Enhancing the Open-Air Auditory Experience

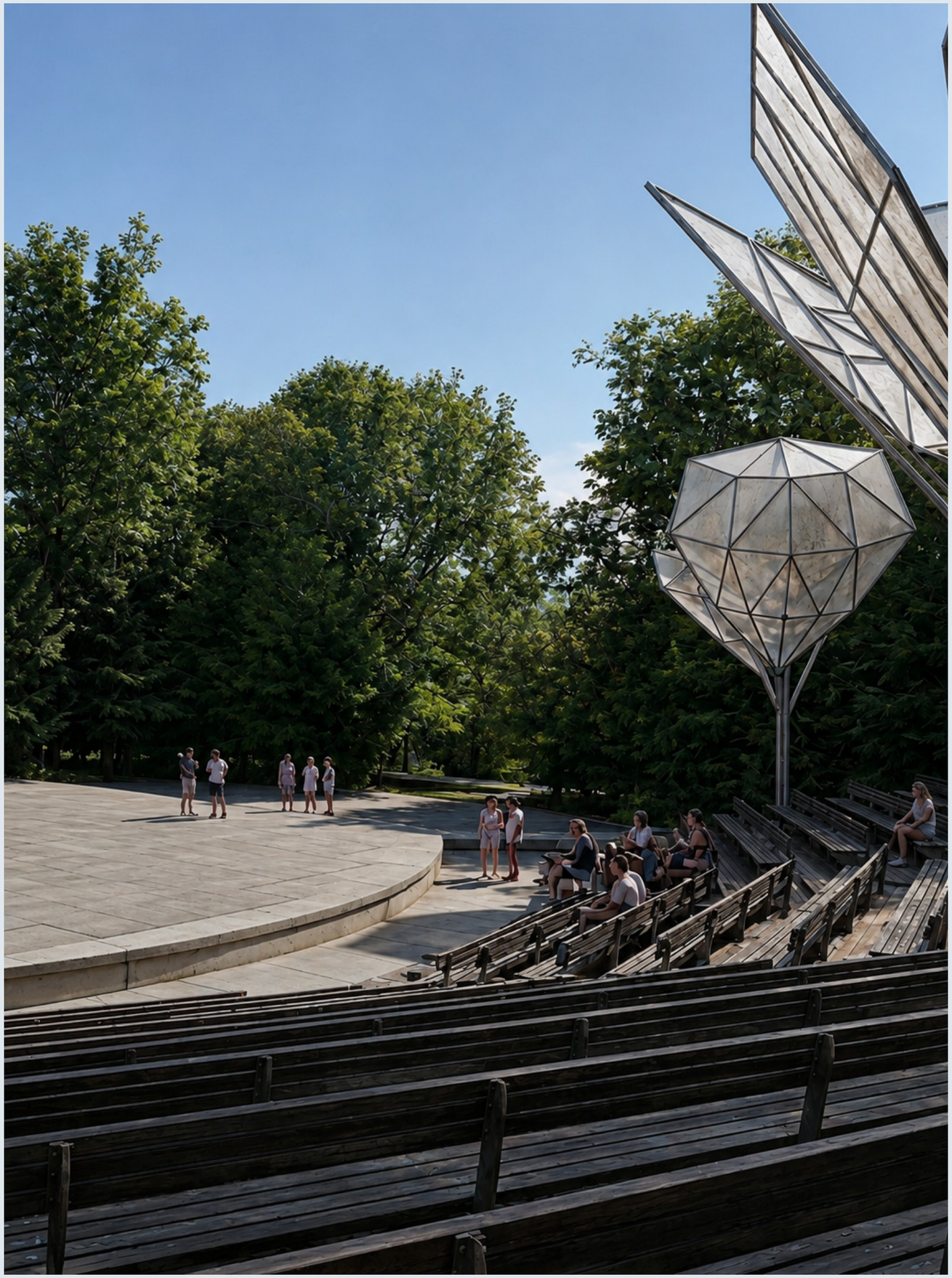
Optimizing Acoustic Uniformity in Open-Air Theaters using Computationally Designed Crowd-Integrated Reflectors

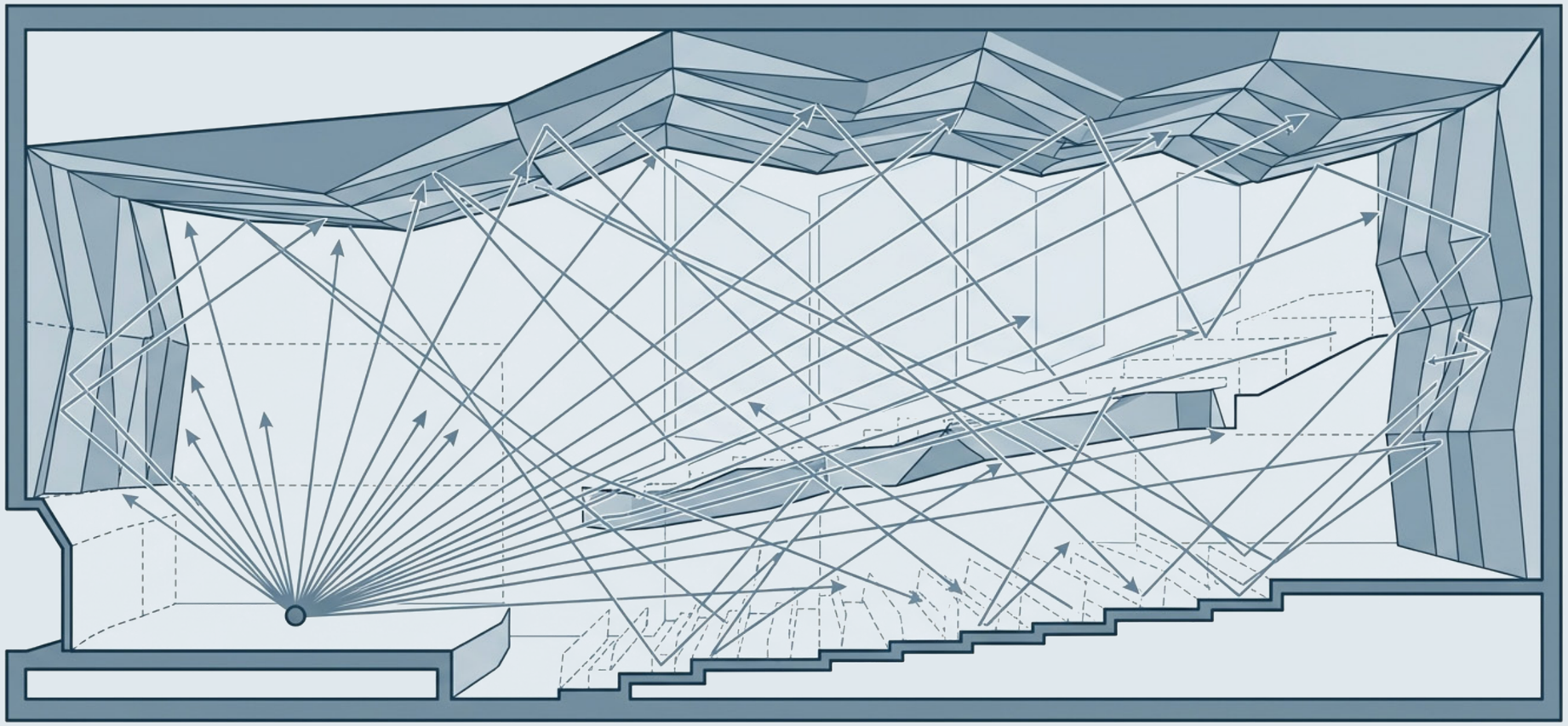
Timo Meester

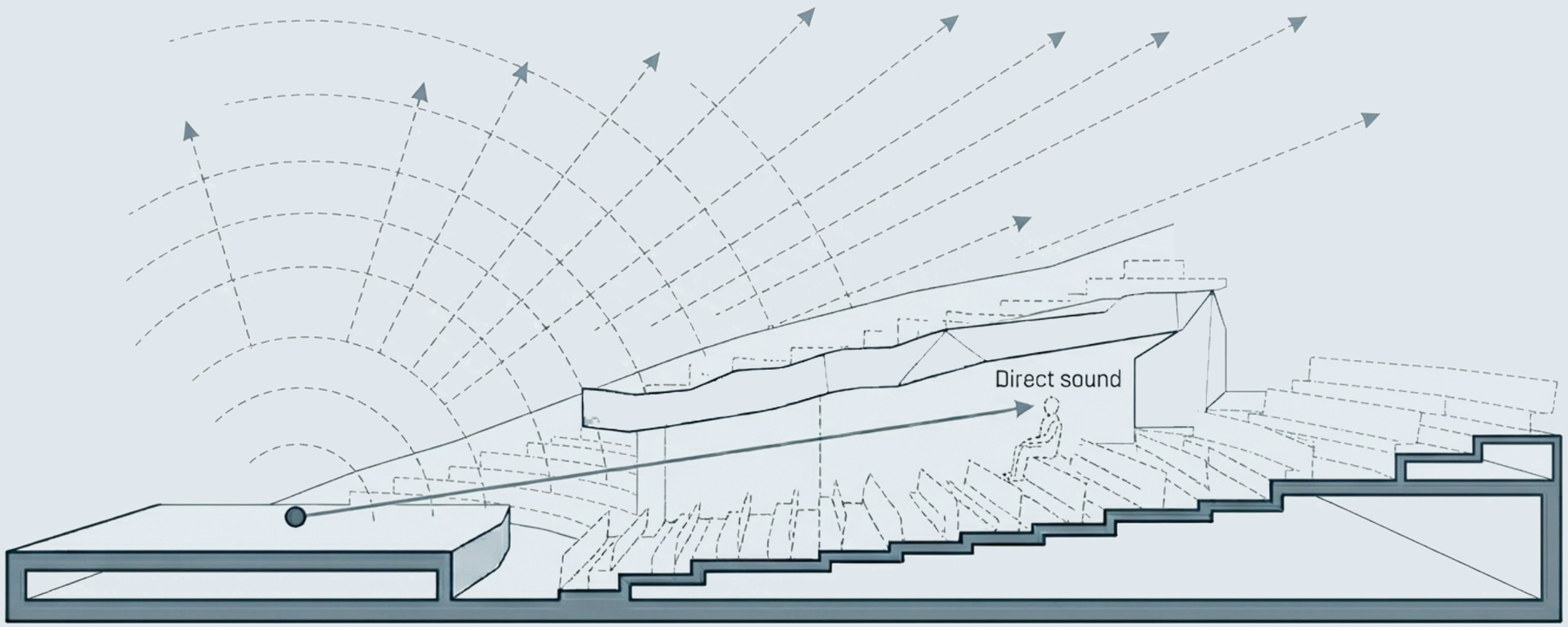
A4 presentation

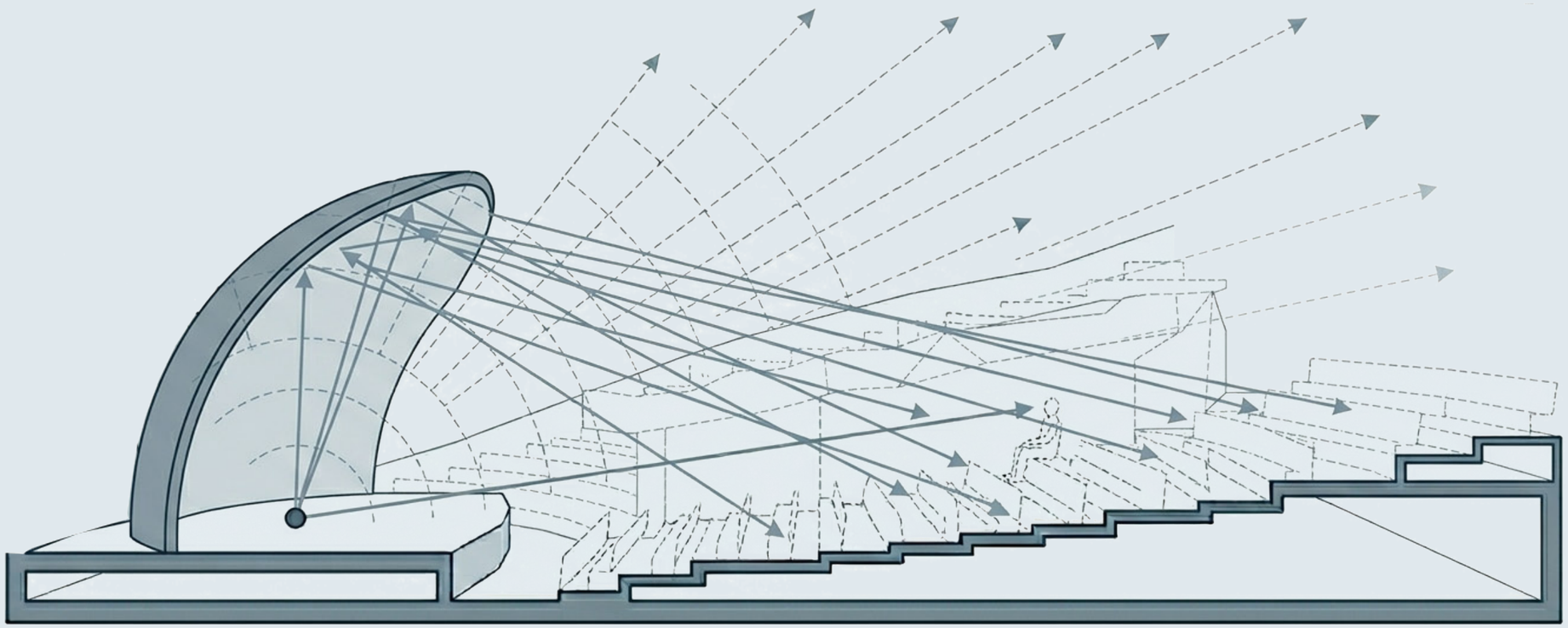
Msc Architecture, Urbanism and Building Sciences
Building Technology
Delft University of Technology

