11

Load bearing masonry walls

We have seen so far how Search algorithms help us gather useful information with complex shell surfaces. It stands to reason that search algorithms are naturally useful in complex geometries, and complex problems, and less so in more established problems with very simple geometry. But there are still very good advantages to the use of search algorithms in simple cases, their exploratory power can be put to good design use, and the information obtained might not always be obvious or otherwise easy to obtain. This is especially the case with simple geometries but with multi-disciplinary problems. In this cases, not matter how simple the geometry, the problem might be highly complex.

In this chapter we investigate the structural capacity of masonry load bearing walls will variable thicknesses and window arrangements. We will look into the complete structure of a rectangular building, considering different set of variables for all four sides of the rectangle. Windows are variable in quantity, dimension and position within the walls. As in previous structural case studies, we will contrast the structural performance of the masonry buildings with their weight, or more precisely, with the volume occupied by the masonry.

11.1 Structural analysis of load bearing masonry walls

As was the case with the masonry shell structures, the load bearing masonry walls need to be studied with great care to take into account the properties of this material. Masonry has no resistance to tensile stresses and therefore the use of linear FEM calculations need to be studied with this issue in mind. Elastic potential energy U_e values alone can be misleading. A more comprehensive analysis, yet simplified for the early design stage, is presented in section 10.4.1. It makes the distinction between tension and compression forces, in oder to study the generated shape accordingly. The same approach is employed in this chapter for the study of masonry walls.

11.2 Parametrization of walls and windows

Simple geometries tend to have simple parametric models, especially with the use of sophisticated CAD software. However, a parametric study made for the purposes of search algorithms is only as good as the possibilities it can offer the designer. Parametric models should be able to generate all of the possibilities that the designer wishes to investigate without creating problems for the search algorithm.

In this case, the parametric model needed to include the possibility of generating different size rectangular windows, in any position in the wall. Also, the most important requirement in this model, would be the possibility to allow the search algorithm to select not only the shape and position of the windows, but the amount of windows as well. The search algorithm should be able to generate as many windows as required in each wall, and also have the possibility to generate no windows at all. This important issue represents an interesting challenge in the programming of the parametric model. Wall thickness on the other hand presented no challenges, as in the case of the shell surfaces.

11.2.1 Isomorphism: A failed parametric model

A first attempt to parametrize the above described model is made following the same ideas presented in (Wright & Mourshed 2009). Wright and Mourshed present a parametric model of a wall with variable windows for energy efficiency optimization. Figure 11.1 shows the parametric scheme used by Wright and Mourshed. They model the wall and their windows in a binary way. They discretize the wall area into square elements, then generate a binary number with the same number of digits as the number of elements. A window is assigned to those squares associated with a 1, and wall for those elements associated with a 0. In this way, the parametric model is capable of generating windows in variable numbers, size and position. However, the generated windows are not strictly rectangular, as specified in our case. As seen in figure 11.1c, using this scheme, windows can be joined at their vertices, be discontinuous and also have wall elements inside them. This is not desired in our case, therefore a modification of the model has to be made.

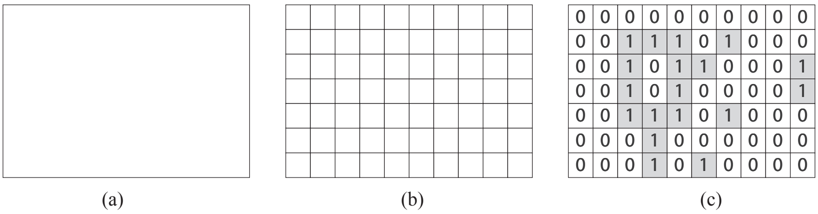

Figure 11.1: Parametric modeling scheme for wall with openings used in (Wright & Mourshed 2009).

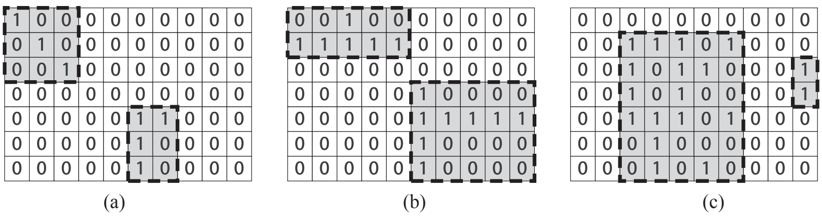

Figure 11.2: Parametric modeling scheme for wall with openings modified to include only rectangular and continuous windows.

Figure 11.2 shows the modification made to the model presented by Wright and Mourshed. An additional rule is implemented, where by window segments directly adjacent to each other, or window segments sharing a vertex, are combined into one single window. Figure 11.2c has the exact same binary input as figure 11.1c, but with very different resulting windows. With the addition of this rule, only rectangular windows are generated, and none of them have wall segments inside.

This modification however had negative unintended consequences, not present in the Wright and Mourshed model. Figure 11.3 shows 3 different binary digits, all of them generating the same window configuration inside

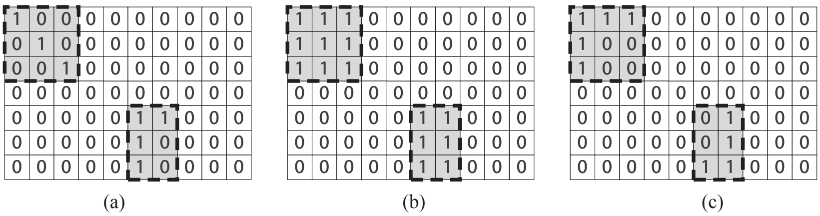

Figure 11.3: Three Isomorphic walls with different binary inputs.

the wall. This means that different genetic inputs generate exactly the same individual and therefore the same fitness function values. In genetic lexicon, this phenomenon is known as "encoding isomorphism" (Wang et al. 2006).

> "Encoding isomorphism means that chromosomes with different binary strings may map to the same solution in the design space. This leads to representational redundancy, which is not beneficial for the GA if the genetic operators cannot gain useful information from representational variants."

(Wang et al. 2006)

Another way of looking at encoding isomorphism is to look at the probabilities of generating different solutions at random. An ideal parametric model should provide the exact same probability of being generated to all individuals in its domain. All possible combinations of variable values should generate one single solution each, and all solutions being completely different from each other. When isomorphism starts being present in the model, there are a few solutions that have more instances of themselves in the parametric domain. Hence, there are higher probabilities of them being selected in a GA. Since this higher probability is not related to fitness values, but only encoding isomorphism, this higher probability is a problem. It influences the GA to select some solutions over others for the wrong reason. In the parametric model just presented, solutions with very large windows were far more likely to be selected that solutions with very small windows. The encoding isomorphism in the presented parametric model is so severe, that the GA, in hundreds of random initial individuals, is unable to generate a solution different from a wall containing only window squares and no wall areas. A better parametric model for this case study needs to be developed.

