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From Architectural Acoustics to Acoustical Architecture Using Computer Simulation

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ABSTRACT
Architectural acoustics design has in the past been based on simple design rules. However, with a growing complexity in architectural acoustics and the emergence of room acoustic simulation programmes with considerable potential, it is now possible to subjectively analyse and evaluate acoustic properties prior to the actual construction of a building. With the right tools applied, acoustic design can become an integral part of the architectural design process. The aim of this paper is to investigate the field of application that an acoustic simulation programme can have during an architectural acoustic design process and to set up a strategy to develop future programmes. The emphasis is put on the first three out of four phases in the working process of the architect and a case study is carried out in which each phase is represented by typical results – as exemplified with reference to the design of Bagsvaerd Church by Jørn Utzon. The paper discusses the advantages and disadvantages of the programme in each phase compared to the works of architects not using acoustic simulation programmes. The conclusion of the paper points towards the need to apply the acoustic simulation programmes to the first phases in the architectural process and set out a reverse strategy for simulation programmes to do so - from developing acoustics from given spaces to developing spaces from given acoustics.

INTRODUCTION

Since the end of the master-builder period the field of building has become more and more specialized in fields such as architecture and engineering respectively. Some works of architecture does, however, transcend the limits of the fields and they prove to be some of the most innovative works pushing the boundaries of both architecture and engineering. Innovation in both fields could therefore be achieved by establishing a practice of this kind of transcending building culture.

The title architect refers to a simultaneous existence of techniques and aesthetics; *architect* = *archi* + *tekton*, *archi* meaning master and the Greek *tekton* meaning builder and referring to a simultaneous existence of art and craft since when the term developed the Greeks did not distinguish between the two. This understanding of artistic expression and the means, with which one brings the work of art into existence, as two mutually interdependent parts, is today represented in tectonic theory. One of the theorists from this position suggest that tectonic architecture should be understood as 'the poetics of construction'[1] thus stressing the expressive power of the construction as well as the ability to work poetically with the constructive elements of architecture.

Tectonic architecture can thus be characterized as an architecture in which the technical aspects such as statics and acoustics play a great role in the overall expressivity of the building.

The newest development in the tectonic interest in architecture, deals with the computer's ability to offer insights even into the realm of the tectonic. The computer simulation programmes are interesting in the sense that they are seen possessing a potential to transform complex technical aspects into manageable input to the design process. The potential is described as: 'In particular, [computers] are allowing us to model – with increasing sophistication – the material properties of architectural components. (…) the *digital* is beginning to be used increasingly in the service of the tectonic. A new tectonics of the digital – a digital tectonics – has begun to emerge.'[2] This development in digital tectonics has so far primarily been the case in connection to the structural aspects of building but it might apply to other fields such as room acoustics. Several studies have shown the reliability of simulation programmes for calculation of room acoustic parameters[3, 4] and recently isolated attempts have been made to explore the possibility of using computer programming in the initial design stages. One of these attempts is the programme ACOUSALLE,[5] which can support decisions in the first phases of the design but which, for the time being, is limited to operating with shoebox room shapes. Another[6] works with a promising combination of three modules to set up an expert system which can support three stages of the architectural process. The system is aimed at architects but fails, however, to take into account the level (or lack) of acoustical knowledge possessed by its target group.

