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Auditorium projects in Denmark since year 2000; room acoustic research and experience materialized

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The first decade of this millennium has brought an amazing number of new, large performance halls in Scandinavia and in Denmark in particular. In Denmark alone, we have opened three 1000+ seats concert halls dedicated to symphonic music (a forth is under way) plus a dedicated opera and a ditto drama theatre. The acoustic designs of these halls were based on the scientific and practical knowledge and design tools that had been developed in the preceding decades. The paper will discuss the acoustic principles which have been materialized in the various designs and how some of these differ from earlier practice.

1 Introduction – the situation before 2000

1.1 Room acoustic knowledge

In the 1960's and 70's, great progress was made in the development of objective acoustic parameters capable of describing and quantifying relationships between sound field properties and subjective room acoustic impressions in auditoria. These parameters, which are based on energy ratios or decay curves calculated from room impulse response measurements, are not perfect (they do not explain 100 % of the variance in the perceived acoustics in concert halls and theatres); but the subjective experimental research behind their development has also told us a lot about important properties of the sound field and why some of the old halls (typically of "shoebox" shape) are very good while others (typically the fan shapes from the modern movement) are regarded poor. Besides, many of the parameters have been generally accepted as being usable and are now adopted in annexes to the international standard for reverberation time measurements in auditoria, ISO 3382: "Measurement of reverberation time of rooms with reference to other acoustical parameters".

It should be mentioned that in recent years we have also seen very promising progress in the development of parameters based on Dau's auditory models [1]. One advantage of this approach is that evaluation can be made from (dummy head) recordings of the actual music or speech signals in the hall instead of using special measurement equipment to acquire impulse responses. However, using the auditory model approach for room acoustic design purposes is still premature.

Prediction of the acoustic conditions of a hall based on the ISO 3382 parameters requires more complex tools and simulations than the traditional calculations of reverberation time. This is also one reason why development of computer modelling software like Odeon and CATT Acoustics was intensified in the 1980'es and 90'es.

In the 80's, a number of researchers started making systematic measurement surveys of concert halls for classical, symphonic music [e.g. 2, 3, 4]. One objective was to get more experience in how the objective acoustic parameters behave in different hall designs. Through funding by the Concert Hall Research Group (an American group of acoustic consultants with Leo Beranek as the driving force) some of us embarked on a measurement tour in the US, and later our data ended up in new editions of his famous book on concert and opera halls [5]. Based on acoustic data from the 35 European halls that we had measured by 1990 and measurement of simple geometric parameters in these halls, statistical analyses were carried out which revealed some basic relationships regarding how - and how much - these parameters are affected by the gross shape and dimensions of the halls [6].

In short: after 1990 we had obtained quite good knowledge and consensus both regarding

1) properties of the sound field which are of importance for our listening experience in auditoria, and

2) how these properties relate to the architectural design of the hall.

This was the status of our knowledge when after the ”poor 1980’es” many plans for new cultural buildings came to the surface in Denmark.

1.2 Performance halls

Before 2000, all major performing arts halls in Denmark except two had been built before 1960. The two exceptions are Musikhuset in Aarhus and the Odense Koncerthus both of which opened in 1982. The hall in Aarhus is fan shaped with a proscenium stage, a single, large balcony and steep floor slope – all aspects mainly addressing the visual needs associated with theatrical performances. Together with a very modest reverberation time and no means for varying the acoustics apart from the installation of an orchestra shell on stage, this hall was soon realized to be less than optimal for symphonic music. However, the Carl Nielsen Hall in Odense was conceived as a “safe” shoe box shape primarily focusing on serving symphonic music. Consequently, Odense got its hall for symphonic music, but Aarhus did not.

The 1990’es started with a number of disappointments – in Copenhagen in particular.

The Odd Fellow hall, a much loved old shoe box shaped concert hall in Copenhagen burned down in 1992!

A large competition for a new concert hall in Copenhagen was settled in 1993; but did not materialize. A major reason was that the winning architect, Henning Larsen, severely criticised the project conditions in his acceptance speech. His main objection was that the chosen site on the harbour front next to the Royal Library was much too small to host all the functions described in the competition brief.

Another failure was a competition for a new drama theatre next to the Royal Theatre at Kongens Nytorv. It was won by the Norwegian architect Sverre Fehn in 1996; but was turned down when a 1:1 scale mock-up raised on the site next to the old Royal Theatre scared the public opinion and the Danish architect establishment away!