11.2.2 Window Area of Influence

A second attempt of parametrizing the above described problem is developed by means of subdividing the walls into areas of influence for each window. Figure 11.4 shows this concept for a single wall, subdivided (a) one single area, and (b) into 4 areas. Only one window can be drawn in each area, but the model is such that an area may or may not have a window.

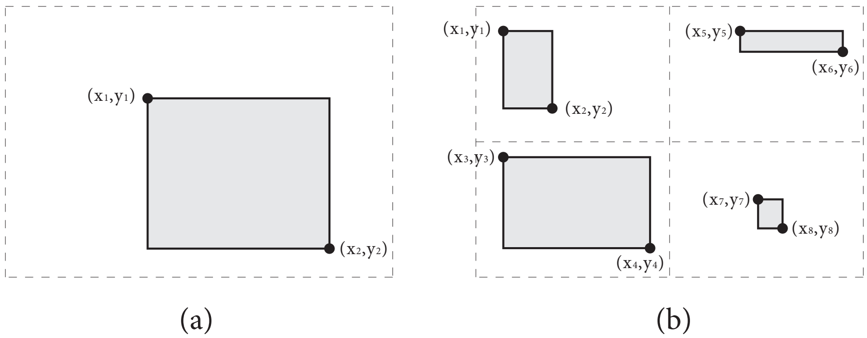

Figure 11.4: Parametric scheme following a window area of influence - (a) with one single area of influence - (b) with 4 areas of influences - All with 4 variables for each window.

Each window has 4 variables, x and y coordinates for 2 window corners. Since all windows are on a flat plane (the wall) there is no need for a third coordinate z. These coordinate values are normalized into values from 0 to 1. The four variables for each window can be expressed in the following way:

Variable	Point	Coordinate	Domain
x_1	1	X	0 to 1
x_2	1	Y	0 to 1
x_3	2	X	0 to 1
x_4	2	Y	0 to 1

In these terms, a window with variable values $x_1 = 0$; $x_2 = 0$; $x_3 = 1$; $x_4 = 1$ would result with the maximum sized window for that area. An additional rule has to he determined for the parametric model to be able to exclude windows from any given area. The rule establishes a minimum window dimension, for example 40cm. In this case any windows containing x or y dimensions under 40cm would be excluded.

Following this parametric formulation we can obtain rectangular windows of variable size, dimension, position and number, just as we set out to do in the problem formulation. There are however two limitations:

- The maximum number of windows is determined by the number of areas defined in the model. As previously stated, some areas can be empty, so the total number of windows is variable, from 0 to the number of areas. This number would be user defined, so it represents a small problem.
- There is no possibility of generating one single window covering the entire wall if more than one area is defined. When more that one area is present in the model, windows cannot be combined into one large window. Attempts to create a parametric model capable of combining windows led to isomorphism problems and were abandoned.

These limitations mean that separate GA runs need to be made for different area configurations. The parametric model cannot change the number of areas during its search process.

11.3 Mesh Discretization of walls with windows

The previous structural case studies included only continuous surfaces. They were mostly complex and double curvature surfaces, but they were all continuous, they had no windows or openings of any kind. This means that they were discretizable in a continuous grid of rectangular or triangular elements. Surfaces with openings are more complicated to discretize. FEM software, such as the ones employed in this PhD research, require certain kind of mesh geometry in order to have accurate results. There are two important characteristics that meshes are required to have:

- The angles between two mesh edges cannot be very small, the more they are 90 degrees for rectangular elements, and 60 degrees for triangular elements, the better the results. In the case of Oasys GSA (the FEM software used for this case study) if angles are not adequately sized the program will throw and error and stop the analysis.

◦ All of the lines or edges in the original geometry, such as wall or window edges, need to be discretized in several lines, therefore more than two points are needed. A good rule of thumb is to use 4 points minimum.

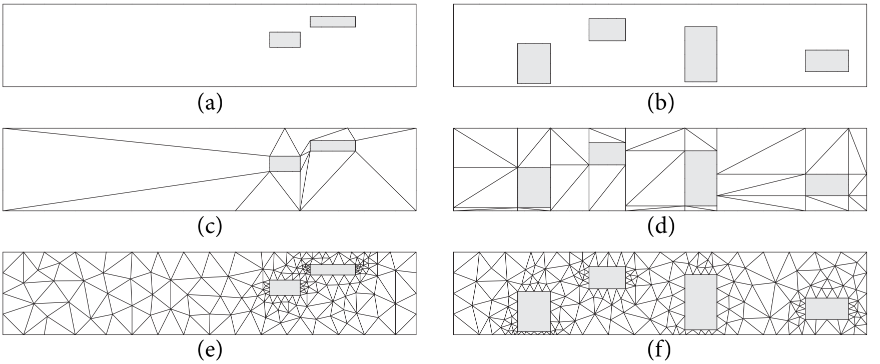

Figure 11.5: Correct and incorrect meshing of 2 walls with different window arrangements - (a) and (b) show the two original arrangements - (c) and (d) are the incorrect meshing of the two walls - (e) and (f) are the correct versions.

Figure 11.5 shows some examples of correctly and incorrectly discretized surfaces with rectangular openings. Since parametric models generate solutions that are quite different from each other, a meshing algorithm capable of respecting the above mentioned rules is needed. For the present PhD thesis Mehpy is used (Klockner n.d.). Meshpy is a Python wrapper for a meshing algorithm developed by Jonathan Richard Shewchuk called Triangle (Shewchuk 1996).

Triangle can generate meshes that contain openings, and that can respect the above mentioned rules. As its name suggests, Triangle generates only triangular meshes. For the purposes of this PhD research, a minimum angle of 30 degrees is imposed to all triangular mesh elements, and a minimum number of nodes of 4 is set for all wall and window edges.

Since triangle works only on two dimensions, in order to generate complete buildings, comprised of 4 separate walls, a few additional operations needed to be implemented. The four walls were calculated by Triangle in one single 2d mesh (figure 11.6), that is then folded into a 3d mesh by a special algorithm developed by the author. The first edge of the first wall needed to be "welded" with the last edge of the fourth wall, as shown in figure 11.7. A slab or roof element also needed to be generated. A separate triangle calculation is therefore implemented, one that generated the slab elements, taking the wall elements as a starting points. In this way, the nodes generated for the slab coincided perfectly with the top nodes of the wall mesh. An additional "welding" operation is then carried out, this obtaining a single mesh that contains all 4 walls and the slab, and no redundant or overlapping nodes or edges are present. A diagram of the entire process is shown in figure 11.7.

