18

The Building Envelope

The sensitivity analysis of energy efficiency in office buildings published by Mechri et al. shows a very strong relevance of the envelope transparent to opaque ratio A_t/A_e and a much lower importance of the building orientation and proportions (Mechri et al. 2010). This finding was supported by the previous case study. In this chapter we will investigate the A_t/A_e ratio by means of multi-objective search algorithms. This study involves the masonry envelope thickness and the window materials and construction.

Goia et al. studied optimal A_t/A_e ratios for 4 european climates, Rome, Athens, Frankfurt and Oslo. They performed a parametric analysis, increasing the A_t/A_e ratio step by step, and calculating a total energy requirement E_{tot} (Goia et al. 2012). They performed this study in all four locations, in North, South, East and West orientations separately.

> "The results clearly show that each climate requires a dedicated optimized solution, being the minimum value of E_{tot} reached for different window to wall ratio, depending on the climate. The south exposed façade module is the one that has the highest variation, if located in a cold or in a hot climate. Furthermore, except the coldest climate, west and east-exposed façade modules are always those with the highest energy need."

(Goia et al. 2012)

Wright and Mourshed used genetic algorithms to optimize fenestration configurations for a large atrium located in the city of Chicago (USA)

(Wright & Mourshed 2009). The objective of their study is that of minimizing E_{tot} by using a window cell parametric model. This model is the same described in chapter 11.2.1. Also in this case, single orientations are studied at a time. The results of the study are described by the authors as follows:

> "Given that, each optimization experiment resulted in a different distribution of window cells, but that the optimized energy and window area was of the same order of magnitude in each case, it is concluded that, for the example building studied here, the position of the window cells has only a "second-order" effect on energy use. However, in the results from all experiments, the optimized position of the windows cells was biased towards the top-west corner of the façade. Locating the windows towards the top of the façade results in the penetration of daylight to a greater depth in the atrium; correspondingly, this reduces the energy use from artificial lighting, particularly when the windows are positioned towards the top-west quadrant of the façade. The position of the windows also has an impact on the distribution of the beam solar radiation on the internal surfaces of the atrium, which in turn affects heat loads through the different heat loss and storage effects of the various construction elements."

(Wright & Mourshed 2009)

The studies presented in this PhD thesis do not consider orientations separately, the search process is conducted with four orientations simultaneously. There are two important reasons for this:

- There is no reason to believe that by combining 4 optimized façades for North, South, East and West orientations into a single building would result in an optimal energy efficiency design. It is only by means of a search process that considers all façade simultaneously that we can be sure to obtain an optimal building design.
- During the early stages of design, architects are most likely to consider the buildings shape, fenestration and orientation as a whole, and not consider them in separate detailed orientations.

The efforts presented in this chapter consider the 4 orientations of an office building simultaneously.

18.1 Case Study 9: Masonry building envelope - Sub-urban context office building

The first case study in this chapter refers to the same office building used in case study 8. A rectangular office building in a sub-urban context with a masonry envelope. The important differences in this case study lie mostly in the parametric model, the problem variables. This case study keeps building size fixed at 20×14 m and the envelope thickness is variable. The buildings are studied in the same 4 climates as seen above: Palermo, Torino, Frankfurt and Oslo.

18.1.1 Parametric model

The parametric model used in this chapter follows the same geometric rules than the one described in chapter 11. As was discussed in chapter 11, this parametric model is dependent on the selection of the number and configuration of window influence areas. Hence, in oder to cover a large part of the solution space, more that one parametric model and search processes are needed. Figure 18.1 shows two parametric models used in case study 9. The first model (a) uses one single window area that covers the entire length and hight of each façade. The second model (b) uses 4 window areas distributed along the length of each façade. In this configuration, each window area covers 1/4 of the length of the façade and its full height.

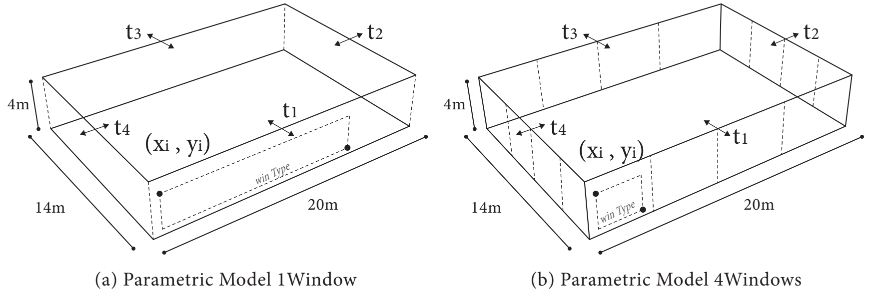

Figure 18.1: Parametric Models for Case Study 9 - (a) Model with one window area per façade - (b) Model with four window areas per façade.

Along with the variable widow configurations, this parametric model also changes the wall thicknesses in each façade, as was previously seen in the structural case in chapter 11. In this case however, thickness variation is used not for structural capacity, but for increased shading on the windows from the masonry overhangs and fins. Increased external wall thickness has also an influence on the thermal transmittance U of the wall. It is the purpose of this case study to consider the influence of the thickness as a shading device, and not on the thermal transmittance of the wall, therefore, for the search processes in this PhD thesis a fixed U-value of 0.33 W/(m^{2}K) was chosen. In order to maintain a fixed U value while still varying the thickness of the brick walls, the thermal insulant EPS was employed with a variable thickness. The EPS thickness for each wall is calculated in the parametric model, in such a way as to have the required thickness to keep U at 0.33 W/(m^{2}K). Table 18.1 shows the materials used in this case study.

Table 18.1: Characteristics of materials for case study 9.

Material	s	λ	ρ	c_p
	m	W/(mK)	kg/m^3	J/(kgK)
External gypsum	0.02	0.9	1800	840
EPS	Variable	0.031	112.1	1450
Bricks	Variable	0.5	1600	840
Internal gypsum	0.01	0.7	1400	840
Floor slab	0.25	0.678	1280	1000
Floor tiles	0.02	2.69	2700	984
Air gap	0.13	R:	0.18	m^{2}K/W

An important difference between these models and the one presented in chapter 11 in the fact that the window construction is also variable. This is the first case in this PhD thesis in which material properties are the subject of the search. The parametric model used has the ability to select a window construction from the ones shown in table 18.2. The model selects one window construction from the table, and uses it for all of the windows in the building. As shown in table 18.2, window constructions vary in the number of glass panels, the presence and position of low emissive coating, thermal transmittance etc.

The number of variables in this case study is a high one. There are 4 thicknesses and one window construction plus 4 variables for each window

Table 18.2: Window constructions for case study 9.

Number	Composition mm	Position low-e coating	U_g $W/(m^2K)$	g_g -	τ_1 -
0	$4g; 12air; 4g$	-	2.68	0.77	0.81
1	$4g; 12air; 4g$	3	1.31	0.60	0.80
2	$4g; 12air; 4g$	3	1.31	0.64	0.82
3	$4g; 12air; 4g; 12air; 4g$	3, 5	0.72	0.50	0.71
4	$4g; 12air; 4g; 12air; 4g$	2, 5	0.74	0.55	0.71
5	$4g; 12air; 4g; 12air; 4g$	3, 5	0.72	0.54	0.75
6	$4g; 12air; 4g;$	2	1.31	0.41	0.71
7	$6g; 16air; 4g;$	-	1.14	0.27	0.60

U_g is the thermal transmittance of the glass construction ; g_g is the solar energy transmittance of glass ; τ_1 is the spectral transmittance of the outer glass pane.

area. This amounts for 21 variables for model (a) and 69 for model (b).

18.1.2 Fitness functions

The object of this case study is to search for energy efficient solutions. We will be using the same 3 separate energy calculations for heating, cooling and lighting energy needs that we used in the previous case study. The fitness functions for case study 9 can be explained by the following expression:

$$Case\ Study\ 9 \begin{cases} Minimize & f_{1(x)} = Q_{H,nd}, \\ Minimize & f_{2(x)} = Q_{C,nd}, \\ Minimize & f_{3(x)} = Q_{E,nd}, \\ subject\ to & 0 \leq x_{winPoints} \leq 1. \\ & 0.05 \leq x_{thickness} \leq 1. \\ & 0 \leq x_{winType} \leq 7. \end{cases} \tag{18.1}$$

18.1.3 Genetic algorithm inputs

NSGA-II explores 100 generations with 50 individuals in each generation. The overall genetic inputs for this case study is as follows:

Case Study 9		
Population Size (N)	50	
Number of Variables	21 for model 1	69 for model 2
Number of binary digits	8 for win Points	6 for thickness
Variable Domains	$x_{winPoints} \in [0, 1]$	$x_{thickness} \in [0.05, 1]$
Mutation Probability (p_m)	0.2	
End Condition	End after 100 generations	

18.1.4 Results

Figures 18.2 and 18.3 show the objective spaces and Pareto fronts resulting form case study 9 and figure 18.4 shows a few relevant solutions from the Pareto fronts. The energy requirements for heating, cooling and lighting for all locations vary greatly in this case study. For example, cooling needs for Palermo vary almost 80 kWh/m^2 a year form the best to the worst performing solution in the Pareto front. When compared to the variations seen in the orientation and proportions study, we can note the great importance of the A_t/A_e ratio as explained in (Mechri et al. 2010).

Each objective space presents results for both parametric models (the one window per façade model, and the 4 window model). Looking at the results we can see that the one window model covers a wider area of the objective space. The best performing solutions in most cases are found by the one window model. There are two possible explanations for this result:

- The one window model contains the best performing solutions for all functions in all locations. The four window model is unable to propose solutions that outperform the single window model.

- Since the four window model has a greater number of variables that the single window model, and the GA ran the same number of generations for both models, the exploration on the first model is greater that the second one. In other words, the search space in the four window model is much larger, and in order for us to make a comparison between models, a greater number of generations need to be performed in the larger model.

The second reason is certainly true, exploration in the second model is inferior due to search space dimensions. The first reason is unlikely to be true. There is no evident reason to state that the second model contains inferior solutions to those in the first model. However, with the results obtained in this study, there is not enough information to rule out this possibility. The purpose of this study is not to compare the two models, but to study the behavior of the proposed buildings with our fitness functions. Therefore we will study the results as they are, and consider solutions from both models, regardless of the exploration level they have achieved.

While heating, cooling and lighting energy need values vary greatly between climate locations, Pareto front shapes for all climates share overall similarities. There seems to be a high level of contrast between heating and cooling requirements, and between lighting and cooling requirements in all locations. There is a very low level of contrast between heating and lighting in all locations. This results are not surprising, but a close examination of the resulting shapes reveals interesting and more specific information found in this study. Figure 18.4 Pareto Solutions for all climate locations. Results will be discussed not by location, but by fitness function.

Cooling Requirements

Solutions A represent the best performing solutions for the cooling requirements for each location respectively. We can see that all A solutions are quite similar to each other, with the exception of Oslo. Solutions A for Palermo, Torino and Frankfurt all have a single wide and short window in the south façade that is positioned very high in the wall. These solutions have very thick walls in all orientations, but most especially in the south façade. High thicknesses means that these short windows are very well shaded by the masonry overhangs. The absence of windows in the east and west orientations is explainable, the GA is avoiding solar heat gains to keep cooling needs low. It could be argued that the best solution for some of these climates could be one without any windows at all. However this is not the case in these results, the solution without windows is outperformed by solutions with the high and wide south facing window. The fact that the window is positioned high in the wall insured an effective lighting strategy. And this is the reason why it outperforms the solution without windows. The lighting fixtures themselves are a significant internal heat source, and since the energy model used in this study uses a dimmer to reduce lighting when it is not needed, the more daylight is present in the room, the less internal lighting heat is introduced. Therefore, if the south facing window is well shaded, but still introduces indirect light, the cooling loads are lower.