A large extension to the National Gallery of Denmark was opened in 1998; but the performance area in the large atrium was unusable due to poor acoustics! However, this flaw was not due to lack of knowledge; but due to that knowledge being neglected elsewhere in the project organization.

Finally, in 1999, as a promise for a more bright future for auditoria in Copenhagen, the Royal Library opened its new extension at the harbour front. This project, which includes a 600 seat chamber concert hall only suffered two problems: it was not yet finished in 1996 when Copenhagen was the cultural capital of Europe, and all the money had been spent before outfitting of the concert hall interior had started. Fortunately, sufficient money to finish the hall was found, and the hall and its acoustics have been well liked ever since.

2 The new halls

In 1999 the Danish government formed a committee who should investigate the possibilities for combining the needs for a proper concert hall for symphonic music and a new, larger opera theatre. Besides, a new drama theatre for the Royal Theatre had long been on the wish list. Fortunately, a combined concert/opera hall was not decided on. The Danish Radio wished to build their own concert hall, and the shipping company Maersk donated the opera. Therefore, the state only needed to care about the drama theatre. Amazingly, all three projects were built before 2010.

Outside the capital, plans started a bit later: In 2005 Aarhus ran a competition for an extension to Musikhuset consisting of a concert hall dedicated to symphonic music and a music conservatory. This building opened only two years later. (It had to be finished by the time the rental agreement between the conservatory and the owner of their previous home expired!) Aalborg planned a similar combination of concert hall and music education with a competition held in 2002; but as the design team could not match their architecture with the financial reality, the project stopped; but was revived in 2007, when Realdania donated more money and took over the project leadership. The hall is currently under construction and should open in 2013. In Sønderborg, a new university campus was being designed by 3xN architects. Quite late in the process it was decided by the owners of Danfoss, the large, local industrial company, to donate extra money for the large auditorium to be changed into a proper concert hall and become the home for the local Sønderjyllands Symfoniorkester. The Alsion hall opened in 2007.

Although the halls opened since 2000 include important venues like the Opera in Copenhagen and the new Drama Theatre on the opposite side of the harbour canal, we will concentrate on the four concert halls in the following.

The author's background for talking about these halls is his involvement as acoustic advisor for the client in three of these halls. These will be described with emphasis on new design aspects compared to earlier practice.

2.1 Acoustic priorities of today

Before discussing the acoustics of these halls, let us look at what the current priorities are in the design of concert halls (for classical music). The major subjective aspects of relevance and the very basic design aspects related to these are listed in Table 1 below. In the column to the right, the related objective ISO measures are also listed.

Table 1: Acoustic priorities in concert hall design

Subjective parameter	**Related design aspects**	**ISO 3382 parameter**
Fullness, reverberance	Large volume, small absorption area	RT, EDT
Clarity	Large absorption area, early reflections – surfaces directed to send reflections from stage to audience, slope of audience floor	C80
Spaciousness	Room geometry to promote reflections from lateral directions	LEF, IACC
Sound strength	Small absorption area, efficient reflection paths	G
Timbre	Choice of materials and surface constructions according to absorption(f)	RT(f) , G(f)
Musician's mutual hearing and support	Risers and surfaces close to the stage to promote direct and reflected sound transmission between musicians	$ST_{Early/Late}$

Among the subjective parameters listed above, spaciousness (the sense of sound source broadening and being enveloped by the reverberant sound) is the aspect which received most attention in room acoustic research in the 1970'es and 1980'es, and the lack of this quality in the fan shaped halls was realized to be the main reason why most of these halls fail as good concert halls. In the 1980'es, also research on the conditions for the musicians started [7].

Without a doubt, current concert hall design is influenced by our ears being used to recorded music. This has raised a demand for new halls to possess both high Clarity (C80) and high reverberance (RT). As seen in the table above, reverberance and clarity are normally counterparts, since a small absorption area will increase reverberance but reduce clarity and vice versa. Therefore, achieving both high C80 and high RT requires control of early reflections independently from factors defining the reverberant energy. The solution is to make sure that the surfaces generating the early reflections are separated from (and closer to the audience) than those defining the acoustic volume.