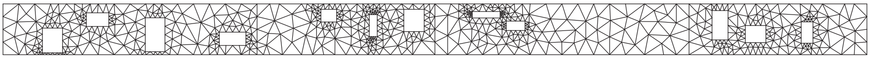

Figure 11.6: Unfolded walls for rectangular wall structure with windows.

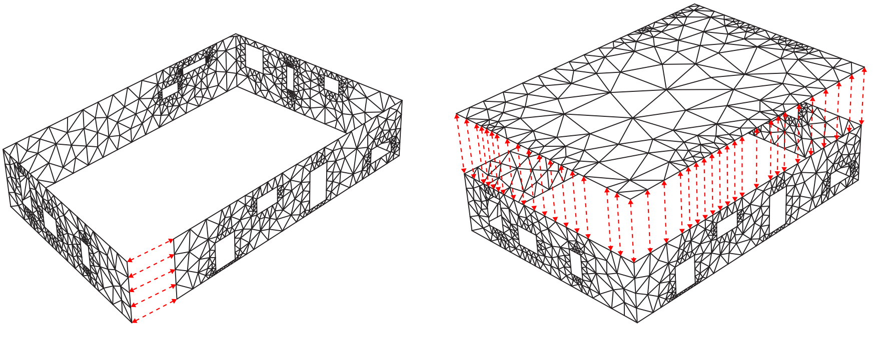

Figure 11.7: Folding and Welding process for wall structure meshes.

11.4 Case Study 5: Load bearing masonry walls

Case study 5 is a multi-objective search problem of a building supported by load bearing masonry walls. The building has a 20 × 14 rectangular plan and 6 floors, all containing offices. The structure is analyzed in only one story, the idea being to study a standard floor. For this purpose the first floor is chosen, the ground floor is not chosen because it is a special floor, and not a repeatable one like the first floor. Each standard floor is 4 meters in height.

The purpose is to generate window and thickness configurations for each wall in a rectangular building that minimize the wall's weight and maximize structural performance.

11.4.1 Parametric Model

The building is parametrized following the window area of influence scheme described in section 11.2.2. Each wall is subdivided into 4 areas that cover all of the height. The thicknesses of the four walls are defined separately, so they are also variables. The parametric model for case study 5 is shown in figure 11.8.

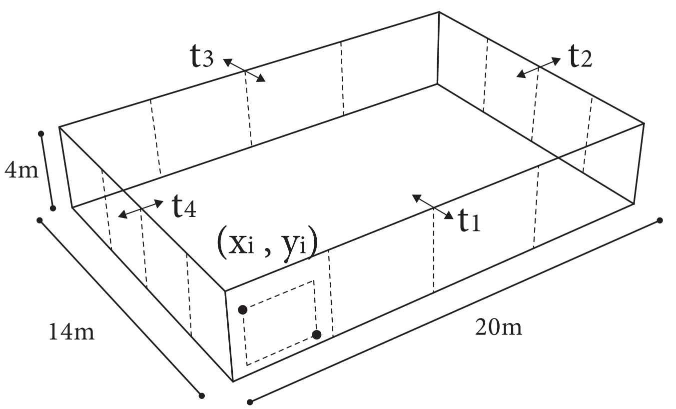

Figure 11.8: Parametric model for case study 5.

Since we have 4 variables for each window, and 4 areas for each of our 4 walls, there are in total 64 variables for the window configuration. To this we add the 4 thicknesses of the 4 walls and we get a total of 68 variables.

11.4.2 Fitness functions

Previous structural case studies in this thesis were mainly focused on roof structures and therefore were studied as such. In this case we are considering the main structural elements of an small office building. Hence it is necessary to subject the structure to more rigorous loads to determine their performance.

A total load is calculated from the buildings floor area and the number of stories. A load of 10kN were used for each m^2. With a floor plan of $20 \times 14\ m^2 \times 5$ stories, a total load of 14.000 kN is used. This represented the total vertical load applied to the structure. But the structure is also studied from a seismic point of view. Two separate loading cases are employed, each one of them includes the vertical load of 14.000 kN, plus one horizontal load equivalent to 10% of the vertical load. The difference between the two loading conditions is the direction of the horizontal loads, as seen in figure 11.9. The first loading case has a horizontal load parallel to the long dimension of the building, meaning that the 20m long walls would be the ones most responsible for resisting the horizontal load. The second loading case has an horizontal load parallel to the short dimension of the building, in this case being the 14m walls most involved.

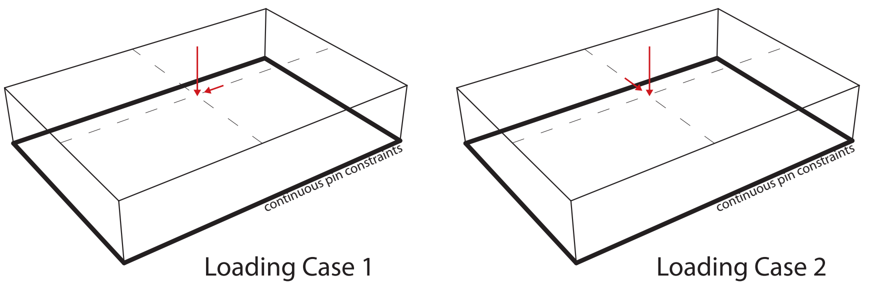

Figure 11.9: FEM model setup and loading cases for case study 5.

From the dimensions of the building, under equal thicknesses and window arrangements, we could expect that the second loading condition would be the most critical. However, since the parametric model used in this case study modifies window arrangements and wall thicknesses, it is not possible to know this beforehand. It is therefore necessary to calculate both loading cases for all candidate solutions. The solutions are then evaluated considering the most critical case for each of them individually.

The masonry walls are studied with the same fitness function created for the shell structures, detailed in equation 10.8. As it was the case for the shell structures, a reference solution is needed in order to calculate our structural fitness function. More specifically, we need to set $max(\tau_0^+)$ and $U_{e,0}$. In this case, the most regular and strongest structure is selected, the structure without any windows and with the thickest walls. This selection implies the fact that the highest fitness values would be the one where $max(\tau^+)$ and U_e are lower or equal to $max(\tau_0^+)$ and $U_{e,0}$ respectively. The only modification would be the fact that it is calculated once for each loading case, and the one with the highest value is used. This modification can be expressed as follows:

$$\begin{aligned} & fit = max(f_{case1}; f_{case2}) \\ where \quad & f_{case1} = \frac{U_e}{U_{e,0}} + \left(\frac{max(\tau^+)^2}{max(\tau_0^+)^2} \cdot w \right) \\ & f_{case2} = \frac{U_e}{U_{e,0}} + \left(\frac{max(\tau^+)^2}{max(\tau_0^+)^2} \cdot w \right) \end{aligned} \tag{11.1}$$

This means that the FEM simulation is executed twice for each solution studied, and the fitness values used would be the highest one. This case study has significantly higher calculation times, not only because of the two FEM calculations, but also because the number of nodes, and elements in each solution is significantly higher than in the previous cases.