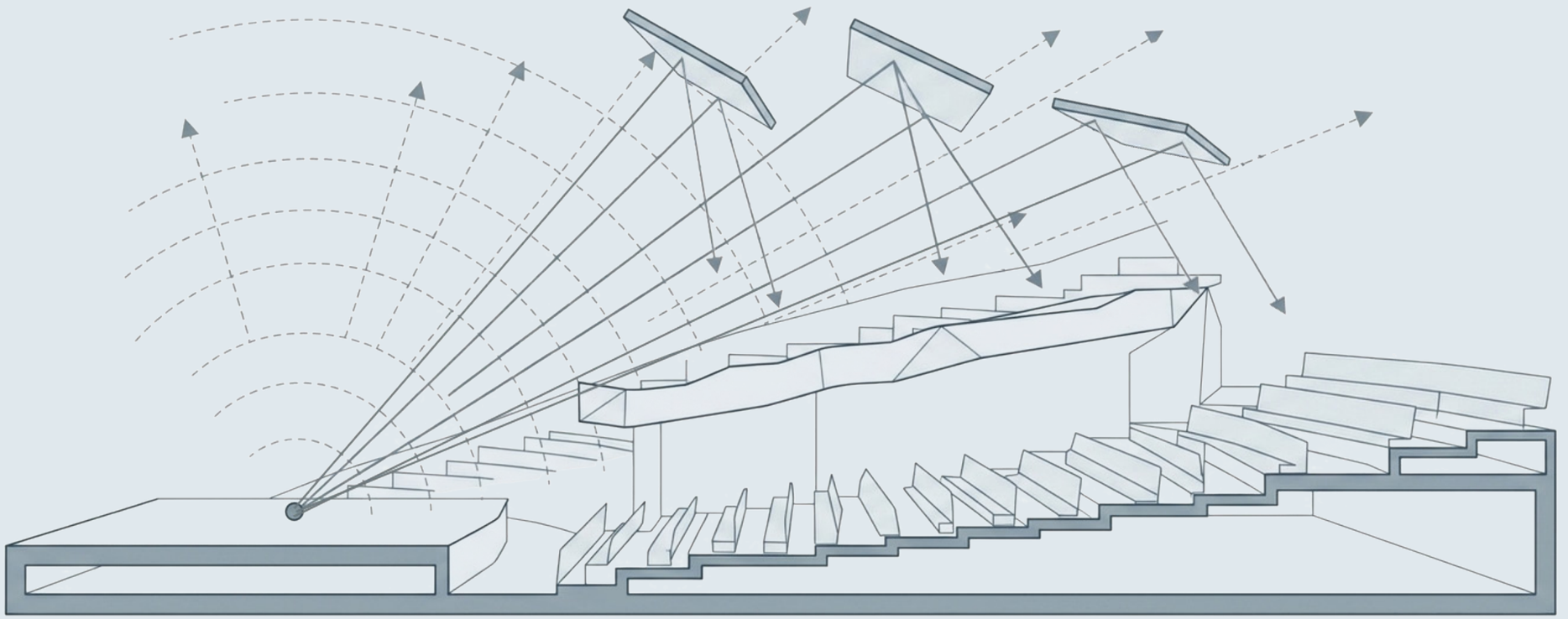
prof. dr. ir. M.J. Tenpierik
dr. G. Mirra






Direct sound





Which performance-based **computational design workflow** can **optimize** a passive, **crowd-integrated acoustic structure** for **maximizing acoustic uniformity** in large outdoor performance venues?

1a.

Literature review



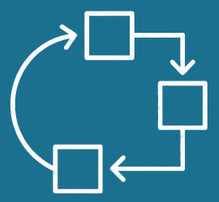
1b.

Design Case



2.

Design of the Computational Workflow



3a. Reflector Design Iteration 1



3b. Reflector Design Iteration 2



3c. Reflector Design Iteration 3



4.

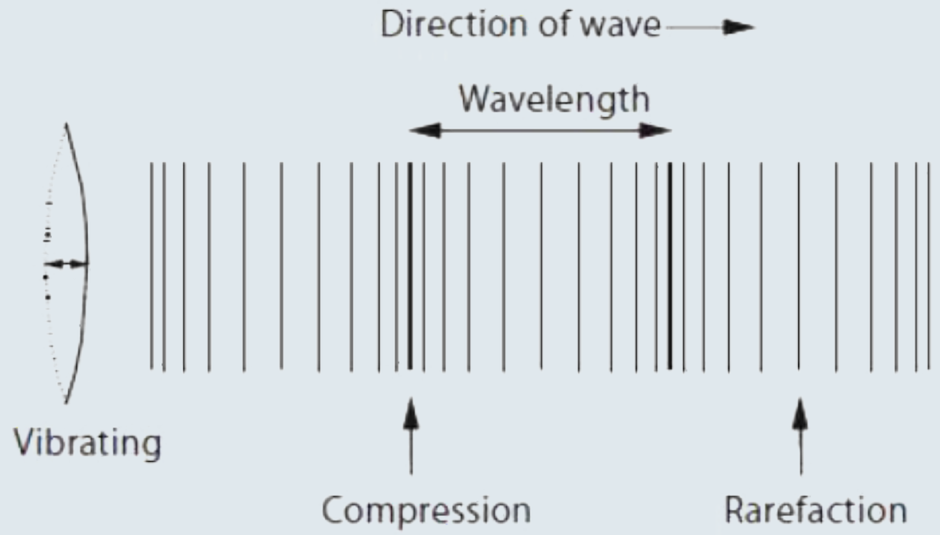
Validation of the Workflow



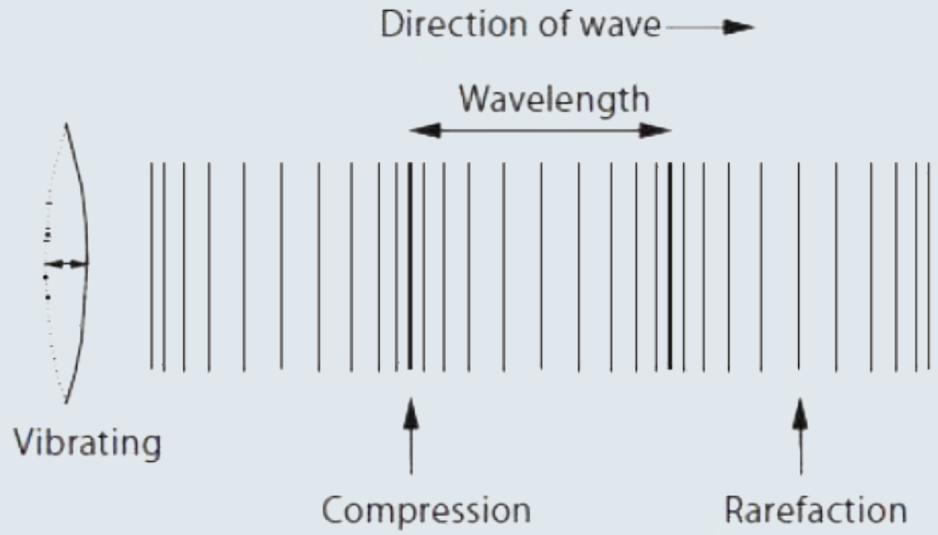
5.

Conclusion Discussion





Visualisation of a sound wave (Barron, 1993)



Visualisation of a sound wave (Barron, 1993)

Sound Pressure Level (SPL)

The local pressure deviation from the ambient atmospheric pressure, caused by a sound wave.

Expressed in decibel (dB)