Three new concert hall design concepts capable of achieving this emerged in the last half of the 20th Century - all developed by visionary acousticians: the Vineyard (Lothar Cremer), the Directed Reflection Sequence (DRS) hall (Harold Marshall) and the addition of "reverberation chambers" to the traditional shoebox (Russell Johnson). Rough sketches of each type are shown in Figure 1.

In the vineyard, the surfaces controlling the early reflections are the terrace fronts, while the acoustic volume is controlled by the ceiling height.

In the DRS-hall, large suspended reflectors and balcony fronts/soffits ensure early reflections independently from the walls and ceiling defining the required volume and reverberance.

In the Johnson version of the shoe box, the narrow inner hall side wall surfaces and side balconies and a stage canopy provide the early reflections while the total volume including that of the reverberation chambers should give the long reverberation (if the openings between hall and chambers have been made sufficiently large to ensure sufficient coupling – which has not always been the case!). However, it should be added, that in a shoe box hall, high reverberance as well as high clarity can easily be achieved without reverberation chambers, if the width is limited, side balconies protrude from the side walls, the main floor is gently sloped and the ceiling is sufficiently high. Consequently, reverberation chambers are by many regarded a feature not worth putting on the budget.

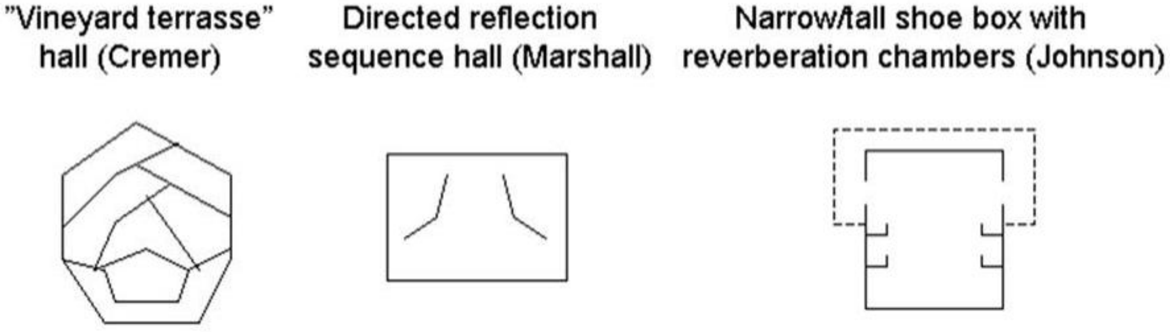

Figure 1: Sketches of three different concert hall shapes capable of achieving both high clarity and high reverberance

In our programming of the new halls in Copenhagen, Aarhus, Aalborg (and Malmö), we have recommended to our clients one of the three concepts to be followed by the competing architects, since this is a basic measure against acoustic failure. Besides, we have written in the competition brief specifications regarding required volume per seat, reverberation time, approximate dimensions and other issues about geometry like subdivision of the audience in main floor, terraces and balconies, guide lines on how to achieve sufficient early reflections and details about the design of audience chairs and stage design. Finally a requirement for variable reverberation time is specified to make the acoustics suitable also for amplified events.

2.2 The Alsion Concert Hall, Sønderborg

Due to the fact that the outer shell was already defined when its function as a concert hall was decided, the shoe box hall in Sønderborg has slightly atypical proportions. It is rather short (40m) with the stage plus a shallow choir balcony occupying about 40% of the floor area and with steeply raked stalls and balcony seating. Both the short distance to the stage and the steep floor slope will tend to increase clarity beyond what one would expect with the given reverberation time (1.9 Sec.) Thus, it is possible for this hall to achieve both high reverberation and high clarity (without reverberation chambers).