Oslo has very small cooling energy needs, and thus the resulting solution in this fitness function is not very significant. However, results are interesting. The Oslo configuration has no window towards the south, it is

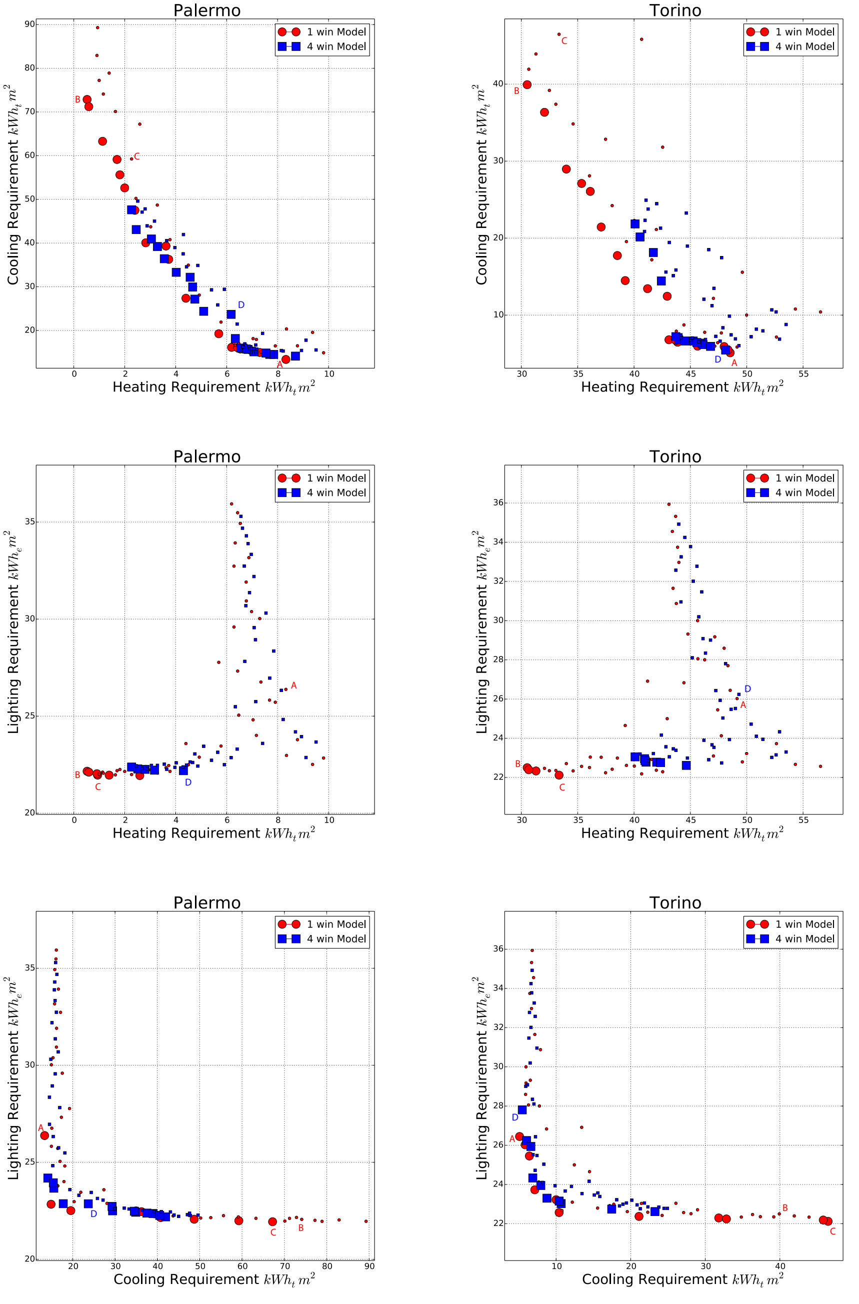

Figure 18.2: Objective spaces for Case Study 9 for Palermo and Torino.

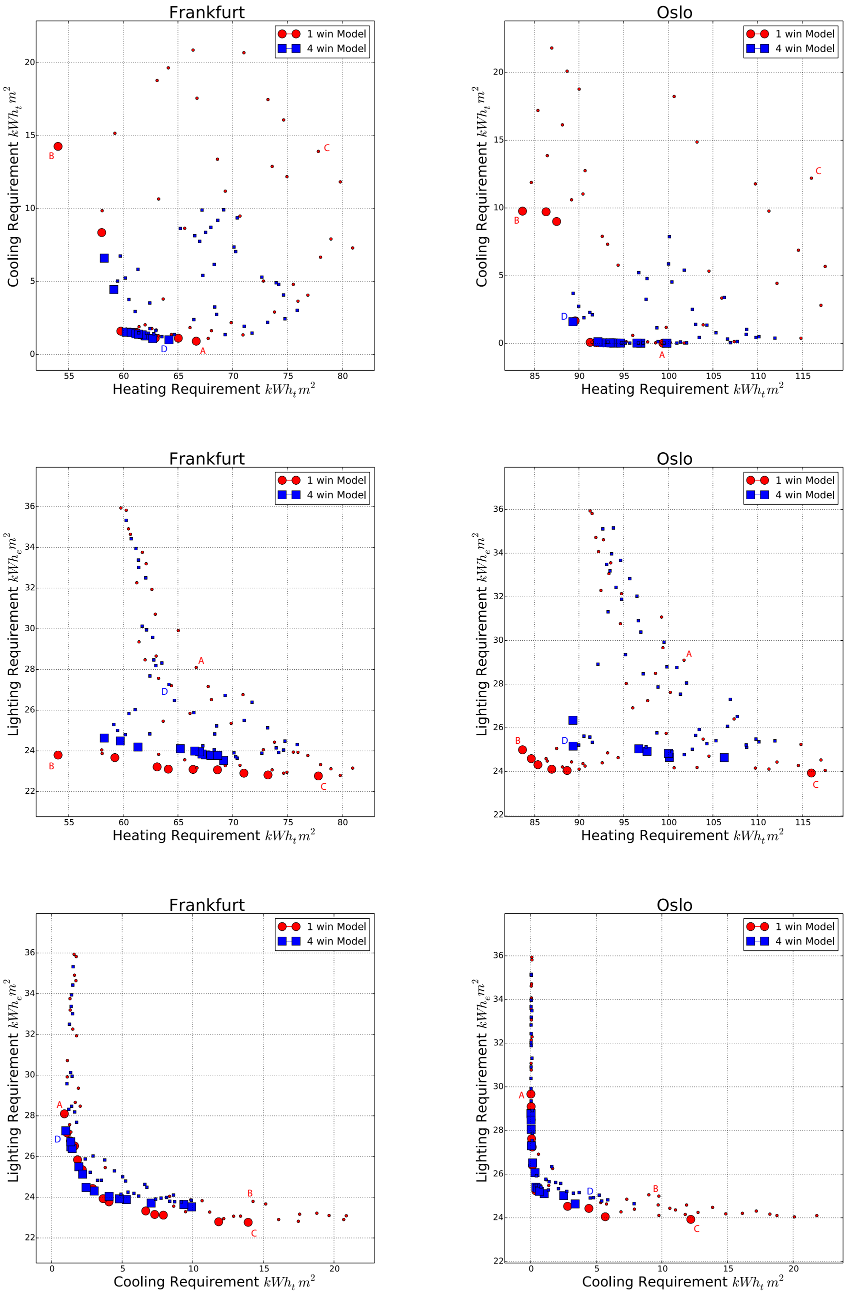

Figure 18.3: Objective spaces for Case Study 9 for Frankfurt and Oslo.

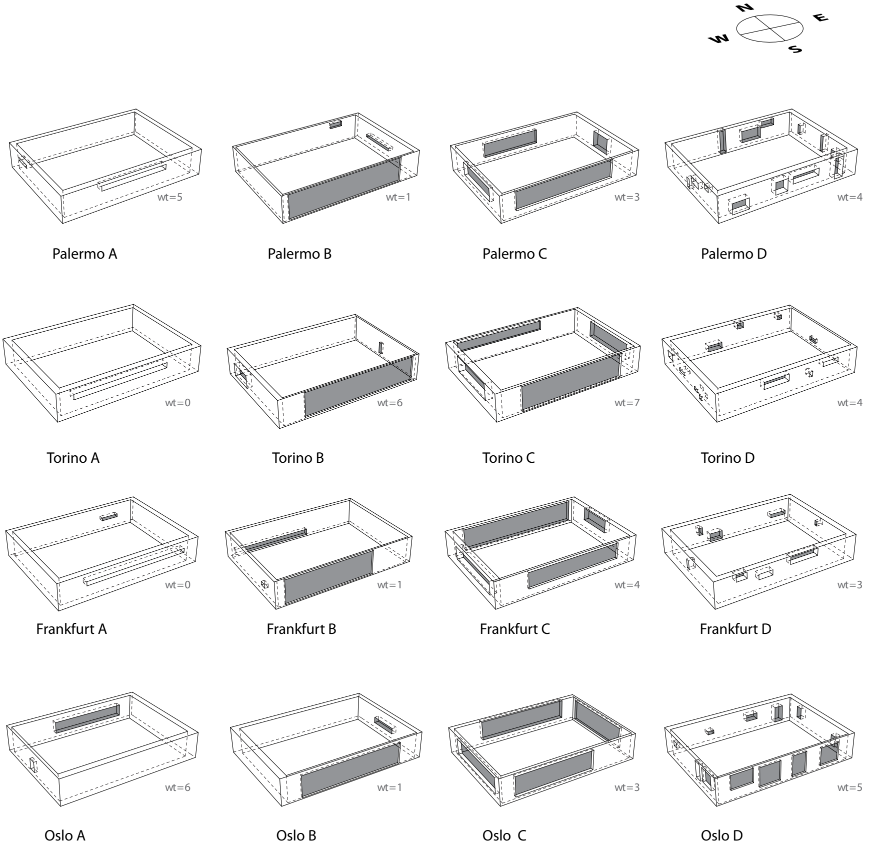

Figure 18.4: Pareto Front Solutions for case study 9.

characterized by a large and tall north-exposed window. This result could be explained by the fact that the sun-paths during the summer months in Oslo's Latitude is not as high as it is in the other climates (see figure 16.4). Lower sun-paths are harder to shade with overhangs, thus the GA opted to have no south-facing windows, and reduce lighting requirements by having a large north-facing window.

Another important aspect to look at in the best performing solutions for cooling requirements is the window type selected by the GA. Window type for Palermo is number 5 in table 18.2, Torino and Frankfurt have window type 0 and Oslo has type 6. Window Type 0 is characterized by having a high visible transmittance of the outer glass pane τ_1, insuring high transmittance of visible light. This selection makes sense because of the lighting internal gains considerations made above. Types 5 and 6 have low solar transmittance values g_g , thus reducing solar gains.

Solutions A tend to be among the worst performing ones for heating and lighting needs since they tend to avoid solar radiation, and introduce just enough light to keep internal gains low.

Heating Requirements

Solutions B are the best performing solutions for the heating energy requirements. Solutions in all locations have very large south facing windows that are not shaded by thickness and are as tall as the wall height. It is clear that the reason for them is to maximize solar gains during the winter months in order to reduce heating loads. Windows in other façades are very few and very small. Solar gains in the winter months are mostly significant only in the south façade, and very poor in the others. Since U values of the window constructions are significantly higher than the wall construction (0.33 $W/(m^2K)$) the GA avoids windows in non-south façades. The small solar gains acquired by east-west windows during the winter months are not worth the loss of energy due to high U window surfaces.

Window types selected by the GA for the winter months are mostly characterized by having among the lowest U_g values, especially type 3, selected for the Palermo and Oslo locations.

Another interesting trend among results is the presence of high thicknesses among the walls with the exception of the south facing walls. South walls are kept thin to avoid shading, but other walls have much higher thicknesses. This is perhaps more evident in the Oslo B solution. The explanation for this finding can lie in the internal mass of the envelope. The office building model uses in this study contains no internal masses apart from the ones introduced by the walls. Having higher internal masses seems to increase the energy efficiency for the winter months, the accumulation of heat in the mass could be responsible for better start-stop heating cycles.

B solutions are very poor performers in the cooling function, but are among the best in the lighting function since they introduce a good amount of direct sunlight.

Lighting Requirements

Solutions C represent the best performing for the lighting function. The lighting function leads the GA to produce solutions that have large windows in all façades. Solutions in this category tend to be poorly shaded, especially in the south façade.

Window types selected for this function (4 ,4 ,3 and 5) are among the ones with the highest τ_1 values, while curiously not selecting the highest (type 2).

A low level of contrast would be expected between lighting and heating functions, and this seems to be true for the Palermo and Torino climates. Heating energy needs vary a little between solutions B and C in these locations, but solutions C are never as optimal as solutions B. Frankfurt and Oslo show a large level of contrast between these two functions. Solutions B and C in these locations have very high differences in heating needs, reaching as much as a 32 kWh/m^2 difference in Oslo. The reason for this was already explained above, high window areas loose heat, and are not worth it in north, east or west orientations.

Four Window Model

Apart from the best performing solutions for each function, other solutions are singled out in this section. Solutions D represent interesting results belonging to the four window model.

Solution D for the Palermo location is an interesting compromise solution in the Pareto front. It has a series of mid-size windows in the north and south façades, and very small ones in the east and west ones. All windows seem to be very well shaded, meaning that they introduce very little direct solar radiation, but a good amount of indirect light. As a result, solution D for Palermo is among the best in the lighting function, and has a fair performance in the cooling function, having $10kWh/m^2$ difference from solution A. Solution D is not a very good performer in the heating function, but since heating need in Palermo are very low to begin with, this fact can be overlooked. Solution D includes window type 4 that has a low g_g value, helping to contain the cooling needs.