The aim of this paper is to approach the problem of using computers to explore initial design ideas in architecture by trying to see the problem from both the architectural and the acoustical point of view. This is done by analyzing and evaluating an existing design tool's ability to promote a tectonic design process during an architectural process and setting up standards for future tools in terms of both aesthetics and techniques. The programme chosen for this study is the acoustic programme Computer Aided Theatre Technique, CATT. The developers of CATT describe their prime users as room acoustics consultants and universities[7] and while the programme is thus not targeted at architects it is chosen as a field of investigation due to being a representative example of the newest development in room acoustic simulation programmes. The potential of the programme will be evaluated in a benchmarking test by comparing the design of acoustical rooms by architects with three different levels of acoustic knowledge: A) the architect is an acoustic illiterate, who does not know how volumes, shapes or surface materials effect the acoustic quality; B) the architect is not an expert but possesses basic knowledge about acoustics such as how volume, shapes and surface materials effect the acoustic result; and C) the architect applies CATT as a tool. The benchmarking is in this case not to compare CATT to methods that is thought superior but to methods seen as defining the field of methods as it is today. The benchmarking thereby set up a frame in which the focus stays on the potentials of the programme in comparison to other methods, not its potential in its own terms. The potential is tested in three phases out of four in the architectural design process. The phases are represented by typical results in each phase. Bagsvaerd Church situated in Bagsvaerd, Denmark, and drawn by the architect Jørn Utzon is applied as a case study. This project reflects Utzon's experience with acoustics obtained from Sydney Opera house[8] and can thus be characterized as an application of method B. In this paper the building will be used to ensure a large degree of complexity in the geometry and to represent typical phases of designing rather than the actual design process of Utzon. A discussion will be carried out in each phase of what a different complexity in terms of design would have signified for the result.

This paper presents the conclusion that in order to be able to apply an acoustical simulation programme to the architectonic design process it is necessary to work from an understanding of the phases of the design process. In addition a strategy is sketched out for future programmes in which a reverse approach to simulation programmes is taken – we should go from developing acoustics from given spaces to developing spaces from given acoustics.

CASE STUDY

The potential of a room acoustical simulation programme in architectural design is closely connected to the design process of the architect in general and it is therefore important to relate the benchmarking test to knowledge about the stages in the design process. The architectural theorist Geoffrey Broadbent presents various understandings of the design stages. In this article the design stages as defined by Thornley in 1962 is used.[9] The phases are in the model by Thornley:

1. The accumulation of Data
2. The isolation of a General Concept or 'Form'
3. The development of the 'Form' into the final scheme
4. The Presentation of the Final Scheme.

This paper will focus on the first three phases, because it is these early phases that are crucial in terms of achieving tectonic design. In addition at least the first two of these phases are generally carried out without the help of specialists.

The starting point of an architectural design is defined by the building programme. For a church room this would include specifications of the approximate number of square metres; the kind of religion practiced in the room and in some cases the manner in which the room should be used. The starting point of Bagsvaerd Church could thus have been formulated as the design of a protestant church of approx. 400 square metres.

Figure 1. Interior of Bagsvaerd Church

Phase 1 – The accumulation of Data

The first phase in the architectural design process occurs before the pencil is put to the paper to draw the first proposal for the building. This phase contains elements like philosophy and visions as well as architectural analyses of issues such as site, building type and target group. All these fields are known to the architect, who will be able to apply expertise knowledge to them, e.g. in the case of a hilly site, the architect will know how to take advantage of the potential. The condition provides input and the architect responds by taking this into consideration when sketching.

For architect A, who does not know anything about acoustics, this phase does not produce any output on the acoustics except from his experience from visits to similar acoustic rooms to rely on. The input to the next phase will thus either not take acoustics into account or be based primarily on already existing rooms. Architect B, who has some experience with acoustic design, already knows a great deal from reading the requirements. The keywords 'church' and '400 square metres', point towards a certain acoustic. His experience tells him that room volume, room shape and surface materials will determine the acoustic quality of the church. He can even do quick calculations that will establish 1) the desired volume based on volume per person, 2) proportions of a cubic room based on the room's natural frequencies. Architect C, who uses CATT for his acoustical calculations, has the same means of input as architect A, since CATT does not provide a possibility to get output without input, so to speak.

By comparison it is architect B who produces the best output in this phase. A and C can apply the knowledge they have of similar rooms and even copy church rooms known to have a beautiful acoustic with a good result but they are tied to these references and cannot go beyond them. Only B can innovate in this phase by his understanding of the underlying theory.