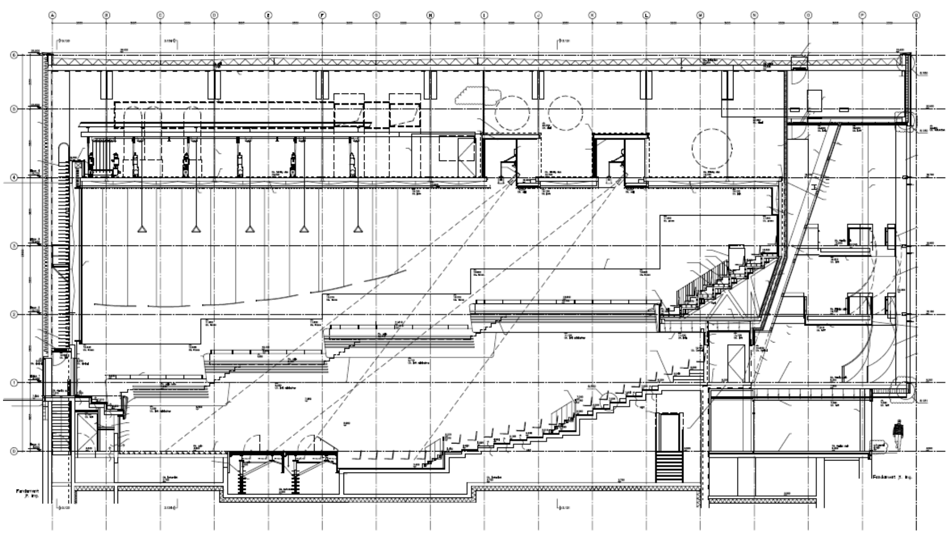

Figure 2: Long section in Alsion Concert hall, in Sønderborg (courtesy of Arup Acoustics)

A few of the 1000 seats are placed on narrow side balconies whose main function is to direct lateral reflections from the side walls down to the audience. As shown in the Figure they step down towards the stage which helps sight lines.

The ceiling height was set to 16m (more was possible within the building volume) to allow for a volume of $10m^3$ per seat. The reverberation can be reduced by banners deployed in front of the upper wall areas. Details about the acoustic design (by Arup Acoustics) are described in [8].

In most classical shoebox halls (like Boston, Amsterdam and Wienna) the main floor and the side balconies are horizontal resulting in poor sight lines and substantial attenuation of the direct sound component in many seats. Another difference is that these days the upholstered audience seating is designed to minimize the difference in reverberation time between empty and full – without the seats becoming voluminous conference or cinema chairs. The important sound diffusing properties of wall and ceiling, which in the old halls was achieved through rich decoration, is accomplished in Alsion through profiling the surface of the precast concrete wall elements.

2.3 Aarhus Musikhus; Symphonic Hall

The 1300 seat shoebox hall for symphonic music in the extension to the Musikhuset Århus was designed by C. F Møller assisted by Cowi (Denmark) and Artec (USA) as acoustic consultants. The brief specified a target for the reverberation time of 2.2 Sec. in the hall fully occupied. Neither the brief nor the budget allowed for Artec to suggest reverberation chambers in this project. Still, the result is a hall with high clarity and long reverberation as seen in Figure 4. This hall has a more gently sloping floor than Alsion and the seats close to the side walls are elevated about a meter into parterre sections which limit the acoustic width of the main floor seating area. In the picture below, also the stepped side balconies are seen. Like in Alsion, the profiling of the side wall concrete panels was achieved in the casting process. Comprehensive means for variable acoustics are implemented: soft cloth covered panels behind the zig-zag shaped side wall elements (like in Dronningesalen) can be made to cover most of the side wall areas from the first balcony level and up, and in the same levels the rear walls behind the audience can be covered with drapes. In the empty hall, the reverberation can be varied between 1.7 and 2.7 Sec. In order to limit the total absorption in the hall – also in the occupied condition - Artec did not wish to install highly absorbing chairs, which is the reason for the high reverberation value when empty. During rehearsals, this can be compensated for by deploying some of the variable absorption.

Figure 3: View of the Aarhus Symphonic hall interior

The measured results shown in Figure 4 reveal that also in this hall high Clarity as well as long reverberation was achieved; but we also had the chance to make measurements illustrating that this trend may originate from the recordings as mentioned in Section 2.1. Shortly after the opening, occupied impulse response measurements were made during a break in a concert which was also recorded for broadcasting. Impulse responses were recorded through microphones in the audience area as well as through the broadcasting chain – including the mixing and signal processing as decided by the recording producer for this production. It is interesting to compare the RT, EDT and C80 data from the two sets of signals in Fig. 4. Due to the microphones being placed close to the instruments, C80 was about 3dB higher in the recording than in the hall; but the recording people also adding artificial reverberation, resulting in the RT from the recording being about half a second longer than the already full reverberation in the hall itself. However, the changes in C80 and in RT compensated each other so that the values of the Early Decay Time, EDT, from the recording and from the hall measurements are almost identical. EDT indicates that during running music the amount of reverberance perceived from the recording and in the hall are very similar. The green graph in the Clarity chart shows the value which one would expect based on the measured reverberation time (the blue curve to the left). It is seen that this is about two dB lower than the value actually achieved in the hall (the blue curve in the middle). Consequently, also this design has promoted early reflections (mainly from canopy, side walls and balcony soffits) which increase clarity beyond what the long reverberation time would dictate. This hall is very well liked by both audience and by the resident Aarhus Symphony Orchestra. A more detailed explanation of the hall and the acoustic results can be found in [9].