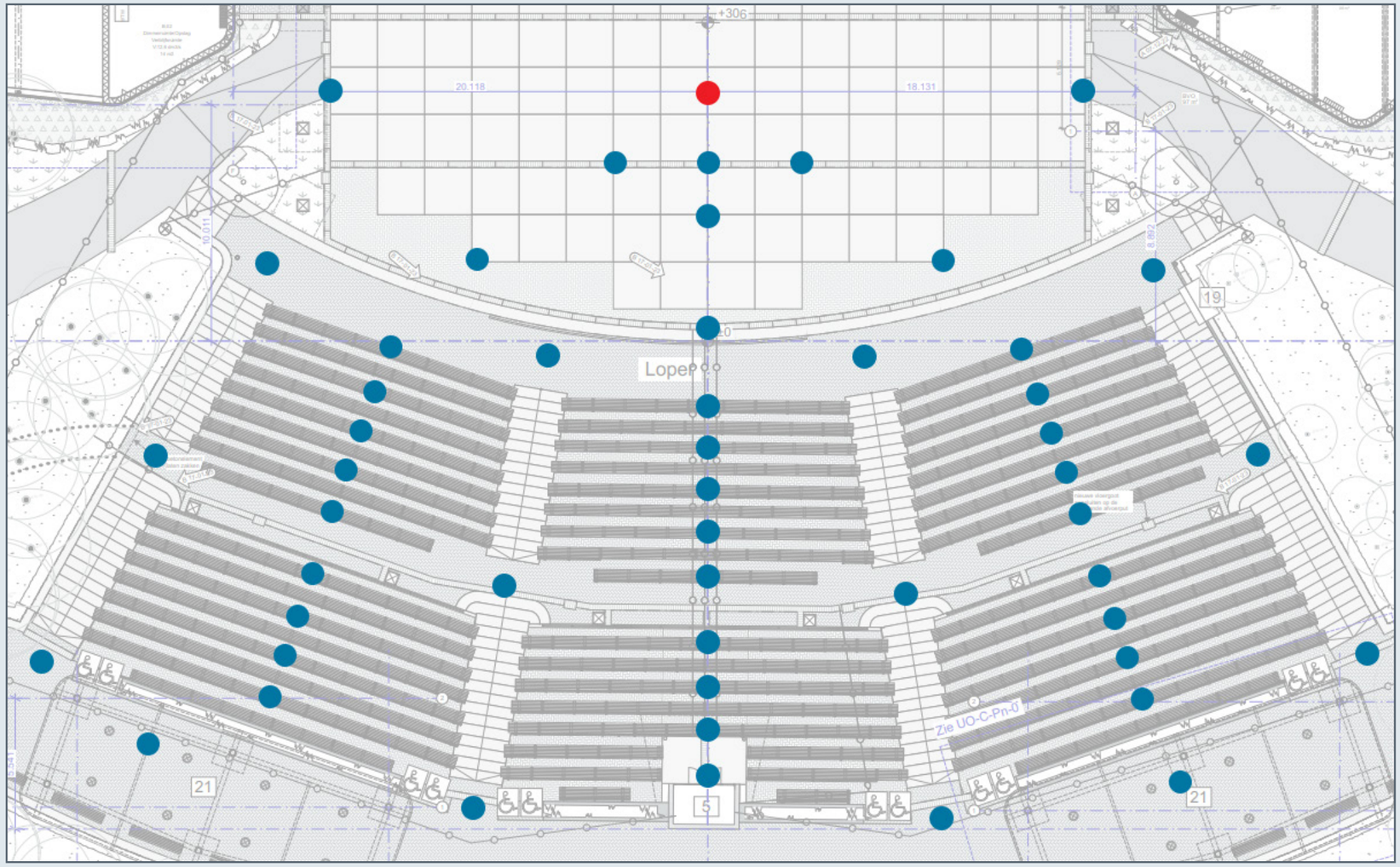
Design Case

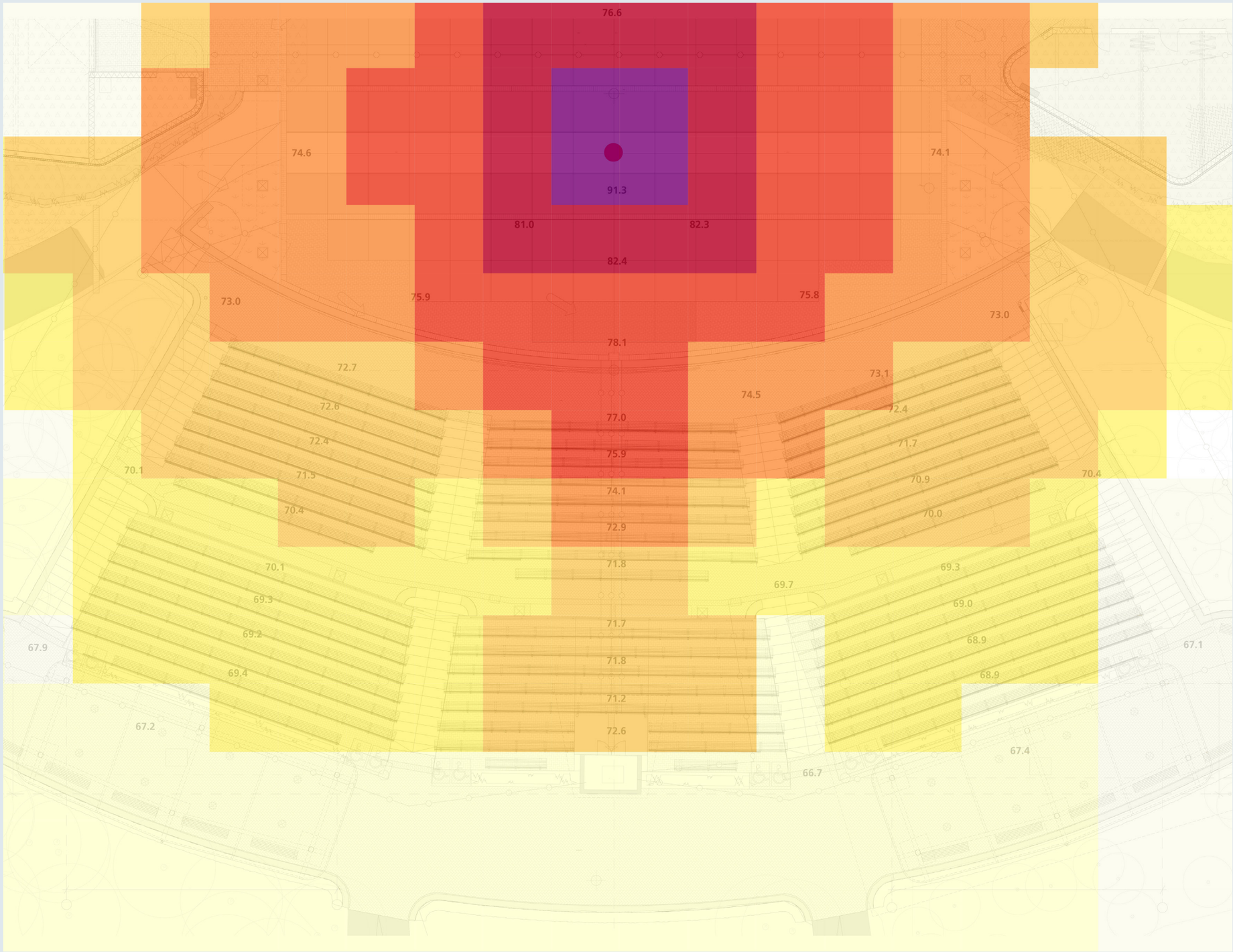
The Amsterdam Bostheater







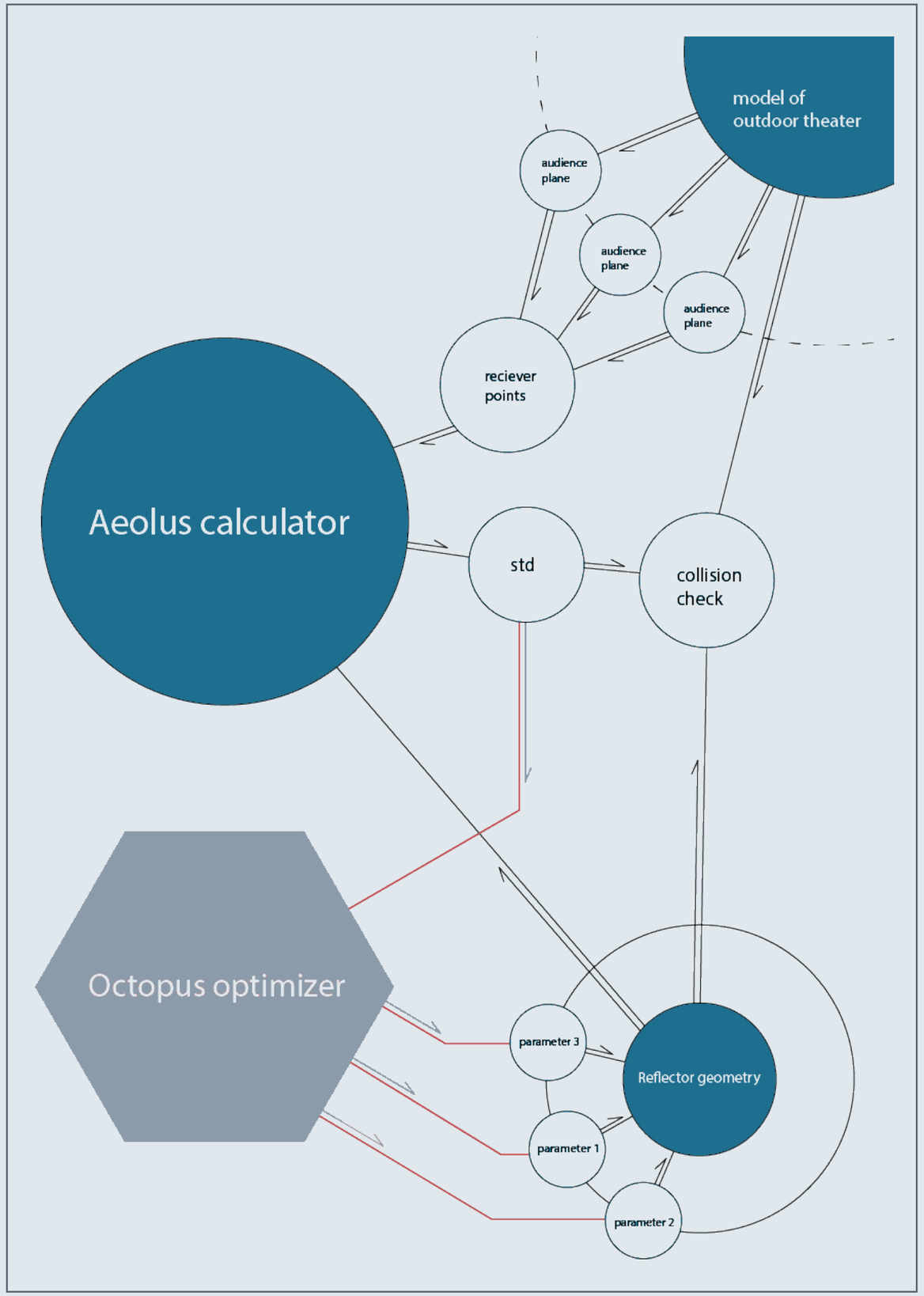

+306
20.118
18.131
19
21
5
21



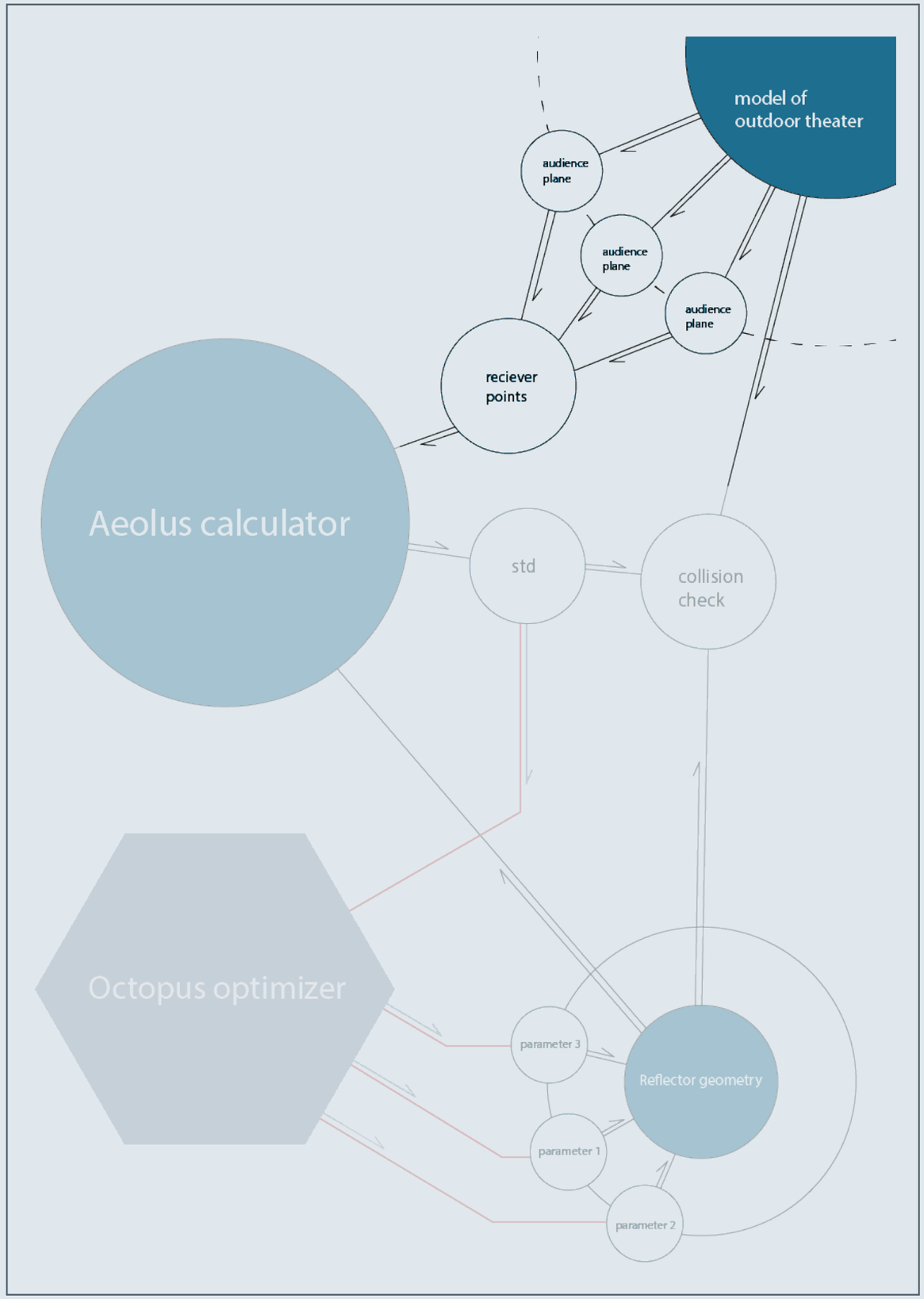
SPL results (dB)