Phase 2 – The isolation of a General Concept or 'Form'

The second phase is the conceptual phase. The first sketches are drawn catching in the bigger picture of the project. An outline of the geometry of building and the room is conceived but no specifications are made. A concept might look like Figure 2.

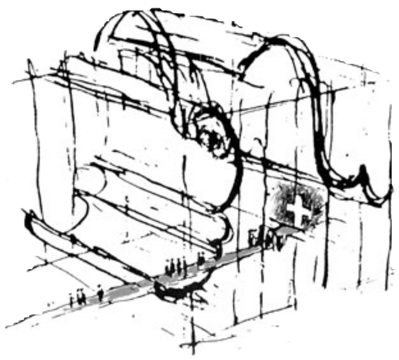

Figure 2. Concept drawing

For architect A, this phase is a potentially dangerous one since he is not aware of the consequence his choices have on the room's acoustics. With the input from phase 1 he can stay on safe ground by keeping to the references but if he chooses not to, he might as well draw a convex shape as a concave one. From his knowledge he is not capable of making a qualified acoustical judgement of the concepts. For an architect such as B, the adequacy of his knowledge is dependent on the problem at hand. This means that he will be able to make qualified choices as long as the geometry stays simple, he will thus be able to predict some possible problems of the concept such as a large volume and long reflection-lengths but because of the limited tools available to him, e.g. drawing of reflection lines, he will have difficulties with the complexity of the geometry. Architect C can evaluate his concepts in CATT but not without having to jump ahead of the actual stage of designing. The precision required to model a building