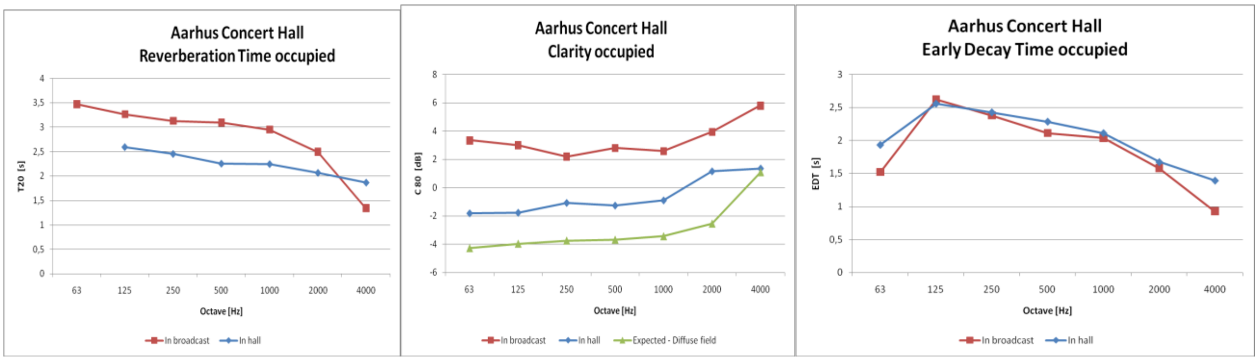

Figure 4: Aarhus Symphonic hall: acoustic parameters measured in hall and from recording

2.4 Aalborg

The planning of the House of Music in Ålborg was a long and complicated story. I acted as client advisor until 2003 when I resigned after having learned that the client wanted an Artec hall. Instead I entered a team of good colleagues to compete for doing the acoustic design. In the mean time the architect competition was settled with the winning team promoting an idea about “Papageno feathers” which were imagined as small reflectors attached to the walls like fish scales. These should be variable in size and angle in order to be able to reflect “optimally” the frequency range of the (solo) instrument or voice in question. Our team (and many others) were rejected because we could not demonstrate “experience with reverberation chambers and Papageno feathers....”. The project stopped in 2006 because the contractor offers substantially exceeded the budget! I was asked to return as advisor in 2007 when new attempt to revive the project was made thanks to Realdania offering extra money – on the condition that they also took care of the project management. This meant that the architect Coop Himmelb(l)au and his design team (including Artec) should be held responsible for the project costs to match the budget. Neither reverberation chambers nor Papageno feathers were included in the revised brief which became much like in Aarhus. The hall is currently under construction.

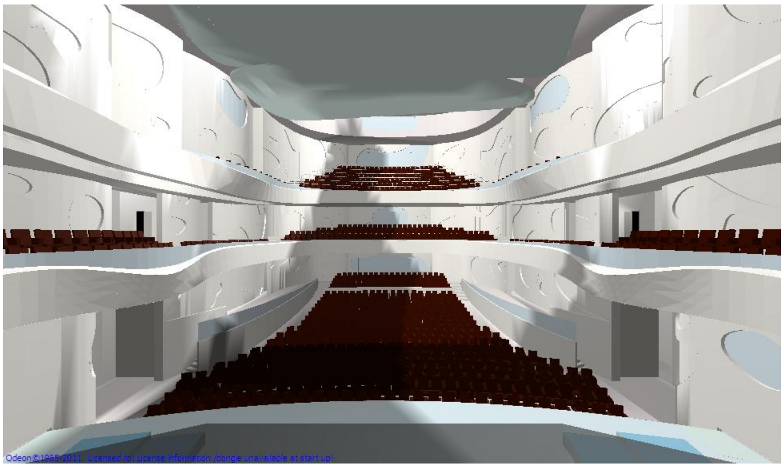
Figure 5: The House of Music concert hall in Aalborg; view from our Odeon model

The main difference between Aarhus and Aalborg is that the strict shoe box shape is now broken up into soft organic curves as shown in Figure 5. Such curved shapes rather than straight lines seems to be a new architectural trend which is also seen in the coming Elb Philharmonie in Hamburg (designed by Herzon and De Mouron / Nagata Acoustics) and the new concert hall in Paris (Jean Nouvel / Marshall Day Acoustics - Nagata), both of which may be called "curved terraced arena" halls. It remains to be seen how they behave acoustically.

