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A New Method for the Acoustic Analysis of Complex Mechanical Services Systems Requiring Low Noise Levels

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Abstract [26]. The new 2,000 seat Concert Hall and 1,800 seat Lyric Theatre at Theatres on the Bay in Singapore were designed to achieve very low noise levels to meet the requirements of the project acoustic consultant, Artec Consultants, who specified an extremely stringent mechanical services noise criteria of N-1 for each auditorium. N-1 is about 12dB below NR15.

Apart from external noise intrusion, the other major noise design consideration was the mechanical services system. A complex system involving 54 air handling units (AHU) supplied each space via numerous supply and return air apertures to achieve satisfactory conditions in a particularly hot and humid climate.

A major source of potential noise was regenerated noise at fittings, branches, dampers, elbows and outlets. Each AHU system had to be analysed to evaluate the individual noise contribution. As each system was very complex, a new method of ductwork acoustic analysis was developed. This paper presents details of a new procedure that provides a rapid and sophisticated analysis of complicated mechanical services systems for low-noise environments.

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1. INTRODUCTION

The recently opened Esplanade -Theatres on the Bay Concert Hall and Lyric Theatre in Singapore has had the primary mechanical services systems noise analyzed by a new software program that undertakes a complete acoustical analysis of a duct work system including the calculation of self generated noise thereby greatly simplifying the downduct noise analysis. This program predicts regenerated noise by key duct elements within the system and provides comprehensive results in a simple-to-evaluate format. A review of the program output enables rapid and systematic identification of elements that may cause ductborne noise problems allowing modifications to be made to the mechanical services design.

2. BACKGROUND

The Concert Hall and Lyric Theatre were required to achieve very low noise levels to meet the requirements of Artec Consultants, who specified a design criteria of N-1 for each auditorium.

Marshall Day Acoustics' role, acting on behalf of the builder and the mechanical services contractor, was to review the detail designs prepared by the contractor. Marshall Day Acoustics (MDA) undertook to review and analyse every AHU system, to demonstrate compliance with the design criterion N-1.

The Artec acoustical guidelines were used in the design of the ductwork systems, but detailed analysis and reports were also required. Given the complexity of the project and its size, complicated by an evolving design, a computer based analysis was considered the only effective solution, and it was soon apparent that only one software package was suitable for the purpose.

3. THE ACADS SOFTWARE

ACADS-BSG, an engineering software house in Melbourne, Australia, had developed a Fortran based program over many years for downduct acoustic analysis. Other alternative software packages and methods were considered, but the ACADS software was selected after review and a sample calculation assessment. Uniquely among most acoustic analysis software, the ACADS system also provides calculation of induct regenerated ('self") noise.

The review indicated the software had the necessary potential however, as part of the assessment process it was necessary to validate the regenerated noise predictions. The results of this validation are presented elsewhere at Inter Noise 2004.

A problem encountered with the initial ACADS software was that it could not "trace" the sound through the duct system and the analysis and results display was inflexible. In addition the presentation did not lend itself to analysis or easy comprehension by the client, see Figure 1.

4. TRANSFERRING 3D DRAWINGS TO COMPUTER FILES

The AutoMULE software package was used to import the contractors' 3D AutoCAD drawings. Using commands on the Windows toolbar, it was possible to trace the centre line of the duct work and digitize all supply and return air networks. It was necessary to break each portion of a network into segments and each segment could be assigned local or global parameters. The program effectively generated the (x, y, z) co-ordinates at the start and end of each segment. Within a given segment, fittings such as bends and branch take-offs are included.

After tracing the ductwork in AutoMULE, it is necessary to place fittings on the duct system. Refer to Figure 2a and 2b for the choices of the branch take-off and bend fittings. Similar displays, with appropriate engineering and acoustic parameters, are available for all other fittings encountered in mechanical system design.

After placing the fittings, duct type, dimensions, minimum thicknesses and other engineering parameters including acoustic lining, could then be assigned. Each supply or return air system could be saved and stored within the project directory; enabling various design scenarios to be saved or updated, with the appropriate analysis outputs saved in a folder with the AutoMULE drawing. The AutoMULE design tools made it simple to change parameters such as dimensions, bend or fitting type and acoustic lining type, etc.