The second fitness function in case study 5 is the weight function, simplified as the wall's volume. The search problem put forth in this case study can be defined as follows:

$$Case\ Study\ 5 \begin{cases} Minimize & max(f_{case1}; f_{case2}), \\ Minimize & f_2(x) = V \end{cases} \tag{11.2}$$

11.4.3 Genetic algorithm inputs

The number of variables in this case study is significantly higher than the ones seen in previous case studies, and the calculations times are higher as well. This represents a big challenge for the MOGA. In this chapter we present the results found with the following genetic inputs:

Case Study 5		
Population Size (N)	50	
Number of Variables	68	
Number of binary digits	8 for window points (x_{1-64})	6 for thicknesses (x_{65-68})
Variable Domains	$x_{1-64} \in [0, 1]$	$x_{65-68} \in [0.05, 1.0]$
Mutation Probability (p_m)	0.2	
End Condition	End after 100 generations	

A population size of 50 individuals and 100 generations might or might not be enough for us to find a final Pareto front. The results obtained in this chapter are presented as found, no metric to determine convergence have been done.

11.4.4 Results

Figure 11.10 shows the objective space and Pareto front for case study 5. It shows a Pareto front that is not as orthogonal as some of the ones we saw in other structural case studies, suggesting a higher level of contrast between f_1 and f_2 in this case.

Figure 11.11 shows 3 examples of Pareto dominant solutions for case study 5. Solution A is a structurally high performing solution, but it is a heavy one. It is characterized by thick walls and very small windows. Structurally high performing solutions in the front have very small windows, or none at all in the short walls. This suggests that they can develop the most strength for loading case 2 in this way. As previously mentioned, loading case 2 is expected to be the most critical under most conditions, and since f_1 selects the most critical case as a fitness value, it is reasonable to expect the small walls to be the object of the most attention, but this is not always so. Another important characteristic of high performing solutions for f_1 is high thicknesses. But thickness is not found to be distributed evenly among the four walls, in most cases, the thickest wall is the long wall opposite the horizontal load in loading case 2. This is most evident when looking at solution A. This fact is evidence that not only walls parallel to the horizontal walls are structurally significant, when thicknesses are high in perpendicular walls, they begin to contribute significantly to buildings structural rigidity.

Solution C is the best performing solution for f_2 (the lightest solution in the Pareto front). As is to be expected, light solutions tend to have very small thicknesses on all 4 walls and larger windows in them as well. Solution C shows the largest windows in the longer walls, while still preserving some thickness for the same long wall opposite the horizontal load in case 2.

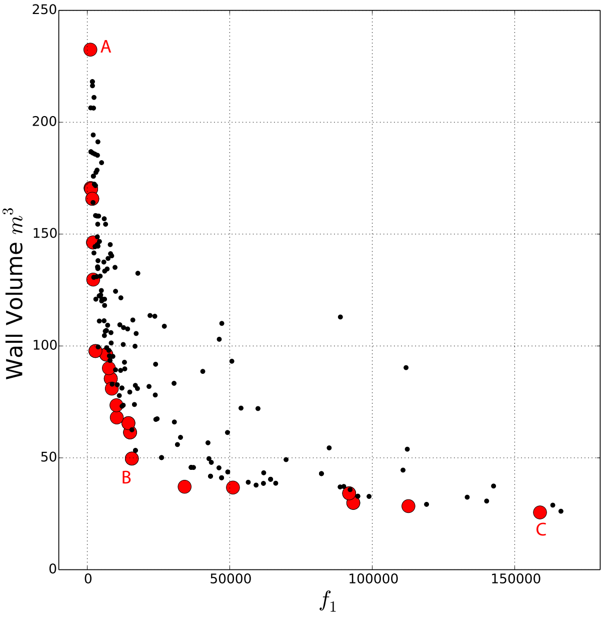

Figure 11.10: Objective space for case study 5 - Pareto Front in red.

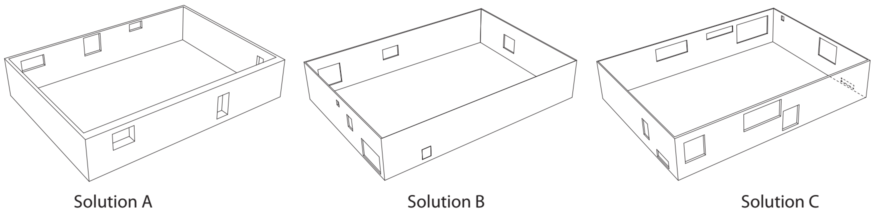

Figure 11.11: Case Study 5 result structures.

Solution B is a good compromise for f_1 and f_2. It is also a very interesting exception to most other solutions in the front. It does not have a thick long wall, on the contrary, it has a very thin one. Most other solutions in the Pareto front are similar to solution A, It also has an interesting diagonal window pattern in one of its short walls. This seems to suggest that a higher level of exploration could accomplish very interesting window patterns that increase rigidity while maintaining very low thicknesses.

Another interesting feature of the results of case study 5 is the fact that solution B is quite different from other solutions close to it in the front. With as many as 68 variables, it is not possible to plot the search space for this study, but if we did, we would find that non-dominated solutions are quite far from each other in it. Pareto-optimal solutions are quite different from each other, and do not form a continuous pattern in the search space. From an architectural point of view, to gather this set of very different but high performing solutions is arguably quite useful, and can significantly increase performance in the early stages of design without hindering creativity.

12

Acoustic Design of Concert Halls

> "Charles Garnier, designer of the Opéra Garnier in Paris, said in his book "The Grand Opera in Paris", that he had pursued diligently the elusive factors of good acoustics, but he confessed that he finally trusted to luck, "like the acrobat who closes his eyes and clings to the ropes of an ascending baloon." "Eh bien!" he concludes, "Je suis arrivé" He went on, "The credit is not mine, I merely wear the marks of honor. It is not my fault that acoustics and I can never come to an understanding. I gave myself great pains to master this bizare science, but after fifteen years of labor, I found myself hardly in advance of where I stood the first day... I had read diligently in my books, and conferred industriously with philosophers - nowhere did i find a positive rule of action to guide me; in the contrary, nothing but contradictory statements. For long months, I studied, questioned everything, but after this travail finally i made this discovery. A room to have a good acoustics must be either long or broad, high or low, of wood or stone, round or square, and so forth... Chance seems as dominant in the theatrical [opera house] world as it is in the dream world in which a child enters Wonderland!""