Solution D for the Torino study has a series of very small windows distributed among all orientations. They are very well shaded and tend to be wide and short. Solution D has a type 4 window. Solution D is a very good solution for the summer months, significantly containing the solar gains. It is not a bad solution for lighting needs, but it is a poor performer in the heating function.

Solution D in the frankfurt location is quite similar to the Torino D. It has small windows well distributed. However, in this location, these well distributed and sized windows not only insure a good cooling and lighting performance, it also means that solution D is above average in heating needs, being close to $10kWh/m^2$ behind the best heating performer.

The Oslo location produced the best compromise in this study. Solution D for Oslo is well above average in all functions, having a less than $5kWh/m^2$ difference from solution B in the critical heating function. It has 4 large windows facing south, insuring a good solar gain in the critical winter months, and very small windows in the other façades. This solution has the best U_g value available, and also has good thicknesses, insuring high insulation and good internal mass.

It was previously stated that the results do not show definitively that the four window model contains superior solutions in any of the functions. However, there is good reason to suspect that with further exploration, this model can vastly improve its capabilities. It also shows very good compromise solutions come out of it, thus justifying further research into higher window area models.

18.2 Case Study 10: Masonry building envelope - Urban context office building

A second study of the window arrangements in an office building in four european climates is performed, this time having an urban context. The sub-urban study did not have any adjacent buildings casting shadows on its façades. As we have seen in previous studies, solar radiation plays a fundamental role in the energy efficiency of the buildings and by consequence the GA selects solutions that make best use of it. Urban context have adjacent buildings shading façades and therefore window arrangements generated by the GA should have significant differences. Figure 18.5 shows the characteristics of the urban context used for case study 10. It shows a grid of 20×14 buildings with a 14 meter street and sidewalk between them.

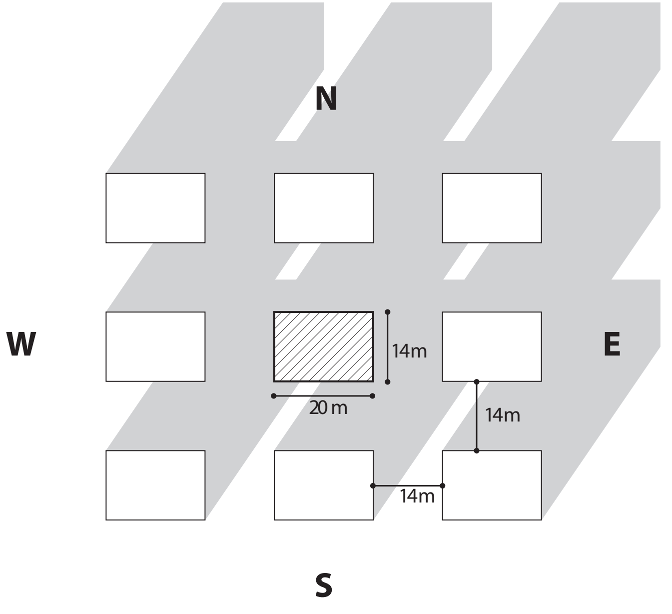

Figure 18.5: Urban context configuration used for case study 10.

18.2.1 Parametric model

This case study employs the same two parametric models used in the previous study, the one window and the four window area models shown in figure 18.1. The model contains the same variable window geometry, wall thickness and window construction types. The window construction types are selected from table 18.2. The building material characteristics are the same as in case study 9. Thermal transmittance of the walls is kept constant at $0.33W/(m^2K)$ as the wall thickness changes, by changing the EPS material thickness as well. As described for study 9, the number of variables is quite different for the single window model an the four window model.

The only difference between case study 10 and case study 9 is the presence of the urban context casting shadows on the building façades. Keeping the same parametric model and the same building characteristics, allows us to properly compare the results obtained in the studies, and discern the influence of the context in the energy efficiency of the buildings. In order for this comparison to be possible, the fitness functions must also be the same.

18.2.2 Fitness functions

The object of this case study is to search for energy efficient solutions. We will be using the same 3 separate energy calculations for heating, cooling and lighting energy needs that we used in the previous energy case studies. The fitness functions for case study 10 can be explained by the following expression:

$$Case\ Study\ 10 \begin{cases} Minimize & f_{1(x)} = Q_{H,nd}, \\ Minimize & f_{2(x)} = Q_{C,nd}, \\ Minimize & f_{3(x)} = Q_{E,nd}, \\ subject\ to & 0 \leq x_{winPoints} \leq 1. \\ & 0.05 \leq x_{thickness} \leq 1. \\ & 0 \leq x_{winType} \leq 7. \end{cases} \tag{18.2}$$

18.2.3 Genetic algorithm inputs

Genetic Inputs for case study 10 are also the same as for case study 9. NSGA-II is used for 100 generations with 50 individuals in each generation. The overall genetic inputs for this case study is as follows:

Case Study 10		
Population Size (N)	50	
Number of Variables	21 for model 1	69 for model 2
Number of binary digits	8 for win Points	6 for thickness
Variable Domains	$x_{winPoints} \in [0, 1]$	$x_{thickness} \in [0.05, 1]$
Mutation Probability (p_m)	0.2	
End Condition	End after 100 generations	

18.2.4 Results

The most evident result in this study is the fact that heating energy needs are significantly higher than those of study 9 for all locations, and cooling needs significantly lower. This is the most important influence of the Urban

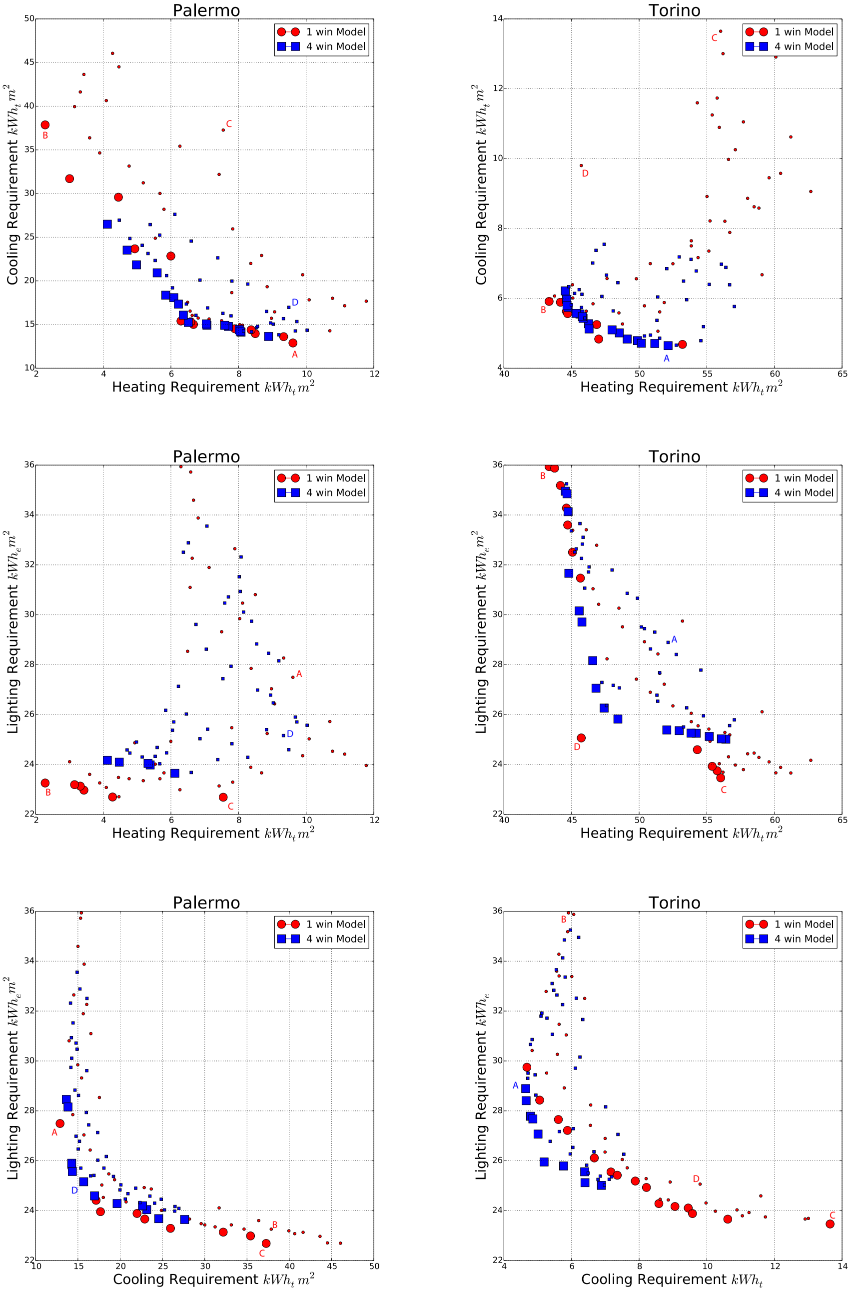

Figure 18.6: Objective spaces for Case Study 10 for Palermo and Torino.

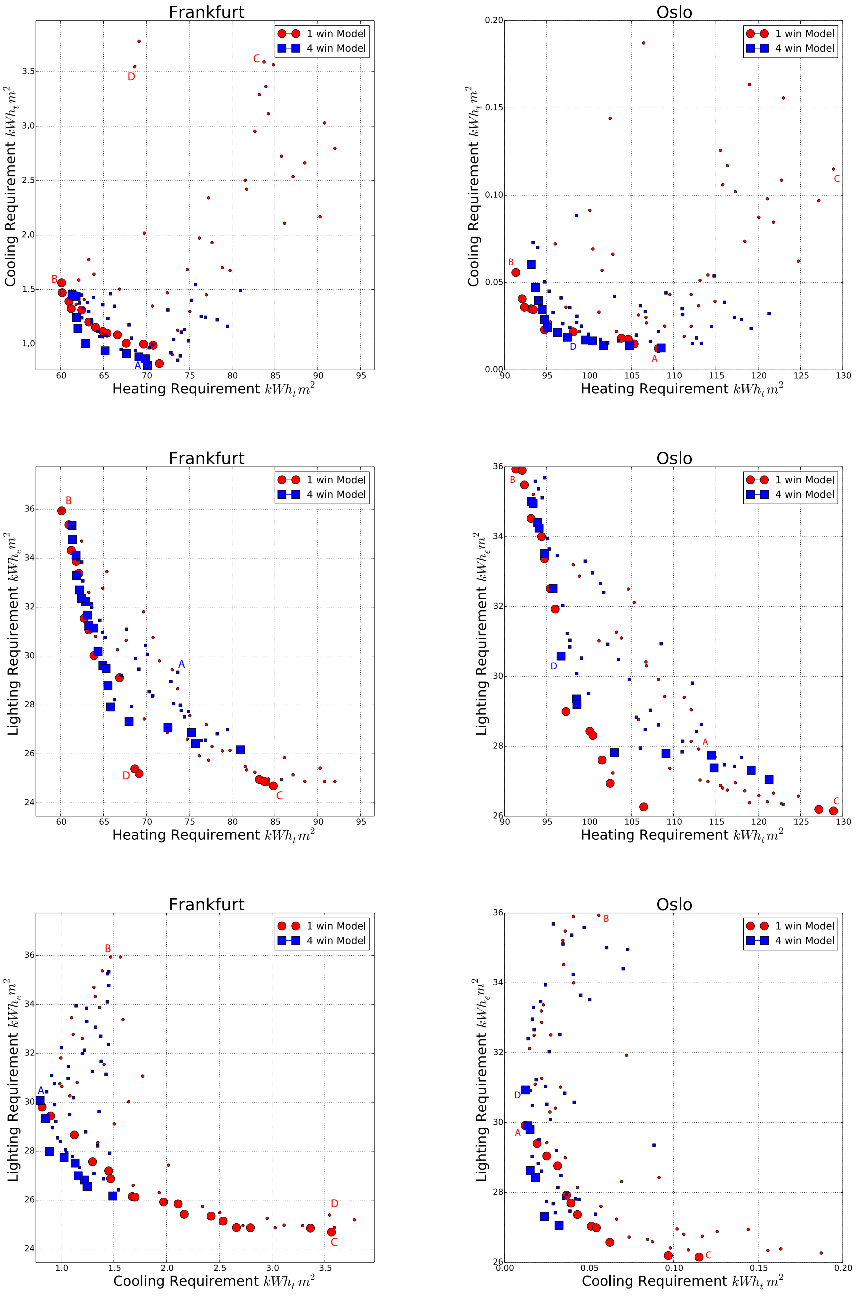

Figure 18.7: Objective spaces for Case Study 10 for Frankfurt and Oslo.

