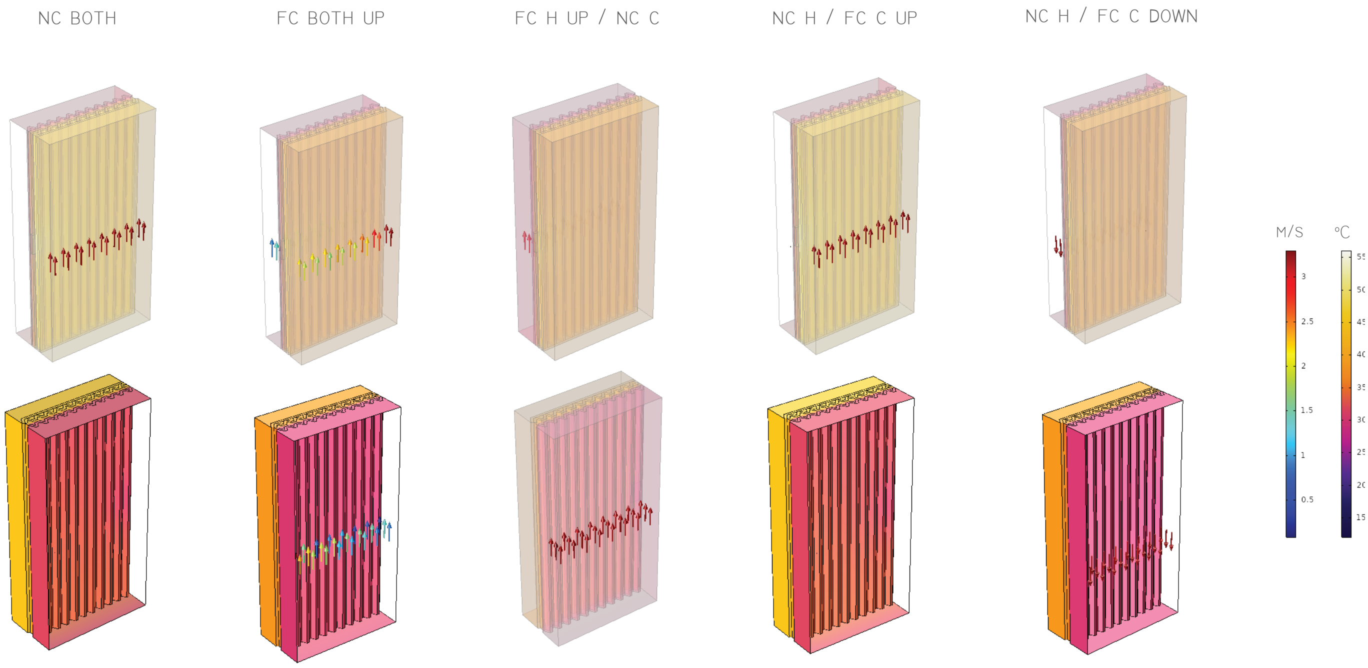


	ALUMINIUM	A. FOAM	A.FOAM + ALU	ALU + TERRACOTTA
Qc	12.16 W	5.70 W	12.08 W	12.16 W
Qh	19.46 W	13.00 W	19.38 W	19.46 W
COPh	2.67	1.78	2.65	2.67
COPc	1.67	0.78	1.65	1.67

Figure 52. Strategy 3 of material exploration, simulation results

04 - AIR FLOWS

PEAK DAY IN SUMMER



	NC BOTH	FC BOTH UP	FC H UP / NC C	NC H / FC C UP	NC H / FC C DOWN
Qc	11.87 W	12.09 W	11.96 W	12.00 W	11.74 W
Qh	19.17 W	19.39 W	19.26 W	19.30 W	19.04 W
COPh	2.63	2.66	2.64	2.64	2.61
COPc	1.63	1.66	1.64	1.64	1.61

Figure 53.Figure 53 Strategy 4 of ariflow exploration, simulation results

impact on the thermal performance is not as visible. A closer look was plotted where a plan view was used to observe more in detail how the airflow velocity changes throughout the heat sink.

Two different heat sinks were compared in order to observe the effect of the heat sink shape on the air flows adjacent to the element. One component is slightly more curved, whilst the other has a more dramatic change of direction. On the cold side of both elements, the channels did have lower velocities on the corners of the channels, and this is more evident on the squared element. On the other hand, in both situations the velocities were higher on the hot side of the element, which makes sense since hot air is less dense and gets an even stronger push by the heat being rejected by the hot side of the TEM. Though comparing the channels, the bottom

04 - AIR FLOWS CHANNELS
PEAK DAY IN SUMMER

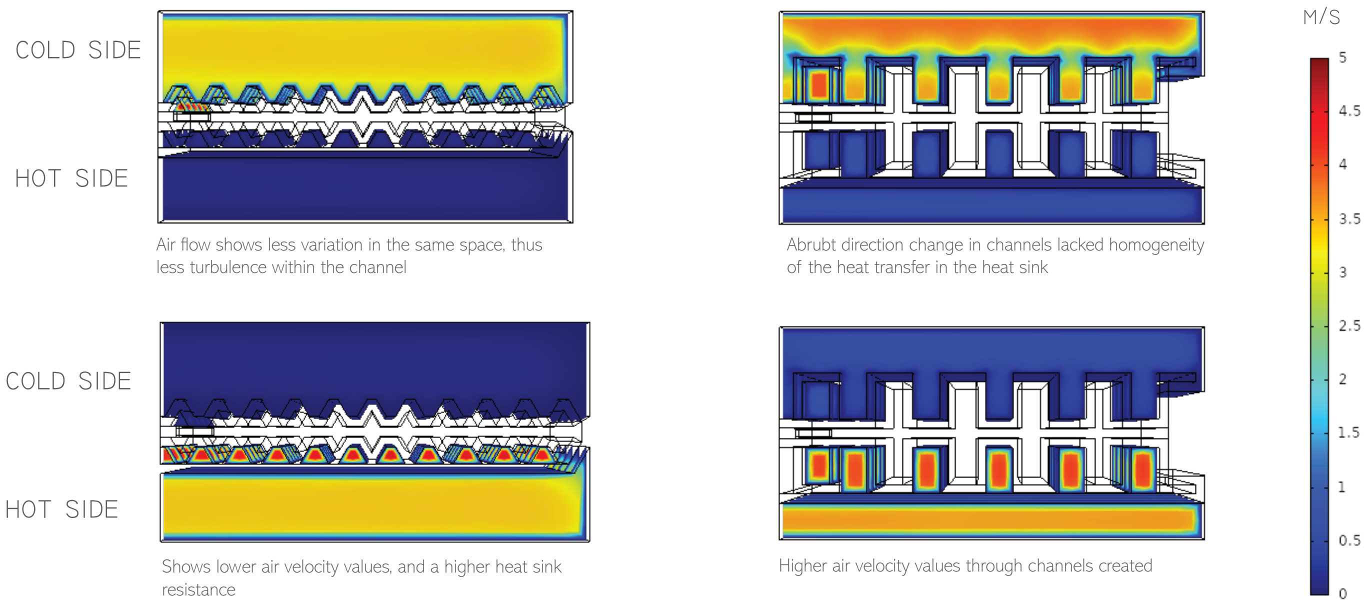


Figure 54.Airflow through channels

ones are "trapped" by the external cladding and the top one is not, they show a higher velocity than the input value of 3.0 m/s. Though in both tests, the corrugated with less abrupt direction changes had a more uniform air velocity and heat transfer. Several air flow velocities from 1.1 m/s to 5 m/s.

Although the simulations show a somewhat uniform temperature in the elements tested, the simulations were done on steady state, which doesn't show the progress in which the heat transfer from the source to the heat sink and how fast this progress could be with the aid of the air flows. In that sense, the simulations have this limitation. Nonetheless, with the simulation is it possible to analyse the effective area of the heat sink not only through the air velocity diagrams but also with the isosurface analysis. In the example shown the effective area reaches around halfway of the panel and seeing as there was not a big jump on the COPc after the panel surface double, it could be suggested that the heat transfer is limited to this area. Thus, two options arise, to further modify the shape to enhance the heat transfer coefficient by the corrugation of the panel and/or compact the panel size closer to the source as it was done with Shape D in strategy 2. Though this last option would mean having a smaller and a more intricate façade cladding system, but this will be further discussed on the analysis section.

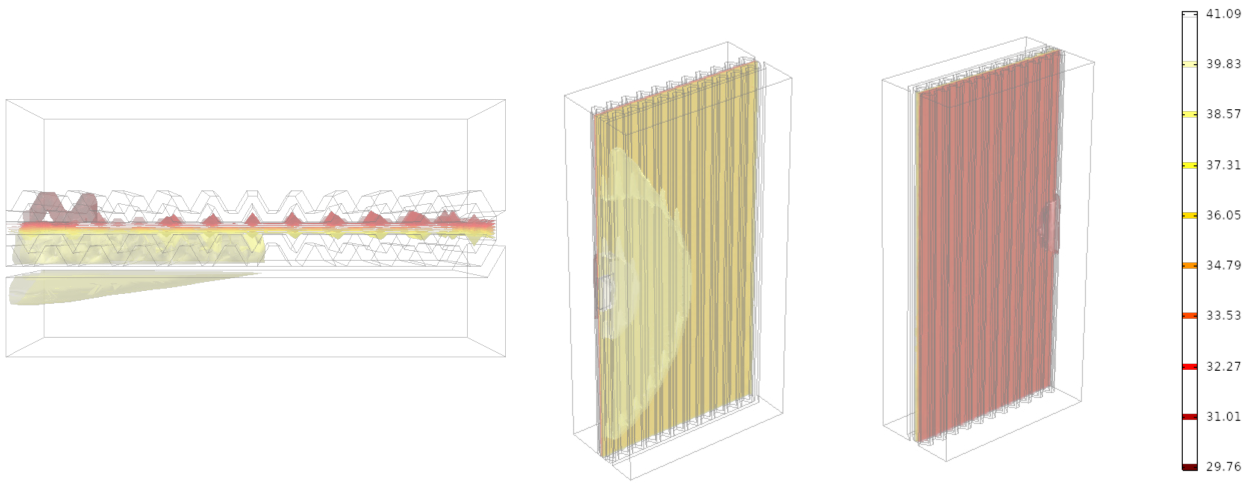


Figure 55.Isosurface of heat absorption and rejection through the heat sink

D.2.3 ANALYSIS OF RESULTS

In order to continue with the design at level B, an analysis and comparison on the impact of each strategies on the component level was conducted to observe patterns in the selected variables. It should be noted that the selection in each test was based on the context used for this study and could not be valid for other climate situations. Another thing to note is that the simulations shown were conducted for a specific peak time in the summer, so simulations representing other moments of the year should also be made to assess the overall performance of the final component. For all the decisions, the shapes chosen with the idea in mind that this will be part of a façade system and with a focus on the best performance, but personal taste could also have affected when selecting the best geometrical shape from the results.

Focusing on the stepped methodology used for the design strategies applied, the result from the studied strategy were influenced by the previous results obtained at a previous step. For the shape development, different variations could have resulted in different results, this could be seen in the variations at strategy 2, although the findings at the knowledge phase were used as major insights for these initial geometries. The ideal performing heat sinks tested by companies, have the disadvantage of being used for small scale components and not up-scaled for the façade, thus based on their suggestions but keeping in mind the needs of the façade, these different shapes were tested. On the other hand, the amount of shapes to test at design

	STRATEGY	00	01	02	02
INITIAL	Ambient Temperature	37.8	37.8	37.8	37.8
	Inside Temperature	30.0	30.0	30.0	30.0
	Paramenter	Baseline	Thickness	Shape	Area Surface
COMPARISON	HS Hot	56.46	46.51	42.07	41.57
	TEC H	55.86	49.08	44.14	41.40
	TEC C	27.30	29.37	28.60	30.09
	ΔT	28.56	19.71	15.54	11.31
	COPc	0.48	1.11	1.38	1.67
	Detail	-	5 mm	250x200/S.D	450x450/S.E
	Summary	-	130%	24%	21%

Table 14. Comparison Matrix of best results by simulations

strategy level could be much more, and a better iteration on how to acquire the best material usage versus surface area ratio could be develop so that this strategy lives up to its potential. In addition, the design strategies applied were based on what was observed on the research projects and literature, as it was previously mentioned.

Strategy 01: This strategy showed the greatest initial impact among all the strategies, and it can be attributed to the importance of having a proper base plate thickness for the heat sink component. The ideal thickness also depends on the magnitude of the heat source that needs to be dissipated, thought it reaches a limit as it was seen on the simulation with a higher thickness. In this case, even though the 10 mm thickness showed a better performance it was not by much, so the 5 mm thickness was chosen.

Strategy 02: On the second strategy several iterations were simulated, with variations on the channel types, variation on the compactness of the elements and exploration on both heat sinks having the same size versus different sizes on each side. The variations in shape showed that indeed it has the potential to be optimized to have a better performance, this was visible even in the experiments conducted at the beginning of this research project. The addition of channels does contribute, but further calculation on the perfect channel quantity versus channel depth would be interesting to explore further. On the other iterations, on compactness versus a larger surface, the value did get better, but there is also a limit in how much the surface can be increased and actually aid the system further, as it was mentioned, the prime surface area of contact impacts more the system, the farther away the channels, the less impact it has on the surface. A proper balance between the better performance shown with COP but also with the cold side reaching a lower value was desired. Thus, for the simulated path, the route of higher COP was used, with a larger component, the corrugated panel and both sides the same size.

Strategy 03: In the material explorations, there were not many options studied or that could be studied that had the desired thermal conductivity. Nonetheless, the combination of materials with the heat transfer was possible to simulate and observe if it had any positive or negative effect on the performance of the system. A higher thermal resistance on the heat sink showed better temperatures on the cold side of the system, so for aluminium foam was the best in that case. When testing material combinations the small aluminium plates that connect the heat sink to the TEM were changed to copper since they have a better heat transfer at contact area than that of the aluminium. The addition of cladding did not contribute negatively to the system, and the channels created were later observed on the air flow simulations, contribute to the heat transfer. Thus, this configuration was chosen, and the air flows tested on it.

STRATEGY	03	03	04	04	04
Ambient Temperature	37.8	37.8	37.8	37.8	37.8
Inside Temperature	30.0	30.0	30.0	30.0	30.0
Paramenter	Material	Material Combo	Airflows Base	Airflows	Airflows
HS Hot	41.57	41.57	**41.78**	41.15	41.41
TEC H	41.40	41.39	41.49	41.15	41.12
TEC C	30.09	30.07	29.60	29.73	29.53
ΔT	11.31	11.31	11.89	11.43	11.59
COPc	**1.67**	**1.67**	**1.63**	1.66	**1.64**
Detail	Aluminium	Alu + Terracotta	NC/S.E	FC/S.E	FC C/NC H, S.E
Summary	No Change	No Change	-	1.8%	0.61%

Table 15. Comparison Matrix of best results by simulations

Strategy 04: For the air flow simulations, the changes were not as dramatic as those observed at strategy 2, and the two best options were when both flows are forced and upward, and when the hot side has natural convection and the cold side has forced convection with an increase of only 0.01 in the COPc. Nonetheless, the temperature at the cold side did show better values when it had forced convection inside, and natural convection towards the hot side. In that sense, when the thermal resistance of the heat sink is higher, it contributes to a lower temperature, though a proper balance must be reached so that the system can still work and not overheat during the heating periods of the year. Finally, this counter ventilation was selected, and since the difference found with the addition of forced convection versus natural convection was minimal, natural convection on both sides was selected so as to achieve this desired balance. When taking into consideration the additional energy required and complexity to the system's maintenance when including fans to the configuration, the actual advantage in performance of the system might not be visible con adding these other factors to the evaluation.

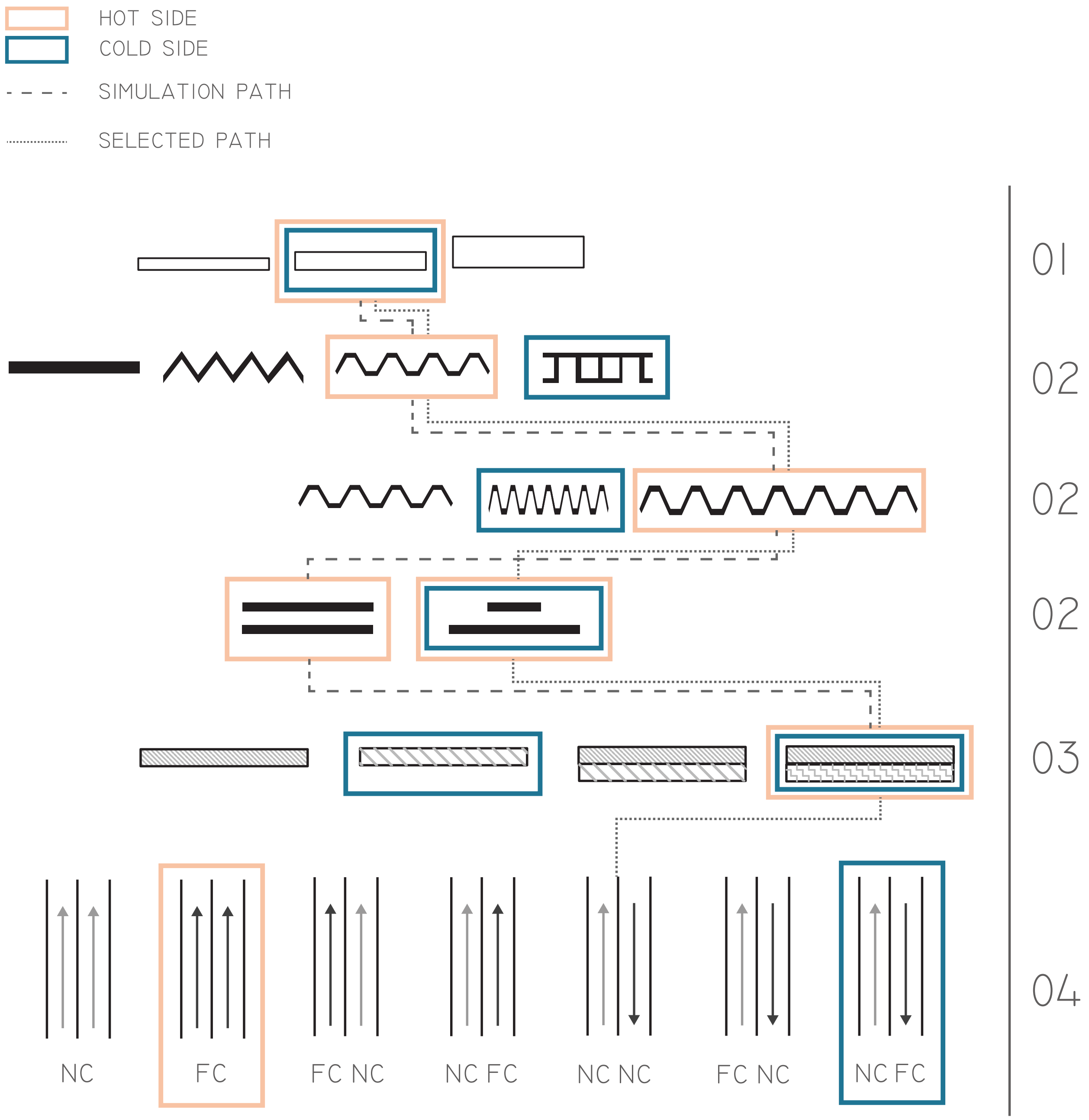


Figure 56.Simulation path and design path ilustrated

D.3 CONCLUSIONS

This chapter gave the overview on how the evaluation and assessment at level C was conducted in detail, to aid in the final design of the thermoelectrical integrated façade system. For each type of evaluation, their set-up, assumptions made, and the major limitations were also addressed. The experimental methodology had to be adjusted a few times due to the back and forth in the familiarization of the tools and the thermoelectric systems. The same happened with the methodology for the COMSOL simulations, familiarization with the software was crucial in order to have a clear idea on how the design strategies could be applied and then analysed. In this case, the much simpler model made necessary the use of Excel for the calculation of the COP of the heat dissipation system. A further development on programming the formulas within the software of COMSOL could be possible, to parametrize the variables and do simulations of various days of the year and for different TEC modules.

A series of experiments and simulations were done at level C of the research design, and even when different elements and strategies were applied and tested, several similarities or trends were observed. The decisions taken were based on results that were favourable for the system to perform better on in specific climatic context, thus this may not be the case when applied on other contexts. On the other hand, other decisions had the aid of previous literature research or suggestions found in the knowledge phase and then contributed on the path of the configuration selected. Although some patterns were visible on the simulations conducted, the shape and design iterations could be much larger, and a limitation was necessary for the further development of the façade system. Through the simulations and calculations the desired thermal resistance of the heat sink in the hot side was found to be at least 0.20 K/W and for the cold side of 1.0 K/W for the cold side, so that for both sides to reach the desired temperatures. This applied only when the TEM operates at a voltage of 5. When adding into the situation the ambient temperature of the summer, or the solar radiation, all these values get affected, and alter the effectivity of the hot side of the heat sink. Further development on the possible shape iterations could be done to achieve the desired heat transfer coefficient to obtain the desired balance when the plate is in contact with the surrounding air. The corrugation of the surface or the addition of channels as extension does contribute, but the simulations on the specific shapes tested showed improvement on the performance.

Furthermore, the simulations were able to show the degree in which each strategy affects or contributes the overall performance of the system and proved to be of aid in the decision-making process for the façade design. Still some assumptions had to be done based on the knowledge phase once we reached the level B of the design process.

E EVALUATION AT LEVEL A

CHAPTER OVERVIEW

This phase includes the experimental and computational process used to determine the effect of each design strategy on its performance as well as their evaluation at level A. The process is based on a stepped design methodology, in which each strategy is assessed and then the best result from each set of evaluations is further developed and tested. Design Builder was used to establish the different effects at the building level. The methodology is divided into four studies. Limitations at each one will be addressed. Each study will be described in detail, including simplification process, and main boundaries. In the evaluation phase, the design strategies defined on the previous chapters were analysed and their impact on the thermal performance of the system assessed. At level A, a comparison of the design strategies and their effect on the cooling demand of the office building will be discussed and the answer of the following sub question found: Which passive cooling strategies can be adopted to improve overall energy performance and lower cooling demands for hot arid climates? This phase will end with the design options for level B, based on findings from level A.

E.1 METHODOLOGY

Before the application of an active system for cooling a space, possibilities with passive strategies should be explored to lower the cooling loads of the case study. So, for the design of an optimised office space, a research on passive strategies is necessary. The existing benchmarks, regulations and some publications on passive strategies applied to buildings in hot dry climates will be looked upon and compared to the results obtained from the simulated case-study that will be further designed and optimised. It should be noted that due to the scope of this project the main priority will be on passive strategies that lower cooling loads rather than heating loads. Thus, the main objectives become:

- Reduce Peak Loads
- Reduce Cooling Consumption
- Arrive to recommended annual consumption (city-guidelines)

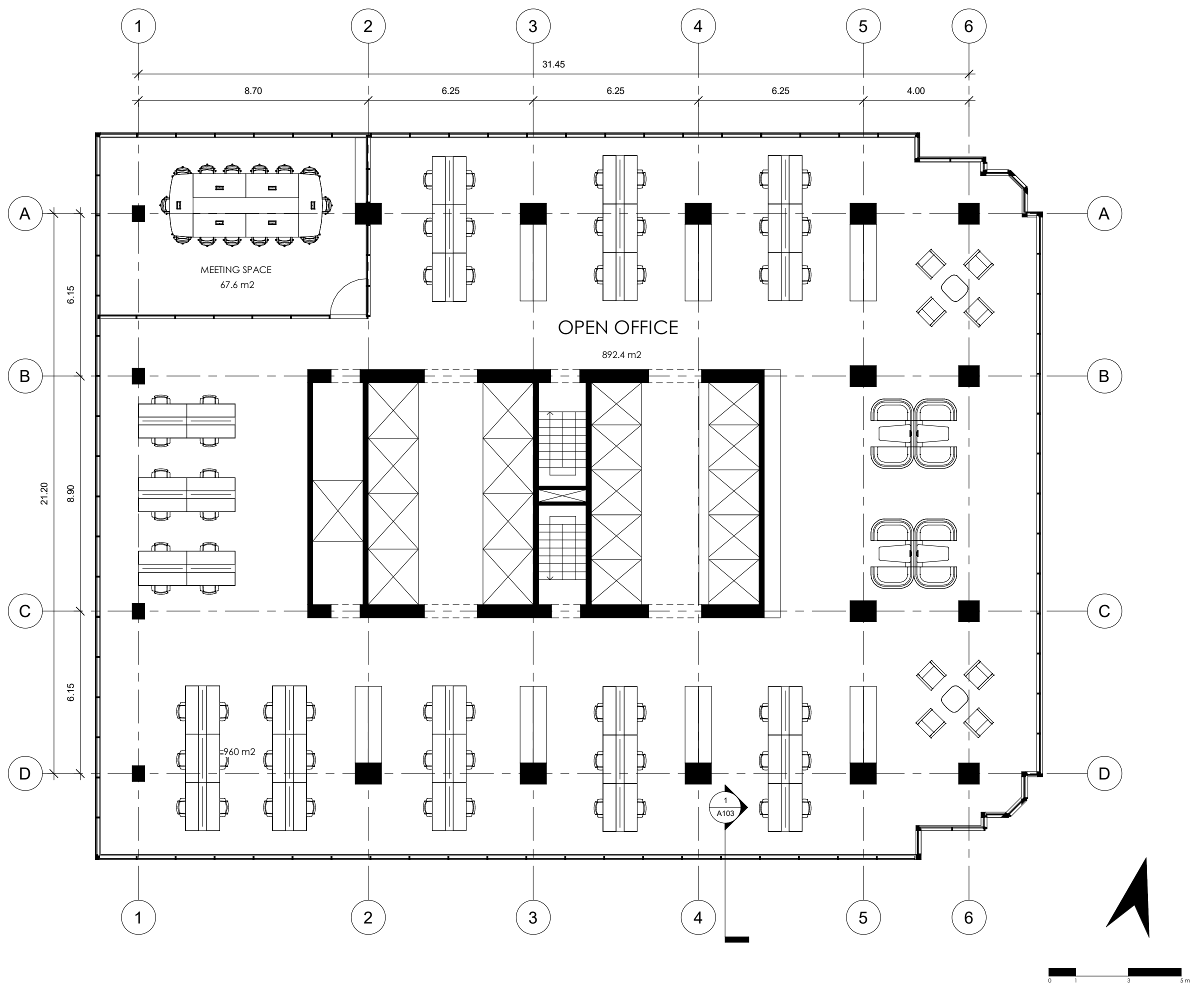


Figure 57.Koi Tower Open office, Type Floor. (redrawn by author)

E.1.1 EVALUATION PROCESS

The evaluation of the strategies will be conducted through an energy simulation software, to discuss and compare results in a controlled environment and accurately assess their impact on the cooling performance. The boundary conditions will be explained in the corresponding section.