2.5 Danish Radio Concert Hall

For the new Danish Radio concert hall in Copenhagen, which opened in 2009, the building committee chose the vineyard or terraced arena shape as the outset for the new hall design. The main reason was that this shape distribute the audience in a more democratic way. With all seats being placed on open terraces, their absorption area is fully exposed to the reverberant sound field in contrast to halls where some seats are hidden under balconies. Consequently, the volume per seat needs to be higher than the rule of thumb of 10m^3 per seat. Thus, in the programme we asked for a volume of at least 22,000m^3 or about 12m^3 for each of the 1600 audience plus 200 choir seats. However, the volume turned out to be as much as 28.000m^3. Some of the terrace fronts are very high which means that the slope in certain terraces is quite steep. This in turn results in the rear seat rows being much elevated and the ceiling being pushed upwards as well. With such a large volume one would expect that it would be easy to meet the requirement for a reverberation time in the occupied hall of 2.3 Sec.; but the result in the empty hall with almost all chairs installed was only about 1.9 Sec. at mid frequencies probably due to rather large wall areas being perforated (to avoid echoes) and due to the audience chairs having very high back rests. The requirement for the values at low frequencies to increase to no less than 2.5 Sec. wasn't fulfilled either. Consequently, most critics also found the hall to be too dry and lacking fullness, while a few others appreciated the high clarity. In the summer of 2010, some of the perforated wall area was closed causing a slight increase in reverberation; but the target has not been met yet. In the autumn 2010 members of DAS carried out measurement during a performance of the Coriolan overture in the fully occupied hall and found the values shown in Figure 6. For amplified events, large draped curtains can be brought to cover the upper side walls resulting in the reverberation time to drop to 1.6 Sec. in the empty hall.

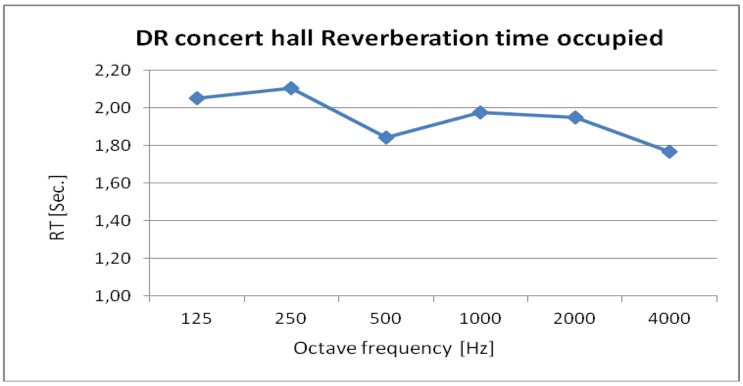

Figure 6: DR concert hall reverberation time measured by DAS 12th Nov. 2010 (Coriolan ouverture)

Figure 7: DR concert hall model with "orchestra" for stage acoustic measurements

Fortunately the DR Symphony Orchestra is very happy about the hall. The musicians find it easy to hear each other clearly. In our testing of the 1:10 scale model, we were much concerned about the convex canopy being placed quite high above the stage (typically about 14m above the stage floor); but it seems that the rather steep circular risers (shown Figure 7) ensures free propagation of direct sound between the players which compensates well for the rather weak reflection from the canopy. The model shown in Figure 7 was ordered by Nagata Acoustics who used it mainly for testing reflection paths, build up curves and risks of audible echoes (through impulse response recordings by means of a model dodec. Loudspeaker and a scale model artificial head.) It was left to me as advisor for the client to measure the ISO 3382 parameters including the support parameters on the stage.