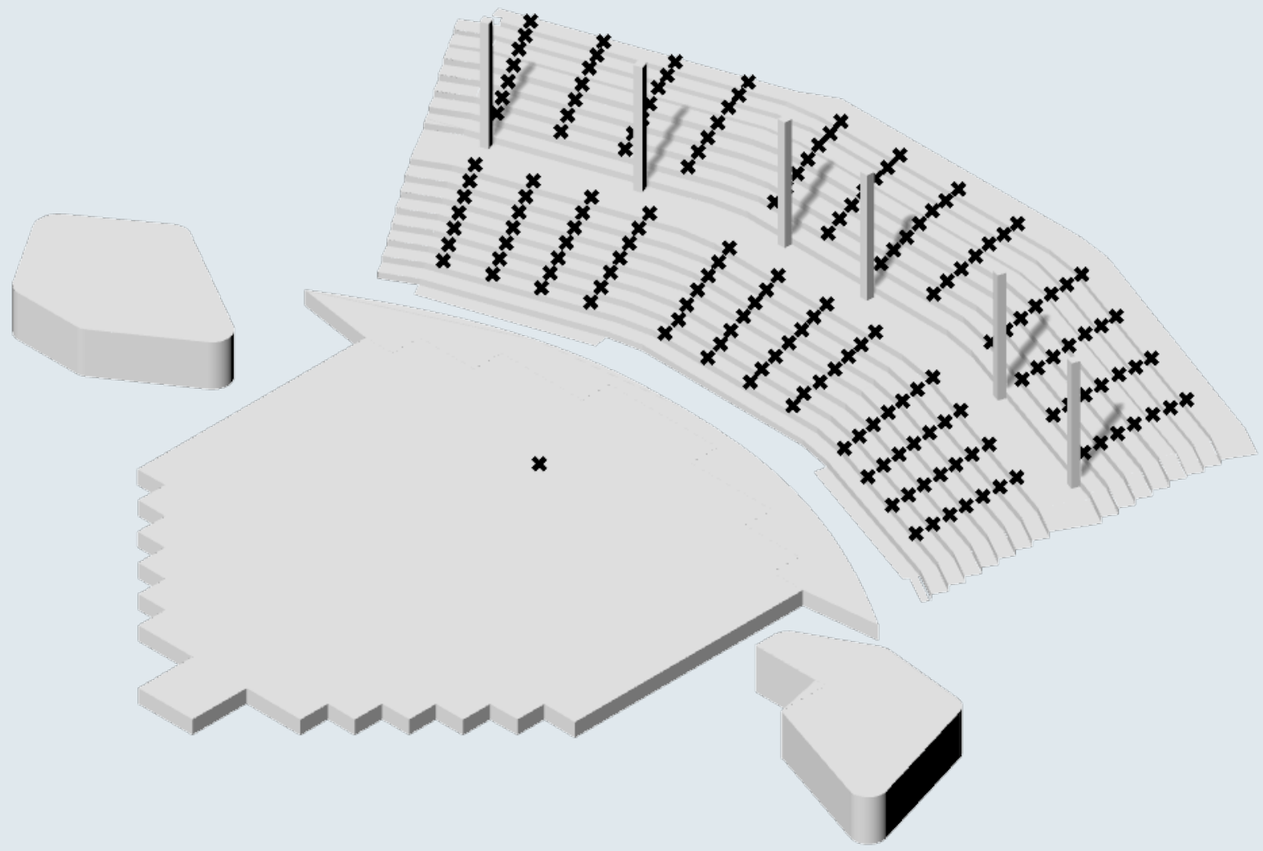
Computational Workflow

Design of the Computational Workflow

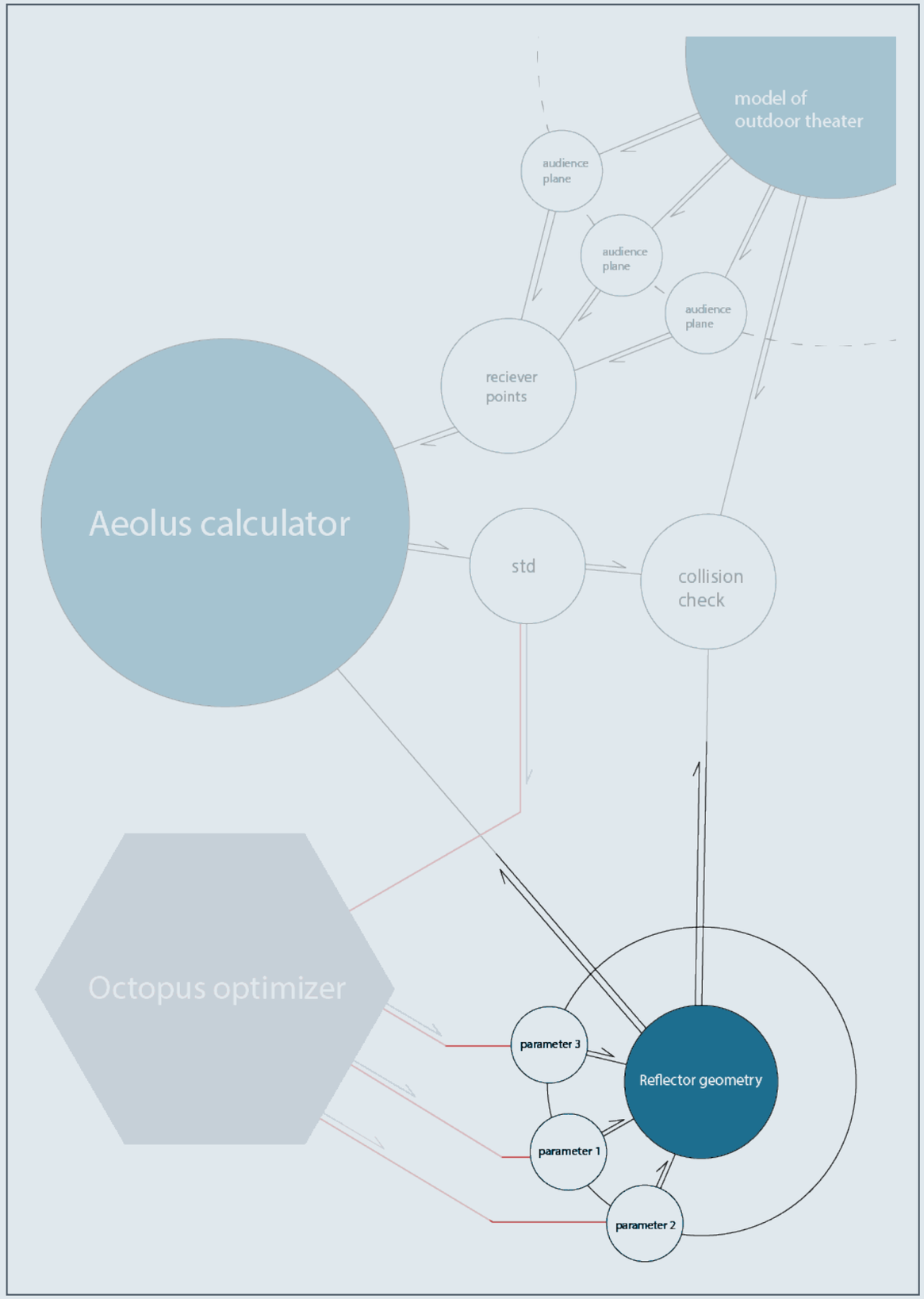


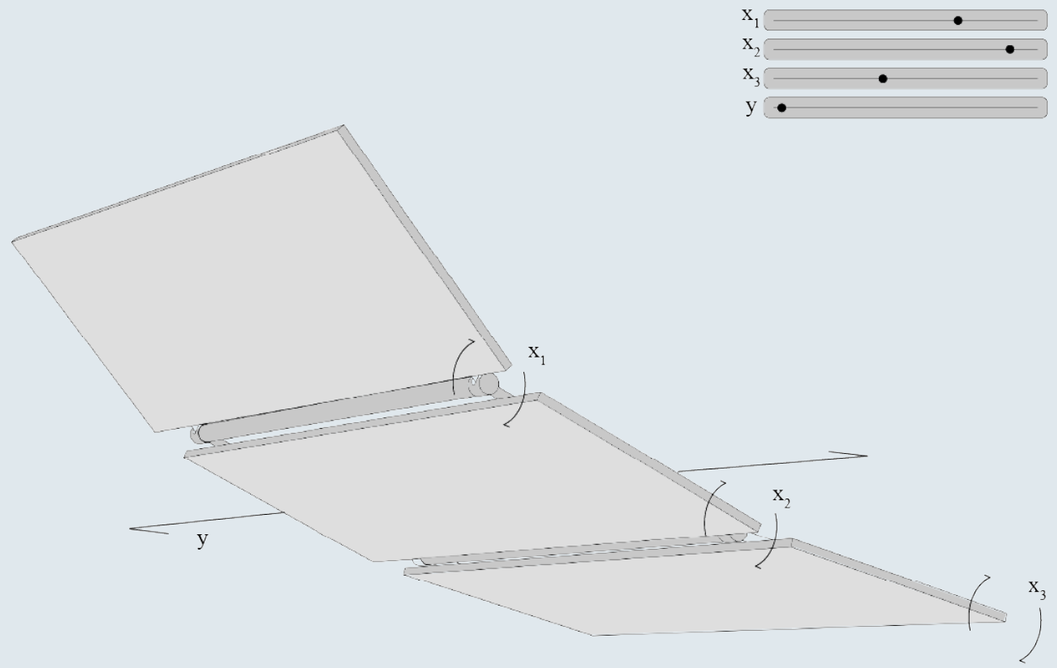
Design of the Computational Workflow

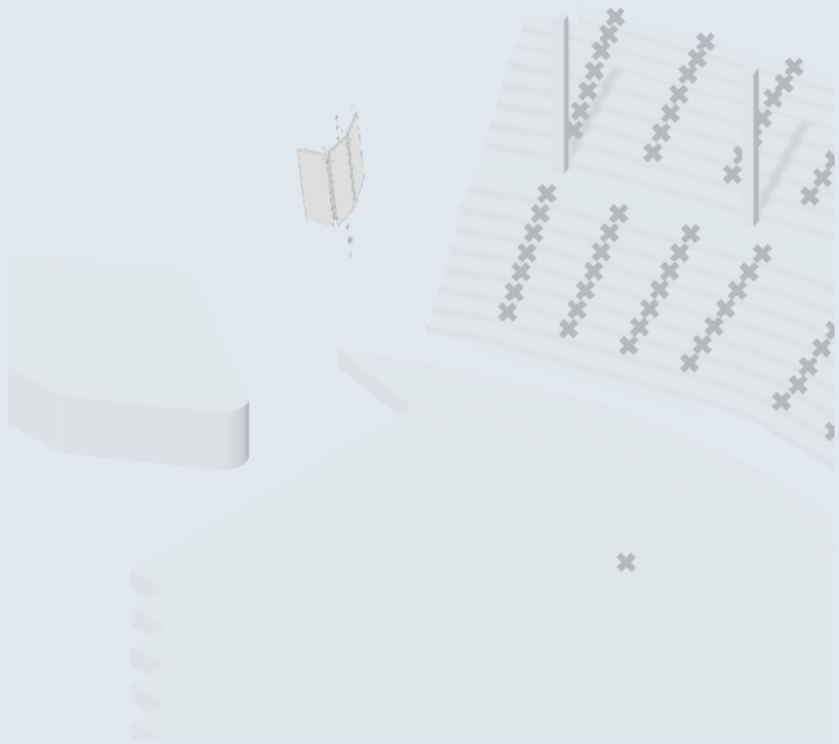




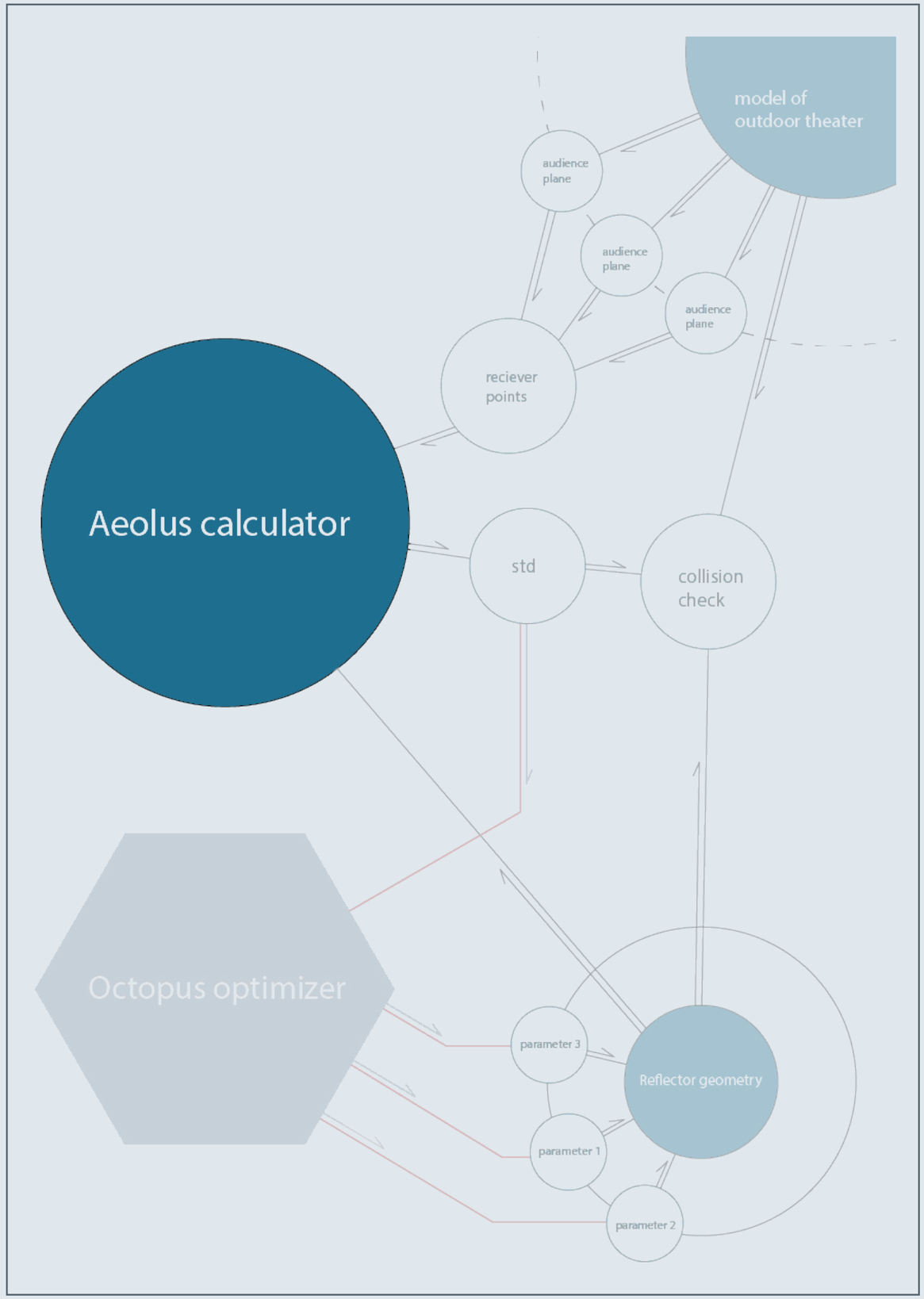
Design of the Computational Workflow

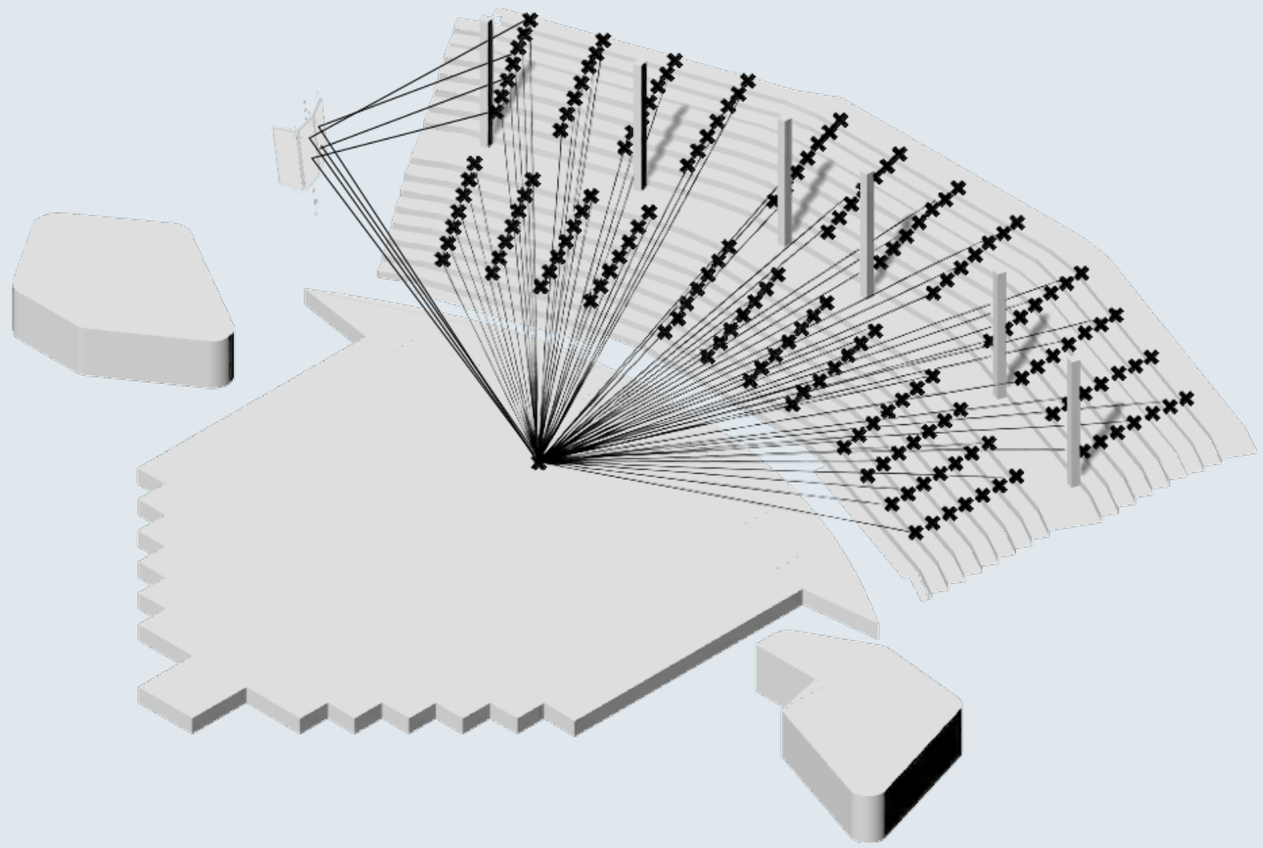




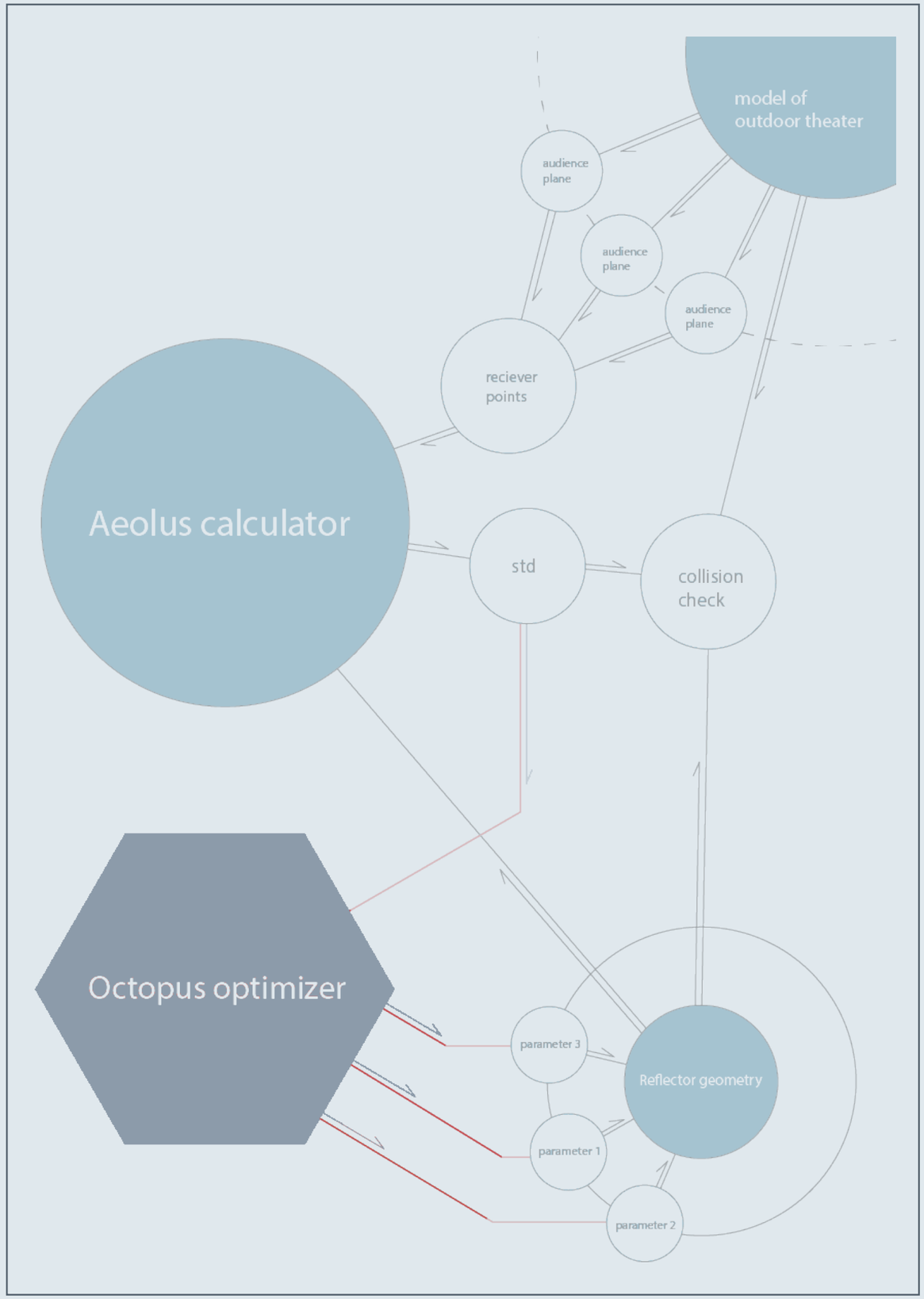


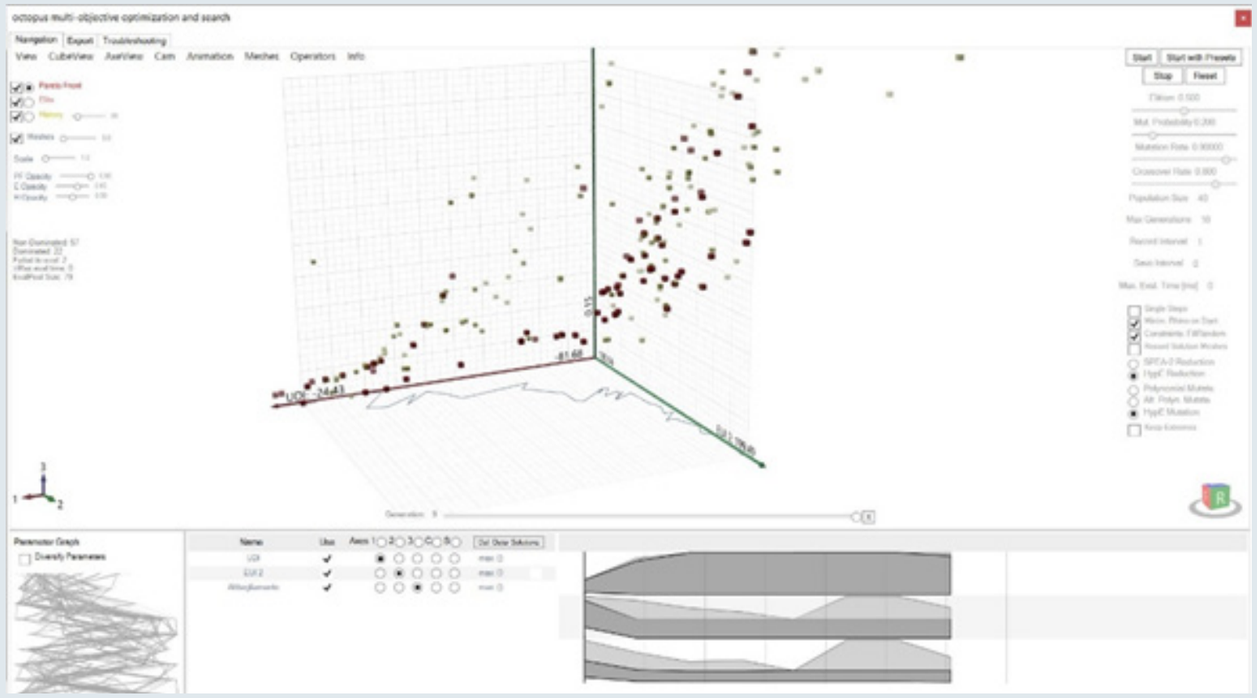
Design of the Computational Workflow

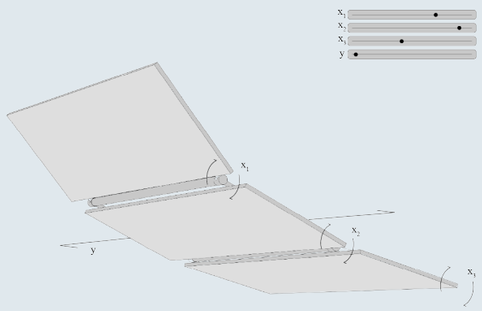


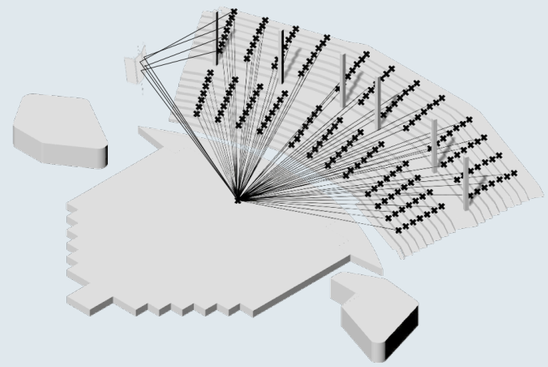


Design of the Computational Workflow





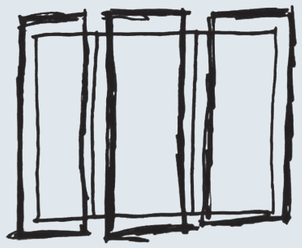