Figure 58. Level A Design Process

E.1.2 SIMULATION SOFTWARE

The baseline model results were validated with hand calculations to make sure the initial model was correct before applying any design strategy. Design Builder v 5.5.02.007 for the interface of EnergyPlus v. 8.6.0.001. The base model done for the optimised design was derived from the case-study Koi Tower, were and open office floor was used for the simulations, see figure. For these simulations, the main focus was on the office area, thus the circulation part of the building was divided as a different room and turn adiabatic so that it does not affect the cooling demand of the building.

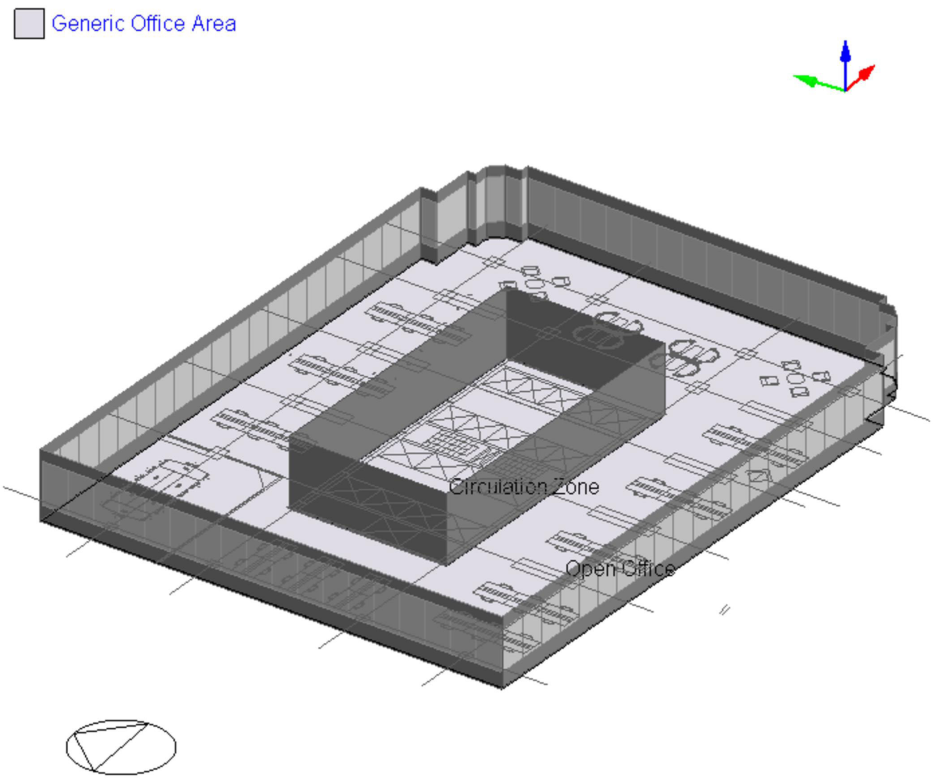


Figure 59.Baseline Design Builder Model – CaseStudy

Since the aim of these studies was to lower the cooling demands of the office building, the peak loads at a peak summer day were used as reference. In these case, July 12th was established as the reference point in the summer.

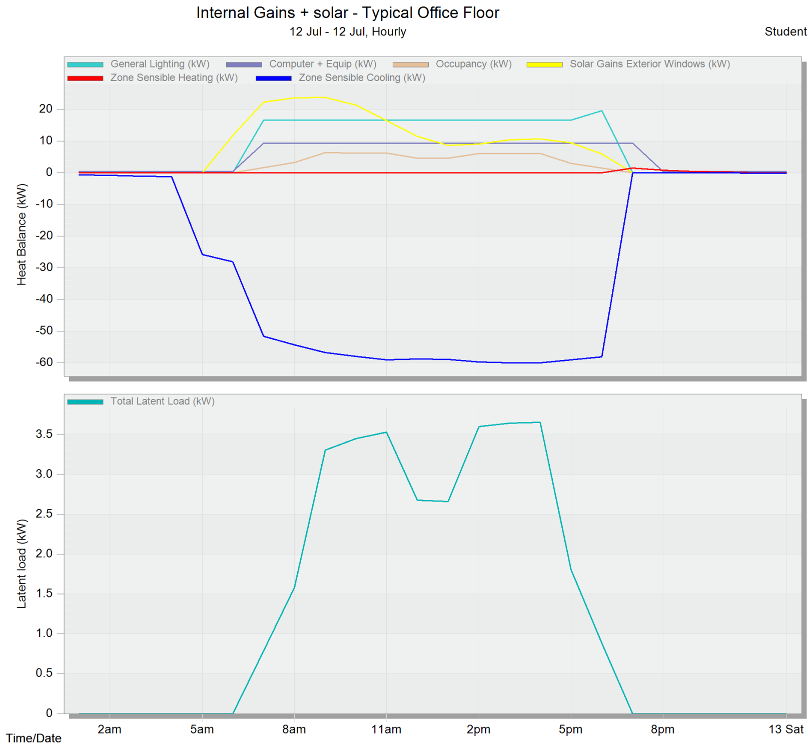


Figure 60.Internal Gains Summer day (July 12)

E.1.2.1 Construction

The façade is the same throughout the whole building and does not respond to any particular orientation. The following specifications will provide the building typology base study:

- The office is an open plan office 31m x 21m x 4.0 m.
- All façades are curtain wall system, (around 60% double clear glazed, 40% spandrel)
- The occupied hours are from Monday to Friday, from 8 am to 6pm.

For the construction of the building, only a typical floor plan was used as reference, though it should be noted that the building has different floor plans throughout, but for the scope of this research, the analysis of this floor should be sufficient. The façade system as it was mentioned, works the same on all directions. The layers on the spandrel areas consist of gypsum plaster towards the inside, 50 mm insulation, assumed EPS lightweight, since it is typically u sed in Mexico, double 3 mm glass sheets with a 13 mm air gap. The spandrel section corresponds to a U-value of 0.644 W/m2K, which is slightly lower than the suggested value of 0.768 W/m2k by the government guidelines found on literature review. As for the glazed area, double blue tinted glass with an air chamber of 13 mm with aluminium frame was used. The corresponding U-value for the glazed area is 1.772 W/m2K.

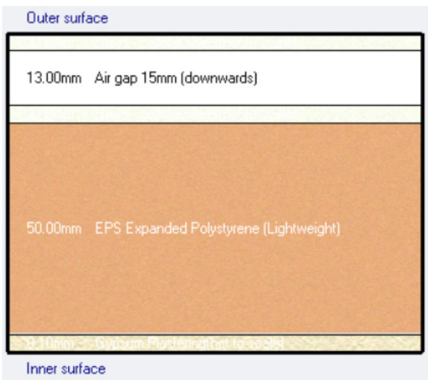


Figure 61.Spandrel construction layers on DesignBuilder

E.1.2.2 Activity and HVAC

As a base, the generic office area template was used and modified to meet the desired parameters for the case study. The heating setpoint value was used as 21.5 ˚C, and the cooling at 26 ˚C, both calculated from the adaptive model obtained at the knowledge phase. The occupancy schedule was modified from the template Office_OpenOff_Occ, to make sure that there was never a 0 on the schedule (no occupancy), which would result in poor air quality. As for the ventilation of the model, the mechanical ventilation was set to min fresh air per person as the definition method. For the cooling, a default system with a COP of 1.19 was used as base for the simulation model.

Area	Open office
Occupancy (people/m2)	0.111
Min. fresh air (L/s/person)	10
Office equipment power density (W/m2)	11.77
Lighting control	On
Target Illuminance (lux)	500
Office schedule	6 days/ week, 8-18

Table 16.Reference Values for office in Design Builder Software

E.1.2.3 Limitations

There are some limitations whilst using the software, especially when looking at the heating loads of the system. Since the equipment and lighting also generate excess heat, the software assumes this heat contributes to the heating of the building and thus, gives lower values for heating loads when taking into consideration the equipment and lighting. A sensible assessment should be made to determine the real heating load and the contribution of this extra factors. Another limitation found is that application of the type of cooling system on the simulation model. As part of the general methodology of the thesis, a final evaluation with DesignBuilder should be made to have the final performance of the design. This means, that a simplification of the system will be in order to simulate it on this platform.

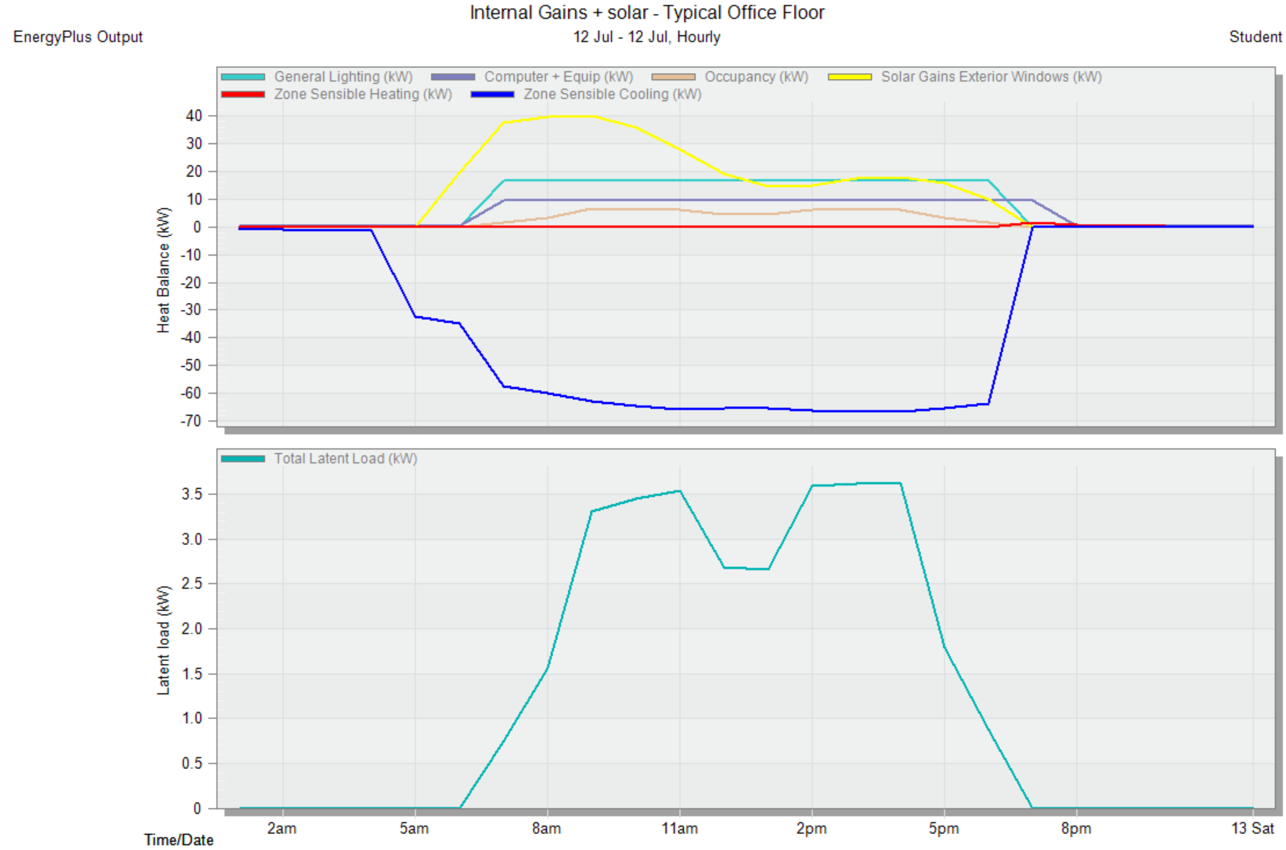
E.2 EVALUATION

The optimization stages will start from a base scenario, as described before and from there the strategies found will be applied one by one to weight its impact and feasibility. The order in which the parameters will be applied responds to the potential found by researchers and previous studies. For the analysis of each design strategy, they were all applied individually on the base case study and the results compared to find the best option for reduction on cooling loads for the office building.

00 BASE	01 WWR	02 INSULATON	03 GLASS TYPE	04 SHADING	05 VENTILATION
	20%	50 mm	Solarban 3mm clear	Exterior	Natural Ventilation
	30%	75 mm	Double, Low-e reflective coating	Interior	Night Ventilation
	40%	100 mm	Double Low- e tint		

Table 17.Simulation Stages at level A

E.2.1 BASELINE RESULTS



General Lighting (kW)	0.00	0.00	0.00	0.00	0.00	0.00	16.63	16.63	16.63	16.63	16.63	16.63
Computer + Equip (kW)	0.50	0.50	0.50	0.50	0.50	0.50	9.32	9.32	9.32	9.32	9.32	9.32
Occupancy (kW)	0.00	0.00	0.00	0.00	0.00	0.00	1.69	3.30	6.42	6.28	6.19	4.61
Solar Gains Exterior Windows (kW)	0.00	0.00	0.00	0.00	0.00	19.63	37.41	39.64	39.93	35.74	27.73	19.28
Zone Sensible Heating (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zone Sensible Cooling (kW)	-0.72	-0.98	-1.22	-1.32	-32.16	-34.76	-57.58	-60.08	-62.89	-64.57	-65.75	-65.44
Total Latent Load (kW)	0.00	0.00	0.00	0.00	0.00	0.00	0.75	1.56	3.31	3.45	3.54	2.69

General Lighting (kW)	16.63	16.63	16.63	16.63	16.63	16.63	0.00	0.00	0.00	0.00	0.00	0.00
Computer + Equip (kW)	9.32	9.32	9.32	9.32	9.32	9.32	9.32	0.50	0.50	0.50	0.50	0.50
Occupancy (kW)	4.63	6.14	6.10	6.09	3.07	1.55	0.00	0.00	0.00	0.00	0.00	0.00
Solar Gains Exterior Windows (kW)	14.51	15.14	17.37	17.86	15.99	9.92	0.04	0.00	0.00	0.00	0.00	0.00
Zone Sensible Heating (kW)	0.00	0.00	0.00	0.00	0.00	0.00	1.40	0.68	0.34	0.16	0.00	0.00
Zone Sensible Cooling (kW)	-65.52	-66.22	-66.49	-66.43	-65.34	-63.76	0.00	0.00	0.00	0.00	-0.15	-0.26
Total Latent Load (kW)	2.66	3.59	3.63	3.64	1.80	0.88	0.00	0.00	0.00	0.00	0.00	0.00

Graph 14.Results obtained by Baseline model in Design Builder

E.2.2 RESULTS VALIDATION

The validation of the simulation was done with steady-state hand calculations at 2:00 pm the 12 of July and compared to the results obtained with Design Builder. Adding all the calculated heat loads before amounts for the total cooling load required by one floor of the office tower.

$$Q_{cooling} = Q_{transmission} + Q_{infiltration} + Q_{ventilation} + Q_{sun} + Q_{internal} \quad (20)$$

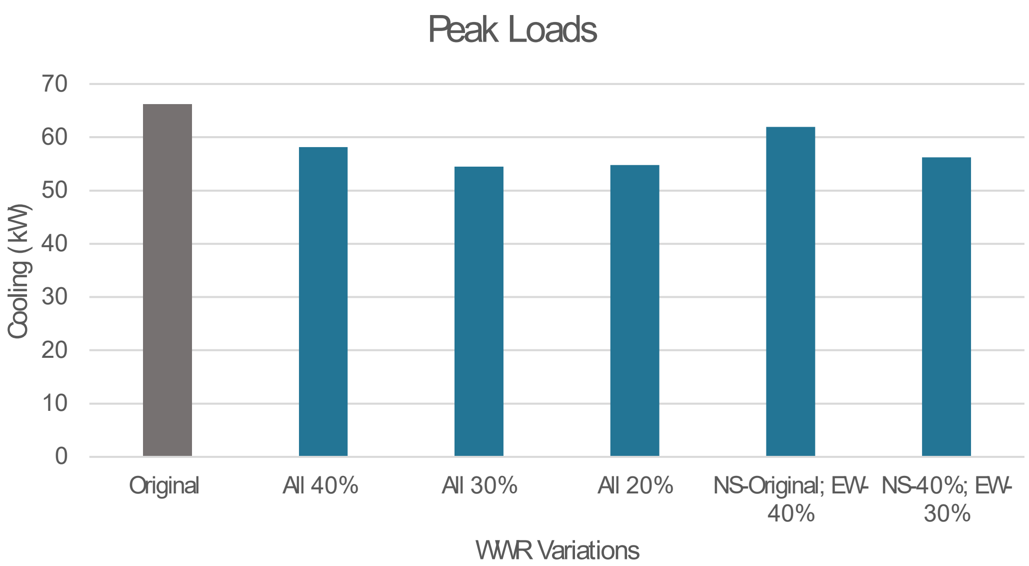
The total cooling is 63.68 kW at 2 P.M., 12th of July. The simulation shows a sensible cooling load of 66.22 kW, which is somewhat higher than the hand calculated results. The biggest difference was found on the heat due to lighting, which was much lower on simulations, but since the light control was on, it could be assumed that not much light is needed in that period of time due to the natural light coming from the windows, and so a lesser value was calculated by the system. For the complete calculation process of the cooling load please refer to appendix I.2.

E.2.3 STRATEGY 1: WINDOW TO WALL RATIO

The first hypothesis regarding the WWR for this office building is that it will have an important impact on the total cooling loads, especially since the complete façade is composed of glazing system, which has a high effect in the summer to the comfort conditions. The percentage of glass area is around 62.5% and the rest is spandrel system in the original office building. According to the ASHRAE, for hot dry climates such as Monterrey, WWR from 20% to 40% are recommended.

(ASHRAE, 2011)In consequence, WWR of 20%, 30% and 40% will be simulated and compared with the original model. Nonetheless, it is important to consider the lighting requirements, if the WWR is reduced too much, the potential of having natural light is also reduced, thus increasing the energy required for artificial light.

Another recommendation by the guidelines is that the most area of windows faced south and north, since solar control is more effective in these two orientations than in the east and west orientations of the building. On the other hand, the aesthetical aspect of the building is of uniformity along all the façades, so a balance between all these aspects should be met.
As it was predicted the highest decrease in the cooling loads comes from the WWR of 20%,



Graph 15.Results in cooling loads compared to the case-study with the WWR variations.

nonetheless daylight should also be considered, and the possibility of combining this strategy with others could result in similar values without compromising natural light, so that the increase in energy usage due to lighting does not increase as much. Such is the case of lowering the ratio for west and east orientations, adding proper shading systems to the south façade, and allowing the north façade to get most of the natural light.

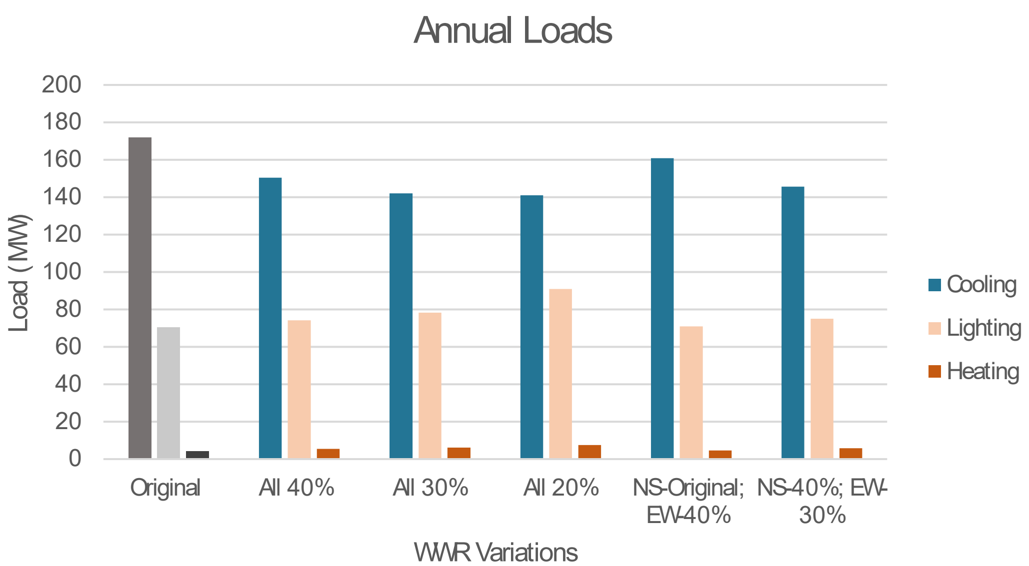
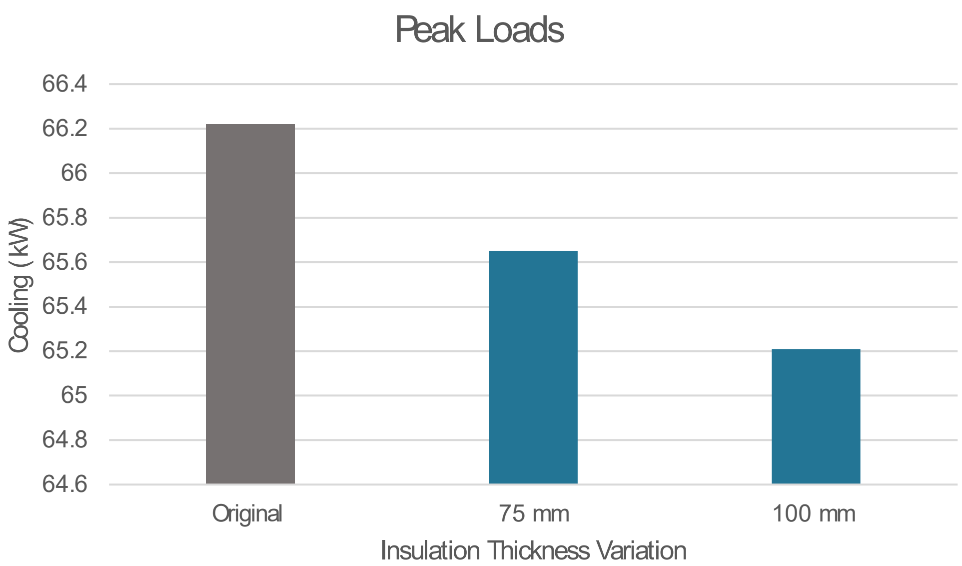


Figure 62.Annual results from simulations in DesignBuilder

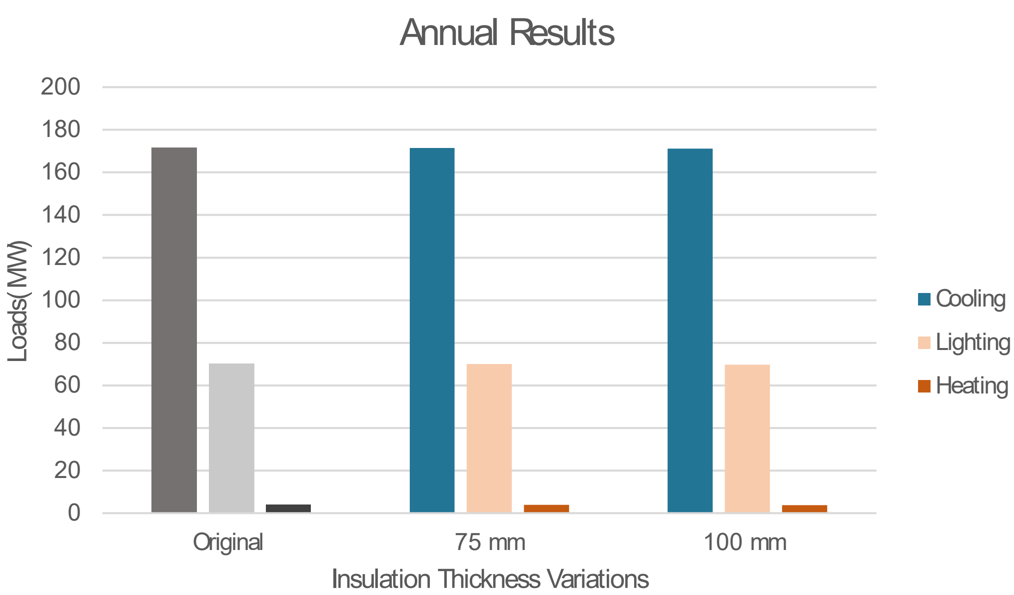
E.2.4 STRATEGY 2: INSULATION

The second strategy to be tested was insulation. Around 62.5% of the façade is clear glass with no insulation material but the resting 37.5% has spandrel panels that have 50 mm of insulation material. Research on the impact of insulation material on hot dry climates suggests that thicknesses of above 50 mm and its location (towards the inside or the outside) should benefit more the energy and thermal performance of the building. (Saleh, 1990) Thus, the application of the insulation with two different thicknesses besides the original were tested, 75 mm and 100 mm of rigid extruded polystyrene foam which is common in Mexico. The location will not me explored in this stage since input on its location was given at level C.



Graph 16.Results in cooling loads compared to the case-study with insulations thickness variation

The different variations of thickness explored showed a small decrease on the total cooling loads of the building but not enough to make a proper impact. Similar observations can be made from the annual cooling loads.



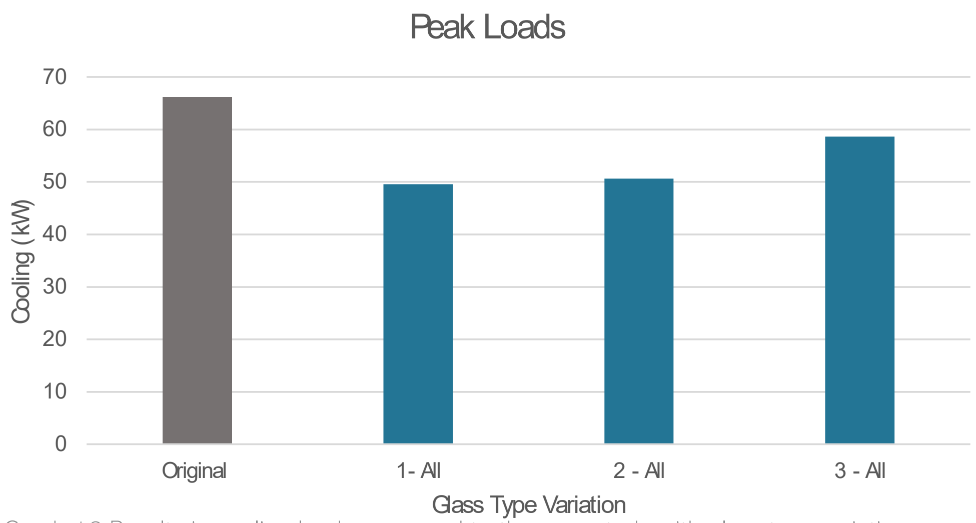
Graph 17.Annual results from simulations with insulation in DesignBuilder.