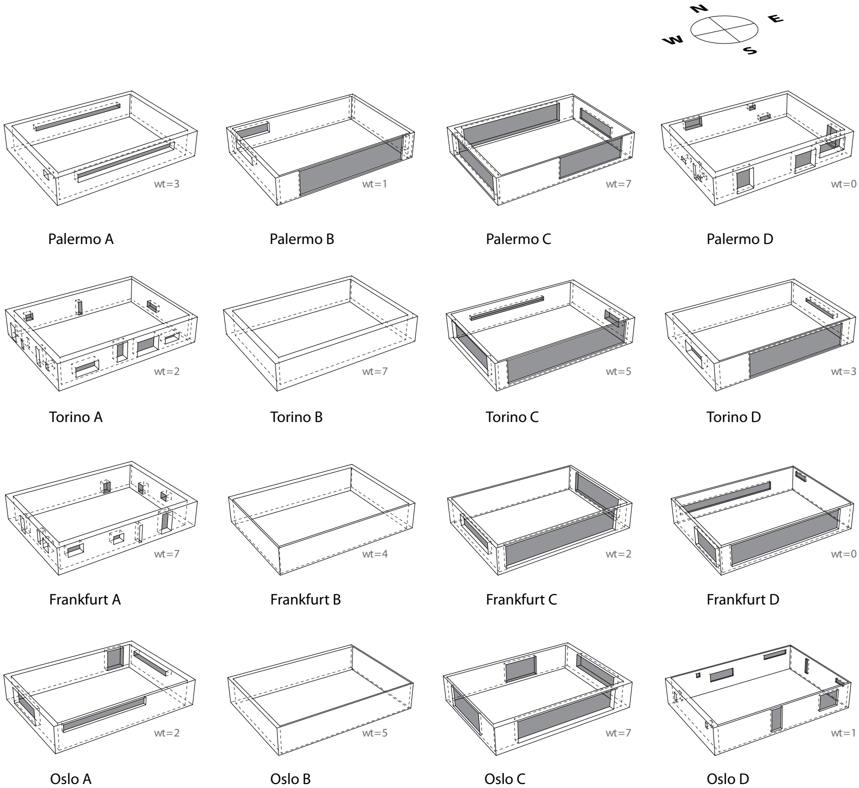

Figure 18.8: Pareto Front Solutions for case study 10.

context, the shading of the adjacent buildings. Variations between best and worst performing solutions for the cooling function are smaller in case 10 than in case 9. This is also a sign of influence of the shading, solar input is much smaller and this from a cooling point of view, solutions are more similar to each other. Lighting variations are similar between the two studies, and heating variations are similar as well, with a slight increase in the Oslo climate.

The overall shapes of the Pareto fronts are quite similar between studies 9 and 10. There is considerable contrast between the heating and cooling functions, and between the lighting and cooling functions. Case study 9 shows little contrast between heating and cooling functions for Palermo and Torino, and more significant contrast in Frankfurt and Oslo. In case study 10 this behavior is different, contrast between heating and lighting functions is very significant in Torino, Frankfurt and Oslo, and still present in Palermo. The reasons for this will be further detailed in the Pareto solutions analysis bellow.

A discussion on the exploration done by the GA in the single window and the four window models presents some difficulties in this study as well. Genetic inputs for case study 10 show that the same number of individuals and generations was used for both parametric models. As was the case in study 9, the single window model has a wider extension of solutions in the objective space than the four window model. This is a sign of higher exploration in this model, and it is explained by the lower number of variables. However, in case study 10 this difference in exploration seems to be less pronounced. Best performing solutions in the first model do not have a large difference from those in the second one. In fact, the best performing solution in the cooling function for Torino belongs to the second model, and in some cases the Pareto front from the second model dominates a good number of solutions in the first model front. These results suggest that, while having had less exploration during the GA run, the second model has an advantage in this case study.

Cooling Requirements

Best performing cooling requirement solutions in case study 10 (Solutions A) share some characteristics with those in case 9. Mainly the presence of the long and shaded window in the south façade (excepting in Torino where there are 4 mid-sized and shaded windows facing south). But the presence of shading adjacent buildings does have an influence. Since allowing daylight into the spaces requires bigger windows than in case study 9, artificial lighting heat gains are lowered by increasing window sizes. Other façades have more openings in case 10 than in case 9, increasing daylight and reducing cooling loads.

Solution A for Palermo in case study 10 is the best performing for cooling. It has a long and shaded window in the south-facing wall as is common in the previous study, but in this case, there is also a similar window in the north wall. This north window improves internal daylight and reduces internal lighting heat gains. Other high performing solutions for cooling have similar window arrangements, window areas in for Palermo are significantly higher in this study, suggesting that the lighting internal gains have an important effect. Window type selection for solution A is type 3, a low U_g construction with relatively high visible light transmittance, further highlighting the importance of daylight in cooling energy efficiency.

Solution A in Torino has four south-facing windows, four small and vertical west-facing ones and a few very small north and east-facing ones as well. All windows are small enough, and the walls are thick enough for them to be well shaded. It seems that the best way to shade the windows in the west façade is to have them be vertical, and shade with the fins, not the overhangs. This configuration found by the four window model outperforms any solution found by the single window model, including the single long and short window that had so far outperformed all others for cooling. This could be because this four window configuration is able to introduce more daylight in our office space without allowing solar radiation in more facçades. Window type 2 gives solution A a high amount of daylight as well.

Solution A for the Frankfurt climate is similar to the Torino A. It is also a four window solution with a series of shaded south-facing windows and some smaller ones in other façades. Shading in east and west façades in this case is also mostly done by the fins since they have vertical windows. Solution A for Frankfurt has window type 7, this is the type that allows the least amount of solar energy in the room.

Solution A in the Oslo climate has the usual long shaded south-facing window, with the addition of a larger and taller west window, a squared north one, and another long window due east. Solution A has the particularity if having some of its windows be placed asymmetrically in the wall, especially the north and south windows. It is unclear if this asymmetry is advantageous from a cooling point of view, if this positions maximize daylight, or if they are better shaded in the urban context. Also in this climate, window type 2 gives solution A a high amount of daylight as well.

Heating Requirements

Heating requirements in case study 10 are significantly higher in comparison with case 9. Solar gains are harder to come by with the presence of the adjacent buildings in the winter months when the sun is low. Solutions B represent the best performing solutions for the heating function.

Solution B in Palermo is quite similar from case 10 to case 9. A very large and unshaded south-facing window maximized solar gains that are beneficial to heating loads. Window type 1 has does not have the lowest U_g value, but it does allow a good amount of solar radiation, having a 0.60 g_g value. Sun-paths in Palermo are still high enough during winter for the sun to find its way over the adjacent buildings into the office space.

Solution B in the Torino climate is quite an interesting result. It has no windows in any façade, not even due south. We saw in the previous study that large unshaded windows on the south wall improve heating considerably by allowing solar radiation indoors. However, in this case study this is not so, because the sun-paths in the Torino latitude (and upwards) are not high enough during winter to irradiate over the adjacent buildings. Large windows therefore provide no solar heat to the internal spaces, on the contrary, they represent a heat loss because of their higher U values. When there is no solar radiation be be had, having a continuous wall with a U value of 0.33 $W/(m^2K)$ is better than having windows with a U_g value of 0.72 $W/(m^2K)$ at best. Window types in this result are irrelevant since there are no windows. We must consider that this result is the valid only when direct solar radiation is very low, and this is true in our case because we are studying a very low floor of our building (the first one above the ground floor).

Having no windows at all clearly represents a problem from the lighting point of view. We can see that solution B is the worst performing solution for the lighting function. Consequently we can note a good amount of contrast between the heating and lighting functions. We assume that internal heat gains due to lighting fixtures are beneficial to the heating loads, but a good amount of contrast is present nonetheless.

Solution B in Frankfurt and Oslo have the same result as the Torino climate, no windows are present. The same reasoning applies to Oslo. The results for Frankfurt show two very similar solutions to be the best performing for heating, one of them is solution B and the other one is also a solution containing no windows, but with the difference of having a much higher thickness of the walls. Solution B outperforms by a very small difference the other no-window solution. Since there are no windows and U

values are fixed (they do not change with the variation of thicknesses), the only influence of the thickness is the internal mass. We see a very small difference in heating energy needs, this means that internal mass has a very small influence in heating requirements for this climate as was shown in (Mechri et al. 2010).

Lighting Requirements

Lighting energy needs do not increase significantly in case study 10. Adjacent buildings have shown to noticeably decrease direct solar radiation, but this is not the case for daylight. Variations in lighting needs are quite similar in both case studies.

The best performing solutions in the lighting function are shown as solutions C. As is to be expected, best performing solutions have large windows in all façades. This is also true in the results for case study 10. Windows are generally unshaded, especially in the south-facing façade. There are also some asymmetrically positioned windows in these results, but the reason for them is unclear with the present study.

Compromises

Solution D in the palermo climate is an interesting compromise solution generated by the four window model. It is a very good performer in both cooling and lighting functions (the most critical functions for Palermo). Solution D is not a very good performer in the heating function, but as we have mentioned above, this is not a big problem in Palermo. Solution D has 3 almost square windows in its south wall. These windows seem to be shaded enough, either by the thick south wall, or by the adjacent buildings. The east wall contains one such similar window that is positioned very close to the south edge of the wall. The northern and western façades contain a series of very small windows. Solution D has a less than 5 kWh/m^2 a year difference with the best performing cooling solution, and less than 3 kWh/m^2 difference with the best lighting solution.

Solution D for the Torino climate is an excellent compromise for the heating and cooling needs generated by the single window model. Since in the urban context the cooling needs are significantly reduced, and heating ones increased, we can say that it is heating and cooling that require the most attention in this case. Solution D is a mere 3 kWh/m^2 behind the best performing solutions for both heating and cooling functions. Solution D has a large and unshaded window in the south wall and a couple of mid-sized windows in the east and west facades. Solution D uses the window type with the lowest U_g value, making the best use out of the window areas. We have seen above that windows in the Torino climate represent heat loss and very little solar gain, but with this window type this balance is perhaps not completely unfavorable. This high window area also improves significantly the lighting energy requirements.

Solution D in Frankfurt is a very good compromise for heating and lighting functions. It optimizes lighting needs by having very large windows, and solar gains for heating by a large and unshaded south-facing windows. Heating requirements are only above average but lighting needs are near optimal. Cooling requirements are not optimal for this climate, but they are still very low due to the fact that Frankfurt has low cooling requirements in the urban study.

Solution D for the Oslo climate is a very good heating performer with an above average cooling performance as well. Lighting is not very well solved in this solution. Solution D has a series of small windows in all of its façades, and window type 1 that allows a good amount of solar radiation to enter the room.

18.3 Conclusion

The case studies presented in this chapter show the fundamental role that the window arrangements have in the energy efficiency of the office building in question. Solar radiation seems to be the key aspect in all functions and climates. Hence there is a big difference between the urban and sub-urban contexts, both in the energy requirements and the resulting solutions. The window to wall ratio was determined to be the more important aspect to study when compared to the orientation and building shape.

The MOGA was able to provide us with detailed and useful information on the configurations that best dealt with the fitness functions, climates and contexts studied. Optimal configurations for all functions and climates were found and the important relationships between the functions were deduced from the Pareto fronts. Good compromises, solutions that are good performers in at least two important functions were also presented in each climate, but most importantly, the characteristics that made these solutions work were noted in the search process. The information provided by the MOGA was site and context specific, making it quite useful in the early stages of the design process.

Not all of the aspects that need to be considered in the design of the building envelope were subject of study in this chapter. For example, the visibility from the interior to the interior, the visual connection of the people inside to the external environment. Not only was is not considered, some solutions proposed by the GA had no windows at all, and some have windows so high that visibility is only possible with the sky. Visibility, as many other important considerations can be determined by the designer during the search process in the following ways:

- Designers may use parametric models that have a minimum window area as a constraint. Meaning that all solutions generated would have at least some percentage of windows. Windows may also be constrained in space, allowing the GA to move them only in certain areas where designers consider them to have the most visibility, or for them to have some aesthetic value.

- Designers may let the GA generate any kind of window arrangement or no windows at all (as was the case in this chapter) and then choose a final solution considering not only their fitness values, but also considering visibility, aesthetics, etc*.

- Designers may chose to interact with the GA during its search process, keeping visibility as an implicit goal not present in the fitness functions†.

*This issue is also discussed in section 7.7.
†This possibility is discussed in section 1.7.

19

Multi-Disciplinary Search

Section 1.1 of this thesis gives a description of the early design phase of architectural design. Particular attention is given to the multi-disciplinarity and the contrast of the design problems faced in this stage of the design process. This PhD thesis presents two series of multi-disciplinary problems based on the studies presented above.