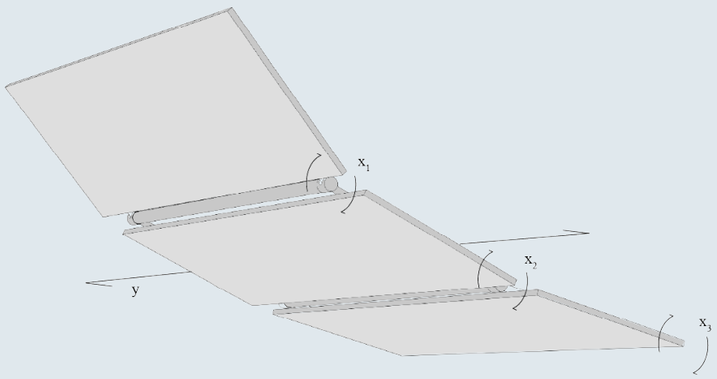


Reflector Design

Bringing the **acoustic qualities** of the **indoor** to the **outdoors**, without sacrificing the **spatial qualities** that make open-air performance irreplaceable.

Engineered approach

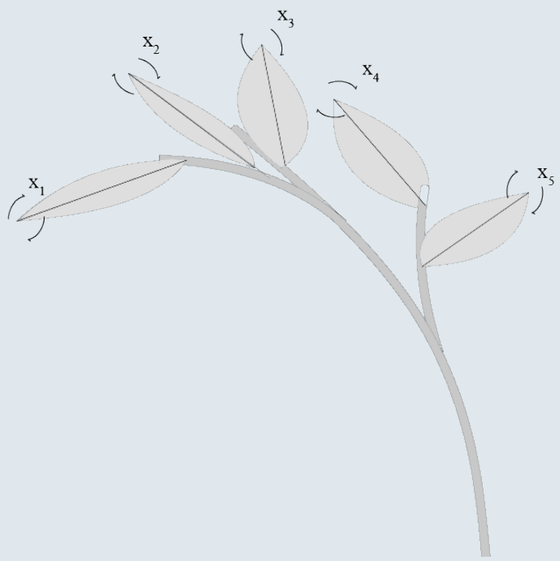




Acoustics	2.5 / 4
Spatial	1.67 / 3
Technical	2 / 3
Total	6.17 / 10

Architectural approach

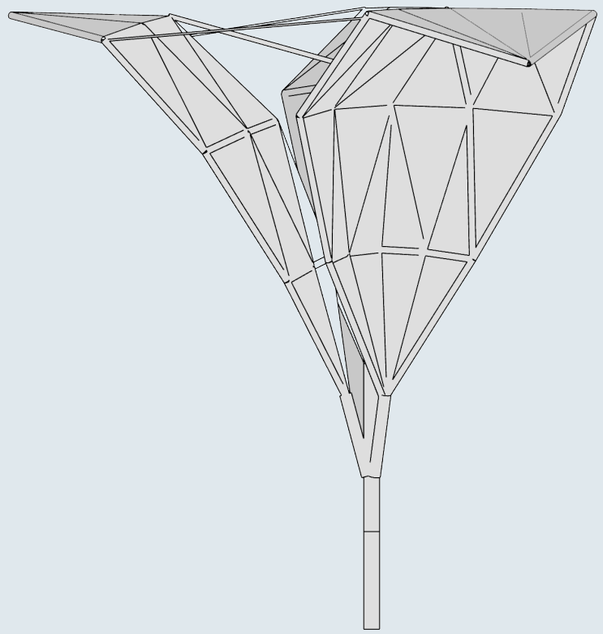




Acoustics	1 / 4
Spatial	3 / 3
Technical	2 / 3
Total	6 / 10

Final design

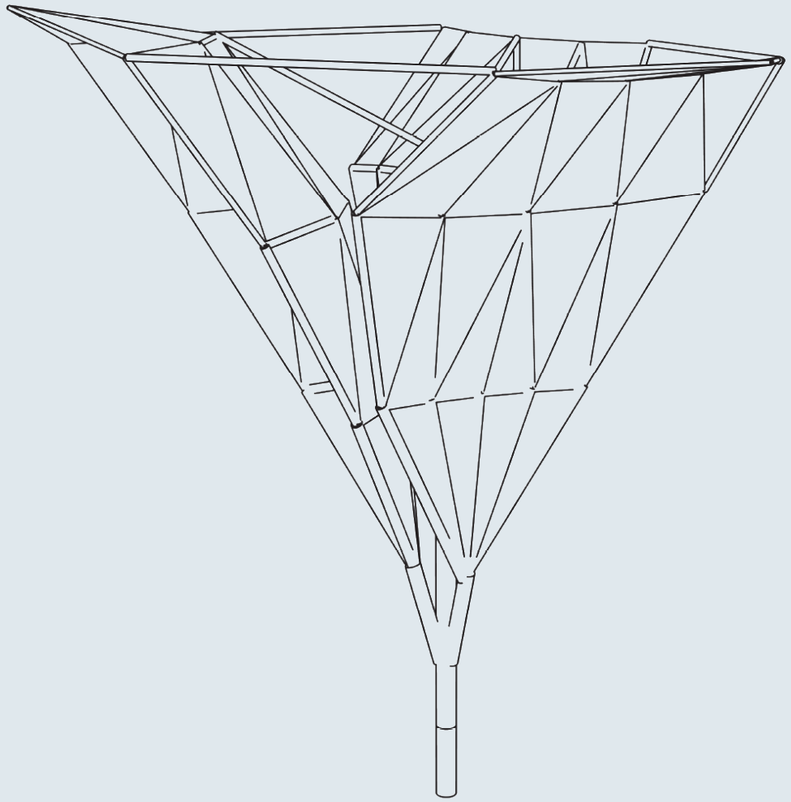




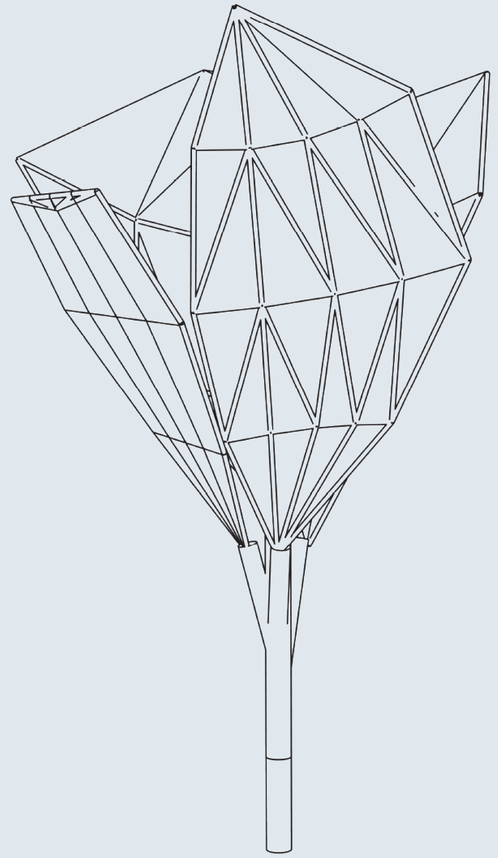
Acoustics	2.5 / 4
Spatial	3 / 3
Technical	3 / 3
Total	8.5 / 10