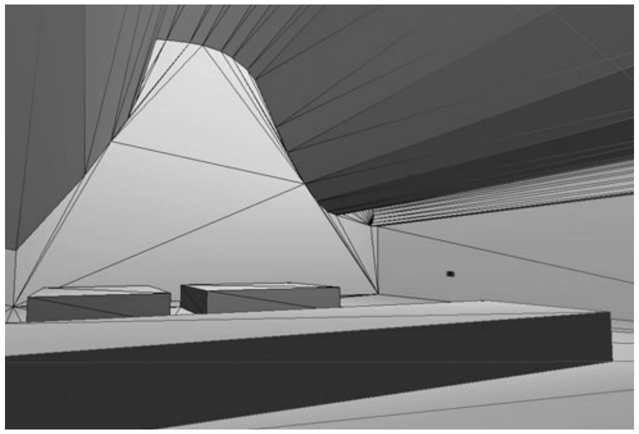

Figure 3. Concept modelled in CATT

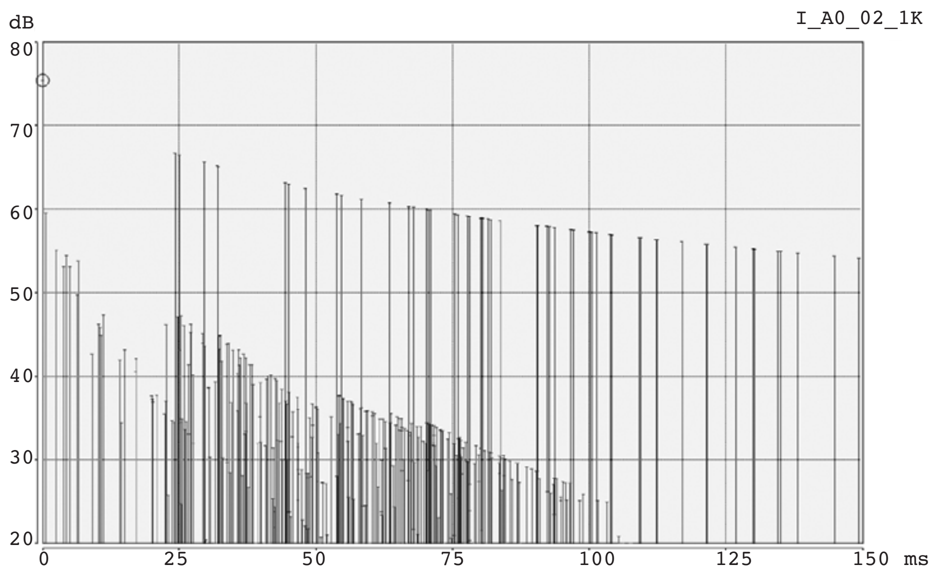

Figure 4. Echogram 1kHz

in CATT, as seen in Figure 3, is far beyond what is needed for a concept sketch as in Figure 2. In this phase the architect would not know all the details and as a reflection of this it is assumed that the materials are not yet specified. While the values for reverberation time are not valid without material specifications, the room can be evaluated concerning echoes and support. Figure 4 shows a 1 kHz-echograms for a

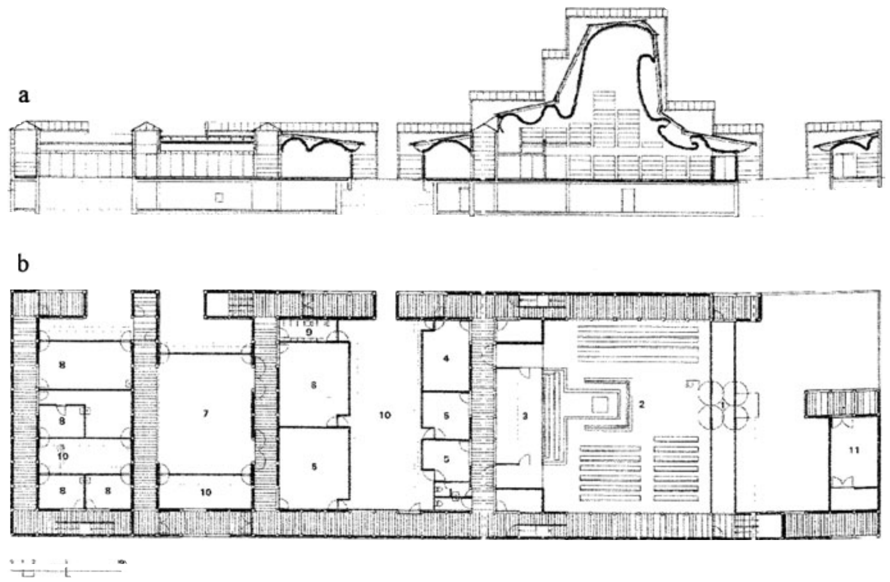

Figure 5. Detailed design in phase 3.[8] Shows a section (a) and a plan (b) of Bagsvaerd Church. The acoustical room in question is indicated.

critical receiver-point in which a delay around 25ms occurs; this reveals that some areas in the room have poor support and risk of echo. The receiver-point for this echogram is in the region under the highest point of the ceiling and therefore does not receive any reflections from above while the receiver-points under the low part of the roof are much better supplied with early reflections. The evaluation of the concept thus points towards the importance of the geometry of the ceiling. Architect C will only come to this conclusion of the importance of the geometry in terms of early reflections if he is able to interpret the information output and knows where to look for it. The nature of the output from CATT is detailed and precise but also difficult to interpret for an architect not extensively trained in acoustics.

By comparison architect A is in terms of acoustics in a much worse situation than B and C in this phase because this architect does not obtain any new input. While B's output is dependent on the geometry in question, C's is dependent on the interface of the programme.

Phase 3 – The development of the 'Form' into the final scheme

In the third phase the architects further develop the concept or concepts into more detailed proposals with suggestions of materials, details, construction; see Figure 5. This is done by simultaneously focusing on the detail and the overall design.