In a few words, Turrin et al. describe the reasoning behind the use of performance based search processes in the early phase of architectural design:

> "Despite the fact that conceptual design is well known to be initiated based on a set of design requirements, traditionally the conceptual phase of architectural design addresses only a rather limited selection of requirements (in most cases, functional and esthetic aspects prevail), while key disciplines tend to be entirely omitted in this phase and postponed. In contrast with this tendency, the concept of performance oriented (also called performative) architecture has recently emerged, as a design approach in which building performance, broadly understood, becomes a guiding criteria."

(Turrin et al. 2011)

Building performance based search processes are proposed by Turrin et al. among many for the early design stages. They employ structural FEM simulations coupled with energy simulations in long span roof case studies (Turrin et al. 2009, 2011). Their parametric models include two types of variables, a first group determines the overall shape of the structure, and a second group determines the shape of a louver system on top of the structure. The structural performance of roof would depend solely on the overall shape, while the energy performance would depend on both, arguably mostly on the second. They use GA's to search for high performing solutions to both functions and discuss the importance of such tools in early architectural design.

A previous study developed by the author also discussed the relevance of multi-disciplinarity (Méndez Echenagucia et al. 2008*a*). In this case the attempt was that of embedding the multi-disciplinary efficiency onto the architectural shape. While Turrin et al. take an approach that suggests that different components can address different issues, the case studies presented in this PhD work try to generate single, continuous and homogeneous shapes that are advantageous for multiple performance metrics.

The previous chapters presented search processes that involve performance analysis of different architectural shapes. Multi-disciplinary search processes are carried out in two kinds of shapes, and for two kinds of performances:

- Complex curved surfaces are studied for their acoustical *and* structural capabilities. As we have seen in the previous chapters, curved surfaces present a great deal of opportunities in their ability to evenly distribute sound energy inside concert auditoria, as well as carry structural loads efficiently, with very little material and with very interesting shapes. We have discussed in this thesis different methods for studying both kinds of performances, and to parametrize and discretize (when needed) complex curved surfaces. This gives us all of the tools we need to study these shapes multi-disciplinarily.

- Masonry building envelopes are studied for their energy *and* structural capacities. The study of a rectangular building with a masonry envelope form both structural and energy points of view has been shown above. In both cases the GA was able to generate geometries that optimize different functions, drawing Pareto fronts that reveal important information about these buildings.

The use of the multi-objective approach described in this PhD thesis on multi-disciplinary problems is a fundamental tool in the study of these geometries. Knowledge on the contrast (or lack there of) in these functions can be used by designers to effectively define more efficient and informed geometries, early in their design process.

19.1 Structural and Energy Search

Many traditional and contemporary buildings have used the envelope as the main structural component. From historical masonry buildings, balloon frame houses to steel façade skyscrapers, the envelope is an habitual and logical part to place structural supports, but it is also inevitably the most important environmental filter, and as previous studies in this PhD thesis as well as other research has shown, it bears a big responsibility in the energy consumption of the building. This chapter studies the structural and environmental capabilities of building envelopes.

19.2 Case Study 11: Masonry building envelope - Urban context office building

Case study 11 follows the work presented above on masonry building envelopes. It combines the work developed in case study 5 on structure and studies 9 and 10 on energy efficiency.

19.2.1 Parametric model

The Parametric model for case study 11 is the same used in case studies 9 and 10 and shown in figure 18.1. It contains the same variables (window configurations, wall thicknesses and window construction). Wall material construction is the same used in cases 9 and 10 and described in table 18.1. The window constructions available to the GA are also the same ones used in the previous case studies and shown in table 18.2. Case study 11 does not use the single window model, it used only the four window model described in figure 18.1b.

Case study 11 is set in an urban context, the same urban context used in case study 10 and described in figure 18.5. The only climate chosen for this case study is the Palermo climate. Average monthly temperatures for Palermo are shown in table 16.2 and solar radiation diagrams are shown in figure 16.4.

19.2.2 Fitness functions

Case study 11 proposes the structural and energy study of masonry envelopes for rectangular office buildings. Fitness functions for this study are directly taken from studies 5 for the structural part, and 9 and 10 for the energy aspects.

Case 5 employs equation 11.1 to determine the structural adequacy of load bearing masonry wall envelopes. This equation is also chosen to study envelopes in case study 11. Case 5 also studied the weight of the walls as a contrasting function to equation 11.1, but in case 11 weight is not used. The contrast between structural and energy functions is the only subject of this study.

Cases 9 and 10 use the energy needs for heating, cooling and lighting separately as 3 functions that study the total energy needs of the buildings. Case study 11 uses these 3 functions as well, along with the structural function. The multi-objective problem studied in case 11 can be summed up in the following equation:

$$Case\ Study\ 11 \begin{cases} Minimize & f_{1(x)} = Q_{H,nd}, \\ Minimize & f_{2(x)} = Q_{C,nd}, \\ Minimize & f_{3(x)} = Q_{E,nd}, \\ Minimize & max(f_{case1}; f_{case2}) \\ subject\ to & 0 \leq x_{winPoints} \leq 1. \\ & 0.05 \leq x_{thickness} \leq 1. \\ & 0 \leq x_{winType} \leq 7. \end{cases} \tag{19.1}$$

19.2.3 Genetic algorithm inputs

Genetic inputs for case study 11 are also the same as for case studies 9 and 10 with the consideration that only the four window model is used. NSGA-II is used for 100 generations with 50 individuals in each generation. The overall genetic inputs for this case study is as follows:

Case Study 11		
Population Size (N)	50	
Number of Variables	69	
Number of binary digits	8 for win Points	6 for thickness
Variable Domains	$x_{winPoints} \in [0, 1]$	$x_{thickness} \in [0.05, 1]$
Mutation Probability (p_m)	0.2	
End Condition	End after 100 generations	

19.2.4 Results

Figures 19.2 and 19.1 show the objective spaces and best performing solutions for case study 11. The results for case study 11 show similar patterns to those seen in case 10. With the exact same GA inputs, exploration in this case seems to be lower when compared to case 10. This can be explained by the presence of a fourth fitness function. Contrast between energy functions is analogous to the ones found in study 10. For this reason, comments on results for case 11 will be concentrating on contrast between the structural and energy functions.

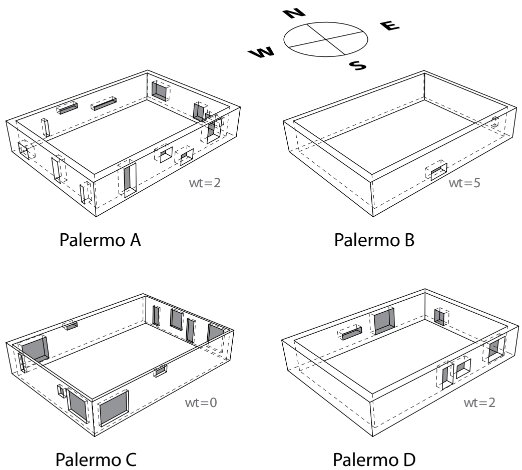

Figure 19.1: Best performing solutions for Case study 11.

Structure

Solution D represents the best performer for the Structural function, its most important characteristic is not its window arrangements, but its thicknesses. Solution D has the thicker walls in all façades than all other solutions in the Pareto front.

Structural fitness functions, material conditions and parametric models for cases 5 and 11 are identical. Therefore comparisons for structure can be made between these two studies. Case study 5 achieved a best performing structural fitness value of 1086, while case 11 was able to surpass this result

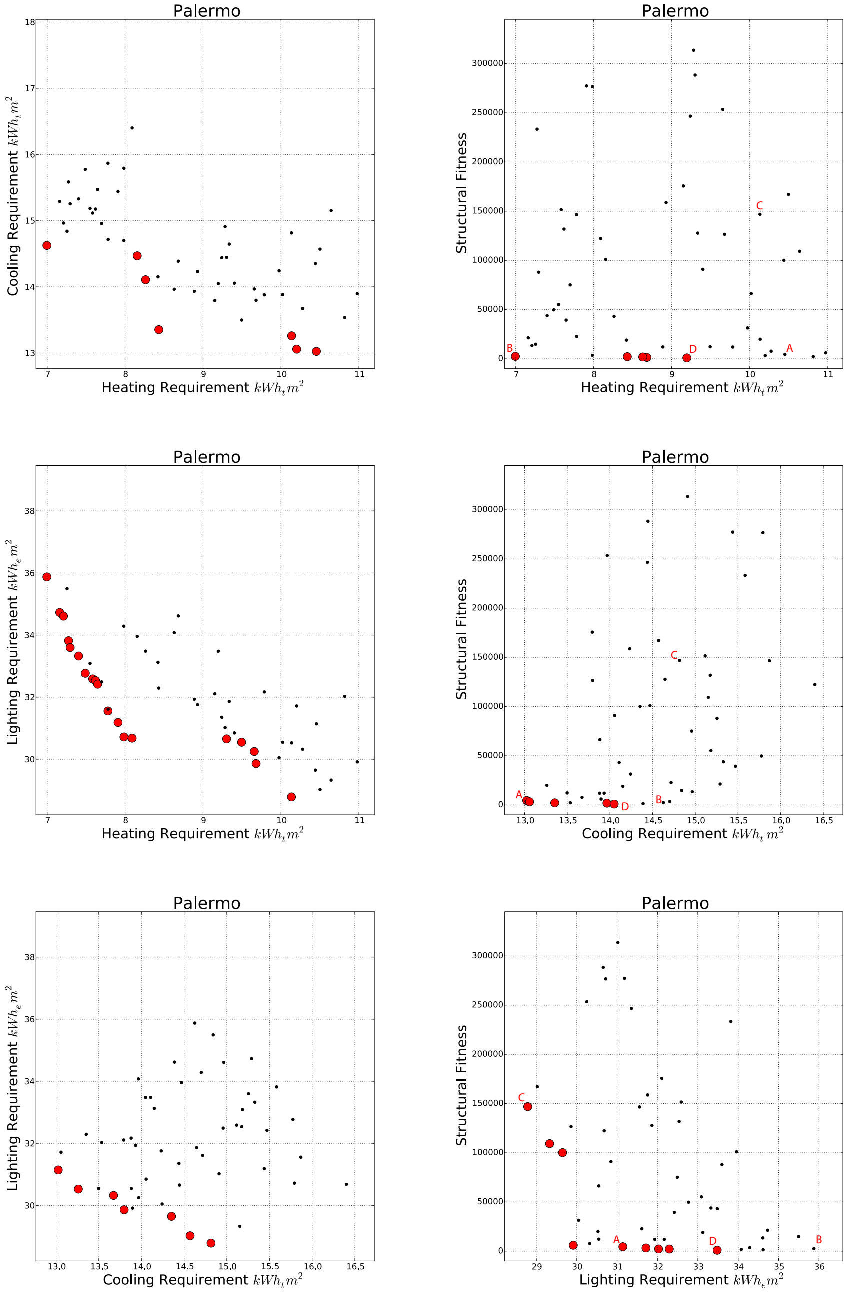

Figure 19.2: Objective spaces for Case study 11.

with solution D, achieving a value of 930*. GA inputs were also the same between case 5 and 11, so the better result in case 11 cannot be directly attributable to better exploration. In fact, there are more fitness functions in case 11, so we could argue that exploration for structural attributes should be diminished. The improved results can therefore be only explained in two ways:

- There is an important random component in the search process done by the GA. Therefore, two identical search processes do not generate identical results. Inevitably one of the two will have better results that the other.
- The weight function is more contrasted to structural efficiency than the energy functions. As it is explained above, results in case 11 show that the wall thickness is the most important variable when it comes to structure. The higher the thickness the better the result. The weight function is the opposite, the lower the thickness the lower the weight. Contrast between the structural function and the energy ones are explained bellow, but they seem to be less pronounced than the weight function. It can be argued that the higher the contrast, the more trouble the MOGA will have in finding results for each single function. Hence, the weight function makes it harder for the GA to find thick walls and optimal structures.

Cooling vs. Structure

Solution A is the best performing solution for the cooling function. It has thick walls that shade its small windows. Shading and thick windows were also shown to be important in cooling functions in the previous case studies. For this reason, contrast between the cooling and the structural functions is not very big. The structural fitness difference between solutions A and D is very small when compared to most of the other solutions found in the population. Other high performing solutions in the cooling function are also high performing in the structural function.

We have established that high performing cooling solutions are also high ranked structurally, but the opposite is not true. Solution B for example is high performing structurally since it has almost no windows and has thick walls, but it is not a good cooling solution. It was established in cases 9 and 10 that solutions with no windows are not very good for cooling since they require high lighting internal gains.

*The structural fitness function is a minimization function, lower values are better

Heating vs. Structure

Heating solutions for the Palermo climate in the previous urban study were shown to have large south facing windows that increased solar gains. These solutions have a heating energy requirement almost as low as 2 kWh^2 a year. Solution B is the best performing solution for case 11, it has a heating energy requirement of 7 kWh^2 a year, not as low as the one in case 10. Solution B does not have large and unshaded south-facing windows. It has only 2 very small and shaded windows, it has a low heating value not because of high solar gains, but because of low U values. The absence of windows keeps the thermal transmittance to a minimum. The high thicknesses and lack of windows give solution B a high structural performance.