E.2.5 STRATEGY 3: GLAZING TYPE

As for the glazing types to compare, there are many options to choose from, for this reason a selection of a few variations was selected from those available in Mexico and the recommendations from the ASHRAE for cities climate zone type 3.

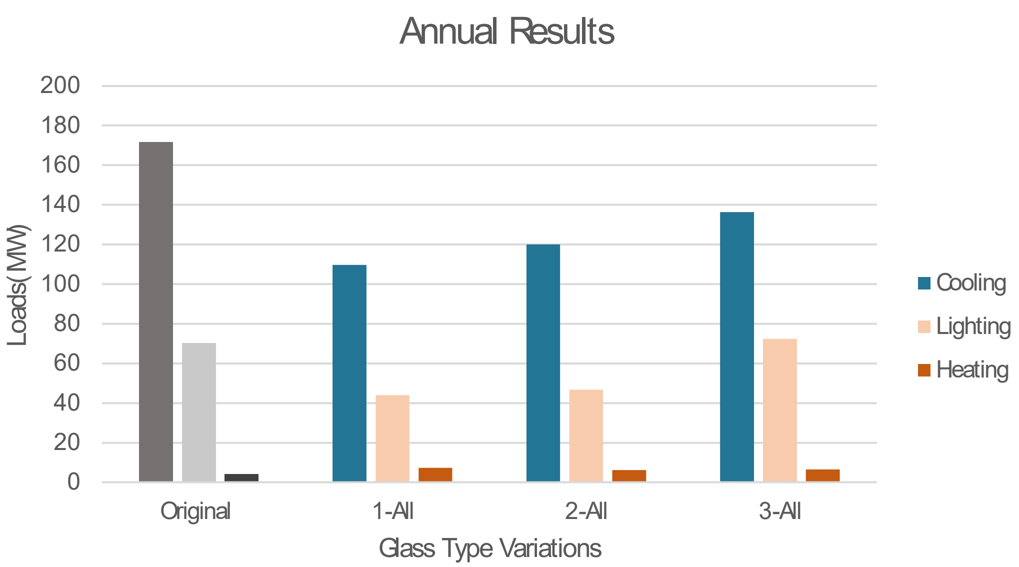
Type	U-Value	SHGC	VT	Glass and Coating	Gas	Spacer	Frame	Mexican Brand
1	1.63	0.22	0.52	Double Clear. Low-e coating	Air 13 mm	Standard	Broken Aluminium	VitroGlazing
2	1.49	0.364	0.28	Double Clear. Low-e reflective coating	Argon 13 mm	Standard	Broken Aluminium	VitroGlazing
3	1.33	0.25	0.48	Double Clear. Low-e coating	Argon 13 mm	Standard	Broken Aluminium	VitroGlazing

Table 18.Types of Glazing used for the simulation



Graph 18.Results in cooling loads compared to the case-study with glass type variation

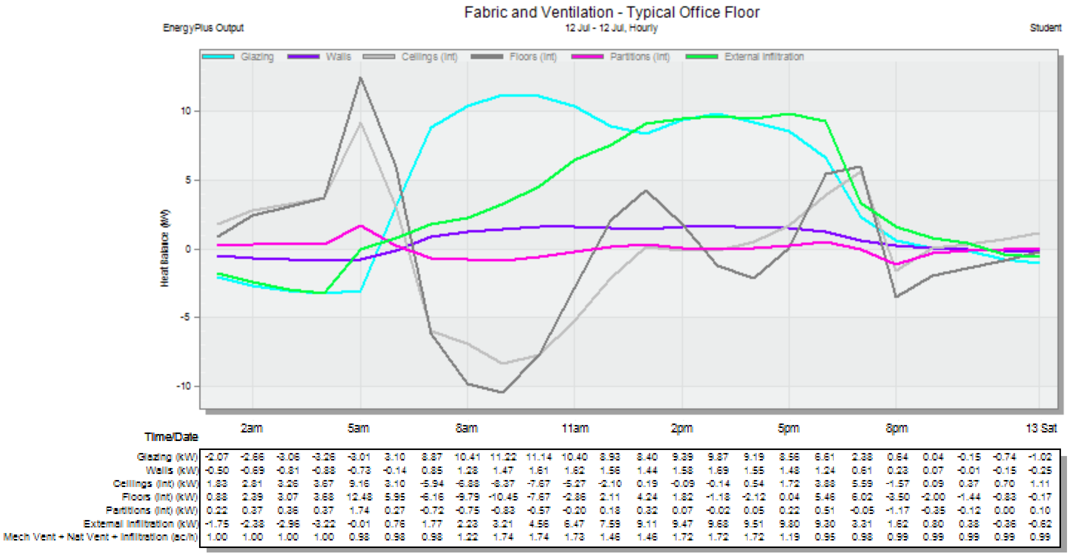
The configuration that lowered the loads the most was type, with the lowest SHGC factor. When applying the variation of glass to all the glazing of the façade the cooling loads lowered around 25%. Although it should be noted that the application of a better type of glazing on the façade orientations that are more vulnerable to solar exposure can lower the cooling loads around 15%.



Graph 19.Annual results from simulations with glass type in DesignBuilder

E.2.6 STRATEGY 4: SHADING

The existing office tower has no shading system to protect itself from the solar rays, and as it can be seen in the Design Builder graphic of the base case, most of the heat gain from the glazing occurs in the afternoon, which was inferred from previous strategies tested. Although with other strategies applied this excess load could also be lowered, a simulation with a proper shading system on the west façade will be explored to see the extend in which it lowers the cooling loads compared to only changing glazing type or having a different WWR.



Graph 20.DesignBuilder simulation results for the peak loads at zone level

A small radiation analysis on the case study was conducted, since there are some tall buildings surrounding it that could also affect the total radiation on the façade. The façades facing the east and south had the most radiation through the year, nonetheless on summer peaks, most of the heat gains come in the afternoon from the west façade. As it was mentioned before, a controllable shading system for the east and west façades is sometimes more complex, so tests will be done for the south façade.

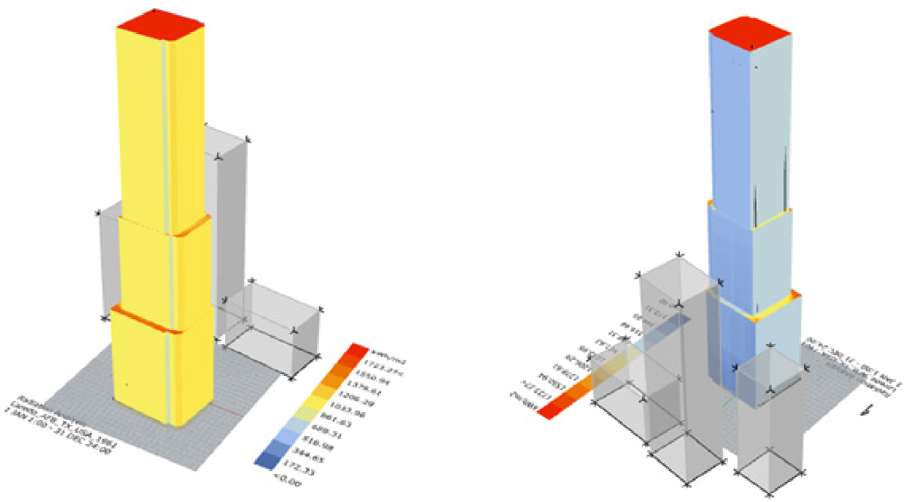
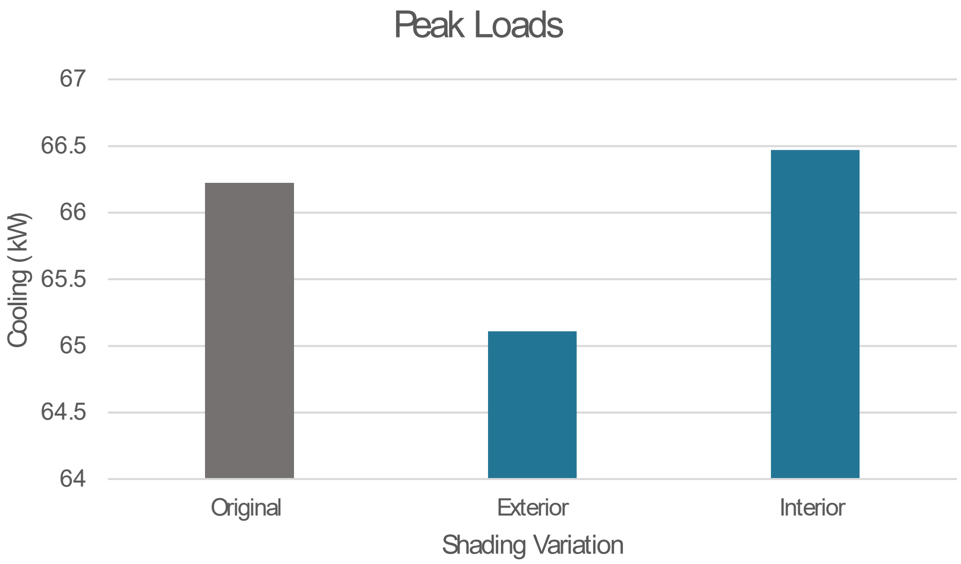
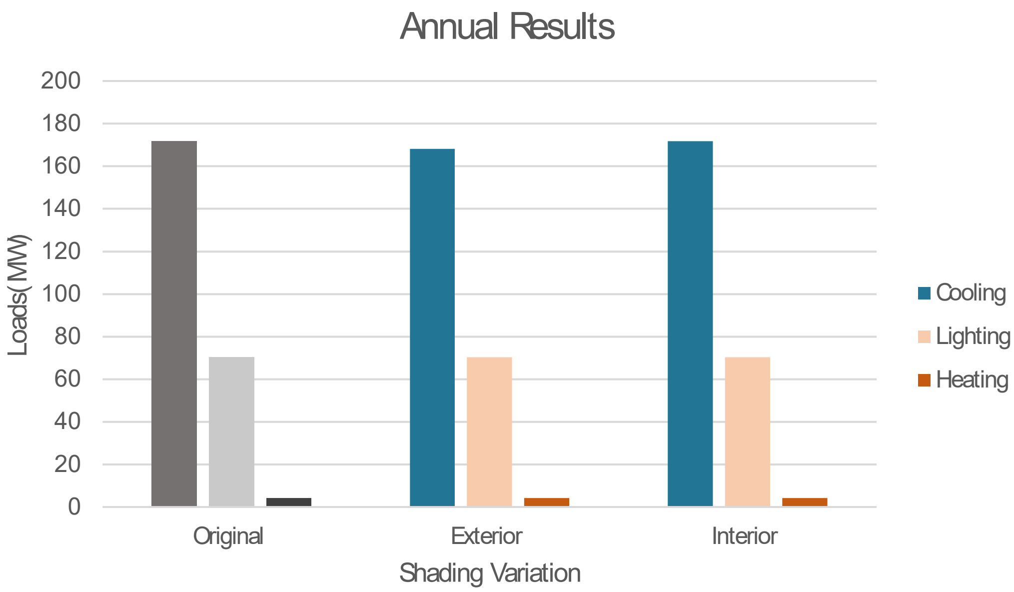


Figure 63.Simplified Radiation analysis of complete year, left: Southeast view; right: Northwest

From the different types of shading systems studied in the knowledge phase, three different options will be simulated and compared. Although studies prove that exterior shading is the most efficient for energy saving, tests with interior controllable and intra-windowpane controllable will also be made. The idea is to compare the results with the best possible one, since applying external controllable for such a tall building will be harder to maintain and will also give it a bulky appearance. Also, since this project is searching to apply the TEC system, could it be possible to have a less complex system? Adding external controllable shading to the south façade did lowered the overall cooling loads but it was less than expected.



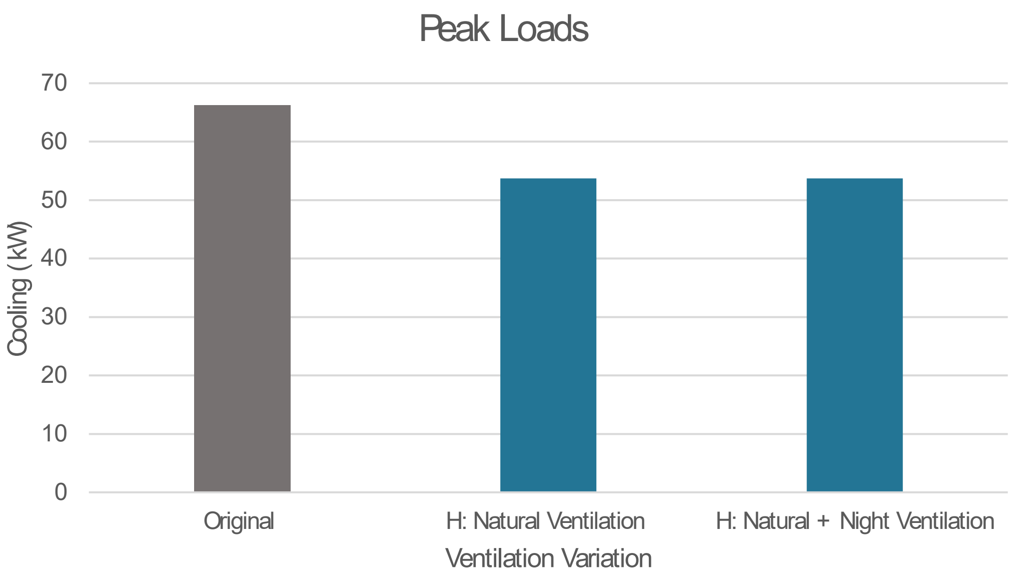
Graph 21.Results in cooling loads compared to the case-study with shading variation



Graph 22.Annual results from simulations with shading in DesignBuilder

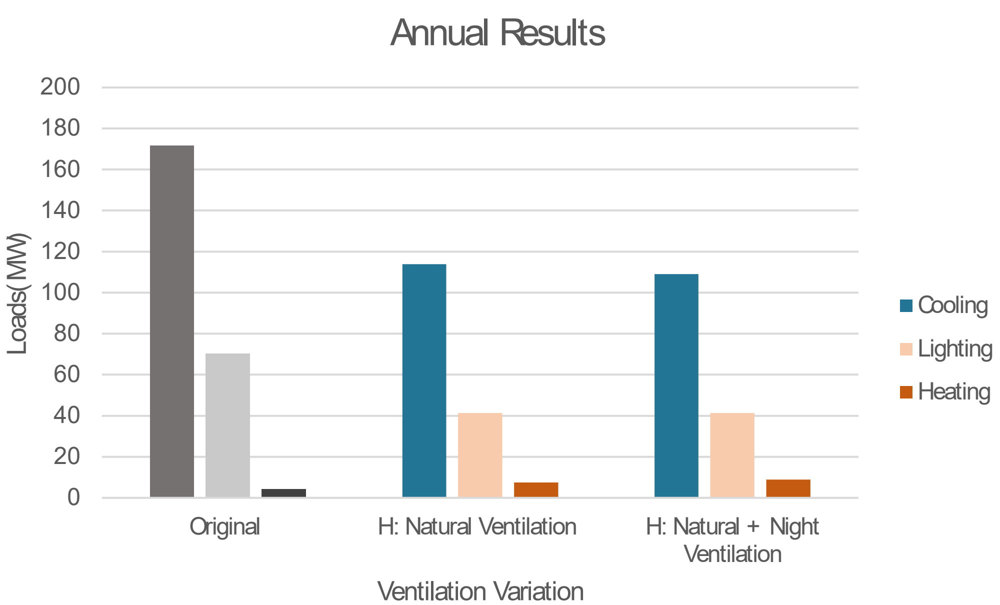
E.2.7 STRATEGY 5: VENTILATION

As it was mentioned on the knowledge phase, a proper ventilation system could amount to high energy savings in the building, thus a few strategies will be tested to assess which makes sense to apply on the office building. The case-study as it is right now using mechanical ventilation with the minimal rate of 10.0 L/s/person. The ventilation strategies to test are the possibility of natural ventilation, and night ventilation, all in combination with the base cooling system. Although studies in desert like cities show saving percentages up to 79% with a proper strategy also with high thermal mass, the city of Monterrey has different construction tendencies, and the results might differ to studies due to this.



Graph 23.Results in cooling loads compared to the case-study with ventilation variation

Observing the implementation of natural ventilation and night ventilation during peak loads in the summer, the decrease is of around 4kWh, a more evident decrease is shown on the annual saving when applying these strategies. For natural ventilation hybrid mode, there were savings of 18% compared to the base case, and the inclusion of night ventilation showed similar saving during summer but up to 36% in annual saving, also considering the change in heat loads for both scenarios.



Graph 24.Annual results from simulations with ventilation in DesignBuilder

E.2.8 CHOSEN STRATEGIES

For each strategy, an evaluation of the overall energy savings was done, so that the best scenario could be chosen and later combined. In strategy 1, the chosen scenario was that of north and south façade with a WWR of 0.62 and 0.40 for the west and east façades. Although this is not the scenario with the highest savings, it was chosen since it is very close to the ideal one, with the added advantage of allowing a higher ratio for the south and north façades, but also does not increase the heating and lighting loads as much as the other scenarios. This also gives the possibility of maintaining the aesthetics that the architect envisioned.

Strategy 1: WWR				
	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Lighting Load (kWh/m2)	Savings (%)
Baseline	217.13	5.26	88.85	
WWR 40%	190.18	6.80	93.79	6.6%
WWR 30%	179.62	7.83	98.95	8.0%
WWR 20%	178.34	9.51	115.02	2.7%
NS-Baseline; EW-40%	203.36	5.71	89.56	4.0%
NS-40%; EW-30%	184.13	7.18	94.91	8.0%

Table 19. Overall Energy savings on strategy 1

On the second design strategy, the different insulation thickness did not show much change in energy savings, the highest being of 0.6% with the 100 mm thickness. For this reason, the original thickness of 50 mm was chosen for the passive design. The application of insulation on cooling dominant climate could be counterproductive on the summer, where the undesired heat should be easier to leave the building instead of being trapped inside.

Strategy 2: Insulation				
	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Lighting Load (kWh/m2)	Savings (%)
Baseline	217.13	5.26	88.85	
75 mm	216.85	4.97	88.51	0.3%
100 mm	216.35	4.79	88.14	0.6%

Table 20. Overall energy savings on strategy 2

As for the energy savings on strategy 3, they all showed a great improvement on the cooling loads, specially type 1, double clear, low-e coating with 13 mm of air in between. It is worth noting that the application of a different glazing type on only the east and west façades amounts for 21% of savings, compared to the 34% when applied to all the façades, which gives evidence that most of the solar radiation from the morning and afternoon contribute substantially to the cooling loads of the building.

Strategy 3: Glass Type				
	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Lighting Load (kWh/m2)	Savings (%)
Baseline	217.13	5.26	88.85	
1-All	138.63	9.24	55.59	34.6%
2-All	151.66	7.80	58.96	29.8%
3-All	172.31	8.29	91.49	12.6%

Table 21.Overall energy savings on strategy 3

In the fourth strategy, the highest percentage in savings goes to the exterior shading on the south façade, which was to be expected. Nonetheless, the difference between shading on the interior or exterior is not much, only around 1.4% lower for the exterior shading, and the interior actually contributed to more cooling loads. Since a dynamic exterior shading system will require much more maintenance for it to operate accordingly and could also be more costly, the chosen shading system was applying fixed exterior shading system in the south façade, mid-pane medium reflective blinds.

Strategy 4 Shading				
	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Lighting Load (kWh/m2)	Savings (%)
Baseline	217.13	5.26	88.85	
Exterior South	212.63	5.28	88.85	1.4%
Interior South	217.23	5.27	88.85	-0.04%

Figure 64.Overall energy savings on strategy 4

The last strategy evaluated was the addition of natural ventilation. The chosen scenario was that of hybrid system of natural ventilation with night cooling when possible. A scenario with no cooling and only natural ventilation was also explored, and although the loads were much lower, the comfort levels inside the building were not the desired, thus this was discarded and only hybrid situations were simulated.

Strategy 5 Ventilation				
	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Lighting Load (kWh/m2)	Savings (%)
Baseline	217.13	5.26	88.85	
Hybrid Natural Ventilation	144.01	9.52	52.28	33.9%
Hybrid Natural and Night Ventilation	137.76	11.18	52.28	35.4%

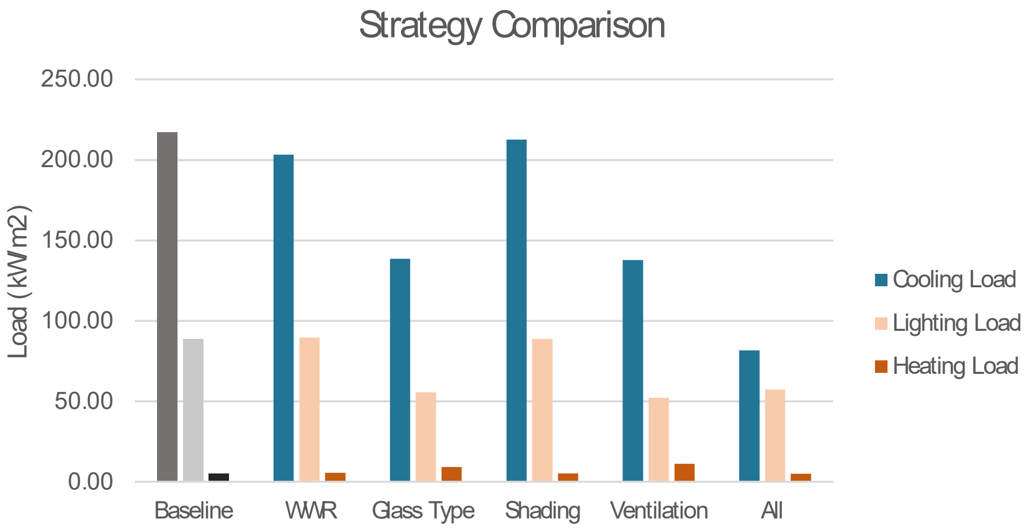
Table 22.Overall energy savings on strategy 5

E.3.9 COMBINED STRATEGIES

The last step on level A, was comparing the chosen scenarios on each strategy including one with all the strategies together. In this case, the best scenario happens when all the strategies are applied to the design, and since none of the strategies affect each other this works.

Strategy comparison				
	Cooling Load (kWh/m2)	Heating Load (kWh/m2)	Lighting Load (kWh/m2)	% Savings
Baseline	217.13	5.26	88.85	
WWR	203.36	5.71	89.56	4%
Glass Type	138.63	9.24	55.59	35%
Shading	212.63	5.28	88.85	1%
Ventilation	137.76	11.18	52.28	35%
All	81.70	5.14	57.35	53.7%

Table 23.Overall energy savings per chosen strategy



Graph 25. Strategy Comparison

E.3 CONCLUSIONS

The application of the all the strategies chosen was the final chosen path for the design at level A, office building. In this case, some the expected outcomes from the knowledge phase did contribute as expected, but others contributed to saving much less than expected, such as is the case with shading and the insulation design strategies. Nonetheless, the glass type and ventilation system chosen did contribute substantially to further savings on the building. It is important to note that although it was also expected that the WWR would contribute importantly to savings, the original design although mostly glazing, it had spandrel panels, contributing to a 0.62 WWR, and thus the gains from lowering this ratio aren't as visible as if the design had 100% clear glazing. Another element that needs to be addressed is the external shading system, which does contribute to energy savings but only by 1.4%. The original design had fixed horizontal shading overhang in the concept design but was discarded once the construction of the building started. Nonetheless, the results at this evaluation stage will contribute to the final design at façade level B.

On the simulations conducted with DesignBuilder for level A, the weather file used had data from 2001 as the earliest. For this reason, there is the possibility of differences on the results with the reality in the studied context. As for level B, the evaluation conducted will be based on previous façade concepts studied, finding on the other levels and an evaluation score system on façade integration. Although no detailed simulations will be conducted in this level, the final design will still be in accordance with the desired aim of this research thesis, which is to increase the performance of the system by means of the heat dissipation system and its integration to the building.

F FINAL DESIGN

CHAPTER OVERVIEW

As the final stage of this research project, level B will be designed with the design inputs obtained in all the levels evaluated in this research project. A brief description on the methodology followed at this stage is presented, as well as the type of final evaluation that the design will go through. The next part shows the active façade cooling concept and the specific factors than need to be defined. The design guidelines for the system will be addressed followed by the façade development following these guidelines and responding to the cooling concept. Finally, the active façade solution is presented and evaluated. Sub-questions answered: Which façade parameters and requirements need to be addressed in this design, for the TEM 's functionality, if situated in an office building, to be integrated? And What is the optimal heat sink design plus its complementary elements, if needed, for the heat dissipation of the active TE system?

F.1 METHODOLOGY

According to the design parameters established on the previous chapter, the last part of the evaluation and assessment is at level B. For this, the design strategies to boost the heat dissipation system are already established and the main passive strategies at level A are also defined. The results from these two levels serve as guidelines for the evaluation and design at level B.

F.1.1 DESIGN PROCESS

Based on the literature review, the configurations found on previous research were studied and a selection of possible configurations based on the results from level A and C was done. From the possible configuration their application and combination with the design inputs obtained from level A and C will be done, and the façade concept options is defined. For the façade concept to be developed properly the cooling concept is also defined and established. Once this is done, the façade concept is developed and detailed, integrated within the office building design so that the final façade design is obtained. Finally, the design is then evaluated based on their integration and feasibility within a Mexican context.