Even if architect A in the second phase chose to use one of his references as a starting point he will in this phase be in need of highly detailed information e.g. about the materials applied that will be difficult to get hold of. Architect B's abilities are again determined by the complexity of the geometry and would be limited in a judgement of the case study shown. For a simple room he could easily calculate room acoustic parameters as reverberation time and reflection lengths but when the complexity of the geometry grows, the reflection lengths will become complex to calculate. The advantage of this method is that it is quick to apply. Architect C benefits in this phase fully from the abilities of CATT. Even though the input required to work with CATT, AutoCad drawings transformed into CATT input-files, are time consuming to produce and often necessary to build over, CATT is an efficient tool when the input is finally there. With the input from phase two, the roof and sidewalls have been reshaped as seen in Figure 6. In addition reflectors have been introduced along the sides of the room. The result of this is visible in Figure 7; an echogram, in the same receiver-point as the previous test, showing early strong reflections thus giving support and no echoes.

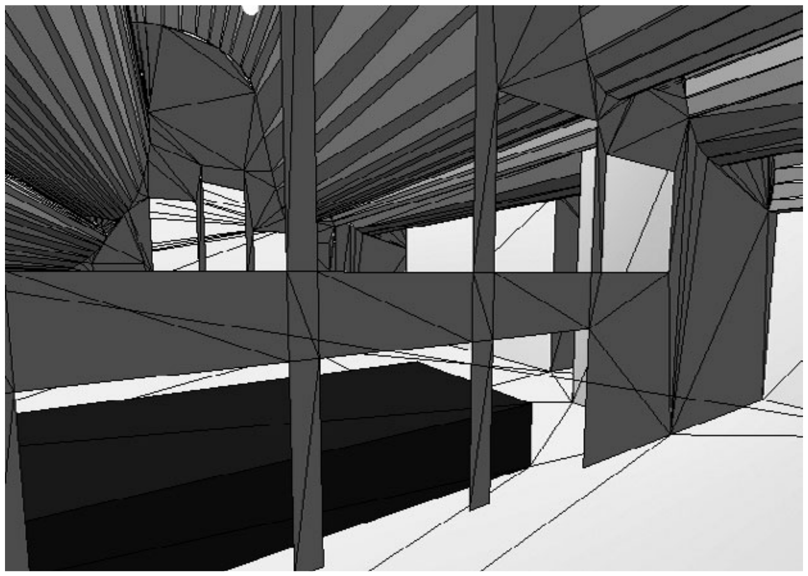

Figure 6. Geometry reshaped

In the process of choosing materials, architect C benefits from CATT's abilities as well. Figures 8 and 9 show reverberation time, early to late ratios, and sound pressure in a case where the materials are defined to be concrete panels on walls and ceiling, a wooden wall in the back and carpet on the aisle. It is seen on the reverberation curve, Figure 8, that the reverberation time ranges from 1 to 2 s and on the list of measures, Figure 9, Clarity (C-80) is measured to 1.1dB, Centre time (T_s) to 100.1ms and Deutlichkeit (D-50) to 45%. While the C-80 and Ts are very satisfying and point towards the room as excellent for music performances; the D-50 is a bit low meaning that speech will be difficult to understand in the church. In CATT it is easy to investigate which effect the materials has on the acoustics, change them and simulate again.

In phase 3 architect C truly benefits from the potentials of CATT. Architect A can no longer rely on his reference since the detailed information needed in this phase is hard