(Beranek 2004)

Charles Garnier's sarcastic comments on the difficulties in the acoustic design of a concert spaces retain some validity even today. He started construction on the Paris Opera house a few years before Wallace Clement Sabine, the father of modern architectural acoustics, was born. Sabine would later collaborate with McKim, Mead and White in the design of the Boston Symphony hall which is still considered one of the best for its acoustics. Since the pioneering work of Sabine, much more is known about the propagation of sound waves in confined spaces, the perception of sound by the human ear and brain, as well as the acoustical preferences of the audiences that attend these concerts. However, as acoustician Lawrence Kirkegaard puts it "What is yet to be learned could be more important than what we already know" (Beranek et al. 2010). Many uncertainties still make the design of concert auditoria a notoriously complex task even in contemporary architecture.

The purpose of acoustic design of concert spaces is to create the conditions for the enjoyment of music in the room, to enrich the experience of the musician and concert goer. This means generating the acoustics that the is user's preference for the music being played. Subjectivity is highly present in this field, and it is partly responsible for its complexity. Concert hall design is part architecture, part physics and part psychology. The user's opinion of a hall may be affected not only by the physical characteristics of the room, but also by many other unrelated issues such as cultural background, education and taste, and even by the reputation of the room.

Over the last 100 years, with the work of many experts that carried out interviews, questionnaires and laboratory experiments, the listener's and the musician's preferences in the acoustics of rooms destined for specific kinds of music have been studied, and some important characteristics have been laid out. The first and most important of which is reverberation, but it is by no means the only one:

> "In concert hall acoustics there are at least five independent dimensions. This was first established by Hawkes and Douglas (1971) and in the last three decades the nature of these different dimensions has been refined. The major concerns are that the *clarity* should be adequate to enable musical detail to be appreciated, that the *reverberant response* of the room should be suitable, that the sound should provide the listener with an *impression of space*, that the listener should sense the acoustic experience as *intimate* and that he/she should judge it as having adequate *loudness*. This list is by no means complete or definitive. It omits any reference to tone colour or timbre, which is certainly also important. Yet the five qualities: clarity, reverberance, spatial impression, intimacy and loudness provide a useful starting point for discussion."

(Barron 2009*a*)

In this passage, Barron describes five major acoustical attributes considered to be important to the listener's preferences in concert halls. Figure 12.1 shows the questionnaire he administered to study the acoustical quality of British concert halls. In it we can see the five attributes or "dimensions" and their characterization by the user. When it comes to clarity, rooms can be muddy or clear, they can be dead or alive when it comes to reverberation, the spatial envelopment can be expansive of constricted, the room can be remote or intimate, loud or quiet. These are subjective impressions by the listeners of the sounds they heard, the physical phenomenon occurring during the concert.

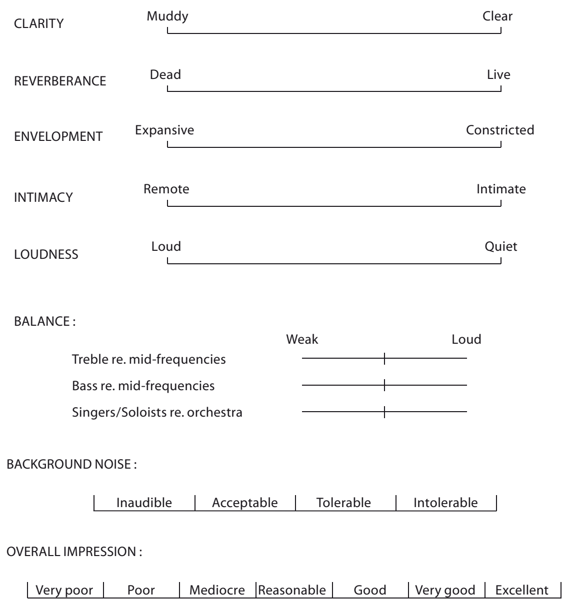

Figure 12.1: Questionnaire used by Barron for subjective survey of British concert halls.

A fundamental part of the puzzle of room acoustics is the connection between the physical characteristics of musical sounds and the listener's preferences, the relationship between subjective preferences and objective measurements of sound. Physical studies and descriptions of sound fields inside concert spaces have been extensively made. Recordings of music, gunshots and balloon bursts have been used to measure and quantify different aspects of the physical phenomena at play in these spaces during the enjoyment of music. These recordings have been translated into countless measurements, visualizations and methods to try and make this connection between subjective and objective. An agreement among acousticians as to the best objective description of subjective preference is still not existent (Bradley 2011). However, most concert halls today are designed following one of these methods, most commonly the Room Acoustics Parameters described in the ISO 3382-1 standard (ISO 3382-1:2009 International Standards Organization, 2009).

The acoustic design of a concert hall can be defined as the definition of the shape, dimensions, materials and functional configuration of a space, with the purpose of creating the acoustic conditions over the entire audience area that best reflect the subjective preference of the listeners. The most important variables involved in this case are the shape and the materials of the surfaces that reflect the sound from the orchestra to the audience, the volume that reverberates the direct sound creating the hall experience.

Another important characteristic of the rooms is the absence of acoustical defects like echoes or background noise. While these defects have nothing to do with acoustical preference, they surely can lessen the concert experience. Nothing can ruin the concert experience more that the presence of external noise like car horns or ambulance sirens. This issue however is more easily solved, by means of insulating materials, sound barriers and generally avoiding vibration transmission. Noise control however has very little relation with room shape. Disturbing echoes on the other hand are the subject of room shape studies. Sound reflections, commonly from concave surfaces, can be heard as separate sounds (not as reverberation) if they are much louder than the rest of the reflections, and if they are too distant from the original direct sound. Therefore special attention is also given to the room shape in order to avoid sound concentrations and strong late reflections.

12.1 Concert Hall Types

Concert hall shapes have long been the subject of study, with particular attention being placed on existing room types that have good reputations for their acoustics*. Concert halls and Opera Houses are an interesting case in the study of architectural typology. A very large number of concert spaces can be traced back to a small number of types, designers have not strained very far from established designs. Acoustics is considered by architects as a complex and somewhat obscure art, and until recently they followed established recipes, in the form of known types. Concert spaces are very expensive to build and even to repair, so the responsibility imposed on the designers is very high. All of these factors combined give us a scenario in which four simple concert hall types can describe almost all existing concert spaces. Existing concert halls can be classified into four main room types: Shoeboxes, fan shaped rooms, hexagonal rooms and vineyards (Meyer 2013). Equal volume, dimensions, materials and even reverberation could be achieved in all of these concert hall types, but they all have a particular sound.