The exploration in this case was not enough for it to find high performing heating solutions such as the ones found in case 10. This is also probably due to the fact that the GA is looking for high thicknesses for structural reasons. This gives us a low degree of contrast between these two functions, but looking at the results in case 10 is easy to assume that better performing heating solutions would not be as good performing in the structural functions. However, the results found show that the contrast is not very high, the GA is able to find good compromises between heating and structure, such as solution B.

Lighting vs. Structure

Lighting is the function that shows the most contrast with the structural function. Solution C is the best performing solution for the lighting function, it has larger windows than all other solutions shown, and these windows are not very well shaded (low thicknesses). This allows sunlight to enter the room freely. As was the case with heating, solution C is not as good a performer as the solutions found in case 10.

Large windows and low thicknesses give solution C a very bad structural performance, and this is true for *all* other high performing lighting solutions. This explains the high contrast between these two functions.

19.3 Structural and Acoustic Search

The acoustic case studies shown above make use of various simulation tools that obtain sound quality descriptions inside the rooms, and in turn shape those rooms to better distribute sound quality. The overall shape of the room was shown to be important in determining the distribution of quality, but also singular surfaces can have a great impact as well, particularly the roof surface.

Complex surfaces have also been shown to be very interesting in structural problems. Compression only surfaces for example are presented in this PhD thesis show low weights and high structural performance. Concrete shells are also studied above in terms of maximum displacements and weight.

Complex surfaces are becoming more and more present in contemporary concert spaces, and shell structures are also being employed by architects as expressive and efficient structures. This chapter considers the possibility of combining the study presented on shell structures and acoustic surfaces, in order to study the relationship between these two types of functions.

19.4 Case Study 12: Concrete shell roof for a concert hall

Case study 12 is the result of the combination of the studies on concrete shells (cases 1 and 2) and the study of complex acoustic reflectors (case 7). A concrete shell roof for a 20×42 shoebox concert hall is studied for both its acoustic and structural capabilities. Case study 12 involves free-form curved surfaces, hence it involves the use of the acoustical study of early sound developed for this PhD thesis and discussed in chapter 15.

Since reinforced concrete is capable of resisting tension forces and not only compression forces, concrete shells are much less constrained form a shape point of view than compression only shells. They are able to take concave and convex shapes without loosing structural capacity. We can say that FEM calculations of the maximum displacement in specular shells (identical shapes, one concave and one convex[†]) under the same loading conditions, would not show any difference. For this reason, previous structural results are found to have no preference for concave or convex shapes. The acoustic study detailed above, on the other hand, shows that there is some preference for convex surfaces that avoid sound concentrations in the audience area. While some concave curves are shown in the study, especially in the longitudinal section, most solutions exhibit convex shapes. For this reason it is interesting to se the resulting level of contrast between structural

[†]Since this is also an acoustic study, shapes are referred to as concave or convex from the point of view of the audience, hence from the bottom of the shells. Shapes that are convex towards the audience tend to avoid sound concentrations.

and acoustic fitness functions.

19.4.1 Parametric Model

The parametric model used for case study 12 is the same one used in case 7 and shown in figure 15.2. The model presents a 20×42 shoebox concert hall, with a 15° inclination of the audience area. The shell roof is supported all along the perimeter of the room, meaning that the roof structure has a span that is 20 meters in its transversal section. No special reflectors, balcony fronts or overhangs are present in the room. The sound source is placed in the center axis of the room, four meters behind the stage front edge. An aisle of 2 meters in width was left all around the audience area, and this area was subdivided into flat segments of 3.2×3.2 meters.

The variables in this case are also the same ones used in case study 7 and detailed in table 15.1. This variable settings imply that symmetry is imposed in the shell surface, thus reducing the number of possible solutions by excluding asymmetrical configurations that would most likely be low performing in acoustical fitness functions.

19.4.2 Fitness functions

The fitness functions used for case study 12 are taken directly from the structural and acoustical case studies of shell surfaces.

The structural performance of of the concrete shell is studied by means of the maximum displacement of the structure in the Z axis. A FEM simulation of the shells behavior is performed for each individual solution. A NURBS surface is discretized into small triangular shell elements of the FEM study. Gravity loading is applied in this case study, meaning that only the weight of the shell itself is considered.

A weight function was also used in case studies 1 and 2 as a contrasting function to the maximum displacement. In case study 12 only the contrast between the acoustic and structural function is object of study, therefore the weight function is not included in this study.

The acoustic fitness functions are the same ones used in case 7 and described in equation 17.1. Three separate time-windows are used in this study of acoustical quality of the early sound inside the room. The first time-window starts at 0 ms from the arrival of direct sound, until 80 ms after, the second window goes from 80 to 120 ms and the third one from 120 to 200 ms.

The fitness functions used in case study 12 can be expressed in the following equation:

$$Case\ Study\ 12 \begin{cases} Minimize & f_1(x) = max(\Delta_{Z_i}), \\ Minimize & f_{2(x)} = E_{tot,0-80}, \\ Minimize & f_{3(x)} = E_{tot,8-120}, \\ Minimize & f_{4(x)} = E_{tot,120-200}, \\ subject\ to & 5 \leq x_{1,2} \leq 20. \\ & 10 \leq x_{3-6} \leq 20. \end{cases} \tag{19.2}$$

19.4.3 Genetic algorithm inputs

Genetic Inputs for case study 12 are described bellow. NSGA-II is used for 100 generations with 50 individuals in each generation. The overall genetic inputs for this case study is as follows:

Case Study 12		
Population Size (N)	50	
Number of Variables	6	
Number of binary digits	8	
Variable Domains	$x_{1,2} \in [5, 20]$	$x_{3-6} \in [10, 20]$
Mutation Probability (p_m)	0.2	
End Condition	End after 100 generations	

19.4.4 Results

Figure 19.3 shows the objective spaces for all 6 combinations of fitness functions used in case study 12. The objective spaces shown in the left column are all regarding the structural function in combination with the first second and third time-windows. Figure 19.4 shows a few signaled out solutions resulting from the study.

The objective spaces found in case study 12 show a moderate level of contrast between structural and acoustic functions. The highest level of contrast being present in the first time-window f_2, as evidence by the fact that the best performing solution in this time-window is one of the worst performing in the structural function f_1. In the other acoustical functions the contrast is fairly low, solutions that are high performing acoustically are very high performing structurally as well, but there is still a small level of contrast between these functions.

While the level of contrast is moderate between structural and acoustic functions, acoustic functions among themselves are very contrasted. The

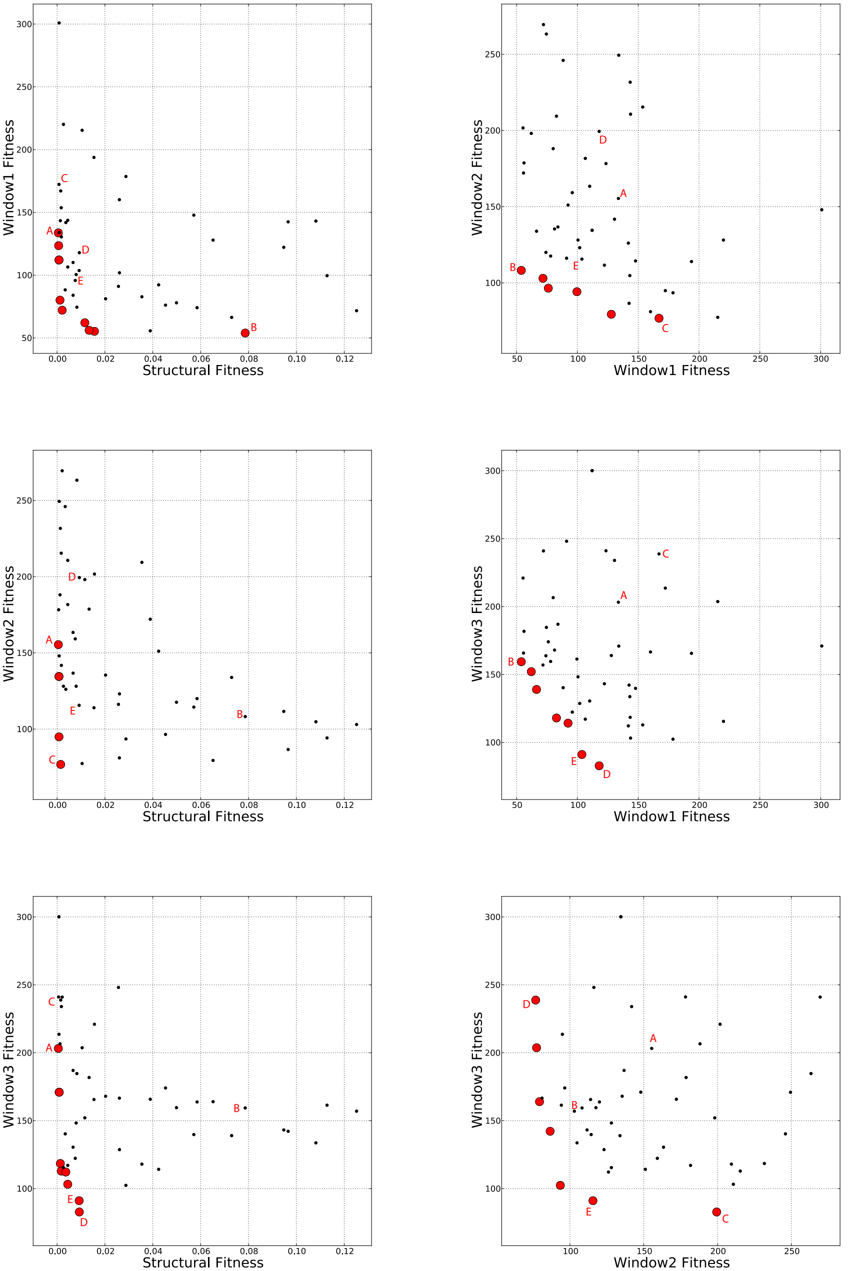

Figure 19.3: Objective spaces for Case study 12.

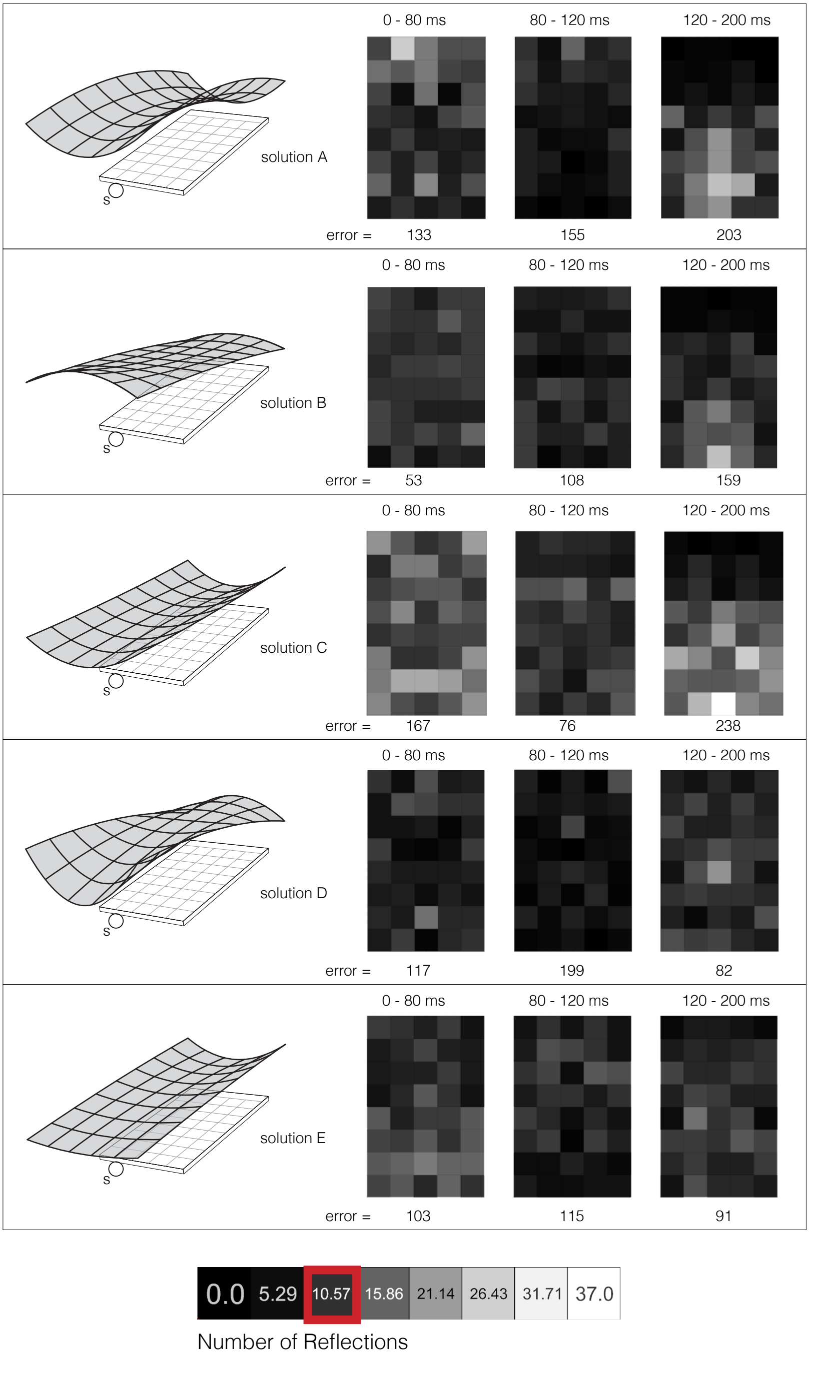

Figure 19.4: Pareto Front Solutions for case study 12.