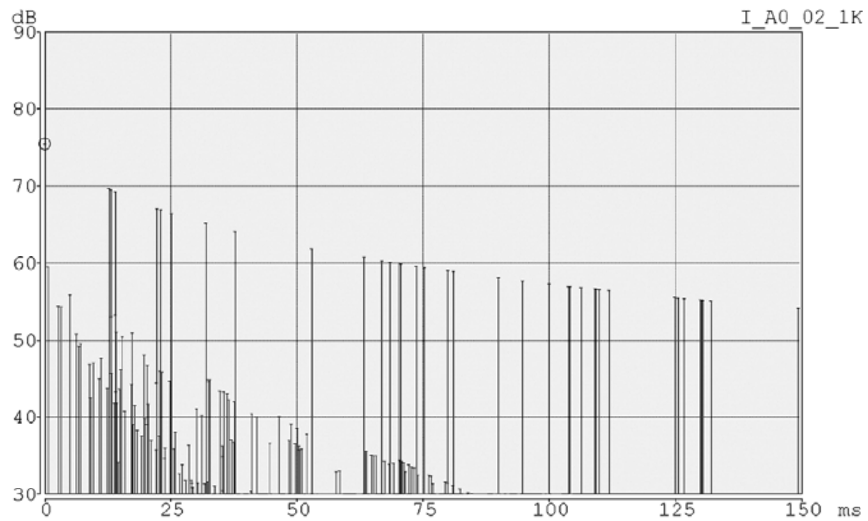

Figure 7. Echogram for geometry in Figure 5.

to provide. Architect B can evaluate the room by simple room acoustic parameters such as reverberation time and reflection lengths in quick and easy calculations but these parameters have the disadvantage that they are far from the experienced acoustic quality of the room. CATT on the other hand can because of its strength in calculations provide information about a range of parameters such as D-50 and C-80 which are objective parameters closely connected to the subjective experience. Regarding materials,

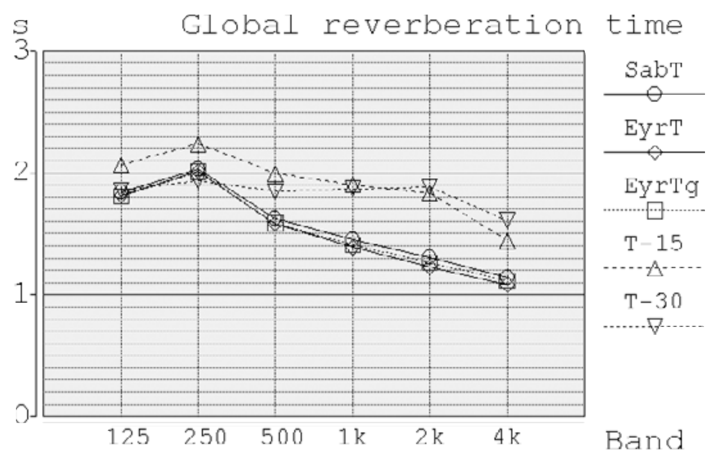

Figure 8. Reverberation curve

EDT	1.66	s
T-15	1.90	s
T-30	1.87	s
D-50	45.0	%
C-80	1.1	dB
LFC	35.3	%
LF	21.8	%
Ts	100.1	ms
SPL	81.5	dB
G	11.5	dB

Figure 9. Data list for geometry Figure 5.

reflectors and other minor changes CATT is likewise very helpful after a lengthy process of producing the data required.

EVALUATION

In a comparison between the three methods of the three architects, the method of architect A clearly has its limitations in all three phases; this method is dependent on the architect to apply known references but without knowing why the reference room works it is easy to damage the acoustic quality unintentionally. Methods B and C each have their strengths. B provides valuable input about volume and proportions in phase one, about shapes of the geometry in phase two and on the effect of different materials in phase three. B's knowledge is most valuable in phase one and two because of the simplicity of the calculations carried out; especially when the acoustic room has a complex geometry; B's potential would be quite sufficient in all phases if the geometry was shoebox shaped. It could be argued, however, that it is unrealistic to expect this level of acoustic knowledge to be mandatory to architects. Method C, CATT, on the other hand has its strength primarily in phase three. It does not provide any input in phase one and in phase two it is only possible to obtain rather limited information about the geometry without specifying e.g. materials. At the point when CATT is strongest is close to the point when an acoustic consultant would be introduced to the project. In order to improve CATT as a tool for the architectural design process the two first phases should be the prime target.