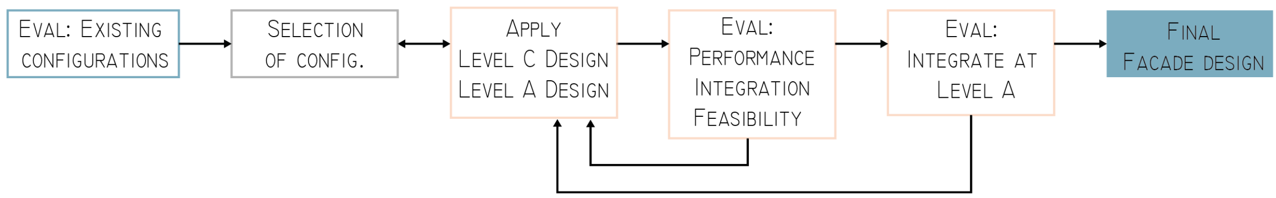


Figure 65.Level B Design Process

F.1.2 EVALUATION

For the evaluation of the façade design, the identified barriers for façade integration and score system from Prieto et al. will be used. The elements to assess are the technical feasibility, the physical integration, durability and maintenance, performance, aesthetics and availability (Prieto, Knaack, Auer, & Klein, 2019) Noting that its cultural or contextual feasibility will also be revised.

F.1.3 LIMITATIONS

The complete performance once all the elements are integrated will not be simulated on the COMSOL software, though a performance check will be calculated manually for the cooling power of the façade developed. The problem with using a score system for the evaluation at level B is that a lot of things will have to be assumed, and at the aesthetic value of the façade, the variability will be addressed rather than a subjective value of its beauty.

SOLAR COOLING	ADVANTAGES	DISADVANTAGES
THERMOELECTRIC	• Solid-state technology, refrigerant free. • No moving parts in the core system. • Small size of components comprehend packaging advantages for product development. • Quick operation (to reach steady-state conditions).	• Low power/efficiency of current materials. There is a trade-off between reported efficiency (COP) and cooling power of researched concepts. • Technology in early R&D stages for HVAC application.
ABSORPTION	• Mature technology with high reliability. Current efforts target cost and complexity. • Larger COP than other thermally operated technologies.	• Potential solution crystallisation, which could cause irreparable damage, added to corrosion risk and need to maintain vacuum. • High upfront costs. Economics become more favourable for larger buildings.
ADSORPTION	• Few moving parts and factory sealed units (maintenance free system) • Non-toxic, non-flammable working fluid (silica gel/water) • No crystallisation nor corrosion in inner components	• Large sizes and weight (bulkiness) due to inefficiency of the cycle (expected cooling capacity). • Alternating operation and long cycles (intermittent) under simplest mode (1 adsorption bed)
SOLID DESICCANT	• Non-flammable and non-corrosive materials • Easy to clean and low maintenance costs, due to its operation at almost atmospheric conditions • Temperature and humidity control separately (sensible and latent loads)	• Limited performance of materials (adsorption capacity of silica gel is low while zeolites have low water capacities and higher cost of regeneration) • Slightly complicated system instalment • Generally larger in size/shape than conventional systems
LIQUID DESICCANT	• High potential indoor air quality, capacity of absorbing pollutants and bacteria • Low-pressure drop, for use with low regeneration temp. • Potential small and compact units by pumping solution. • Desiccant storage when heat source is not available	• All aqueous solutions are highly corrosive (plastic materials must be used) • Health hazards due to carry-over with supply air stream • Aqueous salts are subject to crystallisation, and freezing risk.

Table 24. Façade integration and score system of evaluation. Source: (Prieto, Knaack, Auer, & Klein, 2019)

F.2 FAÇADE COOLING CONCEPT

At level B, there are several elements that play an important role in its design, as it was mentioned on previous sections. In the case of the integrated thermoelectrical façade, the configuration established and found during the component evaluation at level C is one important factor. In addition to that, the façade should also fulfil the typical requirements of a building envelope and achieve a U-value of 0.768 W/m2K, according to Mexican regulations for Monterrey. So for this section of the project, several objectives are defined: design of active cooling system, define number of TE modules needed per façade module, define different types of façade modules (if needed), design of ventilation concept (pre-cooling of ventilation air), and finally the design concept of façade module that responds to the typical façade functions.

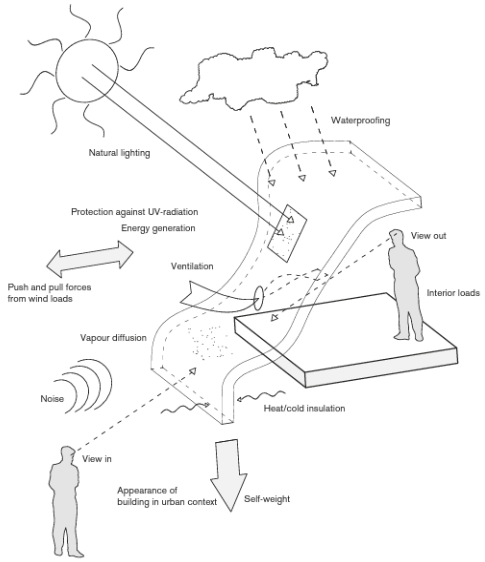


Figure 67. Façade main functions. Source: (Knaack et al., 2007)

F.2.1 CONFIGURATION

With the conclusions obtained at level C, the simplified configuration at component level was obtained. It should be noted that this configuration only takes into consideration one Peltier module, so once the analysis and evaluation at façade level were conducted, the final configuration was adapted to properly respond to the façade necessities.

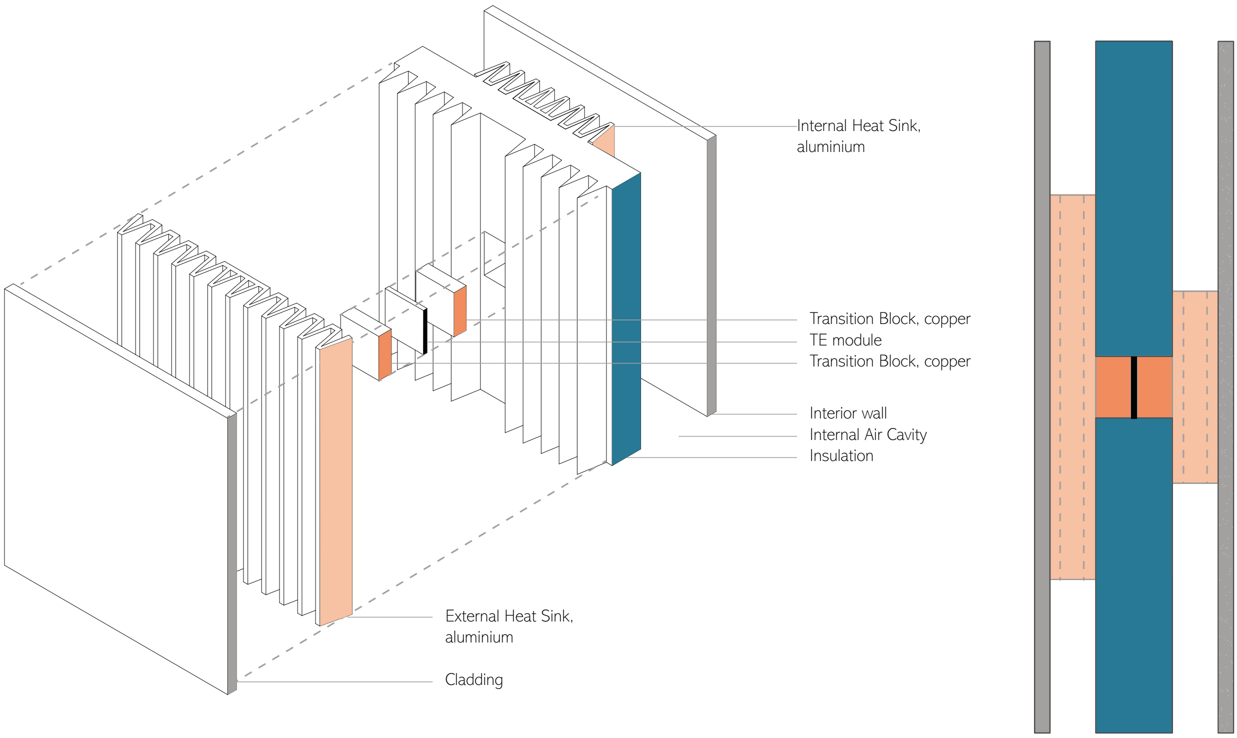


Figure 66. Final component configuration.

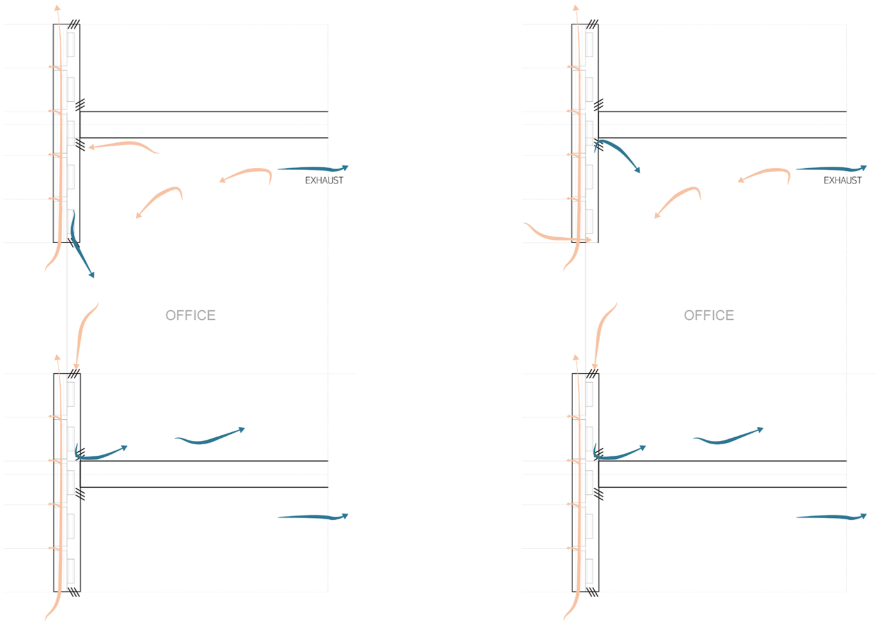


Figure 68.Cooling and Ventilation concept. Left: recirculation of interior air to cool down the interior. Right: top area to cool down incoming fresh air.

F.2.2 COOLING CONCEPT

F.2.2.1 Air delivery concepts

It was derived from studies at level C that best configuration was one with forced convection towards the interior, but by a small difference of 0.01 in the COPc value. Moreover, it is important to note that the use of fans will also use extra energy which will affect the COP of the complete system, in consequence natural convection was used for the design of the façade. For this reason, a final performance evaluation needs to be done to evaluate the contribution of the façade. The possibility of the ventilation and cooling of the office building was explored with two concepts.

For summer time, the flow is normally restricted due to the thermal comfort requirements in the inside, since the outside is much hotter than the inside of the office building, and if the Peltier module is also rejecting heat through the façade, this could contribute to heating the air further that its going inside. In an ideal concept, the active façade system should be able to contribute to pre-cool the air that goes inside to the precinct as the minimum fresh air requirements plus being the primary cooling system in the inside of the office. Nonetheless, with the simulations realized on level C, it is expected that the system will require a lot of Peltier modules to complete cooling power the office requires.

F.3.2.2 System loads

The cooling power the system needs, to meet with the cooling demands, is of 38.63 kW for a single office floor; obtained from DesignBuilder simulations. Different months of summer were simulated, and the cooling power required varies from 35.5 kW to around 41.3 kW. Calculating the Qc from the best component from level C, its cooling capacity responds to 11.90 W per element, with an input power of 7.3 W, and responding to a COPc of 1.64.

$$Q_c = \alpha I T_c - \frac{1}{2} I^2 R - k(T_h - T_c) \qquad (5)$$

$$Q_h = \alpha I T_h + \frac{1}{2} I^2 R - k(T_h - T_c) \qquad (6)$$

$$P = \alpha(T_h - T_c) + I^2 R \qquad (7)$$

$$COP_c = \frac{Q_c}{P} \qquad (8)$$

$$COP_h = \frac{Q_h}{P} \qquad (9)$$

In addition, taking into consideration the minimal fresh air requirements to achieve hygienic room air conditions, 10 l/s per person, and assuming an occupancy of 0.111/m2, the required ventilation is 0.87 m3/s, and a mass flow of 1.04 kg/s, which responds to a ventilation load of 12.68 kW. Various factors also need to be considered when assessing the possibility of this initial cooling concept, that contributes to both the fresh air and the cooling, the first is the power needed for the TE components used. This is ruled by the following equation

$$P = Nx\,Vx\,I \quad (21)$$

Where the N responds to the necessary TEM elements for the cooling system, V for the voltage used by the elements and I for the current. There needs to be a proper balance that responds to the quantity of modules and input power that the system uses, since more Peltier modules would respond to a higher cooling capacity but a lower COPc and the system, responding to more input power needed(Khire et al., 2005). In addition, more Peltier modules would respond to higher cost and so a more expensive cooling system since each component also requires their heat dissipation elements to work properly. Even assuming the Peltier modules connected together all perform equality, achieve the expected delta T, and have no alteration in the overall COP of the system, the resulting amount of Peltier modules per m2 would be around 14, with a total amount of 3786 modules per floor.

Complete system	
Q floor	38.63kW
Q vent	12.68 kW
Qc per Peltier	11.89 W
P total	32.27 kW
N (Peltier module quantity)	3786
N per facade element (1.5m*2.5m)	54
Air volume/h	1.04 kg/s

Table 25.Overall system values

The number of TE modules is very high since they have a very low cooling capacity and only 5 volts per module are being applied, as to allow the system to work more efficiently cheaper. The evaluation on feasibility of the system, such as technical approach, cost, integration, etc, will be applied to the final design. Nonetheless, a preliminary performance calculation was conducted with the values obtained from level C to the TEC module used in this research project (TEC1-127), assuming some loss due to the connection of various Peltier modules, responding then to a COPc of around 1.40.

One of the drivers for this thesis project was the possibility of using the Peltier as a lightweight and cheaper alternative for the cooling demand of an office building. Thus, the use of high-tech Peltier modules was not seen in the evaluation section of the project, rather, a basic module that had a maximum cooling power of 50 W was used. Nonetheless, for the ratio between the input power versus the Cooling power to be beneficial, the voltage is between 5 and 6 for the maximum COPc value and a ΔT of 20. See Graph 69.

This means that a large quantity of modules is required for the system to achieve the objectives. A possibility to lower the quantity of modules would be to increase the capacity by applying 6 voltage to the module instead of 5, but there would be a trade-off, since this would also increase the total power that the system requires to function. In addition to this, the weight of all the façade will be higher since each module requires two heat sinks, even when the interior heat sink has a smaller dimension, according to the configuration setting found at level C evaluation. Although an advantage of working with Peltier modules at a lower voltage is that the thermal resistance needed for the heat sink design is not as strict, thus the heat sink size can be much more compact as it was also found in the previous section of this thesis project, However, this would still mean that all the perimeter of the floor requires to be an active facade. Another possibility would be to only provide the cooling necessary for the incoming fresh air of the office, as it can be seen on the schematic diagram, Figure 70, of the air flows in the system.

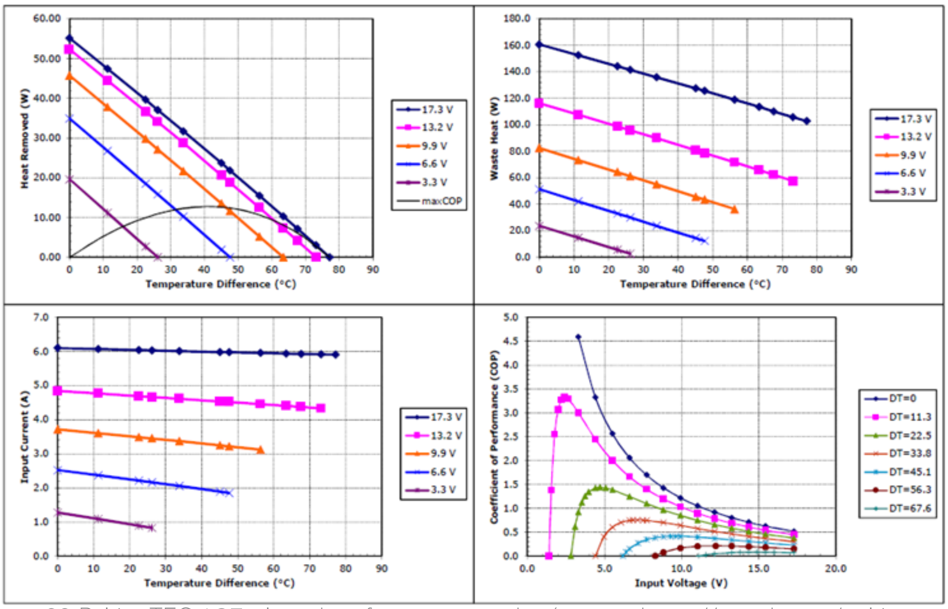


Figure 69.Peltier TEC-127 plotted performance graphs (source: https://tetech.com/peltier-thermoelectric-cooler-modules/high-performance/)

The required Peltier modules for the pre-cooling of the fresh air would be 1172, and if they are distributed throughout the complete façade, allowing for the window openings, this means 14 modules per 1.5 m of façade perimeter.

As it was defined previously, for a total of fresh air volume of 0.87 m3/s, so some calculations on the proper ventilation duct size was done, as well as the electricity consumed in the ventilation type C, natural supply and mechanical exhaust. Some initial assumptions are defined in order to define the required façade modules. The desired pressure drop was defined in 0.4 Pa/m as to avoid loud noise due to the passing of the air flow and aimed air velocity going through the façade is 3 m/s (velocity studied at level C).

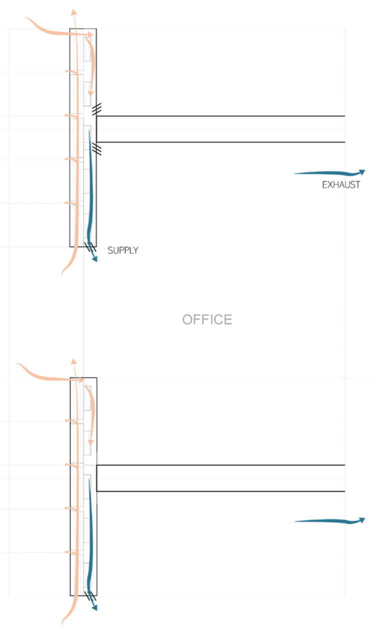


Figure 70. Fresh air pre-cooling concept.

F.2.3 FAÇADE TYPES

The following steps will be done assuming the ideal situation is chosen, where the façade functions both for fresh air and cooling of the interior of the building, even though the drawbacks of these were addressed. According to findings on level A evaluation there will be two WWR, for the east and west facades the ratio is 0.4 and for the north and south it is 0.62, as per the original ratio of the façade, so the space available to place the Peltier modules is also restricted by the solid space. Following findings from level C that each Peltier module needs at least 250 mm of space for the heat sink in length and width, the panels are divided and defined.

The final number of modules will change once the other requirements of the façade are met, which involves the connection of the panel element to the floor slabs, the connection between the solid modules and the glazed elements, to mention a few conditions.

In addition to this, the façade will be divided in fresh air supply module 1 (inlet from outside), fresh air supply module (inlet to the building), fresh air supply pre-cooling module (cooling down of fresh air modules), and air recirculation façade module (FS 1, FS 2, FS 3 and FS 2.1).

	Façade	Linear m	TEM per 1.5m	Façade Modules	Total TEM
F1	NS 62.5%	62.5	36	42	1500
F2	EW 40%	63.5	54	42	2286
					3786

Table 26.TEM quantity per panel type

F.2.3.1 Fresh air supply

The fresh air supply will enter to the façade at 4 different points, at each orientation, and thus the total fresh air was divided equally. dividing the quantity of TE modules required for the cooling needed and those required for the pre-cooling of the fresh air.

Complete Air fresh system	
Total fresh air volume	0.87 m3/s
Desired Pressure drop	0.4 Pa/m

Table 27.Initial values for air distribution in the façade

For the divided system, the total fresh air flow was divided by the quantity of façade elements that will provide this air supply, to give a total of 0.2175 m3/s each. The duct diameter was obtained with correlating the desired air volume versus the desired pressure drop, and a 0.30 m duct diameter was found. Since the system is working within the facade cavity, the equivalent values for a rectangular duct were calculated to a width 0.08 m and 1.4 length. Where de is the equivalent diameter, a and b are the sides of the duct.

$$d_e = 1.30((a * b)^{0.625}/(a + b)^{0.25}) \quad (22)$$

For the complete ventilation, 1240 Peltier modules are needed, but if these are divided among the four air supply systems, 324 Peltier modules are required. This is further divided among 6 façade elements. Which respond to one FS 1, five FS 2, one FS 2.1 and one FS 3, façade modules for façade type 1; for façade type 2, one FS1, one FS 1, two FS 2, one FS 2.1 and one FS 3, façade module.

Divided Air fresh system	
Fresh air volume	0.2175 m3/s
Duct Diameter required	0.30 m
Desired air velocity	3.0 m/s
Duct Width	0.08 m
Duct Length	1.4 m
CSA(cross sectional area)	0.1 m2
Actual air velocity	2.72 m/s
TEM quantity per system	324
Façade elements per system	6 (F1)/ 8 (F2)
TEM quantity per façade	54 (F1) / 36 (F2)

Table 28.Initial values for fresh air divided system

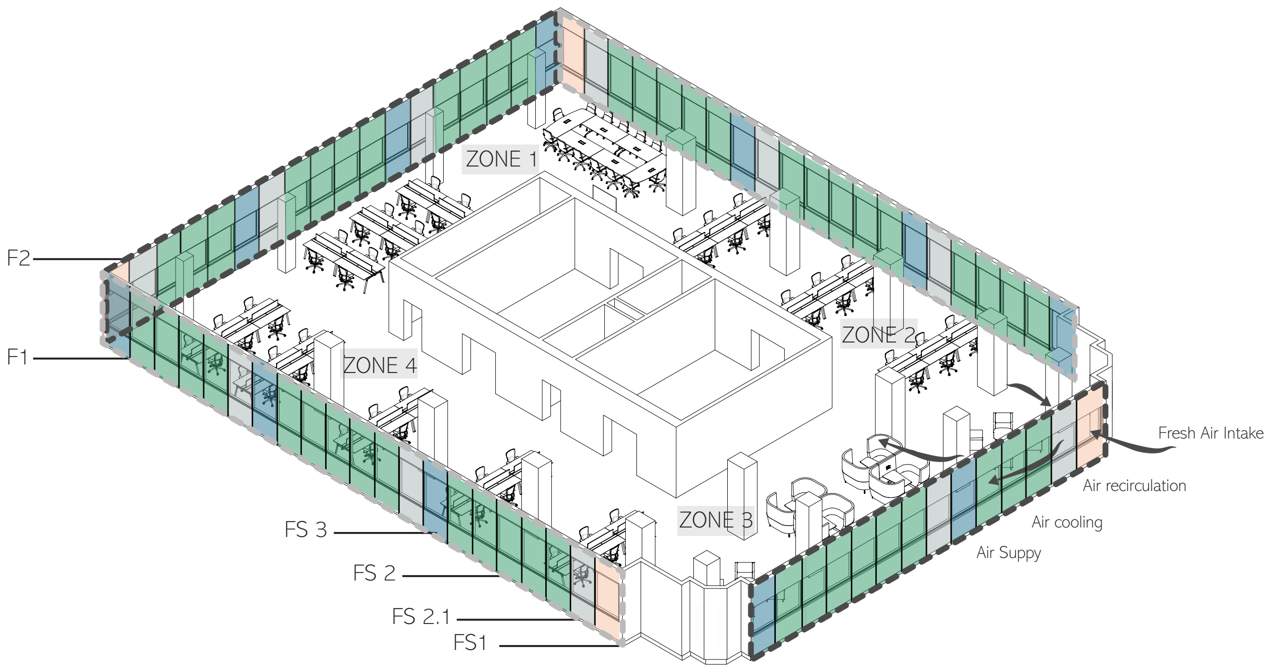


Figure 71.Façade module type assignment per floor plan

F.2.3.2 Cooling

The rest of the façade modules in the floor plan can serve for recirculation and cooling of the inside air of the building office. Similar conditions apply for the rest of the façade modules, where the space is divided in 4 different zones, and they will each be provided by the remaining façade modules (see previous diagram). One important difference will be that the air supplied for the system to cool down will be the existing interior air of the office, allowing for its recirculation and cooling down. The ducting size and air velocity desired remains the same. The sensible heat formula was used to calculate the temperature of the incoming air per system to make sure it is sufficient without reaching condensation temperature when cooling for peak loads.

$$q_{cp} = cp * \rho * v * (T_{in} - T_c) \quad (23)$$

Where cp is the heat capacity of air, q_cp corresponds to the cooling capacity of the system, v is the ais volume flow, T_in responds to the 25.65 ˚C inside the office space and T_c is the air pumped inside the space by the active façade. In this case, the air entering the room will be at 15.46 ˚C for summer conditions. A temperature value lower than 13 ˚C in this particular condition would show condensation, so to avoid this happening, if the complete façade works as the cooling system, the air connection every 8th panel needs to be broken, as to avoid the air cooling more than necessary. This measure will also prevent the incoming air to the office from being too cold for the comfort of the users.

Divided Fresh Air-cooling distribution	
Duct Diameter required	0.30 m
Desired air velocity	3.0 m/s
Duct Width	0.1 m
Duct Length	1.4 m
CSA (cross sectional area)	0.1 m2
Actual air velocity	2.0 m/s
TEM quantity per system	324
Façade modules per system	1 (FS1, FS3, FS2.1) & 5 (FS2)/ 2 (FS2)
TEM quantity per façade	52 (F1) / 36 (F2)
Air pumped inside	15.46 ˚C

Table 29.Initial values for air cooling divided system

F.3 DESIGN GUIDELINES

The experiments, simulations and numerical evaluations were analysed and arranged according to the different levels of design as it can be seen in the diagram. There are several patters and relations that were deducted through the three levels. At level C, the systems' performance was widely affected by the heat sinks geometry and arrangement, such as the case of thickness, channel depth, compactness of the element, and the shape of the channels. In level A, the highest impact was achieved through the control of solar radiation, through less glazing, different type of glass or with proper shading system. Finally, at level B, the cooling delivery system was decided, as well as the proper configuration with the cavity towards the inside of the precinct. It is important to address that although forced convection was slightly better than natural convection, by 0.01 difference in COP, the addition of energy use by the system due to the use of fans would make the system's overall COP lower than initially established.