5. TYPICAL SYSTEMS

For the Theatres on the Bay project some air handling units serviced over 6 levels with more than 200 segments in each of the supply and return air networks. These larger networks were often stored separately, however on smaller systems the supply and return networks could be incorporated in the same file. Segment colour coding was used to differentiate supply and return networks.

Figure 3 shows a typical schematic of a drawing read by AutoMULE. It is straightforward to manipulate. By right clicking the mouse over any segment, the appropriate engineering parameters are identified in a pop-up window and changed if necessary.

6. ANALYSIS USING THE COGEN TOOL

After running the ACADS Fortran analysis program, the text file results (*.out files) are saved and then imported into a customized Excel file, COGEN. COGEN incorporates numerous macros which sort and arrange the results. The display windows include details on all supply and return ducts, fittings and terminals.

The COGEN file presents the results in a user and printer friendly format as shown in Figure 5. The trace section is used to output the results for a given network ie. one identified as having a high noise level. The results display the sound power at each terminal based on 3 parameters, the sound power (at the terminal) due to the fan, the total sound power at the outlet excluding the terminal noise and the sound power generated by the terminal itself. After viewing the summary results, a trace can be conducted to any terminal to identify any excesses within that network.

Figures 4 and 5 show the results from a typical analysis. Figure 4 shows the summary output for a number of terminals. The sound level excluding the terminal at a given outlet is also presented. Figure 5 shows the detailed analysis for terminal 18. The analysis is conducted across all frequency bands and presented so that the progressive analysis is easily traced and understood.

In summary, the user can trace system noise from the fan to any outlet and present the results in a sequential order. Noise generated at fittings, plus any duct attenuation is calculated at the end of each segment allowing a running total to be accumulated and followed. This is a very useful tool for noise source identification. By tracing through the analysis, the point at which excess noise is generated can be observed (refer Figure 5).

The duct velocity and pressure drop across any segment (which might include fittings) is also presented. A noisy section or fitting can then be revised or modified to reduce noise levels. This is then confirmed by repeating the analysis; with a typical run time of 40-60s.

The program calculates in both directions, so noise generated at a supply (or return) terminal is propagated upstream and added to the sum in each segment. The detailed output gives the direct and reverberant sound pressure individually, as well as the total sound level. In this way key external parameters such as distance, number of terminals per AHU system and room characteristics (volume/room/absorption) can be entered as global parameters and used in all analyses.

7. VALIDATION

A recent film studio project in Melbourne was used to validate the prediction technique. When noise measurements were conducted prior to the opening of the Theatres on the Bay, the results were affected by light fitting and terminal noise. Given that the design targets were so low, it was difficult to identify the noise contribution from mechanical services systems. However, ambient measurements conducted in 5 sound stages with the mechanical services systems operating were found to be significantly below the required level of NR25 at 50% flow (“film” mode). With supply air operating individually the results of the analysis (in NR) are presented in Table 1.

Table 1
Summary of studio measurements

Flow	50%	50%	100%	100%
Studio 1	NR 15	NR 11	NR 30	NR 24
Studio 2	NR 15	NR 18	NR 29	NR 27
Studio 3	NR 15	NR 14	NR 27	NR 28
Studio 4	NR 18	NR 17	NR 30	NR 27
Studio 5	NR 19*	NR 15	NR 27*	NR 18
	measured	predicted	measured	predicted

*Note: affected by external noises

This analysis indicates good agreement between the predicted and measured noise levels, given the system complexity, the variability of the parameters and the need for cost-effective analysis.