Multi-source approach

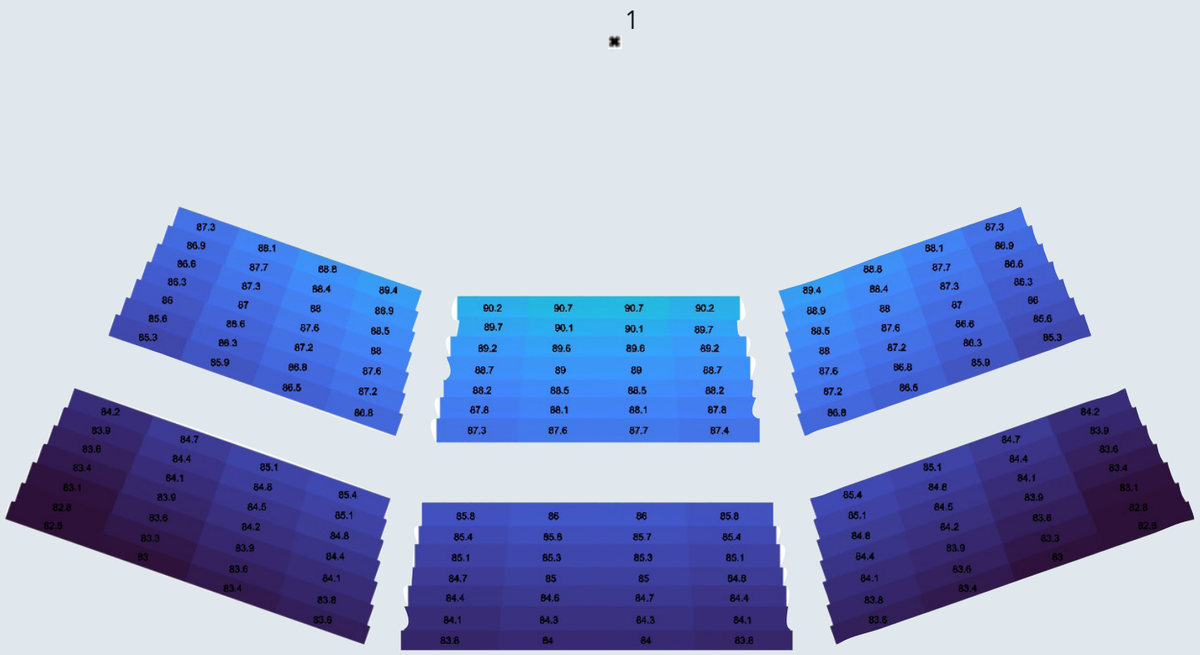


Lateral reflectors



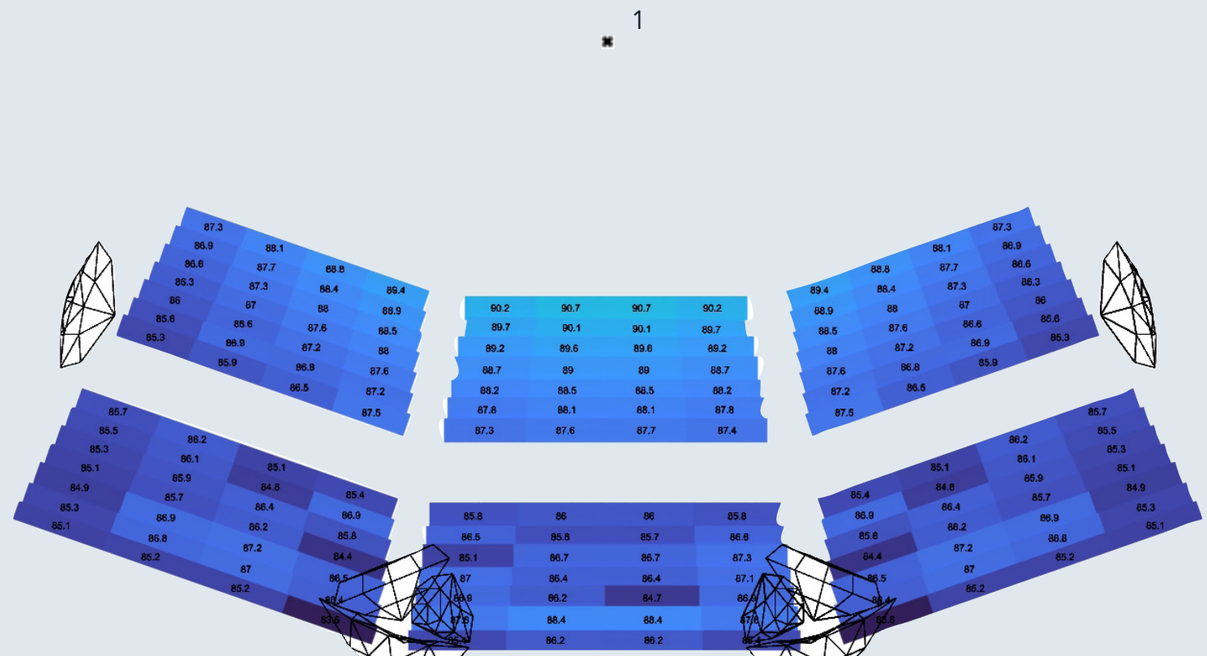
Central reflectors

Iteration 3: combined approach



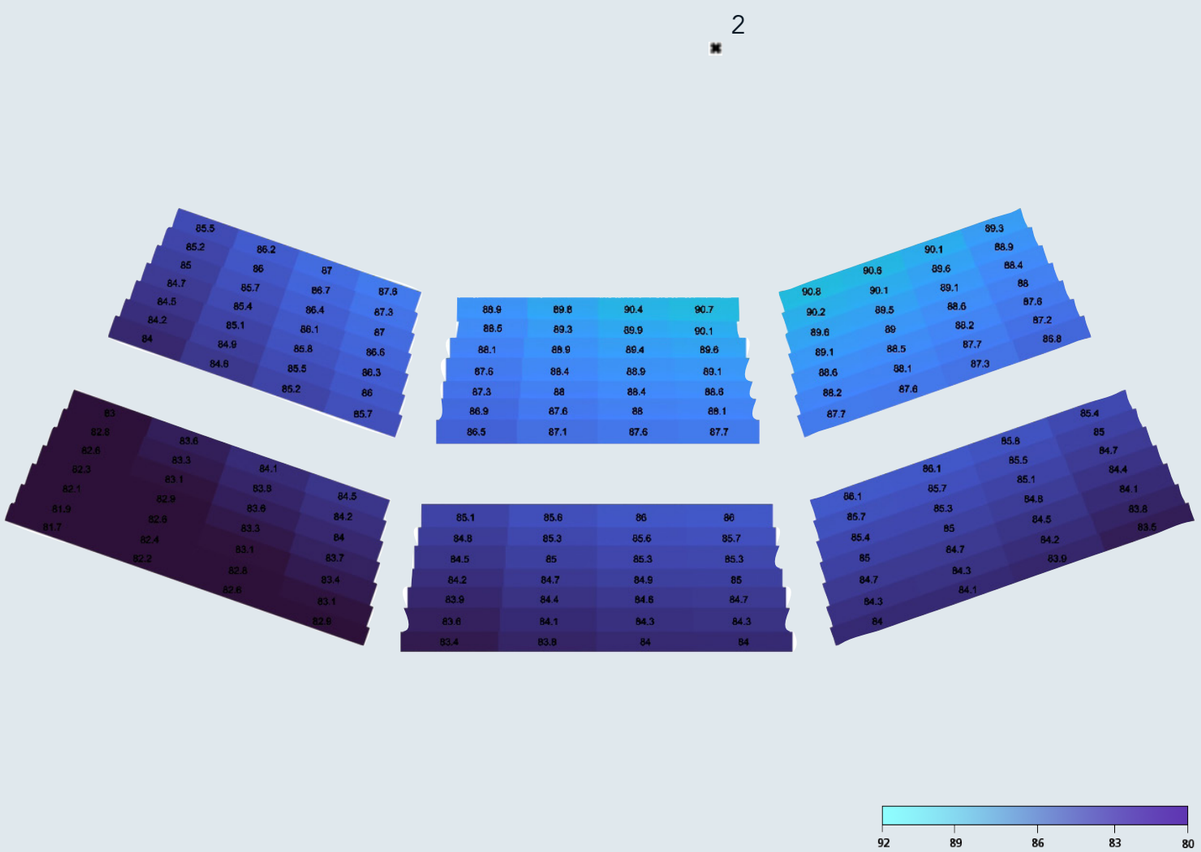
	Baseline
Std SPL Source 1	2.191 dB

Source 1 (central)



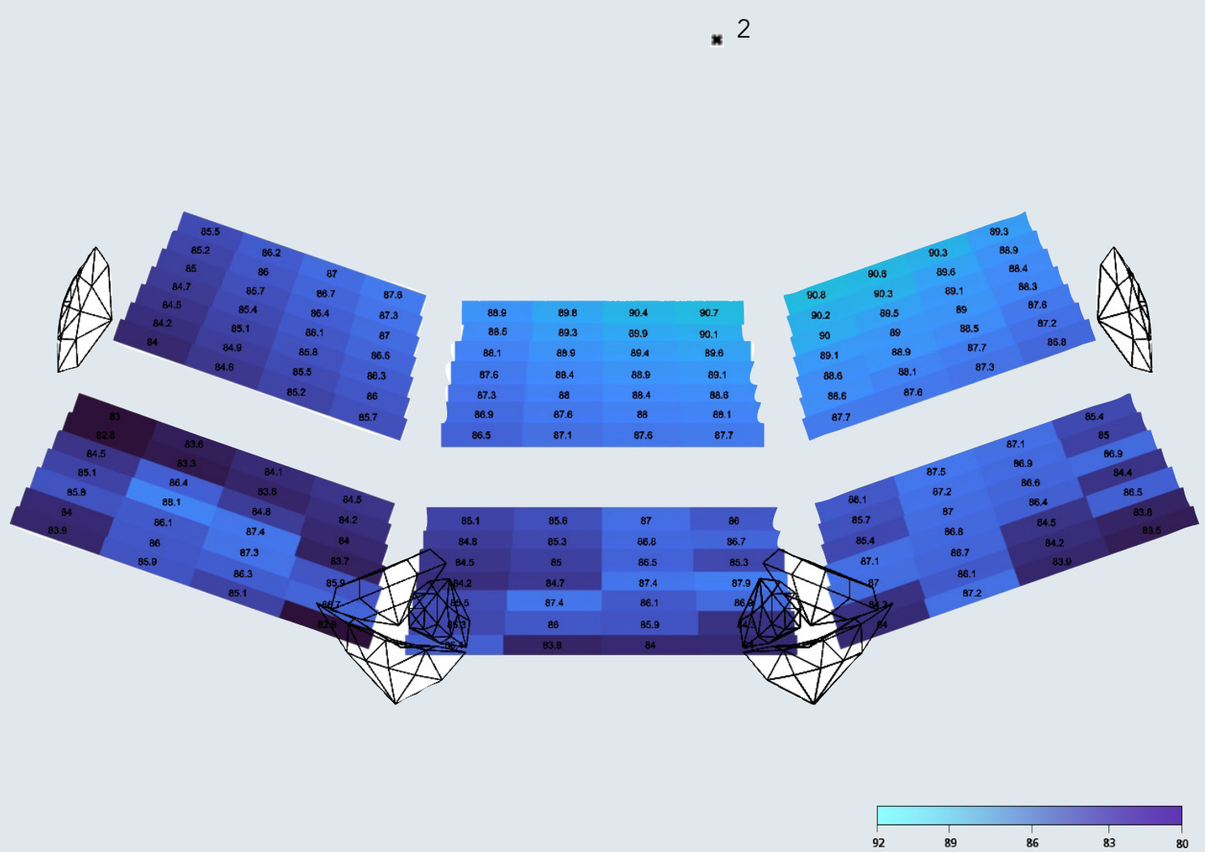
	With Reflectors
Std SPL Source 1	1.441 dB