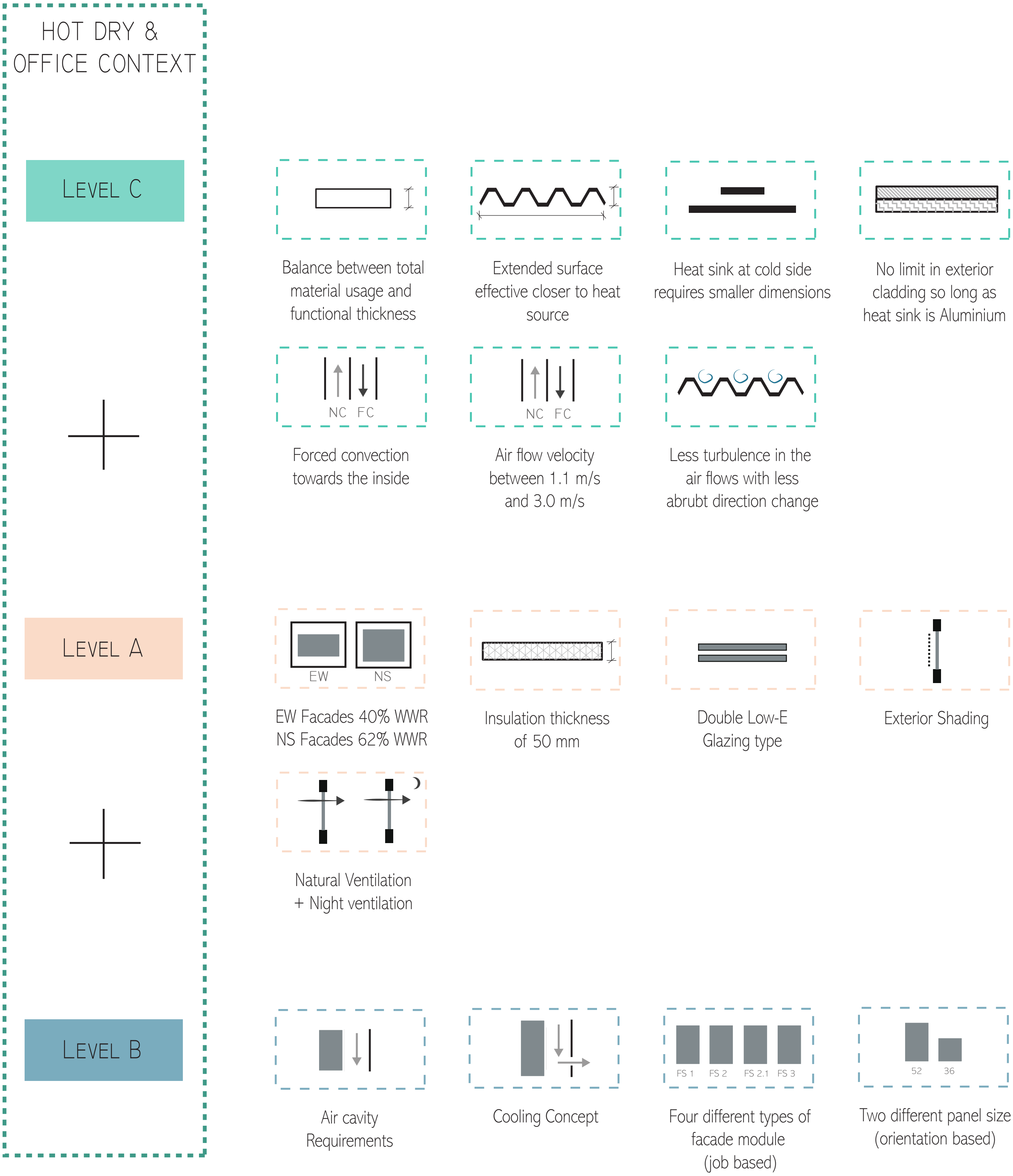


Figure 72. Design Guidelines

F.4 FAÇADE DEVELOPMENT

The ideal active façade system for the hot dry climate in an office context is developed following the design guidelines found in the research project and summarized before plus the cooling concept established in the previous section.

F.4.1 FAÇADE CONCEPT

In this matter, a set of steps was developed for the façade development and design. First, the two general types of façade were defined, as seen on the figure. Façade type one responds to those modules facing the north and south orientation, shading only towards the south orientation. The façade type two responds to the west and east orientation and also has the most allowable space for the placement of the active cooling system. In terms of panel size, a standard 1.5m was chosen to allow modularity to the construction of the façade.

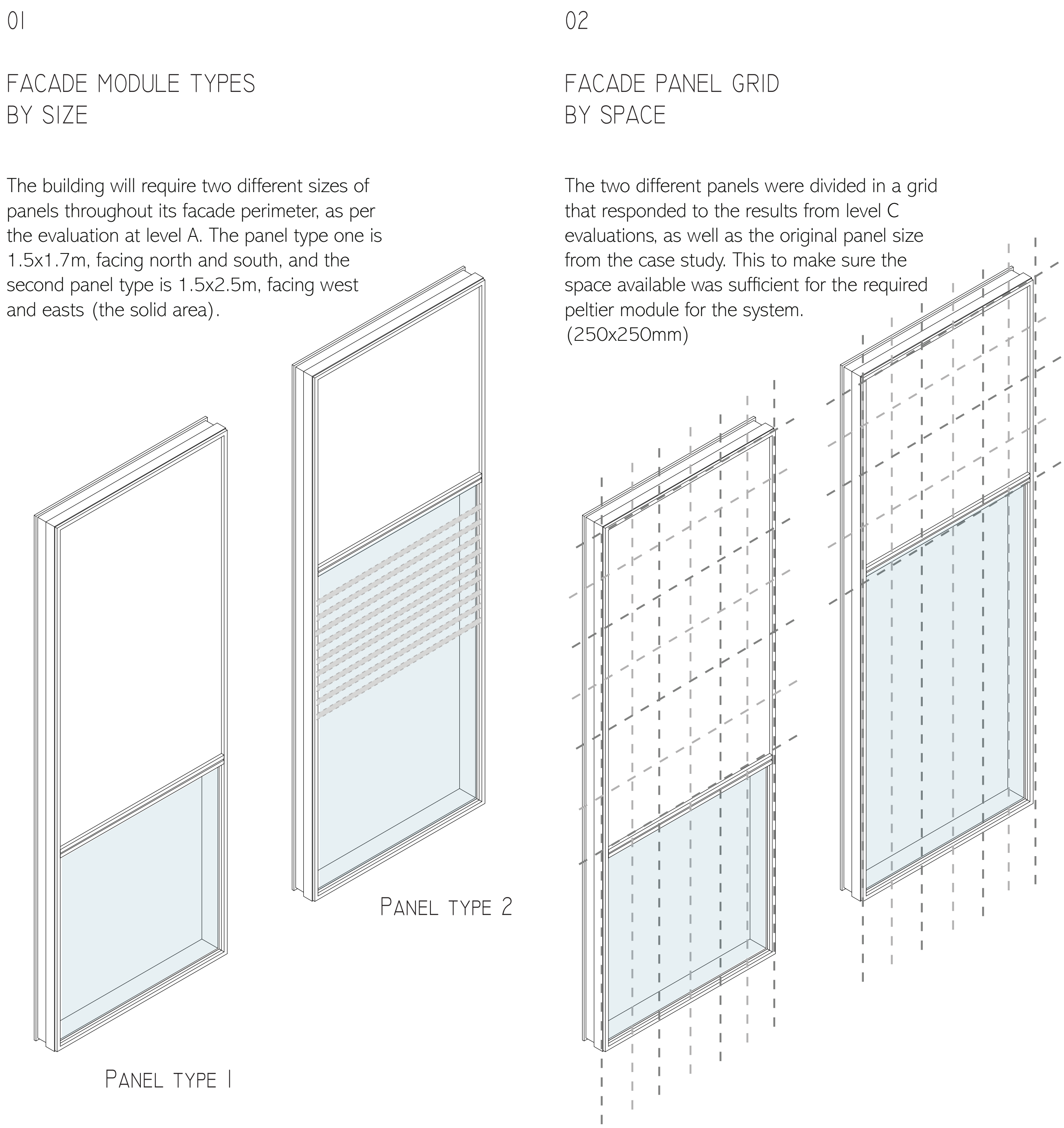


Figure 73. Facade development step 1 and 2

The layers the system required were established as it can be seen in the exploded view. This panel type has 54 TE modules, with 108 heat sinks, thus 2 support profiles in the middle of the largest heats sinks (external) are proposed to assit the unitised panel.

03

FACADE MODULE LAYER
TEM SYSTEM

The next step was to establish the layers the thermoelectrical system required to function, as per the guidelines found on the previous stages.

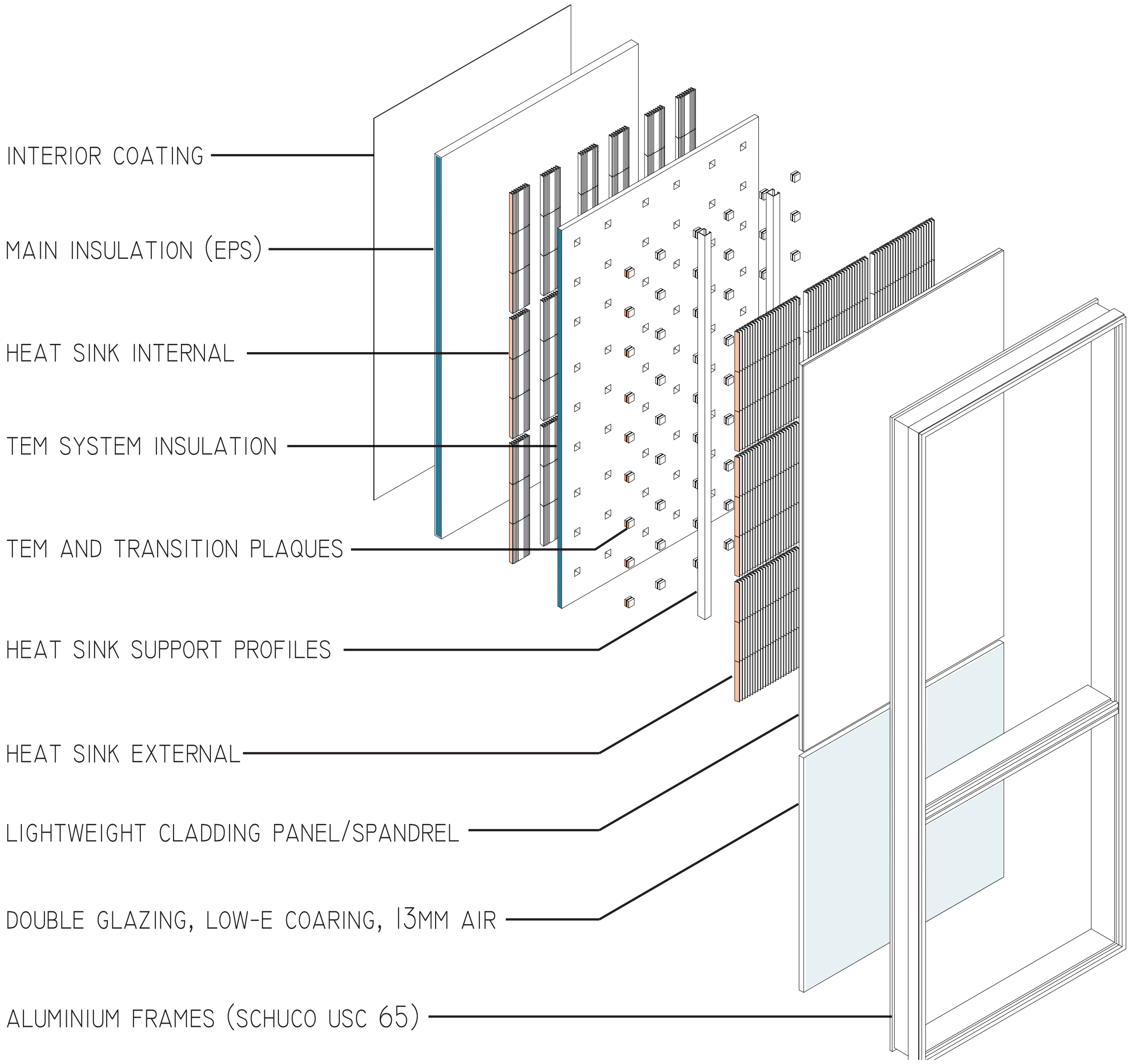


Figure 74. Facade development step 3

The next two steps in the development of the façade panel was to define the ventilation or distribution of the air within this panel. For the part of the system facing the interior of the office, an air cavity was defined that aids in the cooling and distribution of air. In the external part of the system, the ventilation of the heat sink is designed as to avoid overheating of the façade.

04

FACADE AIR CAVITY INTERNAL

For the required intake of fresh air and circulation of air in a floor of the office building was calculated per conditioning zone. With this value the and taking into consideration the space and size of the panel already established, the air cavity towards the interior was defined as 80 mm.

05

FACADE EXTERNAL HEAT SINK VENTILATION

Another important consideration is the ventilation of the heat sinks facing the exterior of the building. The evaluation showed better performance with natural convection, thus air outlets/inlets were placed along the cladding panel to boost the air flow upwards and out of the heat sinks. All panels must allow for this ventilation unless specified.

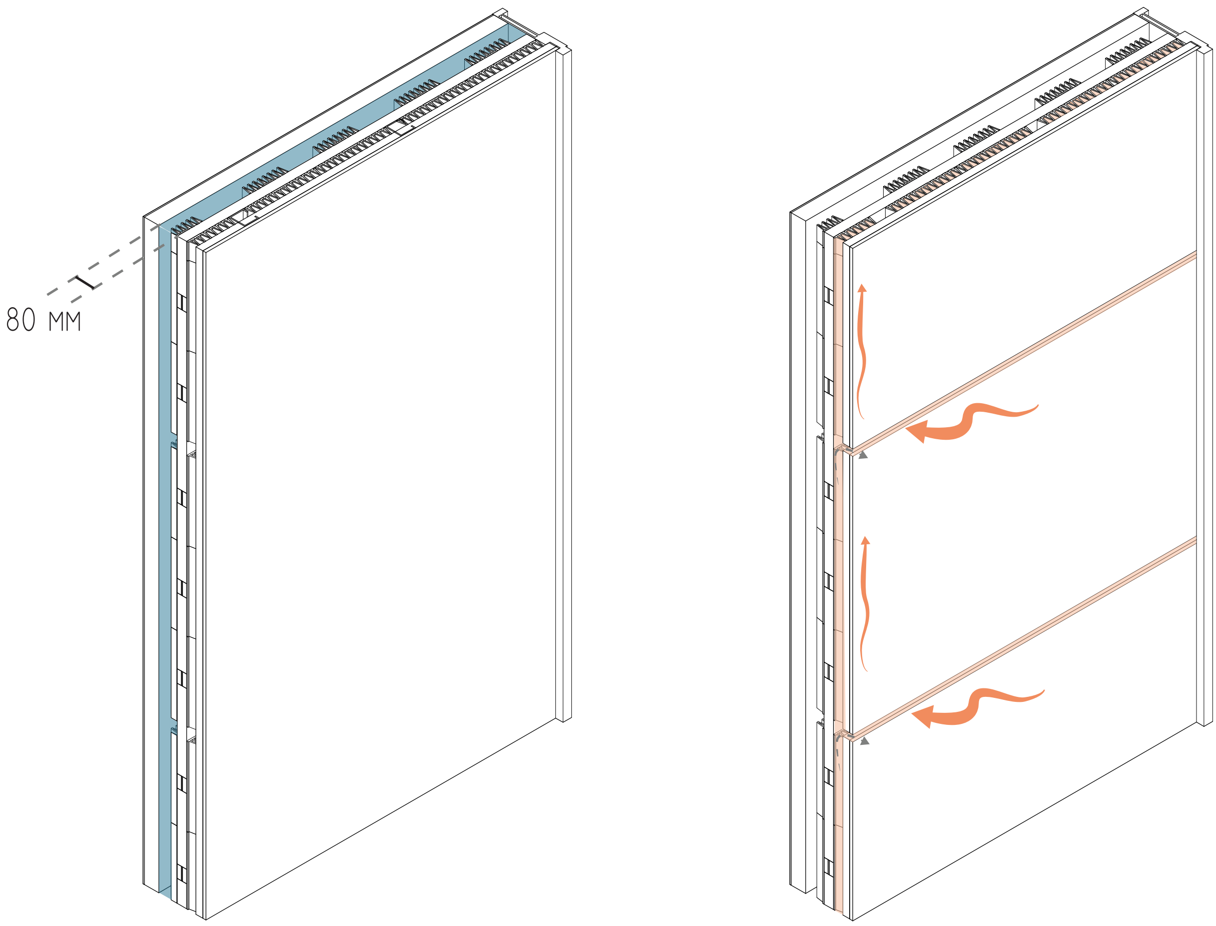


Figure 75. Facade development step 4 and 5

There are different façade panels for the different façade types, and these depend on the function they are performing. The first two panels in the system developed allow for the intake of air. The FS 1 brings fresh air from the outside and the FS 2.1 brings in air from the inside of the office to recirculate.

06

FACADE MODULE BY FUNCTION
FRESH AIR INTAKE

For the required intake of fresh air from the outside, the inlet is located at the top of the panel, below the panel's mullion. It was locoted at the top of the panel as per the results at level C. Additionally, to avoid the mixing of this air with the ventilation of the external heat sinks, this passage is closed off for the module type FS 1, only for the first 500 mm of the panel.

07

FACADE MODULE BY FUNCTION
OFFICE AIR INTAKE

The next panel in the system, FS 2.1 is one that allows air from the interior inside the interior air cavity of the façade. It is closer to the fresh air module since at peak days this air is expected to be lower than the incoming from outside, thus aiding further in the conditioning of the office floor.

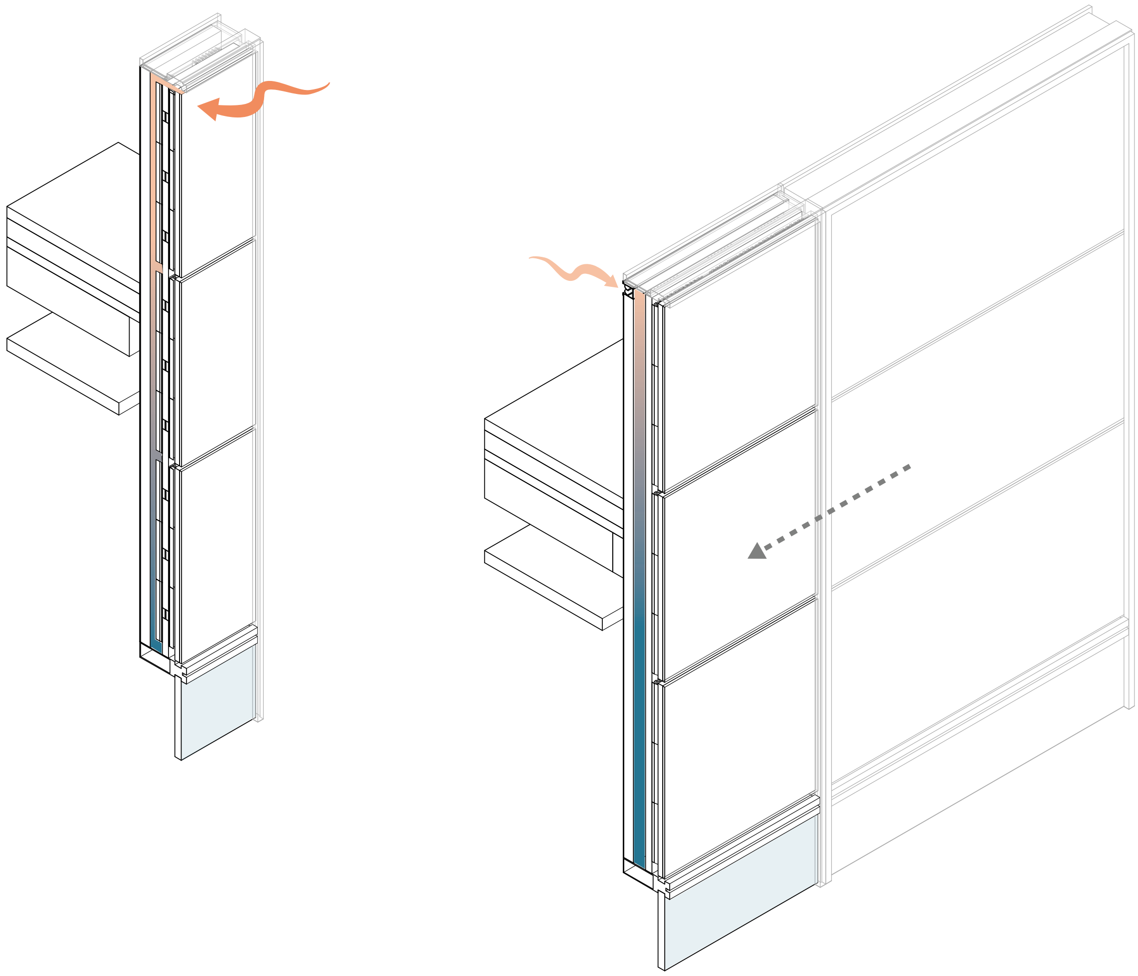


Figure 76. Facade development step 6 and 7

The third and fourth panel in the system is the "normal" panel, FS 2, since they only allows for conditioning and further distribution of air.

08

FACADE MODULE BY FUNCTION
AIR CONDITIONING

The third type of panel, FS 2 is used to further cool down the incoming air. It has no inlet or outlet of air towards the exterior nor interior, and the air cavity works as the air duct. The connection of the panels should allow for the passing of air without any loses as well.

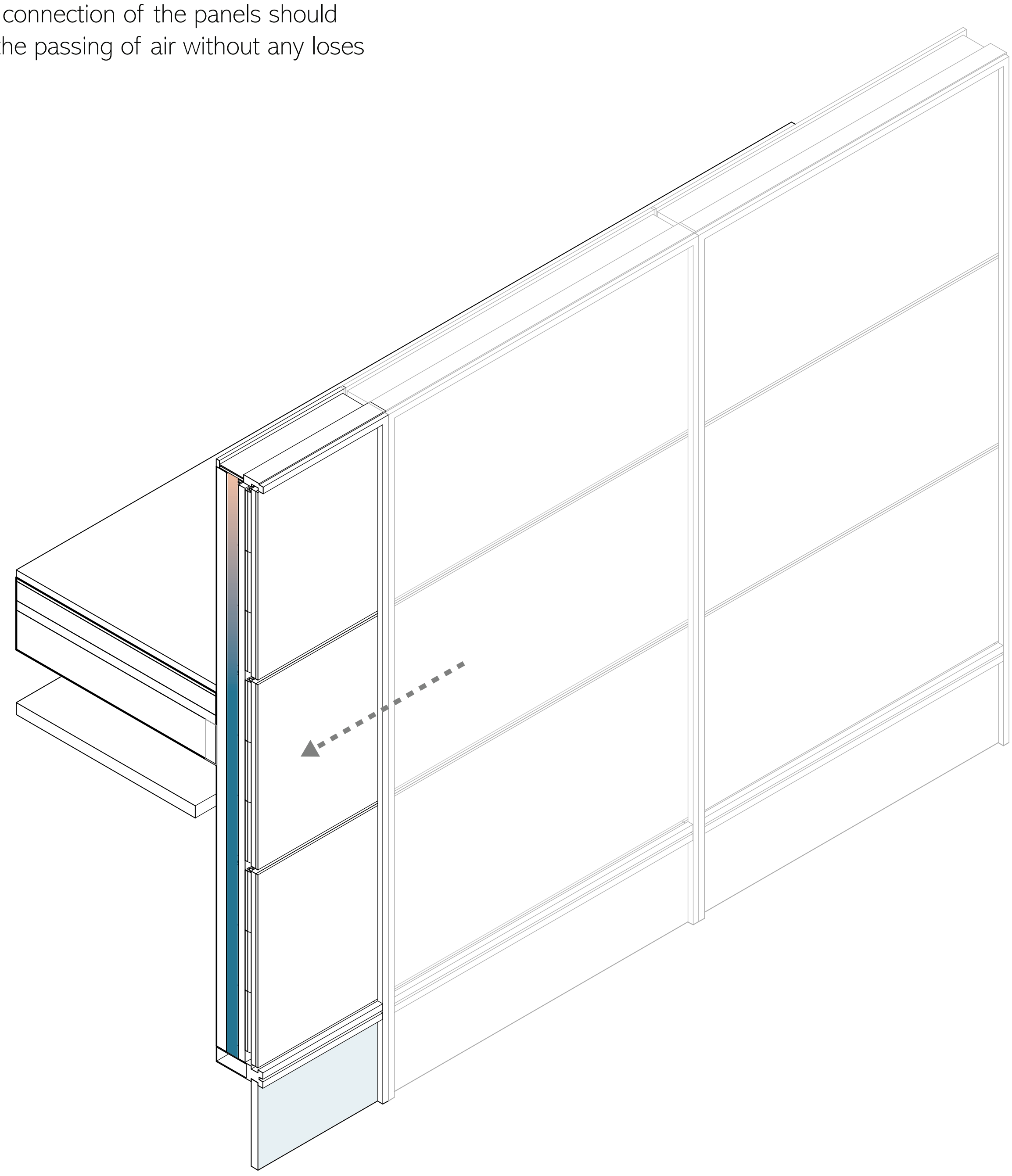


Figure 77. Facade development step 8

Lastly, the fifth panel, FS 3, functions as for air supply in the required zone of the building.

09

FACADE MODULE BY FUNCTION
AIR SUPPY TO INTERIOR

The last type of panel in the system, FS 3, has the air supply inlet towards the inside of the office space to properly ventilate it (200 x 1400 mm). In total, the part of the system for fresh air intake requires 5 modules for this particular type of facade. They all have almost the same layers, but have special features depending on their function. This panel has variant when talking about the recirculation of interior air, where the air suppy outlet is positioned at the bottom of the floor to allow for a temperature gradiant.