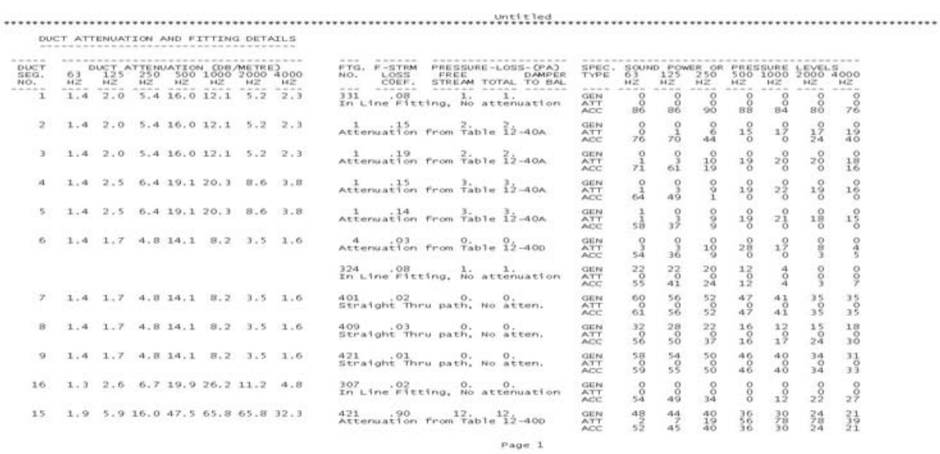
8. SUMMARY

The complexity of AHU networks and the superior method of analysis along with the output results, enables induct noise problems to be rapidly identified and rectified at the design stage. Given the time lines involved in complex Performing Art Centre projects and the need to keep track of ever changing designs, this system has proven itself to be effective and powerful in analysing and confirming mechanical services noise levels in critical environments.

9. ACKNOWLEDGEMENTS

Thanks are given to Peter Holmes who developed the COGEN program and to Murray Mason of ACADS-BSG, to Desmond Hill of Penta Ocean Construction Co, Ltd and Charles Grundy of MAE Engineering Ltd.

Figure 1: *Fortran Output*



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                                                              Untitled
*****************************************************************************************************************
    DUCT ATTENUATION AND FITTING DETAILS
    ------------------------------------

 -----  -----------------------------------   ---  ------  --------------------  -------------------------------------
 DUCT        DUCT ATTENUATION (DB/METRE)      FTG. F-STRM  PRESSURE-LOSS-(PA)    SPEC. SOUND POWER OR PRESSURE LEVELS
 SEG.   63   125  250  500 1000 2000 4000     NO.   LOSS    FREE        DAMPER   TYPE  63   125  250  500 1000 2000 4000
 NO.    HZ   HZ   HZ   HZ   HZ   HZ   HZ            COEF.  STREAM TOTAL TO BAL         HZ   HZ   HZ   HZ   HZ   HZ   HZ
 -----  ---- ---- ---- ---- ---- ---- ----     ---  ------  ------ ----- ------        ---- ---- ---- ---- ---- ---- ----
   1    1.4  2.0  5.4 16.0 12.1  5.2  2.3     331    .08     1.    1.            GEN    0    0    0    0    0    0    0
                                              In Line Fitting, No attenuation    ATT    0    0    0    0    0    0    0
                                                                                 ACC   86   86   90   88   84   80   76

   2    1.4  2.0  5.4 16.0 12.1  5.2  2.3       1    .15     2.    2.            GEN    0    0    0    0    0    0    0
                                              Attenuation from Table 12-40A      ATT    0    1    6   15   17   17   19
                                                                                 ACC   76   70   44    0    0   24   40

   3    1.4  2.0  5.4 16.0 12.1  5.2  2.3       1    .19     2.    2.            GEN    0    0    0    0    0    0    0
                                              Attenuation from Table 12-40A      ATT    1    3   10   19   20   20   18
                                                                                 ACC   71   61   19    0    0    0   16

   4    1.4  2.5  6.4 19.1 20.3  8.6  3.8       1    .15     3.    3.            GEN    0    0    0    0    0    0    0
                                              Attenuation from Table 12-40A      ATT    1    3    9   19   22   19   16
                                                                                 ACC   64   49    1    0    0    0    0