While the difficulties of the method A is primarily a lack of knowledge it is for B the simplicity of the knowledge. For method C the major obstacle of applying CATT in phase one and two is caused by the nature of the data input, output and the interface of the programme. The input-files required to work with CATT are very detailed when taking into account the quick iterative process of the architect. Likewise the nature of the output is highly detailed and addresses itself to specialists in acoustics. To an architect the graphs and numbers would not be understandable and an interpretation of the results would therefore be important.

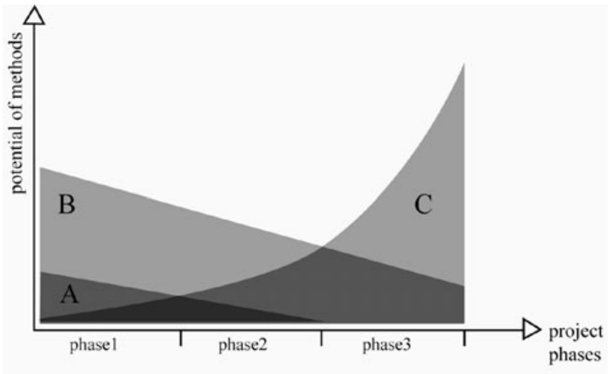

Figure 10. Graph of the potentials of the methods

Room acoustic simulation

To an acoustical expert the proposal for a music hall put forward by an architect uneducated in acoustical matters, such as A, can seem as outrageously ignorant of the acoustical concerns that need to be taken in such a project. But one should remember that the architect is often functioning as the knot-binder, mediating various fields – structural, functional, economical, contextual, etc. – and trying to create an architectural unity from the fragments. With that said one should not ignore that the acoustical field is highly connected to the perception of space and as such potentially can come to play an important and interesting part in creating architecture.

For this to happen, the benchmarking test of the current room the use of acoustical simulation programmes can guide us to how the future software could develop. The main conclusion was that a focus on the first phases in the design process should be taken. In these phases no design – let alone geometrical specifications – has emerged, actually nothing has been decided on yet. This is one of the characteristics of the architectural process that it is possible to shape something that has not yet come in to existence. This calls for a reverse approach to simulation programmes where we should go from developing acoustics from given spaces to developing spaces from given acoustics. The programs should therefore evolve from the current state as being solely evaluation tools to become generative tools that can suggest spatial dimensions and characters. In this sense it should in future software be possible to generate for example dimensions of the acoustical room by taking the desired acoustical quality as a starting point. One suggestion as how to do this; is to begin with the information known; this could be numbers of audience and desired reverberation time. In Figure 11 a result of a generative process is seen where a desired volume (known from number of audience and desired reverberation time), has been distributed into twelve different room dimensions. This is done with reference to guidelines for healthy ratios of length, width and height[10] in order to obtain evenly distributed natural frequencies. Such figures give a first initial shape/dimension of a room with a desirable acoustical quality. This step in the process has, as mentioned, also been suggested in other studies.[5, 6] It is important however, to understand that these boxes are not the end product of the architectural