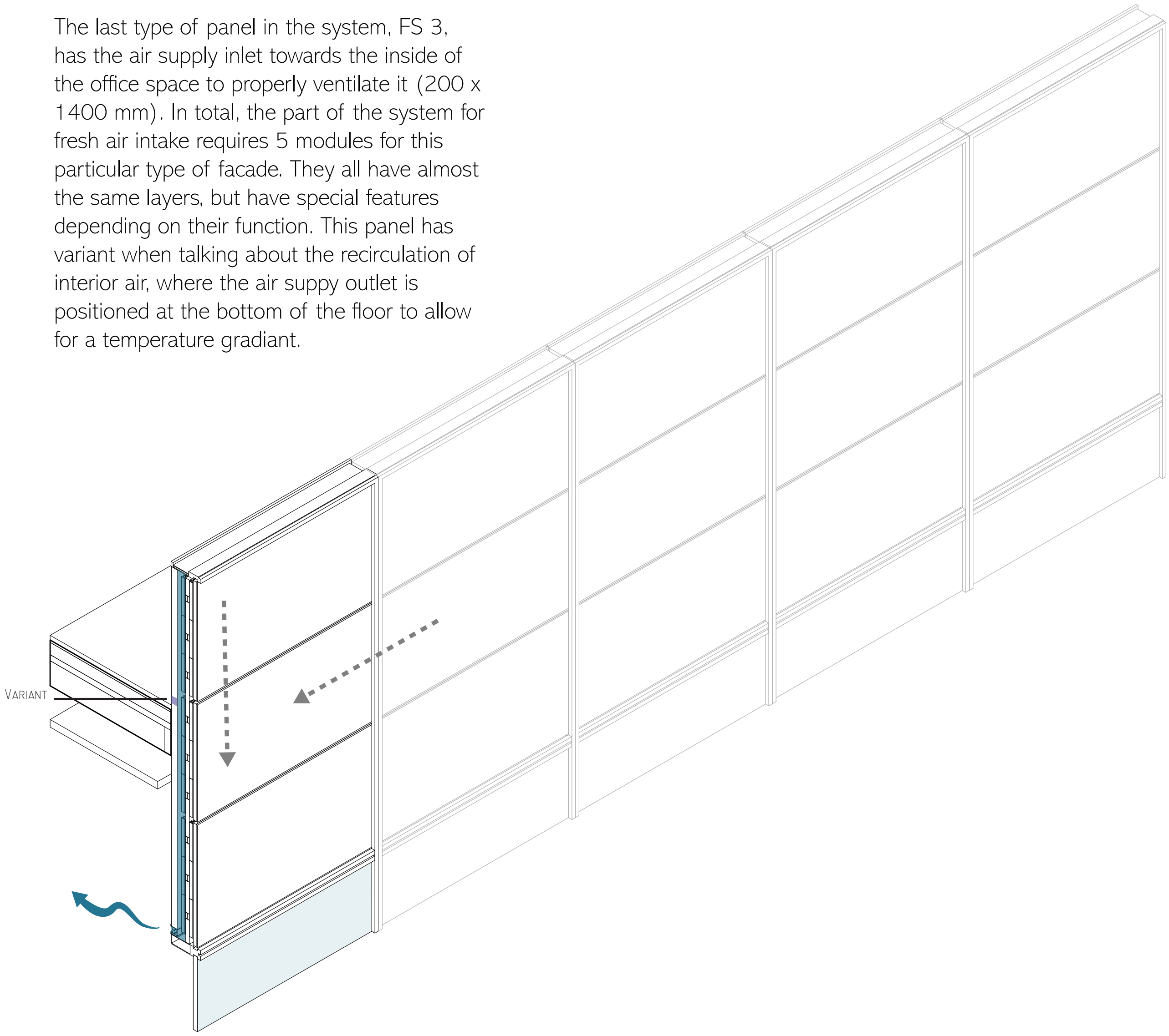
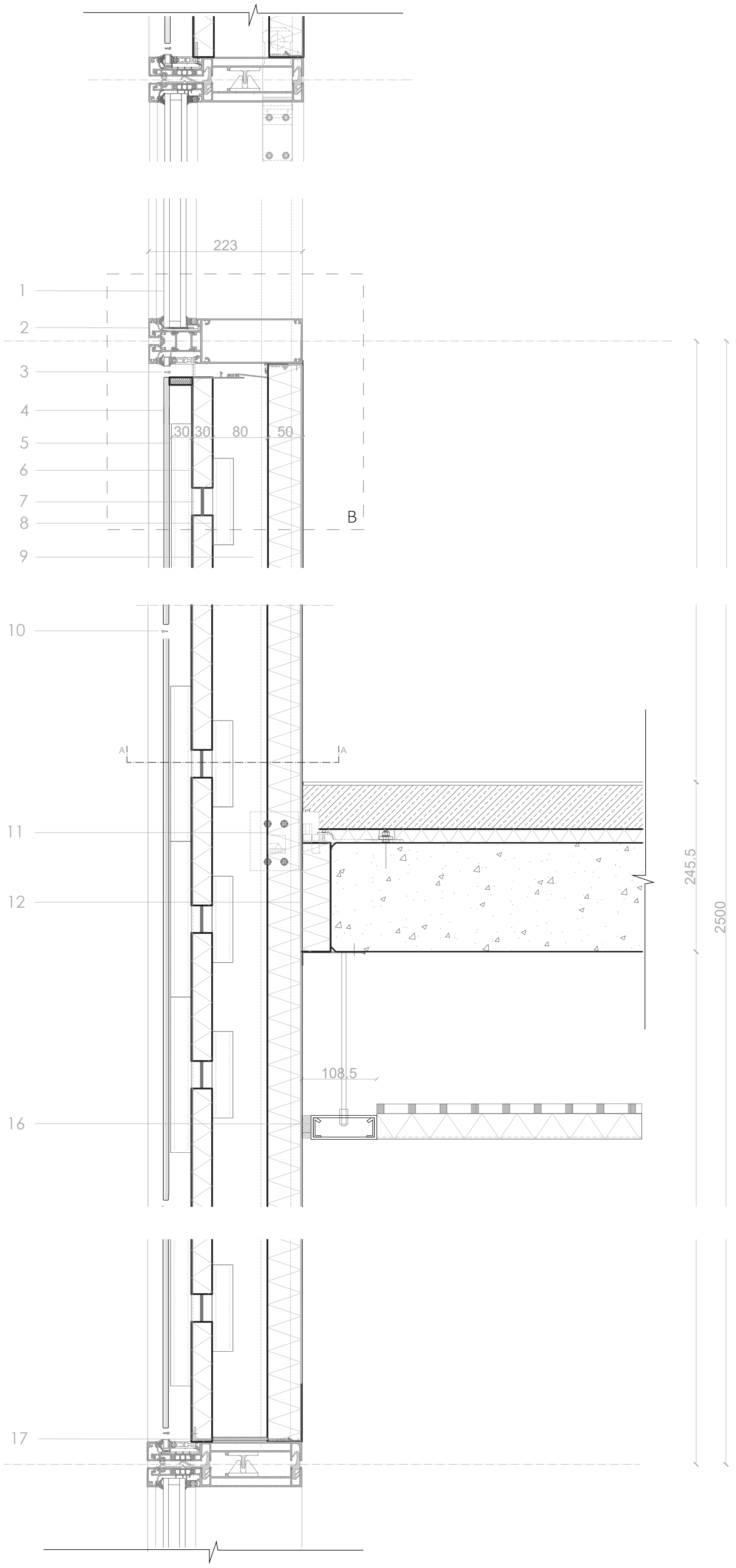


Figure 78. Facade development step 9

F.4.2 FAÇADE DETAILING

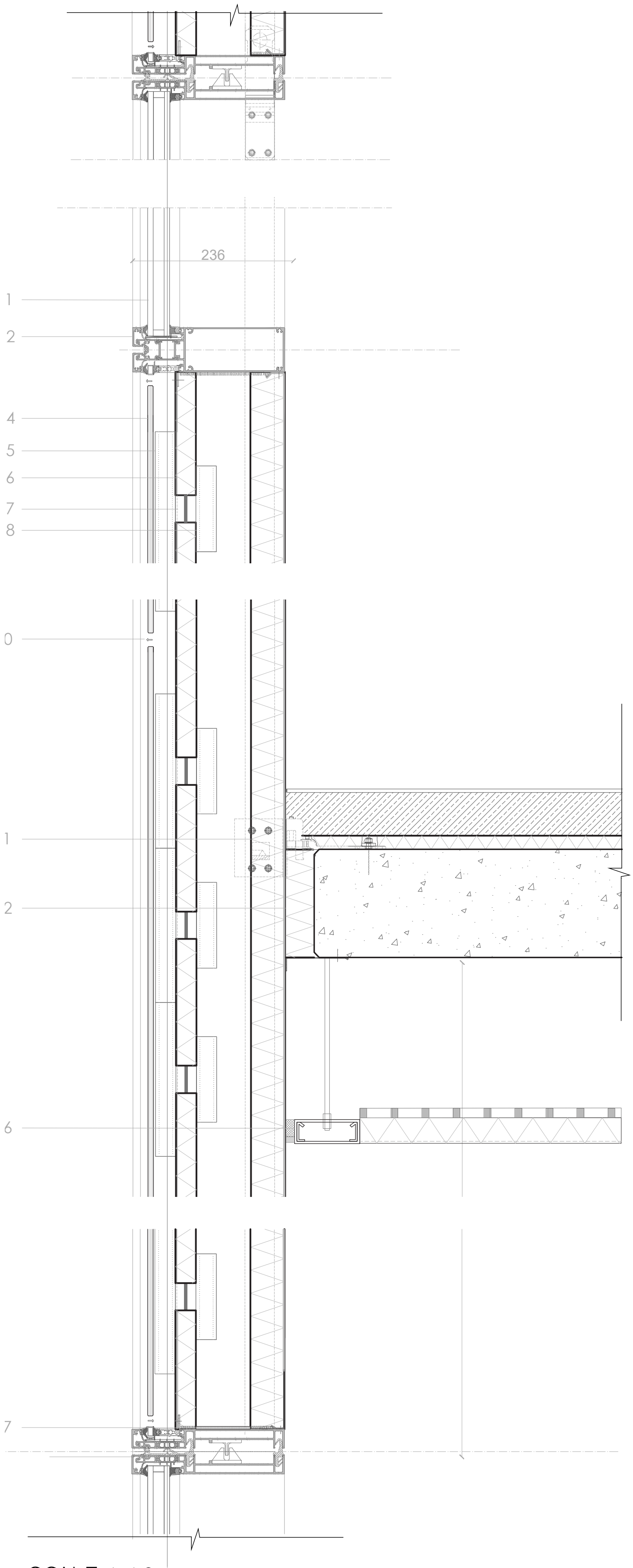
The façade module FS 1, for air intake, is detailed and dimensioned accordingly.



1. Double glazing with low E-coating
2. Standard Schuco unit, transom 150 mm
3. Ventilation slot connected to TEM system
   a. fresh air damper and regulation
4. External Cladding
5. Heat Sink towards the exterior, 30 mm x 225 mm
6. TEM system insulation, 30 mm- EPS
7. TEM system, transition plates plus TE module (TEC-127)
8. Heat Sink towards the interior, 30 mm x 125 mm
9. Air distribution and cooling channel, 80 mm
10. Ventilation outlet for exterior heat sinks, 20mm
11. Anchoring to structural slab/beam
    a. Concrete anchors, 85 mm
    b. I-section fixed to slab by anchors
12. Thermal insulation 40 mm- Mineral Wool
13. Main thermal insulation 50 mm- EPS
14. Steel stud farming system filled with mineral wool
15. Air damper and filter
15. Ventilation grill
16. Acoustic ceiling, mineral fibre and insulated with EPS
17. Rubber for level change for condensation collection at end of panel

SCALE 1:10

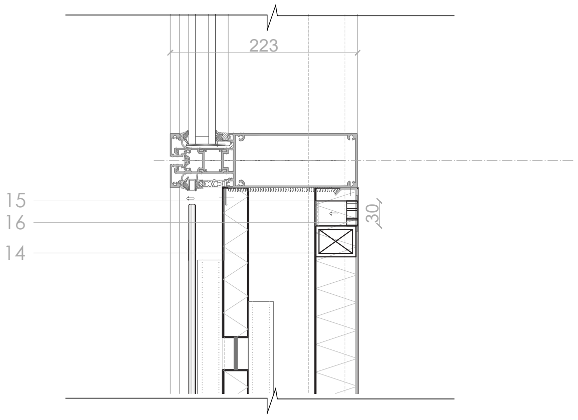
The façade module FS 2, for air conditioning and sitribution is detailed and dimensioned accordingly.



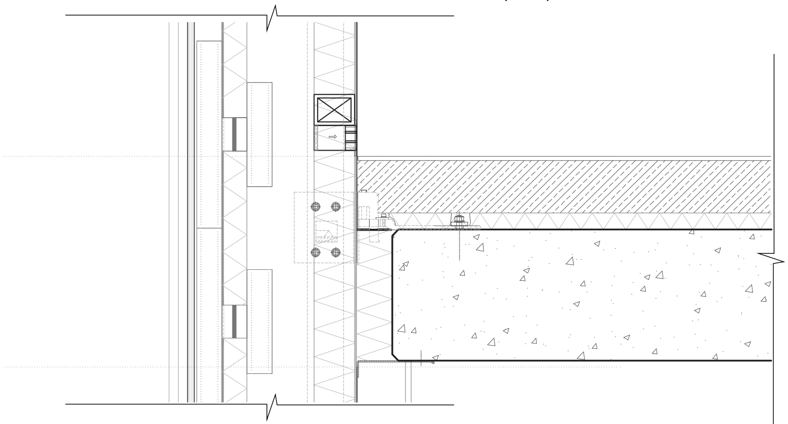
SCALE 1:10

The façade modules FS 2.1, FS 3 V1 and FS 3 V2 are detailed and dimensioned accordingly. FS 3 variant 2 is used for the areas of the façade that only recirculate air rather than get fresh air. The average U-value of the construction is 0.71 m2.K/W which is whithin the accepted values by the municipality of Monterrey.

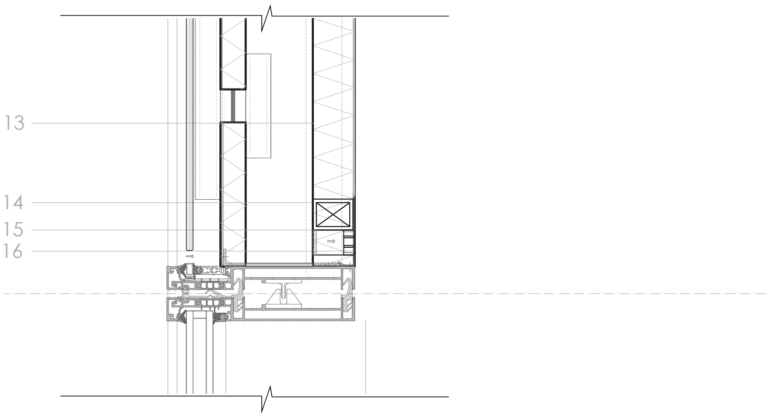
FS 2.1 - AIR RECIRCULATION



FS 3 - AIR SUPPLY INTO OFFICE (V2)



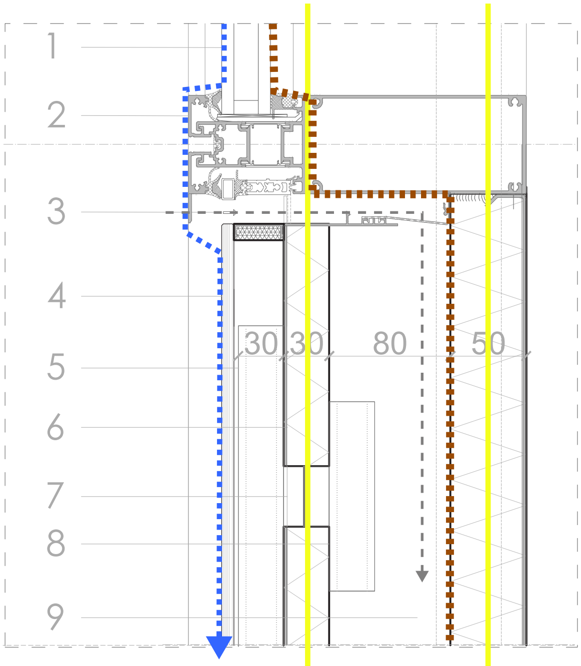
FS 3 - AIR SUPPLY INTO OFFICE (V1)



1. Double glazing with low E-coating
2. Standard Schuco unit, transom 150 mm
3. Ventilation slot connected to TEM system
   a. fresh air damper and regulation
4. External Cladding
5. Heat Sink towards the exterior, 30 mm x 225 mm
6. TEM system insulation, 30 mm- EPS
7. TEM system, transition plates plus TE module (TEC-127)
8. Heat Sink towards the interior, 30 mm x 125 mm
9. Air distribution and cooling channel, 80 mm
10. Ventilation outlet for exterior heat sinks, 20mm
11. Anchoring to structural slab/beam
    a. Concrete anchors, 85 mm
    b. I-section fixed to slab by anchors
12. Thermal insulation 40 mm- Mineral Wool
13. Main thermal insula
14. Steel stud farming s
15. Air damper and filte
16. Ventilation grill
17. Acoustic ceiling, mi EPS
18. Rubber for level cho collection at end o
19. Structural support for heat sinks
20. Interior Coating (desired)
21. Standard Schuco USC 65, mullion 50 mm
22. Panel opening for air (20 mm); special profile connection to mullion and structure; condensation collection

The area where the fresh air enters the main cavity breaks the first insulation line that works with the TE modules. Nonetheless, the main insulation line, towards the interior, is not touched and thus aids to prevent any possible thermal break that would be caused. In addition, the application of the damper that closes when the system is not being used is mandatory to prevent any undesired air going through the cavity. The profile extending from the air inlet to avoid water entering the air inlet.

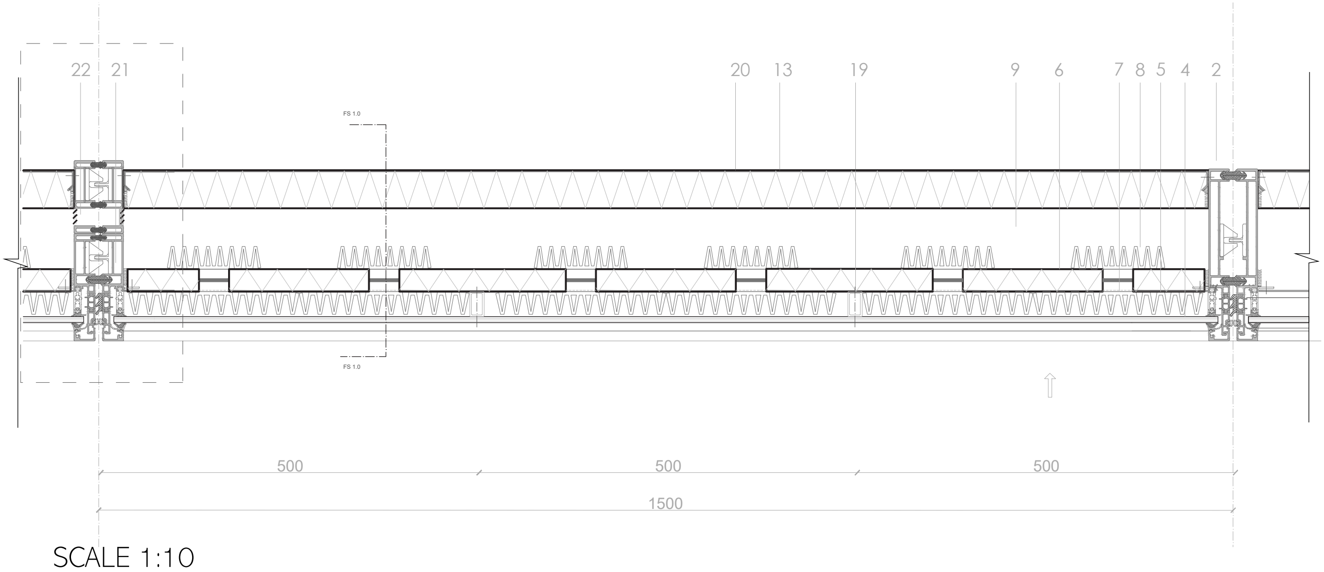
B -FRESH AIR INTAKE



SCALE 1:5

1. Double glazing with low E-coating
2. Standard Schuco unit, transom 150 mm
3. Ventilation slot connected to TEM system
   a. fresh air damper and regulation
4. External Cladding
5. Heat Sink towards the exterior, 30 mm x 225 mm
6. TEM system insulation, 30 mm- EPS
7. TEM system, transition plates plus TE module (TEC-127)
8. Heat Sink towards the interior, 30 mm x 125 mm
9. Air distribution and cooling channel, 80 mm

For the horizontal connection of the panels, a special profile had to be designed when two panels that are distributing air meet. The detail shows the air inlet created by the end profile attached to the panel mullion and to the profile facing the interior. Proper sealants must be added to avoid that any air escapes the system. In addition, the aluminum profiles have to be insulated to avoid undesired change in temperature of the air.



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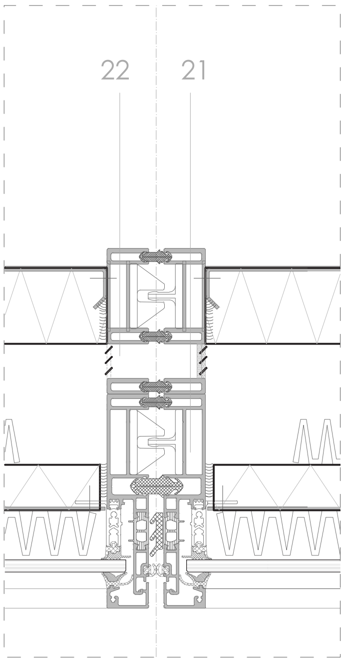
C - PANEL CONNECTION



SCALE 1:5

1. Double glazing with low E-coating
2. Standard Schuco unit, transom 150 mm
3. Ventilation slot connected to TEM system
   a. fresh air damper and regulation
4. External Cladding
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8. Heat Sink towards the interior, 30 mm x 125 mm
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13. Main thermal insula
14. Steel stud farming s
15. Air damper and filte
16. Ventilation grill
17. Acoustic ceiling, mi EPS
18. Rubber for level ch collection at end o
19. Structural support for heat sinks
20. Interior Coating (desired)
21. Standard Schuco USC 65, mullion 50 mm
22. Panel opening for air (20 mm); special profile connection to mullion and structure; condensation collection

A section view of the system application throughout a complete floor and the parts of the system that meet. This particular example shows the air outlet to the interior of the office once the recirculation and conditioning process has occurred on the other panels. The elevation also shows a reduced window size to that of the original building and the exterior cladding can be customized according to taste.