   5    1.4  2.5  6.4 19.1 20.3  8.6  3.8       1    .14     3.    3.            GEN    1    0    0    0    0    0    0
                                              Attenuation from Table 12-40A      ATT    1    3    9   19   21   18   15
                                                                                 ACC   58   37    9    0    0    0    0

   6    1.4  1.7  4.8 14.1  8.2  3.5  1.6       4    .03     0.    0.            GEN    0    0    0    0    0    0    0
                                              Attenuation from Table 12-40D      ATT    3    3   10   28   17    8    4
                                                                                 ACC   54   36    9    0    0    3    5

                                              324    .08     1.    1.            GEN   22   22   20   12    4    0    0
                                              In Line Fitting, No attenuation    ATT    0    0    0    0    0    0    0
                                                                                 ACC   55   41   24   12    4    3    7

   7    1.4  1.7  4.8 14.1  8.2  3.5  1.6     401    .02     0.    0.            GEN   60   56   52   47   41   35   35
                                              Straight Thru path, No atten.      ATT    0    0    0    0    0    0    0
                                                                                 ACC   61   56   52   47   41   35   35

   8    1.4  1.7  4.8 14.1  8.2  3.5  1.6     409    .03     0.    0.            GEN   32   28   22   16   12   15   18
                                              Straight Thru path, No atten.      ATT    0    0    0    0    0    0    0
                                                                                 ACC   56   50   37   16   17   24   30

   9    1.4  1.7  4.8 14.1  8.2  3.5  1.6     421    .01     0.    0.            GEN   58   54   50   46   40   34   31
                                              Straight Thru path, No atten.      ATT    0    0    0    0    0    0    0
                                                                                 ACC   59   55   50   46   40   34   33

  16    1.3  2.6  6.7 19.9 26.2 11.2  4.8     307    .02     0.    0.            GEN    0    0    0    0    0    0    0
                                              In Line Fitting, No attenuation    ATT    0    0    0    0    0    0    0
                                                                                 ACC   54   49   34    0   12   22   27

  15    1.9  5.9 16.0 47.5 65.8 65.8 32.3     421    .90    12.   12.            GEN   48   44   40   36   30   24   21
                                              Attenuation from Table 12-40D      ATT    2    7   19   56   78   78   39
                                                                                 ACC   52   45   40   36   30   24   21

                                                        Page 1
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Figure 3: *AutoMULE schematic file*