Figure 12.2: The Musikverein in Vienna - photo credit: Andreas Praefcke.

The most important type of concert hall, the one with the highest number of examples is the “Shoebox” room. They are mostly characterized by their

*A discussion of concert hall types form a more theoretical point of view is presented in section 3.2. A historical review of concert hall types is presented in (Meyer 2013) rectangular plan shape with the orchestra in one end of the room, their parallel and vertical sidewalls and their flat ceiling (thus the name shoebox). Some of the most renowned concert halls, such as the Boston Symphony hall, the Concertgebouw in Amsterdam and the Musikverein in Vienna (see figure 12.2), are shoebox rooms.

Most of these historical spaces are characterized by an important presence of ornamentation in the form of sculptures, bas-reliefs and frames. These tend to be volumetrically complex and irregular, thus guaranteeing a good level of sound diffusion or sound scattering from their surfaces. In other words, most sound waves are not reflected specularly from the surfaces, but are diffused in many directions. While this is not a characteristic that is present only in shoebox rooms, it is considered to be important in this type, in order to reduce the risk of flutter echoes caused by parallel walls.

Shoebox rooms can have a wide variation in acoustic reputation, from the most renowned to others with very bad reviews. This means that just the parallelepipedal shape is not enough to obtain a high acoustic quality. Studies have been made as to the correct proportions that the shoebox room should have in order to obtain acoustical quality[†]. Most of the best performing rooms in this type tend to be narrow and long rooms, as opposed to wide and short. This might sound counter-intuitive in the sense that long rooms would have a good number of listeners far away from the orchestra, while short rooms would have them closer. But apparently, listeners prefer to have a good number of side reflections coming form the sidewalls, so distance from the sidewalls becomes more important.

Another important room type is the Fan shaped room. As the name explains, the Fan shaped rooms can be best described by their fan or trapezoidal shape in plan, with their angled sidewalls opening up away from the stage. They can be seen as an indoor version of the greek and roman amphitheaters, they have the stage in the center of a series of concentric circles. They provide a visual intimacy in the room, since they minimize the distance between audiences and the stage. They are known to have little initial reflections in the middle of the room, due to their angled sidewalls. Many of them have a concave curved back wall that can cause sound concentrations on the stage[‡]. Examples of this type are the Fredric R. Mann auditorium

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[†]See for example (Klosak & Gade 2008, Méndez Echenagucia, Astolfi, Shtrepi, van der Harten & Sassone 2013*a*)

[‡]See for example Beranek's account of the design of the Aula Magna for the Universidad Central de Venezuela, in which we recounts the solution proposed to these problems (Beranek 2004).

in Tel Aviv or the Aula Magna in Caracas.

A third room type outlined by Mayer is the hexagonal concert hall. The hexagonal rooms are characterized by their hexagonal plan shape, thus having angled sidewalls opening behind the orchestra and closing towards the room. The angled sidewalls offer the same advantages and disadvantages as the ones discussed in the fan shaped rooms. But the presence of the walls closing behind the audience provide a different experience, these walls provide a greater number of side reflections to seats positioned in the center of the room. Examples of thus type are Barbican Concert Hall in London or the Bunka Kaikan in Tokyo.

The Berlin Philharmonie is considered to be the first Vineyard room. This type is characterized by having the orchestra in the middle of the room, and by the presence of many audience terraces and inclined walls providing early reflections to seating positions directly in front of them. As it is explained in chapter 3, this type is very much appreciated by audiences and musicians for their intimacy, the vicinity of the audience to the stage, but also by its acoustical quality. The presence of a great number of terrace walls seems to substitute for large sidewalls that provide early sound reflections.

12.2 Room Acoustics Parameters

In the late 1890's, Sabine developed the concept of the Reverberation Time (RT) that became the basis for the study of room acoustics to come. Reverberation time was defined as the time it takes sound to decay by 60 dB after the sound source was switched off. Sabine noticed that this decay time was related to room volume and characteristics, and developed the following formula to calculate it:

$$RT = \frac{0.16 \cdot V}{A_{tot}} \quad \text{(s)} \tag{12.1}$$

where V is the room volume and A_{tot} is the total absorption of the room and can be calculated as:

$$A_{tot} = \sum_{i=1}^{N} S_i \cdot \alpha_i \tag{12.2}$$

where N is the number of surfaces in the room, S_i is the surface area of the i_{th} room surface and α_i is the absorption coefficient for the i_{th} surface. Since materials have different absorption qualities at different sound frequencies, RT changes significantly for different frequencies in the same room. It is typically measured for several octave bands like 62, 125, 250, 500, 1000, 2000, 4000 and 8000 Hz. Reverberation times, as well as most other acoustical parameters are calculated from the measured impulse response. The impulse response is defined by the ISO 3382-1 standard as the "temporal evolution of the sound pressure observed at a point in a room as a result of the emission of a Dirac impulse at another point in the room" (ISO 3382-1:2009 International Standards Organization, 2009).

Since Sabine's development of the reverberation time, a great number of Room Acoustics Parameters, or objective measures, describing the sound field inside concert have been developed [§]. Most of these parameters describe aspects of the sound field at a single position inside the room based on the measured impulse response, and most of these try to describe one aspect of the subjective impression of the listener. Each parameter is associated with a Just Noticeable difference (JND) and a prescribed or optimal value, minimum-maximum acceptable values or a range of values preferred. Preferred parameters and their optimal values are usually selected on the basis of the purpose of the room, for example, rooms intended for opera, chamber or symphonic music are generally studied by practitioners with different parameters and using different optimal values for them. While there seems to be a general agreement among acousticians on JND values, there is no general consensus on which parameters best describe subjective preference of the listeners, nor the optimal values for them (Bradley 2011). For example, some contrasting optimal values are prescribed by Beranek (Beranek 2004) and Barron (Barron 2009*a*).

Bradley describes four main categories of acoustical parameters (Bradley 2011): Decay times, clarity measures, sound strength and measures of spatial effects. Other authors include other categories such as "Intimacy" or "Warmth", but these will not be included in this PhD research. In this chapter we will go through Bradley's categories and the objective parameters that describe them. They are all calculated by means of the measured impulse response.

[§] These parameters are the subject of the ISO 3382-1 standard (ISO 3382-1:2009 International Standards Organization, 2009). A historical description of the parameters is presented in (Lacatis et al. 2008). A comprehensive study of each parameter, their Just noticeable Differences and proposed optimal values or ranges is given in (Abdou & Guy 1996).