Iteration 3: combined approach



	Baseline
Std SPL Source 1	2.118 dB

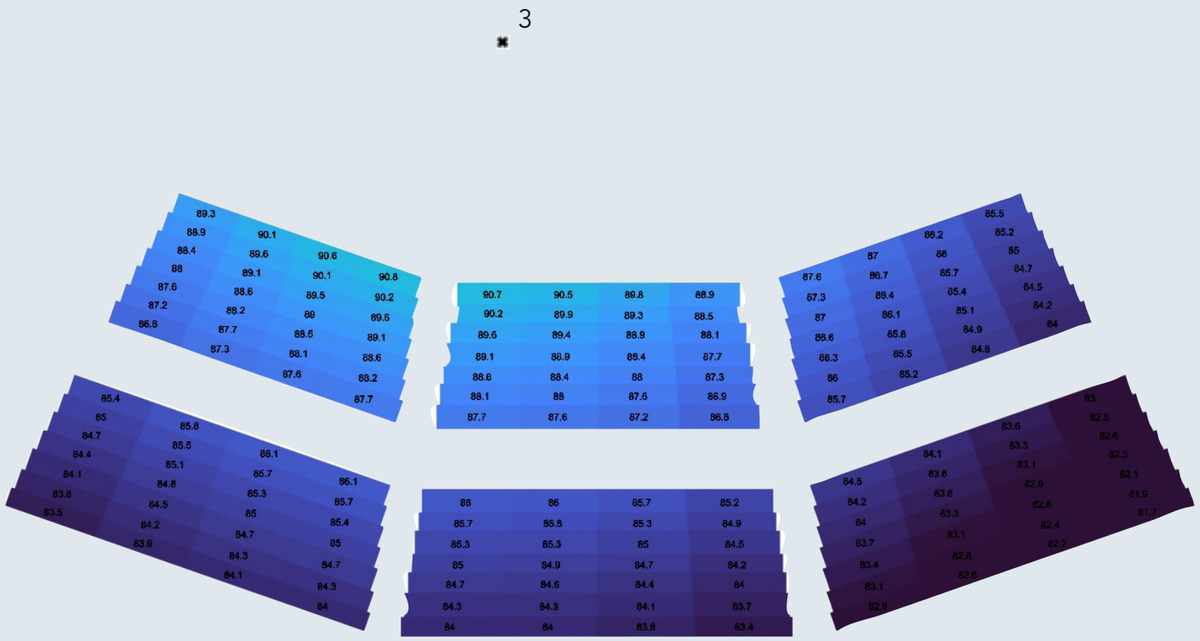
Source 2 (right)

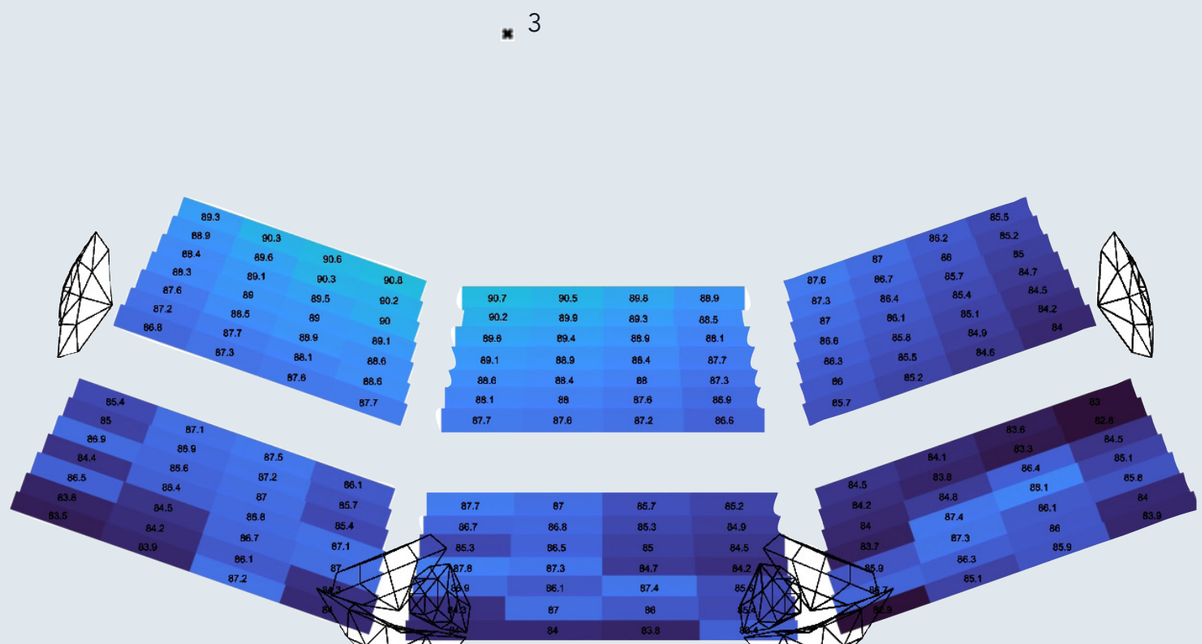


	With Reflectors
Std SPL Source 1	1.904 dB

Iteration 3: combined approach

Source 3 (left)





	Baseline
Std SPL Source 1	2.120 dB

	With Reflectors
Std SPL Source 1	1.907 dB

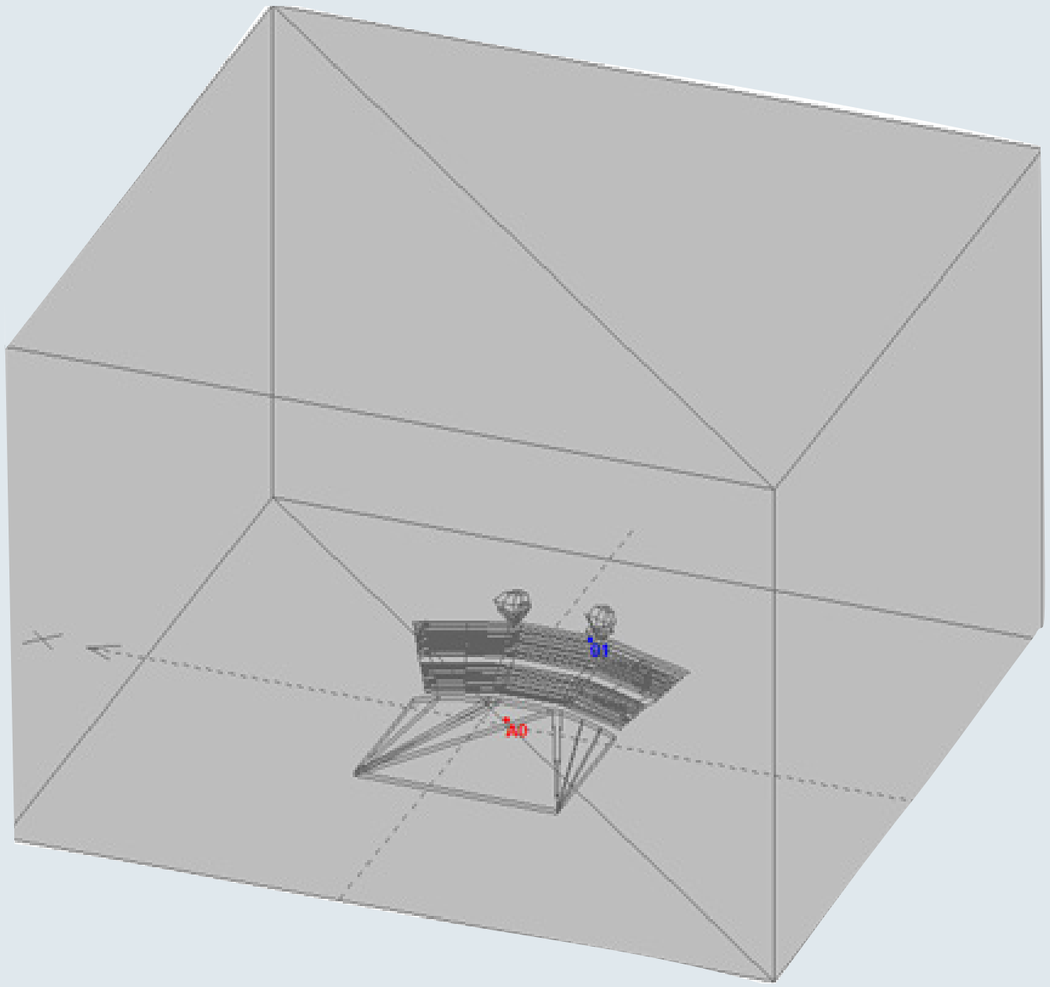
Iteration 3: combined approach

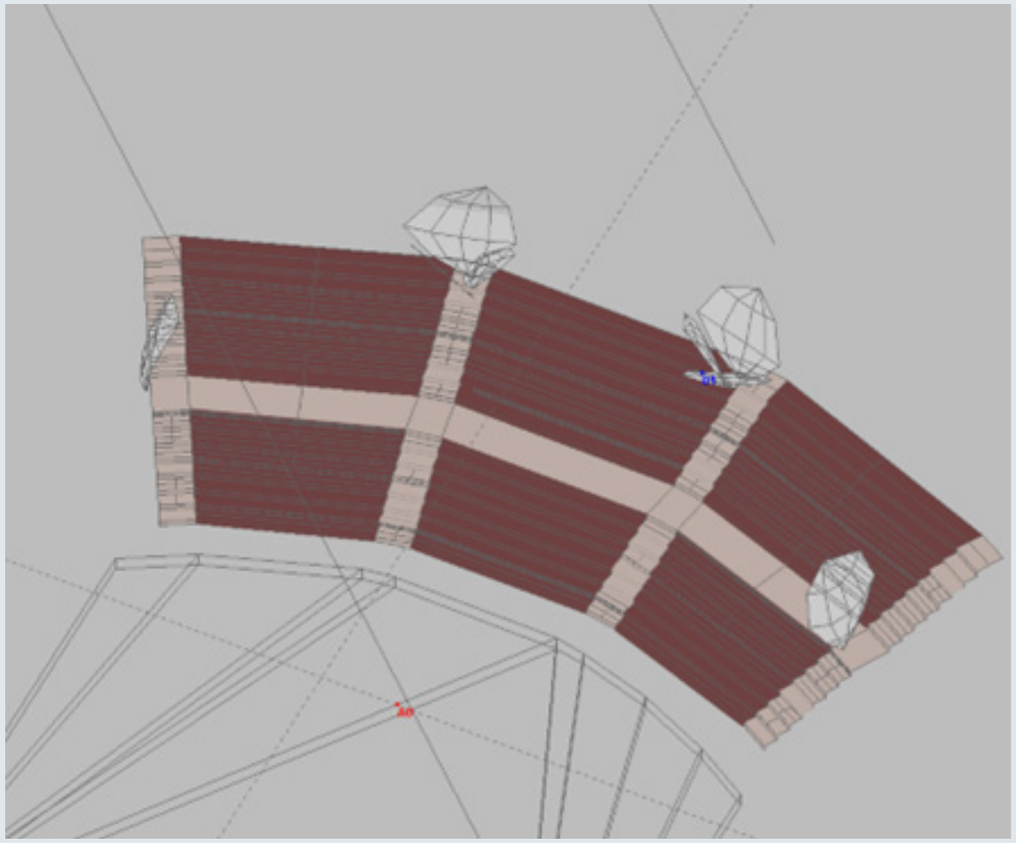


Iteration 3: combined approach



Validation of the workflow


A0
01


A0



CATT-Acoustics - dB(A)

Point	Measured	CATT	Difference
5	75.9 dB (A)	75.77 dB (A)	−0.13
6	74.1 dB (A)	74.78 dB (A)	+0.68
7	72.9 dB (A)	73.99 dB (A)	+1.09
8	71.8 dB (A)	72.69 dB (A)	+0.89
9	71.7 dB (A)	71.08 dB (A)	−0.62
10	71.8 dB (A)	70.43 dB (A)	−1.37
11	71.2 dB (A)	70.03 dB (A)	−1.17
12	72.6 dB (A)	68.17 dB (A)	−4.43
16	73.4 dB (A)	73.40 dB (A)	+0.00
17	72.4 dB (A)	72.83 dB (A)	+0.43
18	71.5 dB (A)	72.30 dB (A)	+0.80
19	70.4 dB (A)	71.59 dB (A)	+1.19
20	70.1 dB (A)	70.17 dB (A)	+0.07
21	69.3 dB (A)	69.51 dB (A)	+0.21
22	69.2 dB (A)	68.99 dB (A)	−0.21
23	69.4 dB (A)	67.38 dB (A)	−2.02
36	72.4 dB (A)	73.24 dB (A)	+0.84
37	71.7 dB (A)	72.68 dB (A)	+0.98
38	70.9 dB (A)	71.78 dB (A)	+0.88
39	70.0 dB (A)	71.30 dB (A)	+1.30
40	69.3 dB (A)	70.10 dB (A)	+0.80
41	69.0 dB (A)	69.41 dB (A)	+0.41
42	68.9 dB (A)	68.98 dB (A)	+0.08
43	68.9 dB (A)	67.42 dB (A)	−1.48