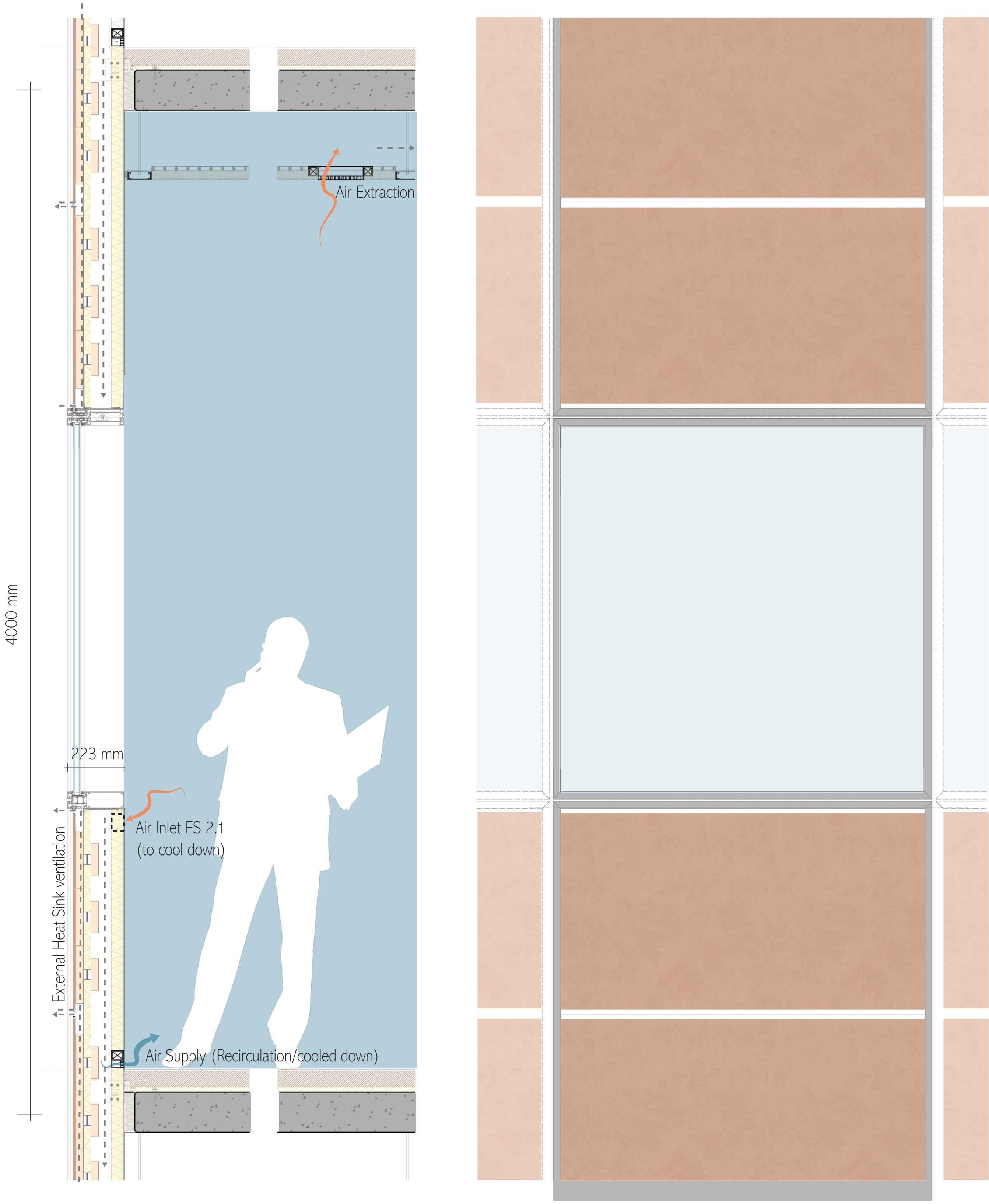

Figure 79. Left: Façade section with air outlet and extraction; right: exterior elevation

F.4.3 FAÇADE VISUALISATION

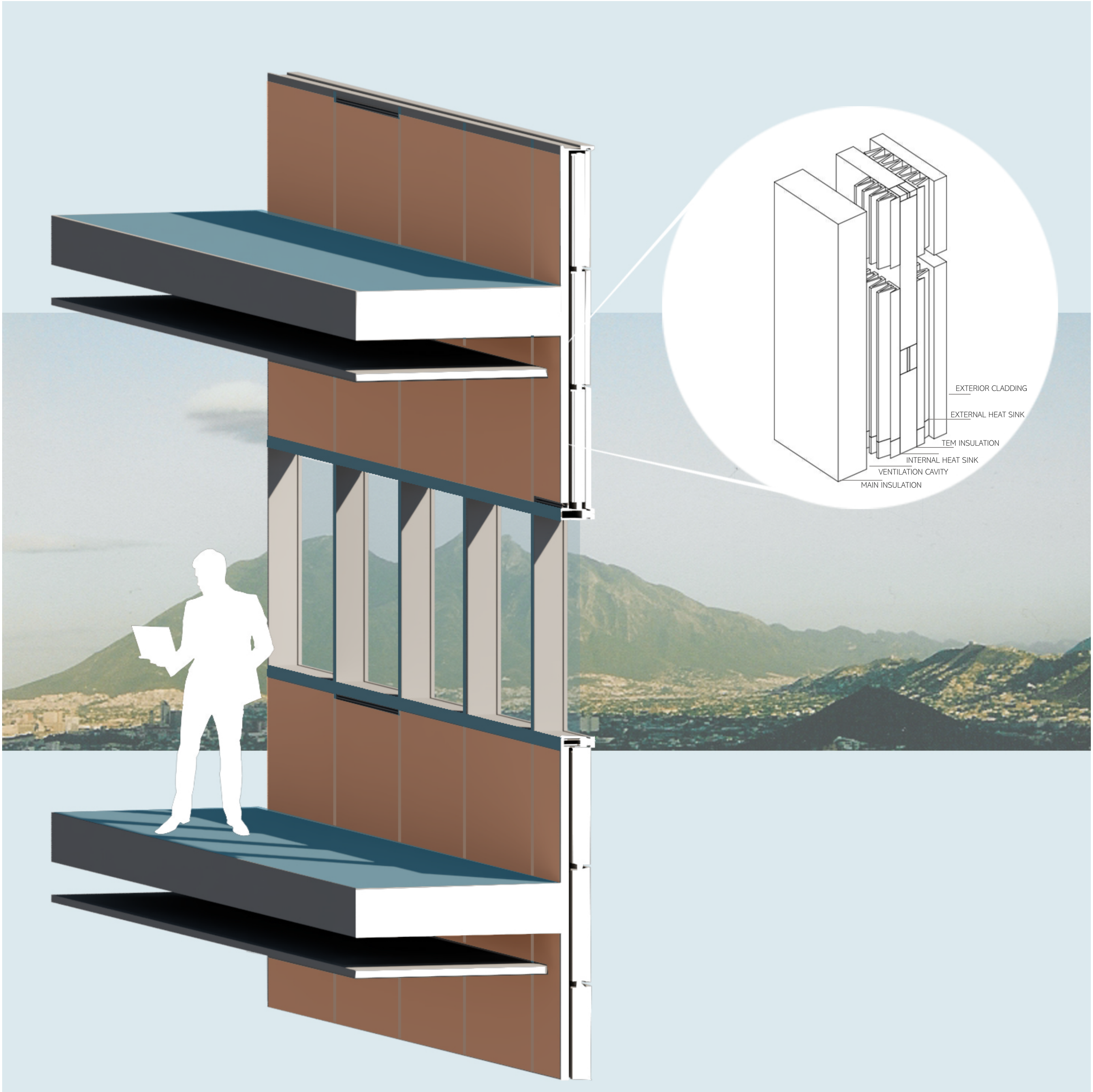

Figure 80. System visualisation with the five working panels

F.5 EVALUATION

A qualitative assessment following (Prieto et al., 2019)'s developed evaluation system will be conducted, followed by a section on other possibilities that could be applied to the current design addressing the positive and negative aspect of the façade developed.

F.5.1 QUALITATIVE EVALUATION

Technical feasibility: the Peltier modules only require direct current, which makes it easier for the system to connect to any residual energy type or even to be powered by solar panels. In addition to this, the Peltier modules are small so it can be lightweight and small whilst having sufficient cooling capacity. In comparison with other systems, the Peltier modules does not make any sound whilst it is working. Although the main idea was to use the façade panel as a stand alone component for the cooling of the space, the extraction of the used air was not integrated in the façade since it would increase its size and complexity dramatically. This means that further development in how to implement this into the system is yet be addressed.

Physical integration: in the developed façade panel, the customisation of the heat sinks at façade scale contributed to a lighter and more compact façade systems, contrary to system's studied at the knowledge phase. The panels were developed in a modular way and the configuration of the TE module system is such that it can be placed easily within the façade layering (following the design guidelines). The system's integration with the ventilation system is considered a positive feature of the designed panel, although special care should be taken so that the integration does not affect the normal functionalities of the façade (water and air tightness). The most complex connection that needs to be tested and developed is between the panels, where it needs a special opening to allow air to go to the next panel for the distribution of air. The quantity of Peltier modules also contributes to the existence of thermal breaks if not properly protected, since that many direct connections at each Peltier module becomes a potential threat for the building, but proper lines of defence can ease down this drawback.

Durability and maintenance: the use of natural convection for cooling the heat sink lowers the maintenance and contributes to its durability. It is known that Peltier are reliable but only if it does not overheat. In that sense it should not require much maintenance, though if a problem arises (not due to the Peltier module but due to connections, air leakage, condensation, etc), tracking that many Peltier elements could make the system less reliable. Thus, proper accessibility to the system components should be possible if something goes wrong, without affecting the working pattern of the office building.

Performance: The configuration used, allows for an increase on the system's COP since the low capacity Peltier modules were used at lower voltages and thus require less power to operate. The use of natural convection also contributes to the overall performance since no extra energy is required beside the one used by the Peltier modules. The advantage of the heat sinks developed is that they contribute to the system's performance whilst having an up to scale disposition that can be assembled within the façade layers. Although, the low cooling capacity of the modules makes it so that there is a limit to how much they can cool down a space even with proper dissipation system. This means that a large quantity of TE modules were used to reach the desired cooling power, so the question remains on whether the material could be also upscaled to meet building's cooling dem ands, in the same way the heat sinks were for this thesis project. The fact the system still performs lower than typical air-conditioning system is still a major drawback when thinking of placing this system in a Mexican context. As it was seen in chapter B.5, on the case study, sometimes important passive design strategies like proper glazing type or the addition of a shading system would be discarded in order to save initial costs by investor. In consequence, this results in higher energy bills for the final user.

Aesthetics and availability: in terms of aesthetics, there are more cladding possibilities if the heat sink is not functioning as the cladding, even though that was also studied during the course of this research project, since the cladding will not be limited by the material and shape, and could be adapted to its context. Although the possibility of using the heat sink as the heat sink was also explored during this project, the use of other material besides aluminium showed a much lower performance of the system, and so the notion was discarded since the use of aluminium as the external cladding the façade would make the façade panels heavier (the heat sink would have to cover the façade plus have the necessary base thickness at the contact area of the heat sink to perform (observed with the isosurface images at chapter D.2). Additionally, the solar radiation that would be absorbed by the heat sink could also contribute to excess heat accumulated on the external side of the building, for the summer conditions, this is especially risky for Monterrey's hot arid climate.

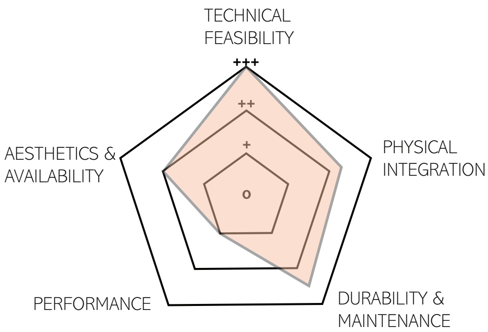

Figure 81.Results following qualitative assessment from Prieto et al., (2019)

F.5.2 OTHER POSSIBILITIES

Section F.4 showed the resulting path from the strategies evaluated, but as it was explained on the knowledge phase and discussed at the façade design evaluation, there are other options that could be applied and contribute further on the performance of the system, that due to time constraints they could not be fully explored in this project.

One of those is the use of a liquid-based heat dissipation system or even PCM materials to serve as heat storage elements for the heat dissipation of the component. In the case of PCM materials, for them to work properly for heat dissipation the outside air temperature needs to be low. This would happen early morning and during the night for warm climates, where the PCM material would be at its solid form; and during high temperatures of the day, the PCM storage works by taking part of this excess heat. For this, a material with proper melting temperature for Monterrey's climate situation would be needed. In this case, in the summer, the temperature on the mornings and evenings reach no lower than 25 °C, and on the days it reaches lower values, the normal natural convection would be sufficient to dissipate the heat (non-summer). For these circumstances to be met, a PCM material with a relatively high melting point would have to be used. Some options with metallic or paraffin PCM materials, whose melting point ranges from -12 to 71 °C, for paraffin, and from 30 to 96 °C, for metallic, could be an option. Nonetheless, metallic PCM have not been studied much, due to its high density, cost and technical limitations. (Akeiber et al., 2016) In the positive side, organic paraffins are known to be safe, reliable, durable and are non-corrosive, which would work in keeping the system simple enough for maintenance. (Tan & Zhao, 2015) In addition, considerations for winter season should also be evaluated, since the heat sink towards the exterior side could reach very low temperatures if the PCM and heat absorption of the TE modules is not properly balanced, thus hindering the system's performance due to the large temperature difference created.

In the same matter, research on liquid-cooled heat sinks for thermoelectrical integrated facades has not been studied enough, but there is potential. A simplified simulation where the air channels of the heat sink were used instead for water flowing through the fins allowed of the heat sink to reach the same temperature as the outside temperature (with natural convection, there was one degree difference). Though for this small test considerations such as the tube material or its proper sizing were not considered, it still gave insight that this could be further investigated. It was found at the knowledge phase that liquid-cooled works much better but requires more maintenance and is less reliable, thus the system should be easily accessible through the inside of the building if there is problem with the cooling of the heat sinks. In this matter, the use of this system would work much better for lower buildings that have an easier access to the façade.

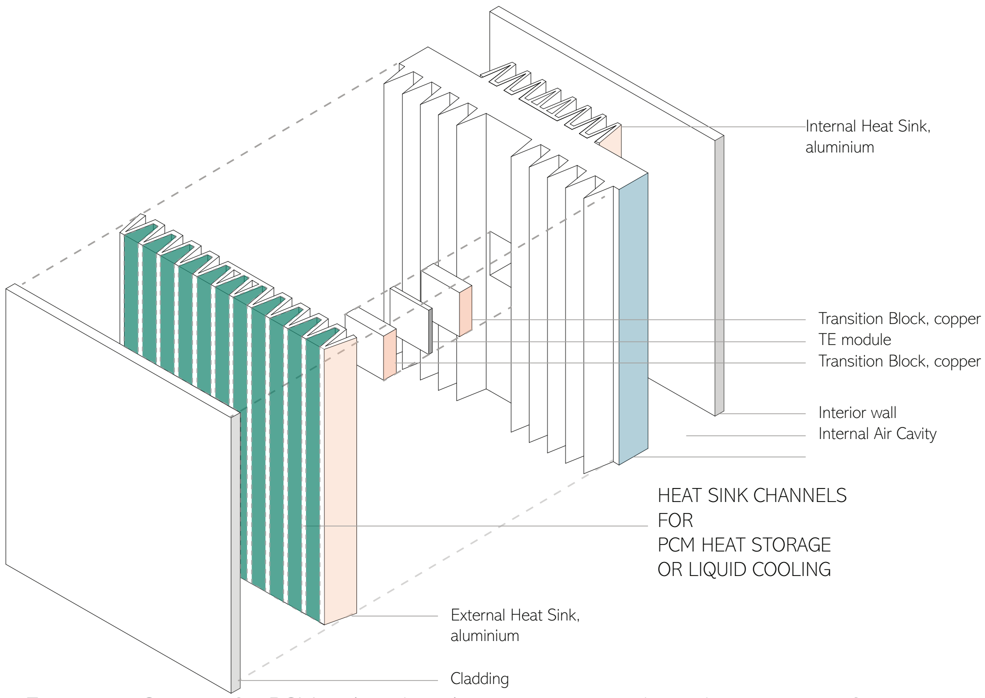

Figure 82. Concept for PCM or liquid cooling integration to heat dissipation configuration.

Another possibility that was widely mentioned in the literature and explored in this research project is the use of fans for forced convection in the system. The real-life experiments showed lower Peltier values for the cold side when a fan was used on the hot side of the module. The problem with the use of fans, beside the extra energy and space that the system will require, was at performance level. When using air velocities, the TE module reached values of around 14 °C, which is in the threshold of creating condensation, thus the use of forced convection does have potential to be implemented but would have to highly monitored or controlled. Adding some temperature and humidity sensors inside the façade could me another possibility.

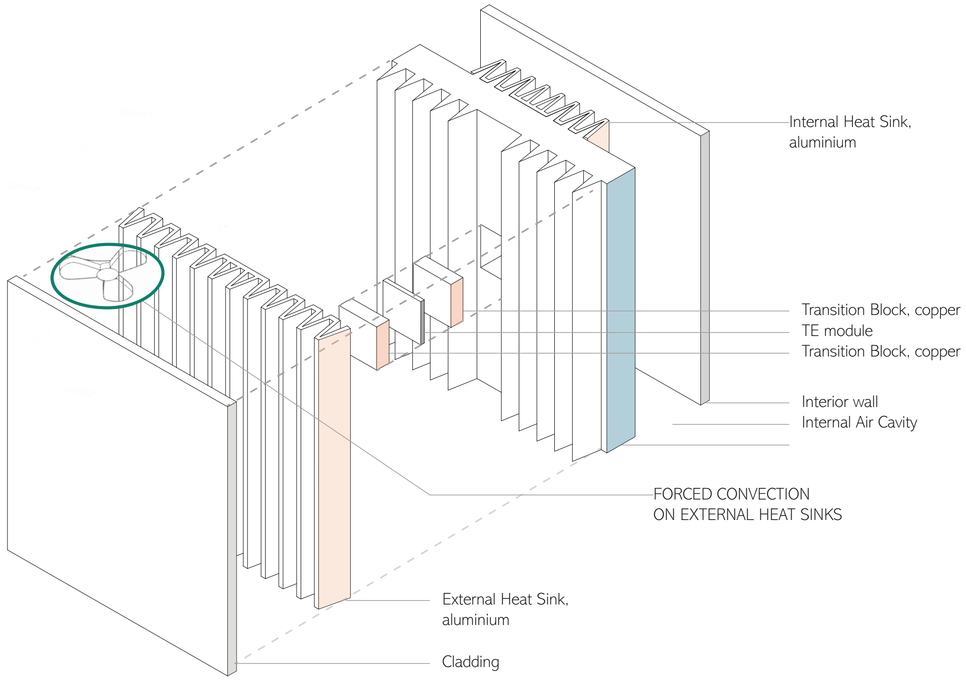

Figure 83.Conceptual integration of fans into heat dissipation system.

The possibility of adding the extraction of air into the façade to make it self-sufficient, could make the façade panel more complex but more complete. The whole façade has 5 different types of panels with similar characteristics but differ in their functionality, the possibility of having a panel that works solely on air extraction could also be part of the system, instead of extracting mechanically through the ceiling. The drawback of this is that the façade cooling system becomes as complex as the air conditioning system traditionally used but adapting this system could be explored.

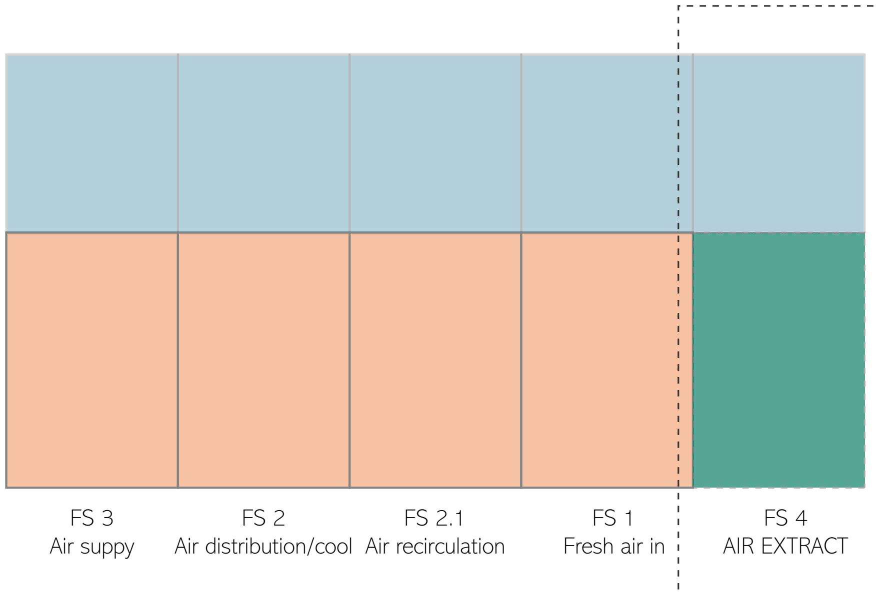

Figure 84.Extra panel for air extraction.

In addition to this, the designed panel does not start with the floor slab, so different panel configurations could be arranged according to taste, but that still respond to the design guidelines and the system order establish in chapter F.4. This allows for different panelling configurations and flexibility, without forgetting to consider the findings on level A with regards to WWR.

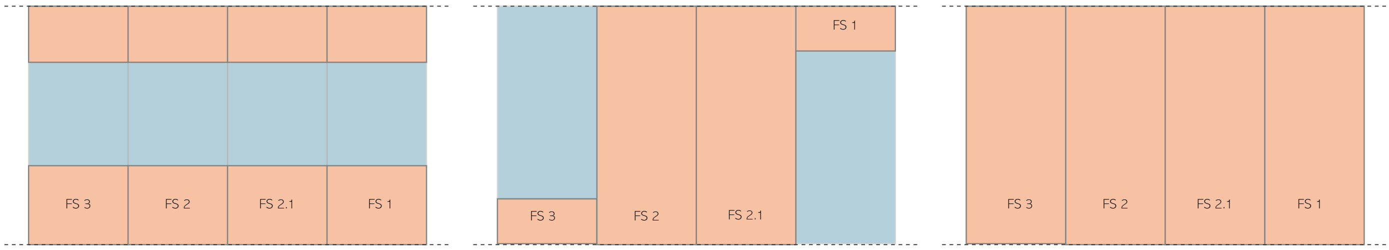

Figure 85.Panel configuration variants.

As it was mentioned, the system as it is designed requires a large quantity of Peltier modules to cool down a complete office floor. As a respond to this, changing its use from an office building to a residential or lower scale building could be another option. The expected cooling loads for residential housing are known to be lower than those in office buildings, since people have a higher comfort threshold at home according to what was found in chapter B.6, and so a cheap and lightweight option with thermoelectrical integrated façade could be possible. As things stand now in the world, the need to have a comfortable space for working from home is growing. If the world starts to shift into working from home, perhaps this cooling demand at residential level will grow and active systems that can aid in energy savings for the household could be an attractive alternative.

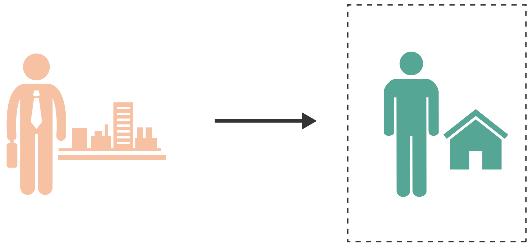

Figure 86. Shift from office studies to residential.

Another option is that everything is congregated into one or two sections of the façade as it was explored by Miryazdi, N. ,(2019), in her thesis project. In that project, a total of five specialized façade panels were needed per floor (with smaller floor plan). This could be pushed than even more to the extreme, where you have a bigger module filled with the TEM system, like vertical ventilation shaft that works as cooling system on one part extracts the air to the outside. If all the cooling system is within one element through the building, this makes maintenance and control easier and accessible.

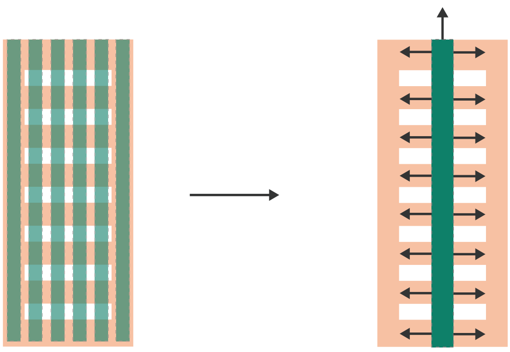

Figure 87. Concentrated system

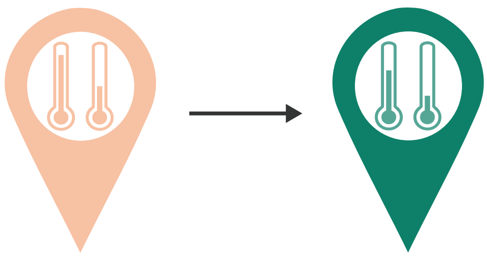

Figure 88. Change of climatic zone

Lastly, adapting the system to a different climatic region could be explored. The TE modules show a better heating capacity, so a climate that has a higher heating demand could be a good option. With the tendency in an increase in cooling degree days in the world as found in chapter A.1, even for typically colder countries, summers will become hotter, and so a system that could have high heating capacity for a temperate to cold weather in winter to enough cooling capacity for the summer could be advantageous.

G CONCLUSIONS

CHAPTER OVERVIEW

This section gives a summary of the final findings of this research Project. First, an overview of how the research questions of this project were answered during the study. A description on possible research that can be followed after this project is also presented. Lastly, some final remarks reflecting on the projected are presented.

G.1 RESEARCH QUESTIONS

Which passive cooling strategies can be adopted to improve overall energy performance and lower cooling demands for hot arid climates?

Based on the hot arid climate of Monterrey and the design parameters found during the knowledge phase, five design strategies that affect all the levels in a certain way, but were assigned to level A to facilitate the process of the study, were found to have an effect on the energy performance of the building. For hot arid climates, an excess of solar radiation affects in many ways, so the first strategy was related to the window to wall ratio. The proper balance of views, natural light and sun block was found for the case study building. The second strategy, the thickness of the insulation did not have an important effect on the overall cooling savings, even though some studies suggested the contrary. Nonetheless, a minimum thickness was used. Thirdly, the glazing type was also essential for the proper regulation of solar gains, but without blocking completely the possibility of natural daylight. For this reason, a Low-E glazing type with no tint proved to be the best solution so as to not increase the energy used through lighting. The use of external shading on certain orientations of the façade was also an adopted strategy for improving the energy performance of the system, and thus horizontal blinds were applied at the southern façade, and if they are dynamic, the system would work even better. The last strategy studied was the use of natural ventilation to aid the building's performance. This last strategy was aimed for observing how much the inclusion of a hybrid system could benefit the energy consumption. The two strategies that contributed the most on the annual energy consumption was the ventilation and the glass type.

What are the main design constraints for the development of heat dissipation system, including possible complementary elements? What implications do these design constraints have on the performance of the TE façade system?

Based on the findings at the knowledge phase, several strategies were studied for the heat dissipation system design such as plate thickness, the extended surface, composition of the heat sinks, material of the heat sink and air flows (natural and forced convection for its cooling).

The first strategy showed the greatest initial impact among all the strategies, since the ideal thickness also depends on the magnitude of the heat source that needs to be dissipated, thought it reaches a limit as it was seen on the simulation with a higher thickness. In this case, a proper balance between material usage and heat transfer its required for the heat sink to be optimal. For the second strategy several iterations were simulated, with variations on the channel types, variation on the compactness of the elements and exploration on both heat sinks having the same size versus different sizes on each side. The variations in shape showed that indeed it has the potential to be optimized to have a better performance. The addition of channels does contribute, but further calculation on the perfect channel quantity versus channel depth would be interesting to explore further. On the other iterations, on compactness versus a larger surface, the value did get better, but there is also a limit in how much the surface can be increased and actually aid the system further, as it was mentioned, the prime surface area of contact impacts more the system, the farther away the channels, the less impact it has on the surface.

In the material explorations, the combination of materials with the heat transfer desired was possible. The addition of cladding did not contribute negatively to the system, and the channels created were later observed on the air flow simulations, contribute to the heat transfer. It is important to note that the explorations with different materials or even presentations of aluminium, such as is the case with aluminium foam, did transfer some of the heat but overall they performance dropped dramatically when compared to aluminium or copper. This suggests that even though the heat sink material is important on the heat sink's performance within the TEC system, the material parameter can stay frozen and explorations on the design strategies can be further addressed. Lastly, the design strategy of manipulating the air flows in the system is addressed. The performance of the system did improve, but not by much when compared to the effect the shape had on the system, only by 0.01 of difference in the COPc. Nonetheless, the counter ventilation had the best results and with forced convection in the inside.

What is the optimal heat sink design plus its complementary elements, if needed, for the heat dissipation of the active TE system?

For this specific context the heat dissipation system is composed of the Peltier modules connected to two heat sinks on either side, with a transition copper plate, the heat sink on the hot side has larger dimensions and is cooled down through natural convection facing the exterior of the building (when in cooling mode), on the interior side of the system, the heat sink requires a smaller dimension since the cooling capacity of the Peltier is lower than that of its heating capacity, and for winter a lower voltage can be used to compensate for the excess heat generation. An air cavity is required, and natural convection aids the heat transfer of the system on the side of the system facing the interior of the building. Finally, proper insulation between the two sides of the Peltier module is required, along with insulation between the two different heat sinks as to avoid any losses in between each other. Although this design showed the best results among the studied components, further optimisation in the shape has potential to increase the system's performance.

Which façade parameters and requirements need to be addressed in this design, for the TEM 's functionality, if situated in an office building, to be integrated?