12.2.1 Decay Times

Decay times describe the way sound levels decay over time. The reverberation time RT, the first important acoustical measurement is of course a decay time, but it is not the only one. From RT on, other decay times were developed with different objectives, but they all describe reverberation in some form or another.

Studies show that the decay time parameter that best describes the subjective impression of reverberation while listening to music is the Early Decay Time EDT (Barron 1995). Mike Barron describes the development of EDT:

> "Atal, Schroeder and Sessler (Atal et al. 1965) conducted subjective tests in which subjects were asked to match artificially reverberated speech and music, with the comparison being made between decays which were linear (regarding sound level) and non-linear. For these artificially reverberated sounds the decay rate over the first 160 ms was found to relate most closely to perceived reverberation. When recordings were made in two concert halls, the subjective reverberation time matched most closely the initial reverberation time measured over the first 15 dB of the decay. Jordan (Jordan 1970) subsequently proposed in 1970 measuring the decay rate over the first 10 dB of the decay, naming it the early decay time (EDT)."

(Barron 1995)

Abdou and Guy describe EDT as the "slope of best fit straight line to sound level decay curve from 0 to -10 dB, extrapolated to -60 dB"(Abdou & Guy 1996). EDT simply extends the decay rate of the first 10dB to the full 60dB in order to be compared to the more historical and traditional RT. EDT values can be either longer or shorter that the RT value at that same point in the room. Barron describes this behavior and the room characteristics that define it (Barron 1995).

As all other acoustical parameters, it is very important to understand how sensible is the human hearing system to variations in EDT, how big a difference is perceived by the listener. This values are called Just Noticeable Differences (JNDs). The ISO 3382-1 standard reports a JND for EDT of 5%.

Beranek writes that the concert halls that obtained the best subjective ratings on his interviews had a mid frequency EDT value between 1.8 to

2.05 seconds for the occupied room measurements and between 2.45 and 3.1 seconds for the unoccupied room (Beranek 2004). These values are not that dissimilar from the values prescribed by Barron, from 1.8 to 2.2 seconds in the occupied rooms (Barron 2009*a*).

12.2.2 Clarity measures

Beranek defines clarity in the following way:

> "When a musician speaks of "definition" or "clarity", he means the degree to which the individual sounds in a musical performance stand apart from one another."

(Beranek 2004)

Clarity measures can then be said to be the objective measurements that try to describe the acoustical conditions in which individual sounds in a musical performance stand apart from one another. The way most of these measurements try to describe these acoustical conditions is by considering the ratio between early arriving energy and the reverberant later sound. There are many such parameters, Bradley includes four of them in his list of clarity measures: Definition D_{50}, Clarity C_{50} and C_{80}, and Centre time T_s. Out of these parameters, the one most used for the description of clarity for musical performances is C_{80}.

Also called the early to late ratio, C_{80} was developed by Reichard, Abdel and Alim in 1974. C_{80} is calculated on the basis of the measured impulse response, and it is defined by the following equation:

$$C_{80} = 10log\left(\frac{\int_0^{80} p^2(t)\mathrm{d}t}{\int_{80}^{\infty} p^2(t)\mathrm{d}t}\right) \quad \text{(dB)} \tag{12.3}$$

where $p(t)$ is the instantaneous sound pressure of the impulse response at a given measurement point. As the formula shows it is a logarithmic ratio of the energy measured before 80 milliseconds and the energy measured after 80 milliseconds. That means impulse responses with a high number of early reflections and low reverberation will give a high and positive C_{80}. Impulse responses with low early energy and high reverberation will have a low and negative C_{80}. Impulse responses that obtain the same amount of energy before and after 80 milliseconds will have a C_{80} value of 0 dB. The ISO 3382-1 standard reports a JND for C_{80} of 1 dB.

In his study of 58 concert hall and opera houses, Beranek notes that rooms that obtained the best subjective ratings on his interviews had a mid frequency C_{80} value between 0 and -3 dB (Beranek 2004). These values are significantly different that those that Barron considers to be acceptable C_{80} values. Barron indicates values from -2 to 2 dB to be in an acceptable range (Barron 2009*a*).

12.2.3 Sound Strength

Sound strength is fairly self explanatory, these parameters look into the loudness or strength of the sound arriving at listeners form the source. The source's output has a big influence on the strength of the sound arriving at listeners, but a great deal of this also has to do with the room. Sound strength is considered by many acousticians to be one of the most important attributes to determine the acoustical quality of a room (Bradley 2011), with Beranek going as far as declaring that room volumes and materials should be calculated considering G as well as RT (Beranek 2011).

Sound strength is generally expressed by two objective measures, Sound Pressure Level SPL and sound strength parameter G. Of these two, the vast majority of acousticians use parameter G. It is defined in the ISO 3382-1 standard as "as the logarithmic ratio of the sound energy (squared and integrated sound pressure) of the measured impulse response to that of the response measured in a free field at a distance of 10 meters from the sound source", noting that the impulse response should be measured with an omnidirectional acoustic source. This definition can be expressed in the following equation:

$$G = 10log\left(\frac{\int_0^\infty p^2(t)\mathrm{d}t}{\int_0^\infty p_{10}^2(t)\mathrm{d}t}\right) \quad \text{(dB)} \tag{12.4}$$

where $p_{10}(t)$ is the instantaneous sound pressure of the impulse response measured at a distance of 10 meters in a free field. The standard also provides this alternate method for determining G when using an omnidirectional sound source of which the sound power level is known. In that case G can be obtained from the following equation:

$$G = L_p - L_W + 31\mathrm{dB} \quad \text{(dB)} \tag{12.5}$$

where L_p is the sound pressure level measured at the desired point and L_W is the sound power level of the sound source used to do the measurement. G values can be positive, when the measured energy is greater that the free field energy at 10 meters, or negative, when the opposite is true.

Beranek explains that loudness in the room is mostly related to the total absorption A_{tot} and that approximately 50% of that absorption is determined by the area occupied by the audience (Beranek 2011). So the number of listeners in the audience, and the area they occupy in the room are a fundamental attribute to consider when designing concert spaces.

The JND for strength parameter G is defined in the standard as 1 dB. Optimal ranges of G can be varied when consulting different authors. Beranek considers that G values for mid-frequencies should range from 4 and 7.5 dB in large symphonic spaces, and should be even higher in spaces for chamber music. Barron on the other hand prescribes a minimum G value that is determined by the source-receiver distance (Barron 2009*b*). According to Barron, for receivers from 10 meters to the source onwards, a minimum value G_{min} is calculated by means of the following equation:

$$G_{min} = 10\log(100/r^2 + 2.08e^{-0.02r}) \quad \text{(dB)} \tag{12.6}$$

where r is the source-receiver distance. This formula prescribes a G_{min} value close to 4 dB for receivers 10 meters from the source, 2 dB at 20 meters, and 0 dB at 40 meters. Above 40 meters Barron keeps a minimum value of 0 dB.