Validation of the workflow

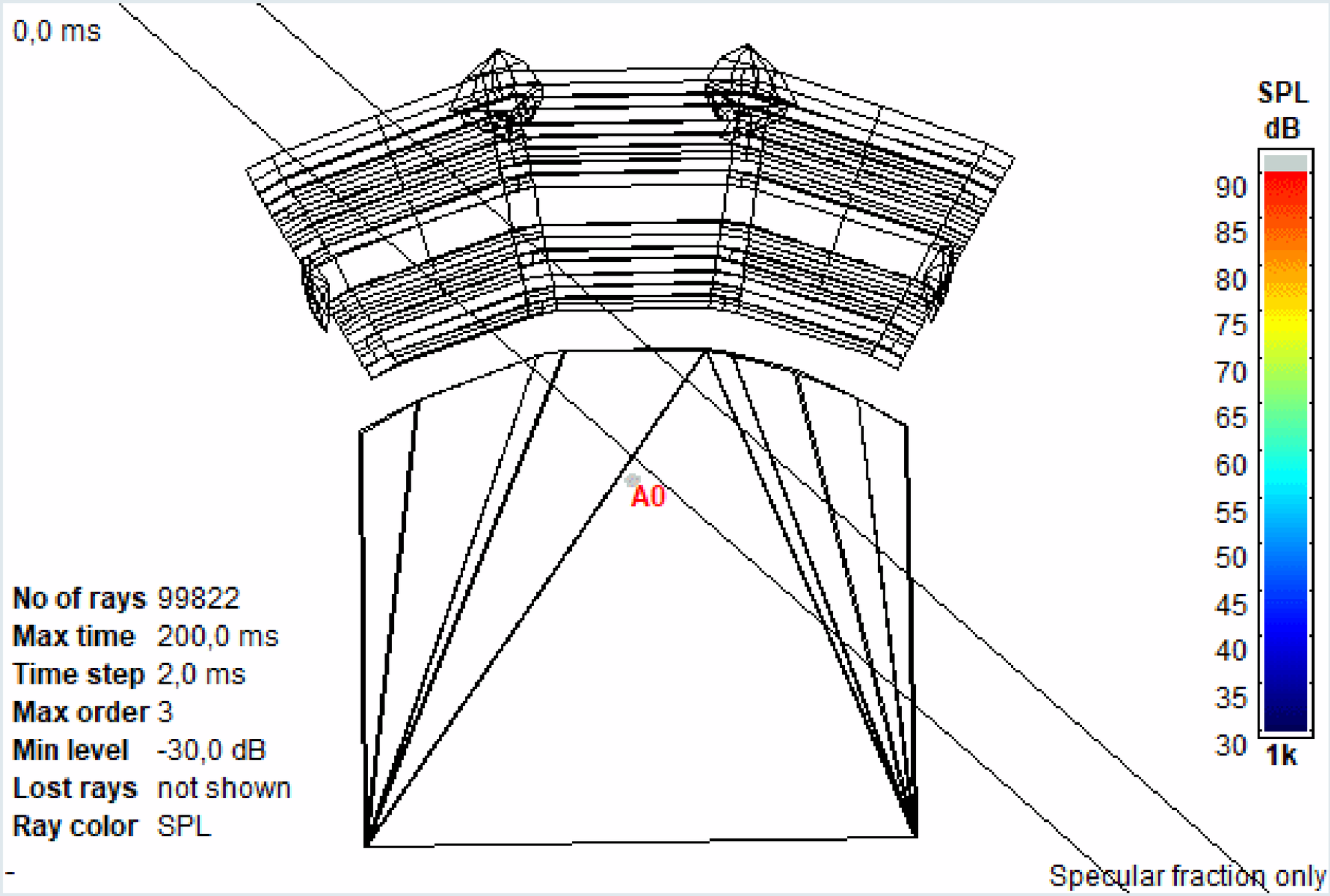


CATT-Acoustics dB(A)

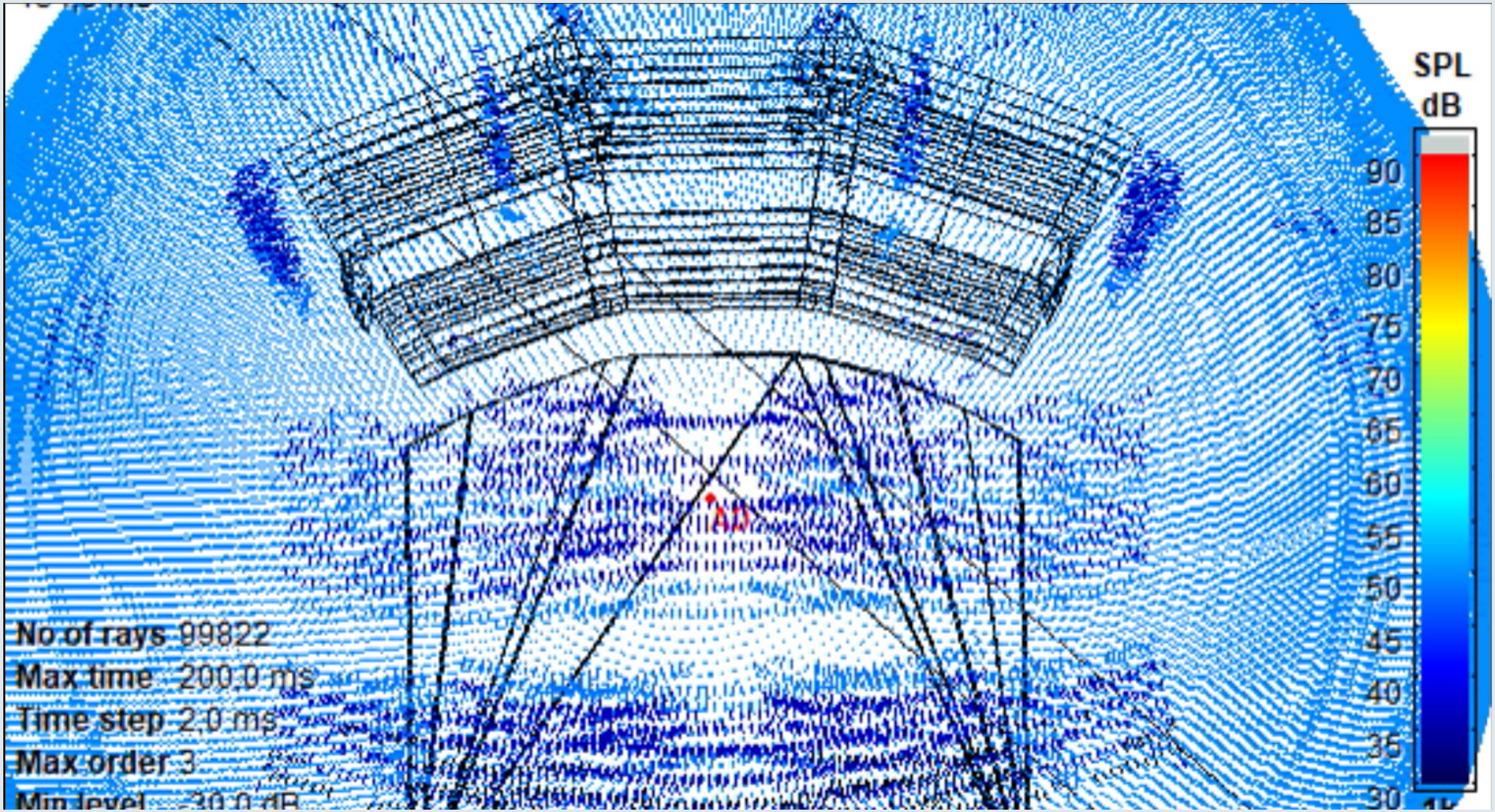


Aeolus dB(A)

	CATT	Aeolus
Std, source 1	2.207 dB	2.191 dB


0,0 ms
SPL
dB
90
85
80
75
70
65
60
55
50
45
40
35
30
1k
A0
No of rays 99822
Max time 200,0 ms
Time step 2,0 ms
Max order 3
Min level -30,0 dB
Lost rays not shown
Ray color SPL
Specular fraction only

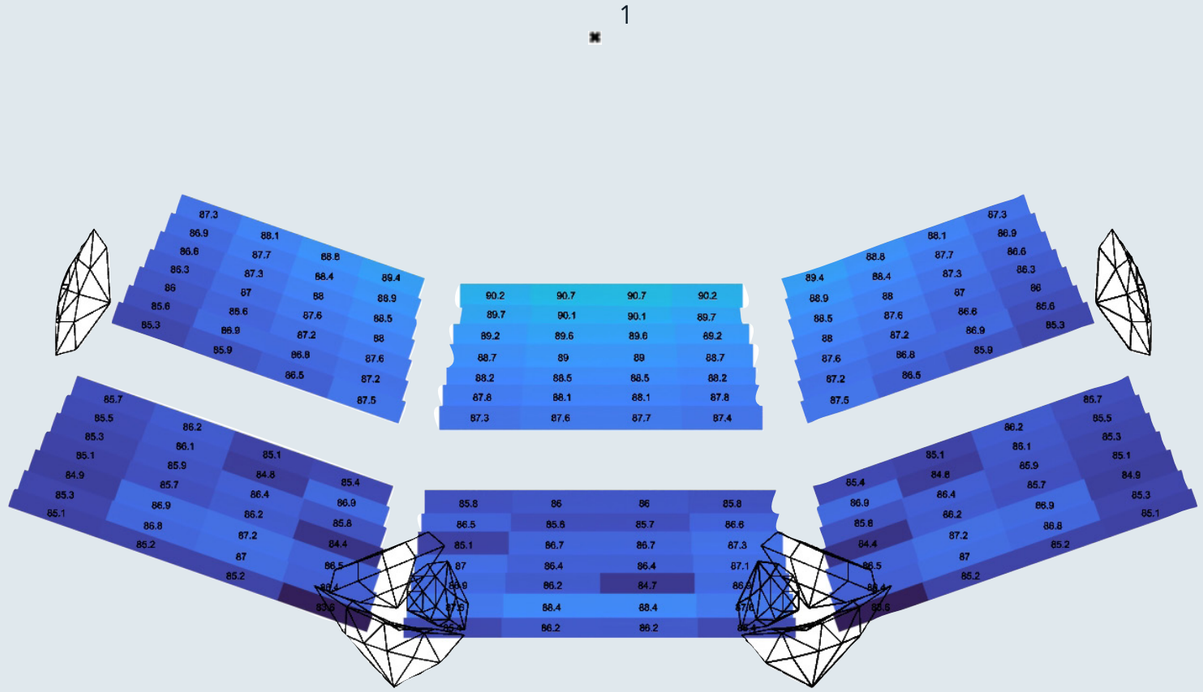
150 ms


SPL
dB
90
85
80
75
70
65
60
55
50
45
40
35
30
No.of rays 99822
Max time 200.0 ms
Time step 2.0 ms
Max order 3

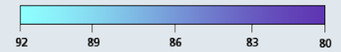
Validation of the workflow



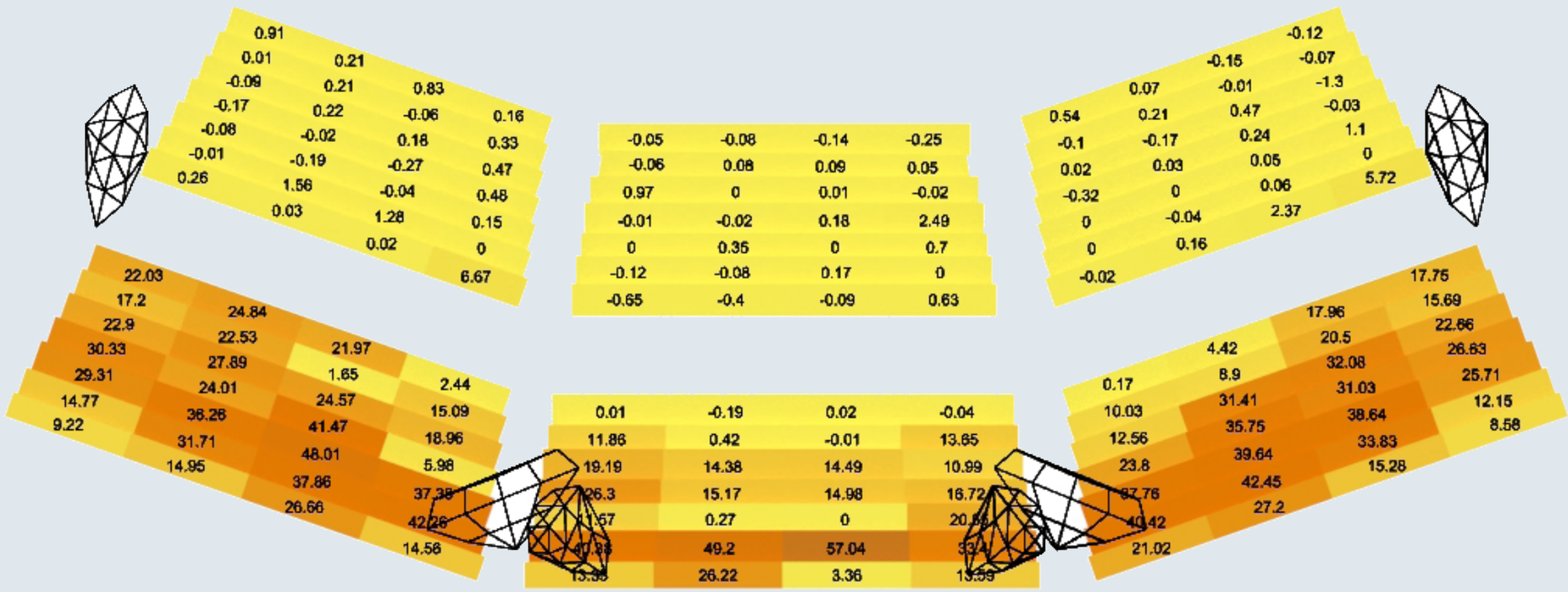
CATT-Acoustics dB(A)



Aeolus dB(A)



	CATT	Aeolus
Std, source 1	1.594 dB	1.441 dB



Difference in Lateral Fraction

	Baseline	With reflectors
Std LF, source 1	3.748 %	13.848 %
Avg LF, source 1	2.854 %	13.340 %



Boning, W., & Bassuet, A. (2023). A ROOM WITHOUT WALLS OPTIMIZING AN OUTDOOR MUSIC SHELL TO MAINTAIN VIEWS AND MAXIMIZE REFLECTIONS. Proceedings of the Institute of Acoustics. https://doi.org/10.25144/16184

Pugnale, A. (2018). Integrating Form, Structure and Acoustics: A Computational Reinterpretation of Frei Otto's Design Method and Vision. Journal of the International Association for Shell and Spatial Structures, 59(1), 75–86. https://doi.org/10.20898/j.iass.2018.195.901

Rindel, J. H. (2025). Acoustical aspects of the development of Greek theaters in the 4th century B.C.E. The Journal of the Acoustical Society of America, 157(3), 2042–2066. https://doi.org/10.1121/10.0036255