Pareto fronts describing the combination of f_2 vs. f_3, and especially f_2 vs. f_4 denote high contrast. Compromises between these functions are very hard to achieve.

Solution A is the best performing individual for the structural function f_1. It has a maximum displacement in the Z axis ($max\Delta_Z$) of 0.5 millimeters in a 20 meter span. It has a hypar shape with a slightly concave longitudinal section and a convex transversal section. From an acoustic point of view it is a poor performer in all time-windows. It causes important focusing in the third time-window towards the stage and has very few reflections falling in the back of the room, as well as few reflections in the second window.

Solution B is the best performer in the first time-window f_2. Its shape is more complex that the one shown in solution A, it has concave cross-sections over the stage and in the back of the room, but has flat and slightly convex cross-sections towards the center of the room. This interesting shape creates a very uniform sound field in the first time-window, and a pretty uniform one in the second one. The third time window shows some sound concentration near the stage due to the concave section over the sound source. From a structural point of view it is not a good performer, having a $max\Delta_Z$ of 78 millimeters, much higher than solution A. High displacements (and lack of rigidity) in the shape are possibly due to the presence of flat portions in the shape of the shell.

Solution C is the best performing solution for the second time-window f_3. It is an almost cylindrical convex surface, inclined towards the audience. It has a flat longitudinal section and only convex cross-sections. Fitness values for f_2 and f_3 are not very good, they are in fact bellow average. Too many reflections fall into the first window, and there are both focusing and dead areas in the third window. From a structural point of view, solution C is very much above average, having a $max\Delta_Z$ value of 1.5 millimeters.

Solution D has the highest fitness value in the third time-window f_3. Solution D has perhaps the most complex and pronounced shape i among the Pareto solutions. It has flat, concave and convex cross-sections, and a slightly concave longitudinal section. It has a fairly good sound distribution on the third time-window, a moderate one in the first one. It lacks a good number of reflections in the second time window, resulting in a low f_3 value. Form a structural point of view solution D is above average with a $max\Delta_Z$ of 9 millimeters.

So far we have only looked at 2D objective spaces and considered contrast between pairs of functions. If we consider all four functions, it is much more difficult to visualize the results. The Pareto front is made up of a large number of the solutions in the population, but it is very hard to come upon good compromises for all four solutions. Solution E is perhaps the best compromise that can be found for all solutions. It has above average fitness values for all functions. Its curvature is not very pronounced but always convex, with an almost flat part towards the back of the stage. It has uniform sound distributions in all time-windows, with a slight lack of reflections close to the stage in the second window. Structurally it performs well, with a $max\Delta_Z$ value of 9 millimeters. Solution E is either on or very close to all of the 2D Pareto fronts, making it a good compromise between all functions in the problem.

19.5 Case Study 13: Masonry shell roof for a religious building.

Case study 13 is a search process based on the previous case studies on shells. Case studies 3 and 4 search for optimal compression only shapes, freeform masonry vaults with optimal structural capacities while still being as light as possible. Case study 7 on the other hand studied freeform shells form an acoustical point of view, selecting shapes that evenly distribute sound energy in time-windows and spatial subdivisions inside the room.

Case study 13 involves a religious building, not a concert hall. Many religious traditions of different faiths involve musical performances during the ceremonies, and all of them involve the listening of the spoken word. Traditional european religious buildings have very large volumes and very few absorptive materials. This results in very long reverberation times, in some cases this is used in the favor of the musical performances. Some choral and organ Christian music appears to have been conceived for this spaces, having very long pauses and slow tempo and making good use of RTs as that go well beyond 3 or 4 seconds. However, this kind of reverberant spaces result in very poor speech intelligibility. The spoken word is not easily understood in such spaces.

This case study is designed to search for shell shapes that have a good structural capacity while also distributing sound energy in such a way as to optimize speech transmission inside the room.

19.5.1 Parametric model

Figure 19.5 shows the parametric model, acoustic setup and FEM model for case study 13. The parametric model is very similar to the one used in case study 3, the shell has a 40×20 plan projection, has 5 variable control points

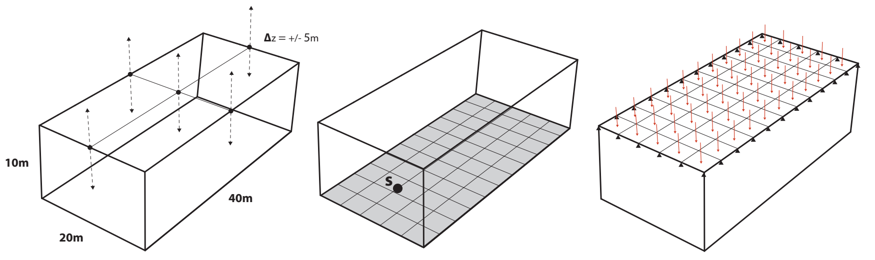

Figure 19.5: Case Study 13 Parametric Model - 40 × 20 Masonry Shell roof for a religious building.

and has a continuous and fixed thickness of 30cm. The base surface is 10m above the audience, but the 5 control points can move 5 meters above or bellow the base surface. These control points are the only variables in this parametric model.

The acoustic setup for case study 13 shows a single sound source placed close to one of the room's ends and in the center line. The audience area is subdivided into square segments that cover the entire room, and it does not have a pitched rake (the audience surface is flat). Sidewalls are of course parallel, and they are also perpendicular to the audience area.

The FEM model used is also the same one used for case study 3. It shows a meshed surface that is loaded in each shell element, loading is related to the surface weight. The surface is structurally constrained in all of its edges since the shell is supported by the four walls.

19.5.2 Fitness functions

Case study 13 proposes the structural and acoustic study of masonry shells for a religious building. Fitness functions for this study are taken from studies 3 for the structural shells, and 7 for the acoustic aspects. The first fitness function is the structural function developed for the study of masonry shells and described by equation 10.8 in page 163. The second and third functions are reserved for the acoustic study of the space.

Case study 7 used three time-windows to study the early reflections of a concert hall. The time-windows went from 0 to 80 ms, 80 to 120 ms and 120 to 200 ms. These time-windows were selected for the study of a shell roof meant for the enjoyment of music, while the building in this case is a religious building. The present case study used two time-windows designed to describe early reflections for the listening of the spoken word. The first window goes from 0 to 50 ms, the 50 ms barrier has been used in acoustical parameters meant for the study spoken word (most importantly C_{50} and D_{50}). The second time-window goes from 50 to 300 ms.

The problem put forth in case study 13 can be expressed in the following way:

$$\textit{Case Study } 13 \begin{cases} \textit{Minimize} & f_1(x) = \frac{U_e}{U_{e,0}} + \left(\frac{max(\tau^+)^2}{max(\tau_0^+)^2} \cdot w \right), \\ \textit{Minimize} & f_{2(x)} = E_{tot,0-50}, \\ \textit{Minimize} & f_{3(x)} = E_{tot,50-300}, \\ \textit{subject to} & -5 \leq x_i \leq 5. \end{cases} \tag{19.3}$$

19.5.3 Genetic algorithm inputs

Genetic Inputs for case study 13 are described bellow. NSGA-II is used for 100 generations with 50 individuals in each generation. The overall genetic inputs for this case study is as follows:

Case Study 13	
Population Size (N)	50
Number of Variables	5
Number of binary digits	8
Variable Domains	$x_i \in [-5, 5]$
Mutation Probability (p_m)	0.2
End Condition	End after 100 generations

19.5.4 Results

Figure 19.6 shows the objective spaces found in case study 13 for all fitness functions as well as some significant resulting solutions. Since there are 3 fitness functions there are 3 possible combinations of them, hence we see 3 two-dimensional objective spaces. We can see that there is a some contrast in all 3 combinations, but the most contrast is found between the 2 acoustic functions. We can see that the first window function has much smaller E_{tot} values. The second window seems to be much harder to solve, this time-window has too many reflections when compared to the first one, which is to be expected.

Contrast between the acoustic and structural functions seems to be lower than expected, but if we look at the numbers carefully we can see that this is not so. The scales in the objective space can be misleading in this case, the structural function has very low values, and the differences between similar solutions is very significant. Good acoustic performers are poor structurally. Concave shells that minimize our structural function cause sound concentrations that create high error values in both acoustic functions.

Solution A is the best performing solution for the structural fitness function. Interestingly it has a negative double curvature shell. Structurally solutions found in case study 13 were inferior to those found in case studied 3 and 4. Case 4 ran for many more generations, but this is not the case in case 3. It can be argued that contrast between structural and acoustical functions is higher that the weight functions used in case 3, thus explaining the better results. In fact, none of the solutions found in case 13 resemble the high performing sail vaults found in cases 3 and 4.

Solution B has the best performance in the first acoustical function (the 0 to 50 ms time-window). It does so by having as low a roof possible while not being convex (probably for structural reasons). The low roof sends a high amount of reflections into the audience in the first 50 milliseconds. But it does have trouble reaching receivers at the end of the room within those early milliseconds. Its structural performance is not as bad as other solutions in the rest of the population, but it is not very good when compared to other case studies. It has one of the worst performances in the second acoustic function (50 to 300 ms). This is due to large sound concentrations in the center of the room in the second time-window.

Solution C is the best performer in the second acoustic function. It is a tall and double curvature surface that is concave in the longitudinal section and slightly convex in the transversal section. It has a fairly good distribution of sound energy in the second time-window in most receivers, but has some concentration near the source and near the back of the room. It has the best performance, but it is however not a perfect solution for this function. It has one of the worst distributions in the first time-window, mainly because of its height. It is too high to have a good number of reflections reach receivers within 50 ms. Its convex cross-section makes it not a good structural performer.

Solution D is a good compromise between the two acoustic functions. It is also a double curvature surface, but most importantly it has a low roof near the source and a high one near the end of the room. This seems to give it a good number of reflections in both time-windows. Spatially however it is not as good as it could be, there are some sound concentrations due to