12.2.4 Measures of Spatial Effects

The collaboration between Harold Marshall and Mike Barron in the 60's and early 70's gave start to the study of the spatial aspects of sound in concert spaces.

> "Before 1960 audible spatial effects were associated with the late reverberant sound (Kuttruff 2000); the experience of sound in a cathedral space clearly supports this connection. A long reverberation time and room surfaces that scatter sound were thought to enhance the spatial effect. Then in 1967 Marshall suggested that strong early reflections from the side were a component of sound in halls with the best acoustics. Whereas in the past there had been no guidelines available regarding the appropriate shape for symphony concert halls, here was a criterion with consequences for auditorium form. Marshall's ideas also

provided an explanation for the high reputation of traditional rectangular plan halls...

...Spatial impression was found to involve a sense of the source becoming broader for loud sounds, as well as a sense for the listener of being surrounded by sound, a sense of envelopment. The two components of spatial impression are called "source broadening" and "listener envelopment"."

(Barron 2009*a*)

The source broadening effect is mostly referred to as Apparent Source Width (ASW) and Listener Envelopment as (LEV). It is now known that ASW is related to early arriving lateral reflections, and that LEV is more related to late arriving lateral energy. ASW is most commonly studied by means of the Early Lateral Fraction parameter LF_{early} and Inter-aural cross correlation of the early-arriving sounds $IACC_{early}$, most commonly expressed as $1 - IACC_{early}$. LEV is most commonly measured by the late-arriving lateral sound strength (GLL)(Bradley 2011).

It is generally accepted that the early sound is most determined by the shape of the room while the reverberant sound is much less dependent on shape. Since this PhD thesis is most concerned with the early design phase and more specifically with architectural form, out of the two spatial effects we will consider only ASW. As it was previously mentioned ASW is studied by the use the means of LF_{early} and $IACC_{early}$.

Developed by Barron and Marshall (Barron & Marshall 1981) LF_{early} is the ratio between the early arriving lateral sound energy and the early arriving energy from all directions. It can be expressed as the following function:

$$LF_{early} = \frac{\displaystyle\int_5^{80} p_L^2(t)\mathrm{d}t}{\displaystyle\int_5^{80} p^2(t)\mathrm{d}t} \tag{12.7}$$

where $p_L(t)$ is the instantaneous sound pressure in the auditorium impulse response measured with a figure-of-eight pattern microphone. Looking at this equation, we can see that LF_{early} is a dimensionless quantity and that it can have values from 0 to 1.

$IACC$ measures the correlation between the impulses response measured inside the two ears of a dummy head. These correlations can take into account different time intervals, in this case we are talking about $IACC_{early}$ so we consider an interval between 0 and 80 milliseconds, the same one used for LF_{early}. $IACC_{early}$ can be expressed by the following equations:

$$IACF_{early}(\tau) = \frac{\int_0^{80} p_l(t) \cdot p_r(t+\tau)\mathrm{d}t}{\sqrt{\int_0^{80} p_l^2(t)\mathrm{d}t \int_0^{80} p_r^2(t)\mathrm{d}t}} \tag{12.8}$$

$$IACC_{early} = max.of \ |IACF_{early}(\tau)| \ \text{ for } \ 1 \ \text{ ms} < \tau < 1 \ \text{ ms}$$

where $p_l(t)$ and $p_r(t)$ are the left and right pressure impulse response measured inside or near the ears of a dummy head and τ is the time interval or time shift.

In his review of acoustic objective measures, Bradley explains what is known about the relationship between LF_{early} and $IACC_{early}$:

> "LF_{early} and $1-IACC_{early}$ measures are conceptually quite different and it is not initially obvious that they are related to each other. However measurements of both quantities in 15 different halls (Bradley 1994) have shown that hall average values are significantly correlated in the octave bands from 125 to 1000 Hz inclusive, but not in the 2000 and 4000 Hz octave bands…
>
> …The two types of measures do assess some similar aspects of the sound fields, but there are other aspects that do not create the same variations in these two types of quantities. One can speculate about the cause of the differences. LF_{early} values are derived from simple energy summations, but $1-IACC_{early}$ values involve cross correlations of signals that could be influenced by interference effects that may not be reflected as changes in LF_{early} values. The important question is, are these audible differences and hence important to perceptions of concert hall sound quality? It seems possible that moving to an adjacent seat might produce measurable changes in $IACC_{early}$ values but not in LF_{early} values. Again, how do such changes relate to what we can hear? We need to understand the importance of the differences in these two types of quantities to know which best tells us about the subjectively important aspects of the spatial characteristics of halls."

(Bradley 2011)

Beranek found that when compared to LF_{early}, $IACC_{early}$ better predicted the subjective preferences in his interviews. But these calculations were made by using the average LF_{early} and $IACC_{early}$ values and not single listening positions. The choice between these two parameters is then not a clear one. For this PhD thesis LF_{early} was employed as a measure of ASW.

12.3 Total subjective preference and Room Acoustics Parameters

As we have seen in the previous sections, there are many subjective qualities to a concert space, and many more objective parameters that try to describe those qualities. But is there a way to describe the overall or total subjective preference of a room? Can we obtain a single number that describes the overall quality of a concert hall?

In two separate studies, Beranek and Ando try to answer this question by employing a weighted sum of a few parameters in order to get a single number. Beranek (Beranek 2004) attributes the sound quality of a room to the following parameters in these respective percentages:

$1 - IACC_{early}$	25%
EDT	25%
SDI	15%
G_{mid}	15%
Δt_1	10%
BR	10%

where SDI is the Surface Diffusivity Index, Δt_1 is the Initial Time Delay Gap, G_{mid} is the G value for mid frequencies and BR is the Bass Ratio. On the other hand Barron describes the relative importance of one subjective quantity over the other in the following way:

> "Several independent subjective quantities are important and people have their own personal bias in terms of what is for them most important. This implies that there is no single quantity that is most important. Rather, several measurable quantities are important and in a well-designed hall values for each quantity

need to be within acceptable limits throughout the auditorium. The concert hall experience is definitely multi-dimensional."

(Barron 2009*a*)

In this PhD thesis, no single acoustical parameter or subjective quality is given preference over any other. In this research the four subjective families described above are treated as separate and contrasting functions, and the search for an optimal concert space is done by means of a multi-objective search algorithm. Therefore, the objective functions are evaluated with the Pareto approach.