There were two main design parameters pertaining the façade system that were addressed at composition level, and the rest were highly linked with the results found at the other two design levels. Thus, at this level the main parameter observed was in terms of system configuration and the cooling delivery type. This to aid in the integration of the façade with the typical façade requirements and also to facilitate its maintenance. The cooling delivery system chosen was air based to allow for pre-cooling of the intake of fresh air and the recirculation of the heated interior air. This two strategies were addressed when following the final façade design always taking into consideration the typical façade requirements such as the natural fresh air intake, allowing for natural daylight towards the interior and outside views, without forgetting the normal protection from the outside.

As a result, the façade developing followed certain parameters that responded to all of the scales studied. First, the available space resulting from design guidelines at level A, gave the façade panel sizing and also modular dimensions to give the design some flexibility. After this, the façade module was given a grid that responded to the quantity of modules per module required for the cooling demands of the office plus the heat dissipation system design size. Thirdly, the layering of the façade panel is establish based on the same parameters plus the proper insulation thickness obtained at level A. Next, required cavities are defined for the heat sinks to function based on the office building ventilation requirements. Lastly, the panels have certain modifications based on their functionality. For the panels to properly work as a system a proper connection between the panels that allows for air to flow in between like an air duct system is necessary, without it having any air losses before it reaches its final destiny.

What should be the design of the active cooling with Thermoelectric integration in the façade?
How could a heat dissipation system for an integrated façade with TE active cooling be designed, for it to cover the cooling loads of a typical office building?

The proposed façade system designed for a hot dry climate in an office context was created through the design guidelines that were developed from the results of the experiments, simulations, and analysis. These guidelines show how the design of the TE façade can improve its thermal performance through the use of specific design decisions and strategies addressed previously. Each strategy was also evaluated through their effect on the system and their relationship with the final solution, thus this could aid the designer on making decisions based on these factors. Another important finding is that an optimized heat sink shape based on its heat transfer allows for more configuration variations in the system, the possibility of making the façade less robust, using the heat sinks as part of the cladding is another one, and having a scaled up system for building cooling purposes and not electronic cooling ones.

It should be noted that not all the strategies showed the same impact on the system's performance, though certain patterns could be observed and the affirmation that the performance of the heat dissipation does improve with the morphology of its shape even more so than with the type of cooling system (forced or natural convection). There is already research on this shape manipulation of a heat sink though still at micro scale for electric components, and not based on bigger scale elements for building, Thus, this work explored the possibilities of exchanging typical component usages into other realms of the engineering world and its potential to increase a system's performance, that would have used the typical heat sink.

G.2 FURTHER WORK

This project was focused on the TE system's performance when integrated to a façade in an office typology in a hot arid climate. Throughout this study, a number of new potential research topics have emerged. The following could also be explored:

- Further exploration on the TE material (not by architects)
- The simulation model for level C could be further detailed by modelling the TE module, for more accurate results.
- The heat sink shape exploration showed important effects on the system's performance, and the geometries that could be tested are many. In this case, a proper optimization process linking another a software that could parametrize the heat sink's shape based on specific objectives coupled with the heat transfer model could give even more possibilities to the design of the system.
- An extension could be to have the development of a parametric design tool for this type of façade cooling system. Further studies and simulations on the optimal heat sink geometries that include channel sizing, protrusions (if needed), volume ration, based on the excess heat generated and the heat absorption of the TEM used.
- Physical experiments exploring PCM or liquid-cooling.
- Simulations at building level showed certain insulation thickness, but no explorations were conducted at level component for the insulation that protects the hot and cold side of the Peltier module and how this insulation contributes to the overall insulation of the complete façade. Could the insulation thickness towards the interior be smaller if the dissipation system also uses insulation in between?
- The space to cool down was too big, resulting a high number of TEMs per m2. Nonetheless, this gives room to other opportunities since its size give much potential for a modular

system that could be adapted according to a specific situation. Thus, exploration on modular systems that can be transported for smaller spaces that need to be adapted but whose main structure should remain intact.

- In that same train of thought, the cooling demands of a residential unit are lower than an office building, so adapting this system for that could also be a plausible research line.
- Could this system be adapted to other types of climates? If the TE façade has a higher heating capacity, explorations with climates where higher heating capacities are needed but lower cooling capacities, could be another possible research path.

G.3 REMARKS

The aim of this research project was to determine ways in which the heat dissipation system could improve the performance of an active thermoelectrical façade in an office building for a hot-arid climate. It essentially consisted an exploration of different design parameters and their effect on the way the system performed. To make the evaluation and design easier to process, the design was divided in three different scales: component level, façade level and building level. At component level, existing research on heat sink design was used to identify different strategies that could affect the heat dissipation performance. At building level, which passive strategies should be applied to lower the energy demands of the office building was researched. For the façade scale, existing research on TE integrated facades was studied and analysed to find the main research gaps and integration possibilities. The design strategies to evaluate were all limited by the contest climate, building typology and the use of TE materials,

A combination of experiments and simulations were used to determine the effect certain design parameters have on the thermal performance of the heat dissipation system. Parallel to this, an office case study was selected, and simulations performed to determine the ideal passive strategies for reduction cooling load in a hot-arid climate. A stepped methodology was used for the experiments and simulations for the heat dissipation system and a comparative evaluation on different passive design strategies for the office design was applied. A simplified heat transfer model for the heat dissipation of the thermoelectrical technology was developed, where a series of design strategies were possible to be tested. Analysing the results determined which parameters had a greater impact on the design, for the heat dissipation system its performance was evaluated through its COP, and for the office design lower cooling loads were the defining parameter.

General trends were identified on both evaluated levels and each show their potential. These were then translated into design guidelines for the heat dissipation system and office building design and then visualized as a final thermoelectrical facade design. The final COP of the cooling system based on the heat dissipation designed was 1.40, nonetheless a final simulation façade scale or a prototype of the system should be performed to corroborate this value. At the end, the system does become somewhat complex since it requires different façade modules that respond to their function and a high number of TE modules. Nonetheless, part of the complexity comes only because it is a technology whose application in interior cooling has just recently been explored.
The results enforced that the system has potential to be further developed. It is still in early staged of research and development, but the different analysis and evaluation process done during the research project showed that proper manipulation at the different scales explored does improve the performance of the system. Searching for different alternatives in existing technologies and how energy efficient buildings are envisioned could be the next step into reaching zero energy usage buildings.

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I APPENDIX

I.1 CASE STUDY SELECTION

A list of the office buildings studied.

#	Building	Function	Facade Type	Main Facade Material	Size	Image	Architectural Firm
1	Torre Koi	Office + Residences	Curtain Wall	Glass	Big		VFO Arquitectos
2	Torre Pabellón M	Offices + Hotel	Curtain Wall	Concrete + Glass	Big		Landa Arquitectos
3	Torre Ciudadana	Governmen t offices	Curtain Wall + Concrete	Concrete + Glass	Big		Coordinación de Proyectos Estratégicos Urbanos del Estado de Nuevo León.Desarrollo. - Oficinista.
4	Torre Dataflux	Offices + Residence	Curtain Wall	Concrete + Glass	Big		Landa Arquitectos

5	Torre Helicon	Offices	Curtain Wall	Glass	Mediu m		Vidal Arquitectos
6	Torre Meridiano	Offices	Curtain Wall	Glass	Mediu m		Pozas Arquitectos
7	Metropolita n Centre	Office + Hotel	Curtain Wall	Glass	Big		Motiva Desarrollos
8	Torre Valle Oriente	Office + Residences	Curtain Wall	Glass	Big		RDLP Arquitectos
9	Torre San Pedro	Offices	Curtain Wall	Concrete + Glass	Small		RDLP Arquitectos

I.2 RESULTS VALIDATION

The validation of the simulation was done with steady-state hand calculations at 2:00 pm the 12 of July and compared to the results obtained with Design Builder.

I.2.1 Transmission

$$Q_{transmission} = \sum U * A * (T_{out} - T_{in})$$

The U is the thermal transmittance of the wall in $W/(m^2 \cdot K)$, A is the area of the wall in m^2, T_{out} is outside temperature in degrees Celsius and T_{in} is the temperature inside the building also in degrees Celsius. Since the whole façade is composed of spandrel and glazing system, the transmission values are only divided in these two elements. The total $Q_{transmission}$ of the building is 5.38 kW.

	Area ($\boldsymbol{m^2}$)	U-value $\boldsymbol{W/(m^2 \cdot K)}$
Spandrel System Wall	203	0.644
Glass Curtain Wall	301	1.772

Table 1 Transmission through wall of Koi Tower

I.2.2 Ventilation

For ventilation the following formula was employed:

$$Q_{ventilation} = V_{ventilation} * n * \rho * cp * (T_{out} - T_{in})/3600$$

Here V is the volume of the room, n is the air exchange rate, 1/hr, ρ is the density of the air, kg/m^3, and cp the heat capacity of the air at constant pressure, J/kgK . The air excahnge rate used was 3 1/hr and total volume of the space of 3072 m^3. The total $Q_{ventilation}$ of the building is 24.95 kW.

1.2.3 Infiltration

$$Q_{infiltration} = V_{infiltration} * n * \rho * cp * (T_{out} - T_{in})/3600$$

For the infiltration calculations, the air exchange rate used was 0.7 1/hr. The total $Q_{infiltration}$ is 5.82 kW.

I.2.4. Sun

$$Q_{sun} = A_{glass} * q_{sun} * G\ value$$

q_{sun} is the intensity of the solar load, W/m^2, which in this case amounts to 0.1 W/m^2; the G value [-] refers to the solar factor, and in the climate zone we are focusing on equals to 0.81. The Q_{sun} equals to 24.46 W.

I.2.5 Internal

The internal loads are composed of the conditions inside the building such as the number of people, the equipment and lighting used. The sum of all these factors amount to a $Q_{internal}$ of 27.50 kW.

$$Q_{internal} = Q_{people} + Q_{light} + Q_{equipment}$$

No. of People	Heat per person (W/person)	$\boldsymbol{Q_{people}}$ (W)
87	100	8700

Table 2 Q people calculation data

Light floor (%)	Floor Area($\boldsymbol{m^2}$)	Light Power	$\boldsymbol{Q_{light}}$ (W)
80	790	15	9492

Table 3Q light calculation data

Equipment Power ($\boldsymbol{W/m^2}$)	Floor Area ($\boldsymbol{m^2}$)	$\boldsymbol{Q_{equipment}}$ (W)
11.77	790	9310

I.2.6 Total Cooling Load

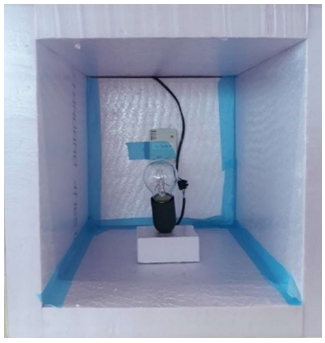
Adding all the calculated heat loads before amounts for the total cooling load required by one floor of the office tower.

$$Q_{cooling} = Q_{transmission} + Q_{infiltration} + Q_{ventilation} + Q_{sun} + Q_{internal}$$

The total cooling is 63.68 kW at 2 P.M., 12th of July.

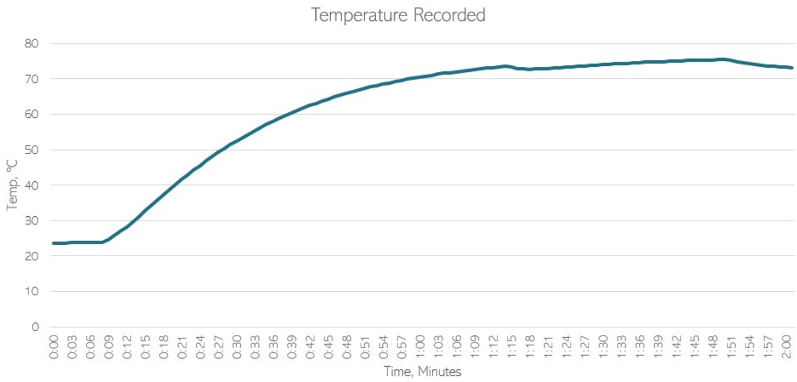
I.3 THERMAL BOX CALIBRATION

The thermal box had to be calibrated to know its actual heat transmission. For this, a 30 W light bulb was used as a heat source and the temperature change within the box recorded to observe when it reached its steady state. The effect on the heat transmission with and without the heat sink was desired, so two tests were conducted with the same conditions, except one had the heat sink at the opening area instead of another layer of extruded polystyrene.



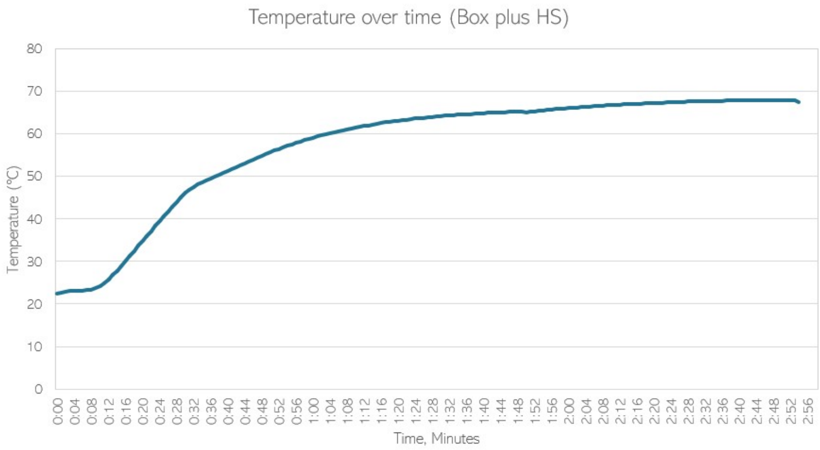
The following equation was used for the simple calculations on both situations, where Q equals the 30 W heat source, the calculated U-value is 0.67 W/(m^2 K) with the heat sink and 0.73 W/(m^2 K) without the heat sink. Solving for ΔT , the expected temperature difference was 46.6 K with the heat sink and 42.0 K without the heat sink.

$$Q = U * \Delta T \ (W/m^2)$$



Graph 26.Temperature recorded inside the thermal box without the heat sink

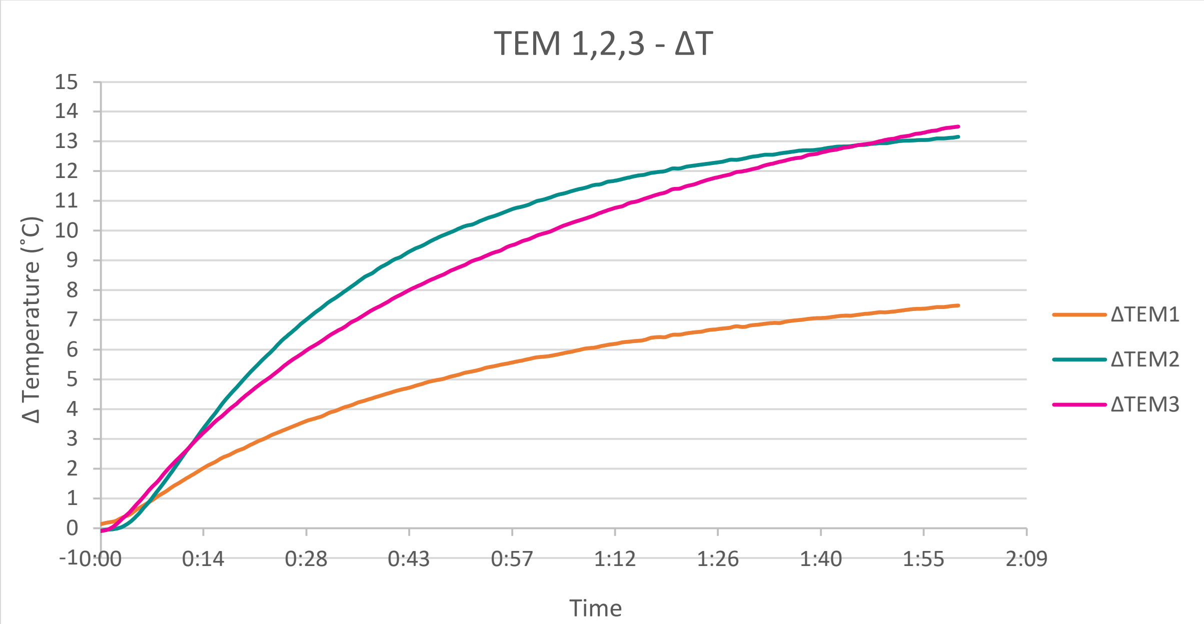
The graph showed that it reached a steady state around one hour in, but then, due to changes in the outside temperature, it readjusted again. Numerical values showed that it would take 40 minutes to reach the steady state, but experimental values show that it took one hour. This could be the case since there is human error present, and the thermal chamber was homemade and built with the available material.



Graph 27.Temperature recorded inside the thermal box with the heat sink

Similar to the test conducted without the heat sink, the thermal box reached a steady state around 1 hour into the experiment and gradually changed due to the change in outside temperature. The experiment values showed a ΔT of 42.0 K with the heat sink and 48.5 K without the heat sink. Calculating the real heat transmission for both situations, the U-value of the thermal box with the heat sink was 1.03 W/(m^2 K) and without the heat sink 1.02 W/(m^2 K). In both cases, the U-value is much higher that of the originally calculated, but there is not much difference between the two situations, which is one of the main aims.

As it can be seen on graph 28, TEM 2 and TEM 3 had a similar temperature increase for the hot side of the module, whereas TEM 1 did not had such a steep increase on temperature. On the next graph, the results for the cold side of the module show TEM 1 and TEM 3 having very similar behavior, TEM 2 reaching a lower temperature but increasing more rapidly than the other two modules.



Graph 28.ΔT against time, of the three modules tested (TEM1, TEM2 and TEM3)

A comparative graph of the ΔT of each module was also made to check their overall performance. From the knowledge phase it was determined that a lower ΔT allowed for a better performance of the Peltier modules. In this case, TEM1 showed the best performance of the three with a maximum ΔT of around 8 ˚C. Since TEM 1 showed a more stable increase in temperature and a lower ΔT, this Peltier module was used to conduct the rest of the tests.

I.5 THERMOELECTRIC PROPERTIES OF TEC1-12706

Calculation of the Seebeck coefficient, the electrical resistance, and the thermal resistance of the thermoelectrical module was done with the following formulas. They were calculated based on the input values obtained from simulation at level C and the manufacturer datasheet and later used for the calculation of the cooling capacity at component level and façade level.

$$S_m = \frac{V_{max}}{T_{h0}} \quad (3)$$

$$R_m = \frac{(T_h - \Delta T_{max}) \cdot V_{max}}{T_{h0} \cdot I_{max}} \quad (4)$$

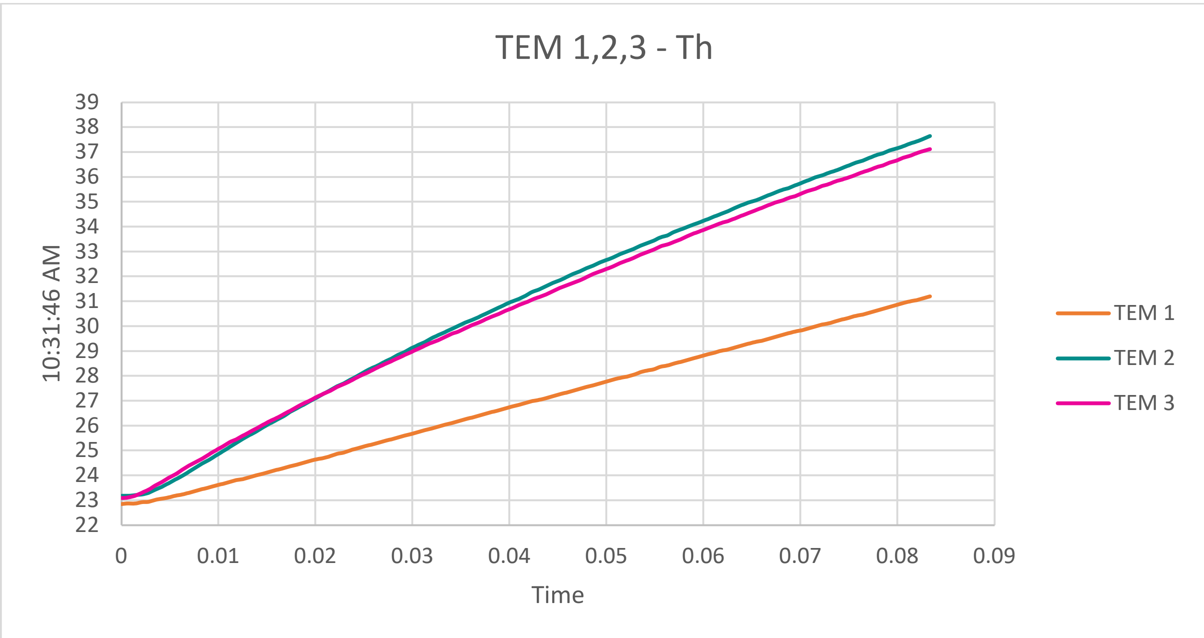
$$K_m = \frac{(T_h - \Delta T_{max}) \cdot V_{max} \cdot I_{max}}{2 \cdot T_{h0} \cdot I_{max}} \quad (5)$$

α at 25 C	0.04832
α at 50 C	0.05075
R	1.8964
K	0.5178

I.4 PELTIER MODULE VALIDATION

The Peltier modules were tested on the thermal box, and the temperature in both sides recorded for two minutes every second with the aid of the external probe of the Dataloggers. (a test of 15 minutes with no heat sink resulted in the Peltier element ceasing to work) The hot side of the Peltier module was facing the exterior of the chamber and the cold side, the interior of the chamber. The power supply used was Minleaf DC Power Supply, model NPS3010W. All the tests were done with an input of 3 volts, and the current was a minimum 0.74 amps and a maximum of 0.76 amps. As for the power required it showed a minimum of 2.21 Watts and a maximum of 2.25 Watts for the same amount of voltage. The ambient temperature had an average of 22.63 °C and the inside of the hot box 23.16 °C during the tests.

TE MODULE TESTING					
num	TE module	TE quantity	Voltage (V)	Current (amps)	Power (W)
TEM1	TEC1 - 12706	1	3	0.76	2.25
TEM2	TEC1 - 12706	1	3	0.74	2.21
TEM3	TEC1 - 12706	1	3	0.75	2.24



Graph 29.Surface temperature change of the hot side of the Peltier module

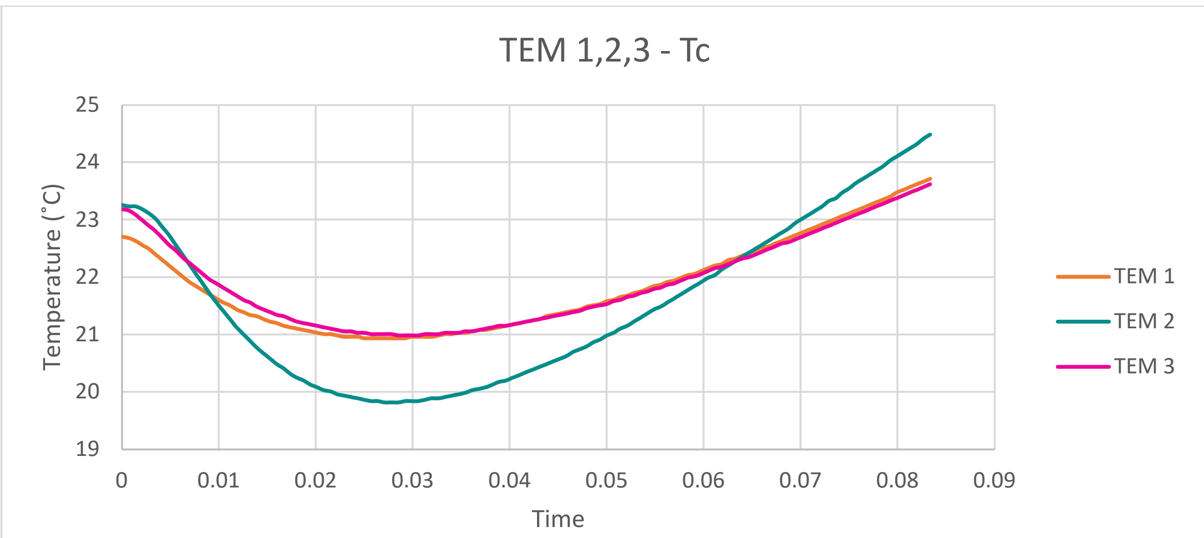
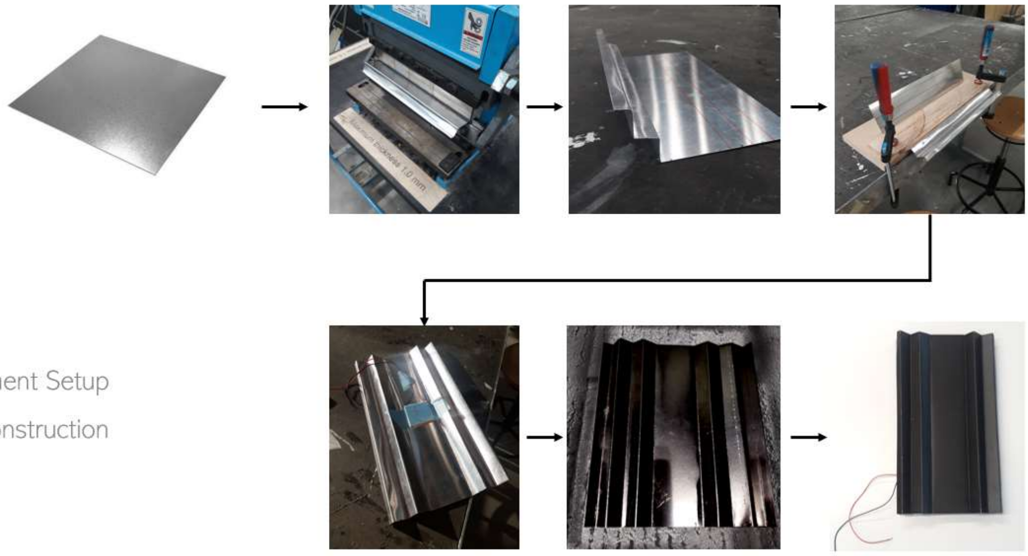


Figure 89. Surface temperature change of the cold side of the Peltier module

I.6 SPECIMEN CONSTRUCTION PROCESS

Experiment Setup

Heat Sink Construction



*Due to machine available, only thicknesses of 0.8 mm and 1.00 mm were constructed