Besides the rather short reverberation time, also the sound from the organ has been criticized as being too "weak". This may of course be related to the reverberation time being too short (not least at low frequencies) for organ music in this large volume; but it is also likely that with the position chosen for the organ (see Fig. 7) in an unusually open casing on the wide "rear wall" framed by flared walls (like in a wide fan shape hall) and absorbing audience seating, the sound lacks the envelopment which we experience from organs behind the stage in narrow rectangular halls – and in narrow churches of course. (It should be mentioned that the instrument itself is very loud!)

Without a doubt, the acoustic (as well as the financial) problems in the DR concert hall are influenced by the client's attitude to let the architect have the final word in combination with the "partnering" model and contracts without sufficient sanctions if the design process was late or the result did not meet the design goals. Nagata has published a description of the hall acoustics in [10].

2.6 KKH Malmö

Finally, it is tempting to mention that another shoe box shaped hall is underway almost in Denmark: in Malmö. This hall will also be of the rectangular shoe box shape and the acoustic brief does not deviate much from those for Aarhus and Aalborg. However, the management of the Malmö Symphony Orchestra has many innovative ideas about alternative orchestra performances and productions being distributed through modern media technology. Therefore, this hall seating 1600 plus 120 choristers will be equipped with more advanced loudspeaker installations and rigging facilities than seen before. The building is drawn by SHL with Akustikon as acoustic designers. The complex will also include a smaller flexible hall, a large conference hall and a hotel. Construction has just started and the hall is scheduled to open in 2015.

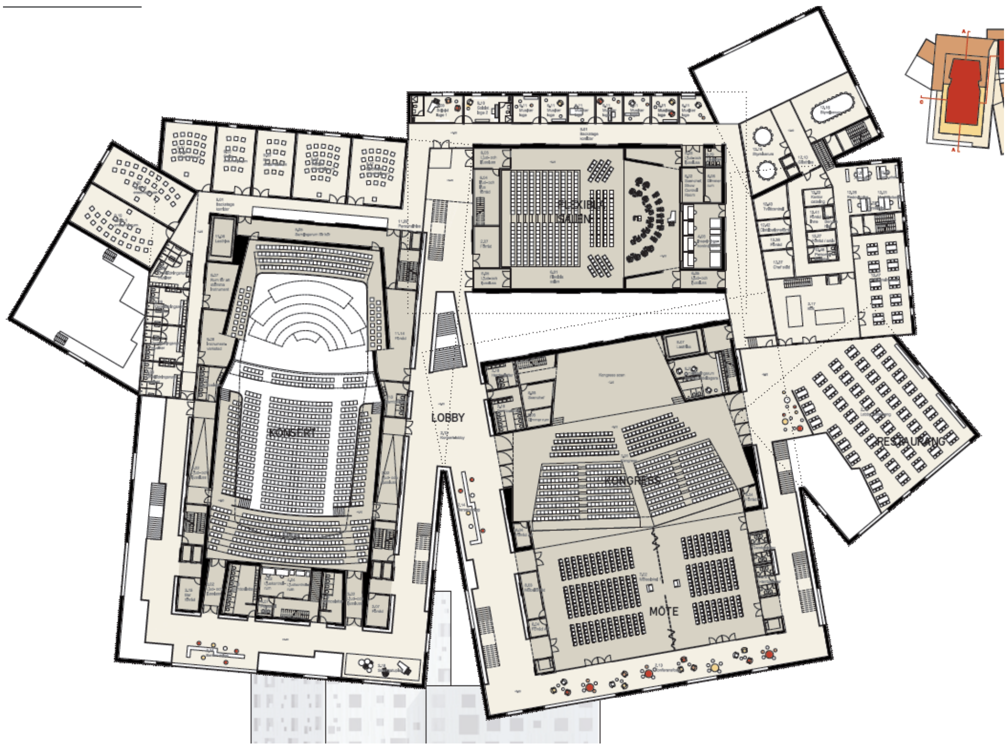

Figure 8: Plan of the new concert hall complex KKH in Malmö, Sweden

3 Conclusions

After a brief historical introduction to room acoustic research and to halls in Denmark built before 2000, we see that the newer concert halls all follow either the shoe box or the terraced arena concept. This return to well proved shapes is a radical change away from the fan shaped halls designed during the Modern movement (between 1940 and 1985). Compared to the old shoe box halls around the world, the new halls put more emphasis on sight lines resulting in a sloping stalls floor and stepped side balconies. Besides, most of them have more comfortable and well upholstered seating and all have variable absorption to allow for lowering the reverberation time for amplified events.

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