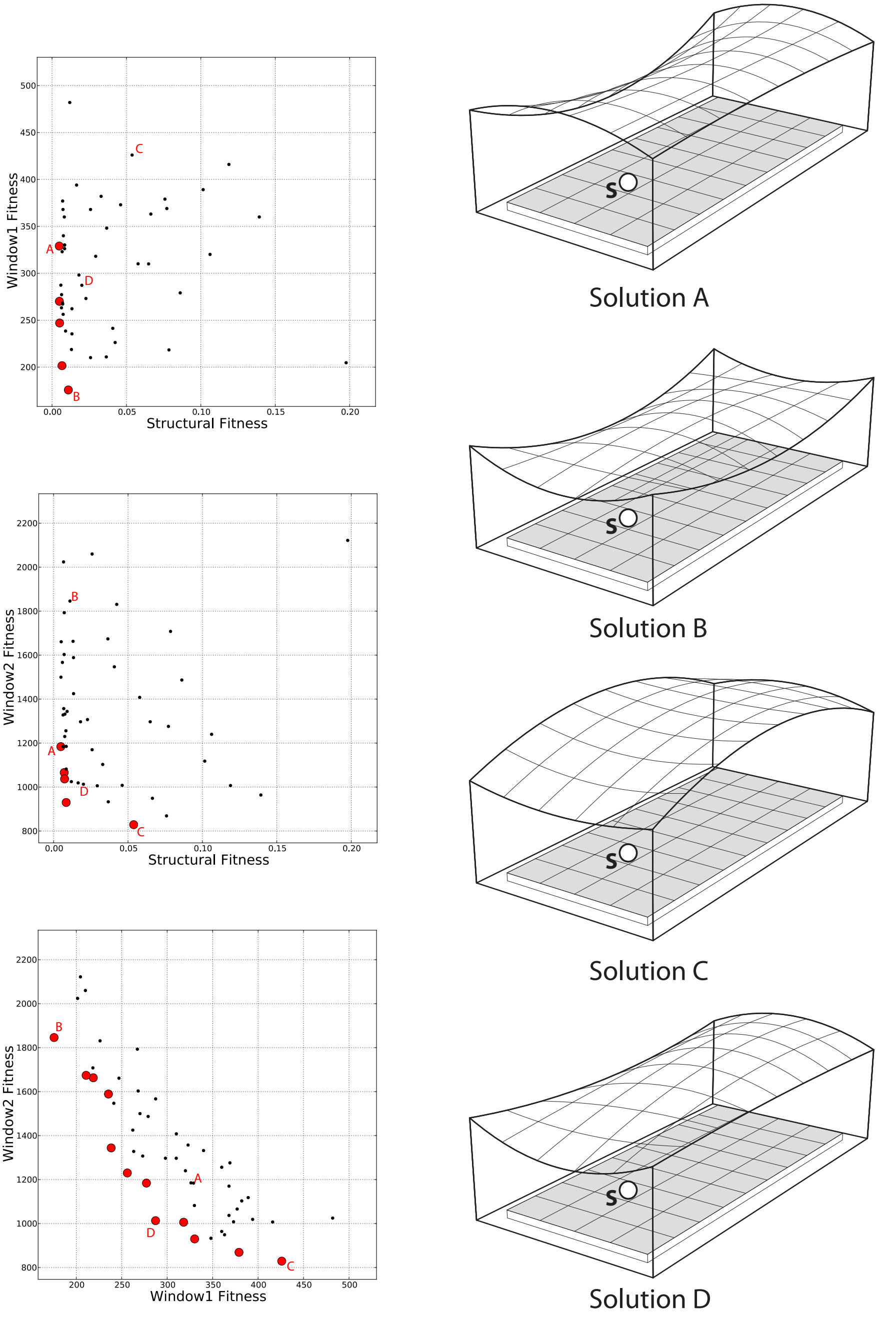

Figure 19.6: Objective spaces and Results for Case study 13.

very concave cross-sections towards the end of the room. This solution is not a very high performer in the structural function.

Conclusions

This PhD research proposes the use of computational search in the early design phase as an exploration and information gathering tool. Search algorithms in combination with parametric models and building performance simulation software are implemented and employed in problems related to structure, acoustics and energy. A theoretical framework on the use of these methods in the early phases of architectural design is presented, opportunities and limitations are outlined as well as a view in how these methods relate to existing design practices. The search algorithms employed in this research are described in detail, as well as the study of multi-objective search itself, contrast between functions is also discussed. Parametric models are introduced from many points of view, theoretical discussions on their use as well as mathematical implementations are shown. Many different parametric models containing geometries of varied nature are implemented in all of the case studies presented. Performance simulation and the physical phenomena involved are made very clear in each case study, presenting in some cases different approaches to the problem and proposing their use in search.

A clear idea on the usefulness and potential of search in architectural design is given through a good number of case studies. Ten studies are devoted to structure, acoustics and energy problems in architectural design, and three multi-disciplinary studies combine these disciplines to increase our understanding of the relationship between them. The information gained in these studies shows that search processes have much to offer designers during the early design phase, they can help designers significantly improve building performance without limiting their creativity or imposing particular solutions.

An important issue was discussed in section 1.6.3 on the dichotomy of design and instrumental knowledge and their encapsulation in software tools, as presented by Andrew Witt.

Search algorithms, parametric models and performance evaluation are instruments that do not originally come from the architecture discipline, they do not fall into the category of what Witt calls the “intrinsic” knowledge of the architect, hence they can be considered to be instrumental knowledge. The use given in this PhD thesis to such instruments is evidence of their usefulness in design processes, their ability to (i) generate practical and project specific information, as well as (ii) general knowledge on the relationship between shape and performance. This second category is not project specific, this information can be generalized and applied in other related problems. Both of this categories however constitute design knowledge, the information found during search processes is design knowledge.

One of the studies presented is intended to study architectural types, it is the parametric study of concert hall types described in section 13.3 (case study 6), where the object is to test the acoustic performance of three different types, while maintaining the same number of audience members. The intent in this case study is that of expressing the defining characteristics of each room type into their respective parametric model. Even more ambitiously, the intent is to include in the study as many instantiations of each concert hall type as possible, with the purpose of having a comprehension of the general type, not just a particular detail. This is done by using very general descriptions of each type, and not including detailed elements in the search process. No balconies, canopy reflectors or ceiling configurations were included in the search process, thus keeping the focus on general room shape, size and proportions. It would not be possible to include all of the possibilities in details pertaining to each type in such a study.

However, this does not mean that the study gives us any less of a clue as to the potential of each concert hall type. On the contrary, because of the generality of the parametric model used, the overall information found should remain largely unvaried for more detailed studies further in the design process. Not only is it possible to compare the performance of the best solutions for each type, but also strengths and weaknesses are found in each type. Contrast between acoustical objectives inside each typology is studied, as well as the geometrical characteristics that are involved in the in the contrast for each type. Good compromising solutions to contrasting objectives were found in some cases, in other cases where contrast is too strong, the new knowledge on the problem hints at possibilities of new formulations and geometric families that could reduce contrast and help us find acceptable compromising solutions.

The knowledge gained in this study is very detailed and specific to the specified requirements, it serves to improve the general knowledge architects have of the concert hall types. We are able to quantify when a shoebox room becomes too wide to include sufficient side reflections, or what angle becomes too open for fan or hexagonal rooms. Weaknesses that are attributed to entire types are sometimes kept constrained to some versions of the type and not all of them, allowing us to consider them and not to ignore them. A clear example of this is the finding in shoebox and fan shaped rooms, not all of the fan rooms are poor distributors of early reflections, and not all shoebox rooms are good providers of early reflections.

If we consider the Pareto fronts found in case study 6 as information regarding the strengths and weaknesses of each type, the room acoustics parameters that are problematic and those which are best achieved by the room shape, a clear picture on kind of sound that is achievable by each type emerges. The information contained in the resulting data, expressed through objective spaces and solution shapes, can be of fundamental help to designers in selecting a room type very early in the design process, and provide them with specific knowledge on the challenges they face further in the process.

The parametric models used in other case studies did not have the ambition to contain or represent easily identifiable architectural types. Many of the shell studies can jump from traditional shapes such as arches or sail vaults, into hypars and free-form shapes. In these cases, the information found is not so easily attributed to known types, but comparisons between the solutions found are still very much possible. Comparisons can be made outright when the search process opted not to chose solutions from a given type, or selected solutions of only one type. In these cases we get information not only on specific solutions, but on the types involved.

Case studies 7 and 12 reveal that not all concave surfaces are detrimental to the acoustic quality of concert spaces, and that in fact some of them help better distribute early sound reflections more uniformly over the audience area. Moreover, case 12 shows that the combination of concave and convex section present in double curvature surfaces can be mutually beneficial to structural and acoustic performances.

The case studies involving the fenestration arrangements of rectangular buildings are also interesting from a typology point of view, in the sense that they can be considered to cover only a specific part of a known building type. The window configurations in study in this case studies do not have a big impact on the general type of the building, but as results show, they have a big impact on their structural and energy efficiencies. In this cases we can safely say that the information found serves as a a guide of the possibilities of the type, while not describing *all* possibilities. Findings in this case study illustrate only a small part of the design possibilities in the type, when compared to results found in other studies.

An interesting result is given by case study 8, in which the proportions and orientation of an office building are investigated for their energy efficiency. Because this study uses a parametric models that changes the general shape of the building, strong changes in energy efficiency were expected. But only very minor changes in energy use are shown by the performance evaluation, due to the importance of the fenestration. This result is both a warning and an opportunity for designers. The selection of shape and orientation is shown to be insufficient to guarantee a good energy performance, fenestration also needs to be considered together with the shape and orientation. Therefore there are two possibilities as to how to interpret this information: (i) designers can consider both shape and fenestration in a more detailed search process, or (ii) designers can select shape considering other performance values or implicit design goals, and leave the design of the fenestration for a later stage of design.

The first alternative presents the opportunity to create solutions that perform much better when compared to solutions that can be generated by the second alternative. If we think of this in terms of search spaces we can say that the first alternative contains a much larger search space than the second. Because in the second alternative energy efficiency is not studied until the general shape is fixed, the search space is confined to the fenestration possibilities that can be generated with that shape. While in the first one, the search space considers the fenestration solutions that can be generated with that shape as well as many others. Since the energy efficiency is strongly determined by the *combination* the shape and the fenestration, it is very likely that the larger search space contains solutions that a far more efficient than those contained by the second.

Future Work

The parametric models employed in this thesis show a small part of the wide range of geometric possibilities that can be achieved with the use of parametric models. The parametrization of geometry is in no way a limit in the exploration of shapes for architectural design. However, the creation of parametric models for search processes during the early phase of design does presents some challenges that could be subject of future research.

The design process is most commonly subjected to time constraints, designers need to make decisions in short periods of time. The use of software certainly helps speed up the design process with more efficient representation methods, and to help increase the quality of the building by means of search processes such as those proposed in this research. However, the creation of parametric models is time consuming, and if the changes desired by designers at any point during the process are not contained among the variables of the model, the model needs to be re-written. This issue is discussed at length by Daniel Davies in his PhD dissertation (Davis 2013). Davis's work addresses techniques for generating more flexible parametric models. The use of such techniques or the creation of other is important subject matter for the improvement of search methods in architectural design.

The use of parametric models in search processes is also subject to problems in their coding strategies as shown in section 11.2.1. There are many other issues related to the models and their coding that are not discussed in this PhD thesis, such as "epistasis". The study of efficient coding strategies could possibly arrive at general and practical information that can be applied by designers in many different models, in order to help them avoid search problems. Coding problems are certainly specific to the type of search algorithm being used.

This PhD research employed only one kind of search algorithm, the genetic algorithm. It also employed the same kind of GA and always used the same operators for all case studies. A comprehensive comparison of different search algorithms, operators and search inputs can also be of great help. The relative efficiency of the algorithms can be established in relation to each other when applied to architectural search problems. Algorithm efficiency is thus related to speed and convergence, how fast does the algorithm find the real Pareto front for example. Robustness of the algorithms is also an important issue to study, how the algorithms perform under very complex and different problems. All of this issued relate to exploration and exploitation, the balance between these two is of outmost importance, and it is determined not only by the algorithms themselves, but also by the search inputs we give them (e.g. in genetic algorithms, the number of individuals, generations, mutation probability and the genetic operators chosen).

In the first part of the thesis, interactivity was signaled as an important characteristic of the search process due to the nature of architectural problems. The case studies presented interactive features only before and after the design process. An interactive parametrization method made for the purposes of interaction *during* the search process was partially developed for this thesis, but it did not produce sufficient results for it to be included in this dissertation. Further research on interaction during the design process is certainly an important step. This issue relates closely with the time consumption in the creation of parametric models and their flexibility. In order for interaction to be present during the search process, designers must be able to modify parametric models in a very quick way, almost in real time.

Case studies in this dissertation involve three very different disciplines, making use of search processes to involve them directly in early in design. Many discipline-specific research can also be done in the future.

The building envelope is a subject of study that is rich with possibilities for a search process, and especially so for multi-disciplinary work. Acoustic insulation was not a topic of study in this work. Sound transmission is very much related to structural integrity, in that rigid structures tend to have smaller vibrations and in higher frequencies. Sound insulation is addressed many ways, one such approach os that of having very massive elements, rigidity is achieved by having massive envelopes. Another possibility is to generate envelopes that are more rigid because of their shape, thus further improving both structural capacity and reducing vibration transmission. Structural analysis can be incorporated with acoustical models that can help shed light on the interaction between sound waves and the vibration of building envelopes. The opportunity of embedding structural, acoustical and energy performances in architectural shapes is very appealing. Normally, envelopes are made up of a big number of separate components that achieve performances on their own, thus decoupling efficiency with shape, and this is arguably not interesting architecture.

Complex shapes were not employed in energy studies in this thesis. This is so because it was not clear, during the development of this research, whether existing energy performance calculation software are able to reproduce, in a sufficiently accurate way, the physical phenomena involved in the transmission of heat for complex shapes. Adequate modeling is certainly possible with computationally expensive techniques such as Computational Fluid Dynamics (CFD). Most of these methods model only one aspect of the problem, CDFs for example do not model radiative transmission of heat. Coupled analysis is a technique that puts together many models in order to create a complete simulation of the physical phenomena involved. This kind of analysis is surely very time consuming and not ideal for search processes, but it might be a good place to start. The opportunities of complex shapes in creating energy efficient buildings are an interesting enough subject to warrant such research.

List of Figures

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