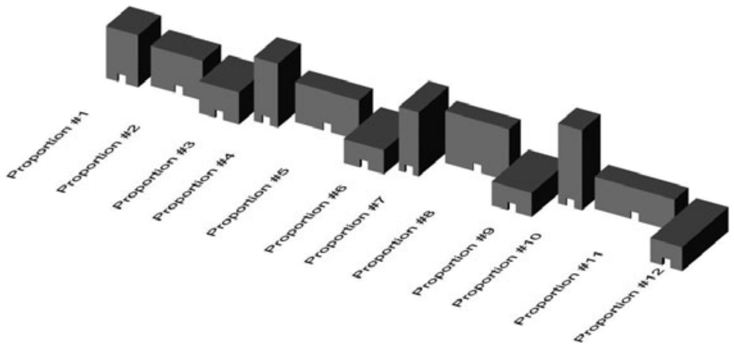

Figure 11. Generation of dimension

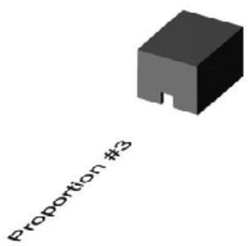

Figure 12. Choice of room dimension

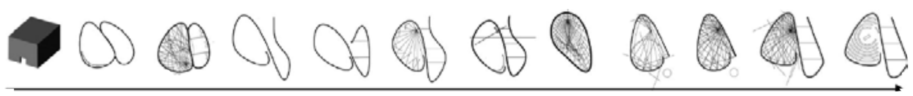

Figure 13. Geometrical modelling of plan of acoustical room

process – in which case we would only be able to produce shoebox shaped rooms – but will serve as information to feed the next step in the iterative process. For the programmes to be interesting from an architectural point of view, the architect should therefore be able to break away from the dimensions given, as seen in Figure 12, and work freely with the volumes.

When the geometry has been somewhat defined in phase two, 'The isolation of a General Concept or 'Form', the evaluation should be quick and easily understandable since the conceptualization does not come as one set solution to the given condition but rather as numerous different approaches. These approaches are evaluated in connection to a number of requirements where acoustic quality is only one of them. One of the reasons that architecture and acoustics are closely related is that the geometry of the space is greatly determining for the acoustical result. Therefore, it is of uttermost importance that it, in this second phase, is possible to evaluate the rough outline of the geometry. This evaluation can be carried out by hand with the help of reflection lines as seen in Figure 13 but the use of acoustical simulation programmes would add the advantage of being able to handle complex three-dimensional shapes. The swiftness of the software is crucial to ensure that the evaluation in connection to acoustics is even carried out.

One of the main concerns to ensure this swiftness of the software is to build in connectivity to other tools of the architect. CATT works well together with AutoCad, but even though this is a common tool for architects, it is seldom used before the third phase. Connectivity to three-dimensional visualization tools such as FormZ, ArchiCad or 3DStudioViz would firstly support the iterative process between conceptualizing and developing and secondly it would on the longer run be possible to build in an interaction module. With an interaction between the programmes, an alteration in the drawing programme would immediately be simulated in the acoustical simulation programme thus enabling fast evaluation. How exactly to build in this connectivity – as compatible files, linked files that update the acoustical simulation when the visualization is altered or as an acoustical simulation plug-in to the visualization programme - is a matter of further investigation.

The last theme to be addressed in the development of future programmes is the outcome of the simulation programmes. This also has to do with the swift use of the simulation programme. In CATT the output is highly detailed and addresses itself to specialists in acoustics, and would not be understandable to an architect. A simplification of the data is necessary and an interpretation of the data should take place. This could be linked to pre-defined specifications of the desired acoustics and contain simple grades to rate the acoustical quality of the room.

CONCLUSION

This study shows three phases in the architectural design process, 1 – Accumulation of data phase, 2 – The isolation of a General Concept or ‘Form’ phase and 3 – The development of the ‘Form’ into the final scheme phase. For each phase the ability to support and help the architectural design process has been compared for an architect with no understanding of acoustics, an architect with some understanding and an architect using CATT. Bagsvaerd Church by Jørn Utzon has been used as a study case to exemplify which input could be produced in each phase. In the first phases the architect with some knowledge has the benefit because of the method’s ability to evaluate a proposal that is not fully specified. The method involving CATT is best applied in phase three when the acoustic room is fully specified. In order to develop CATT’s ability as a tool to support the architectural design in the first phases where intuition rather than specification is dominant, its abilities should be improved in terms of the required input and the nature of the output of the programme. A reverse strategy towards the simulation is suggested – enabling the architect to generate geometries from the programme rather than only applying the simulation as an evaluation tool later in the process. With an improved applicability in the first phases the programme would support the development of tectonic architecture.

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