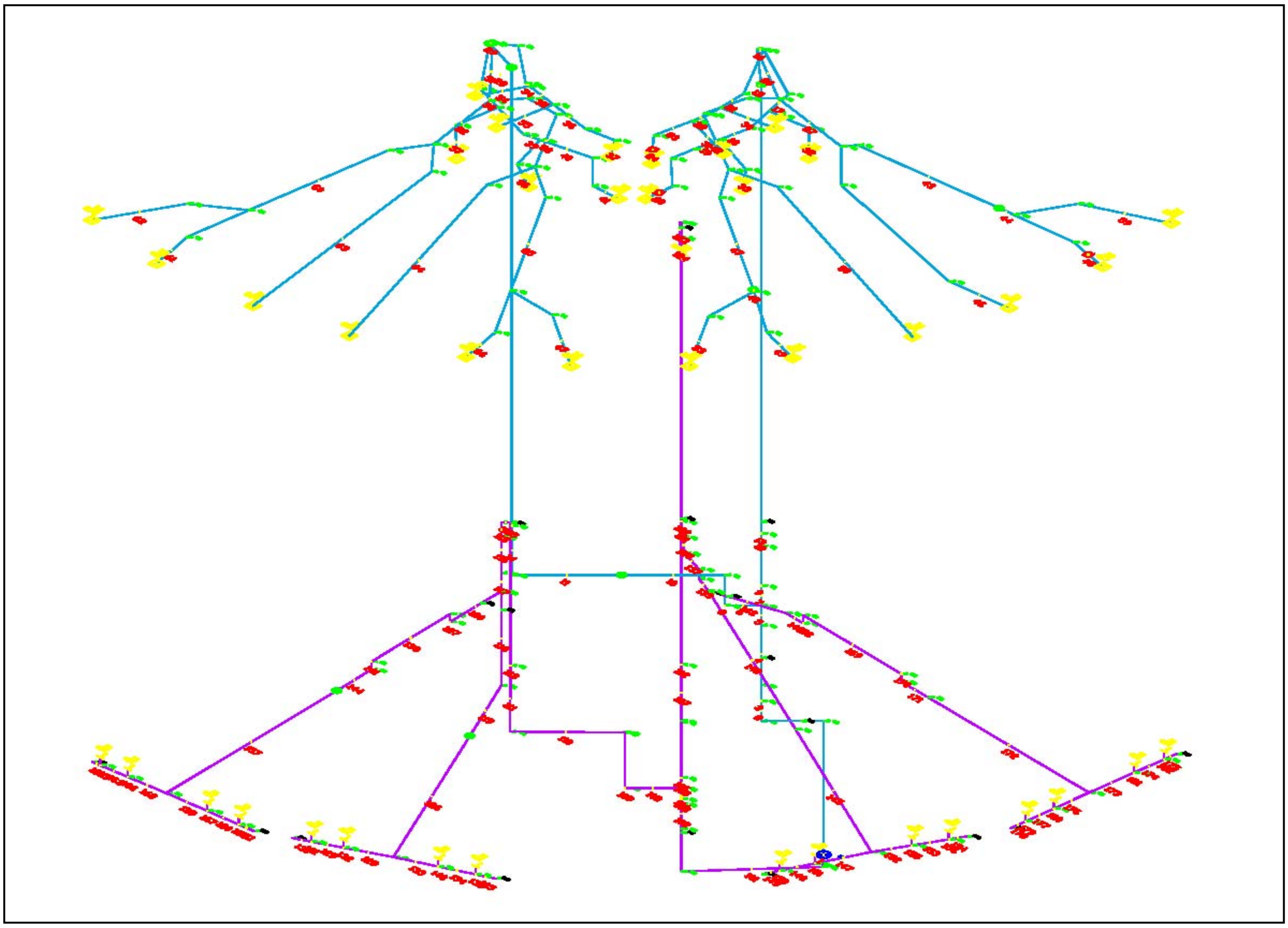

Figure 2a: *ACADS Bend Selection Tables*

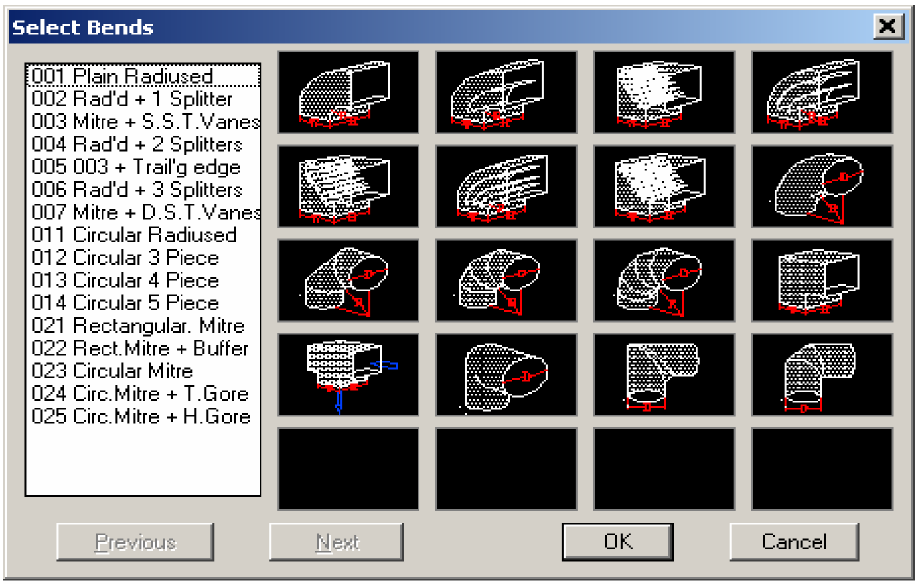

Figure 2b: *ACADS Divided Flow Selection Tables*

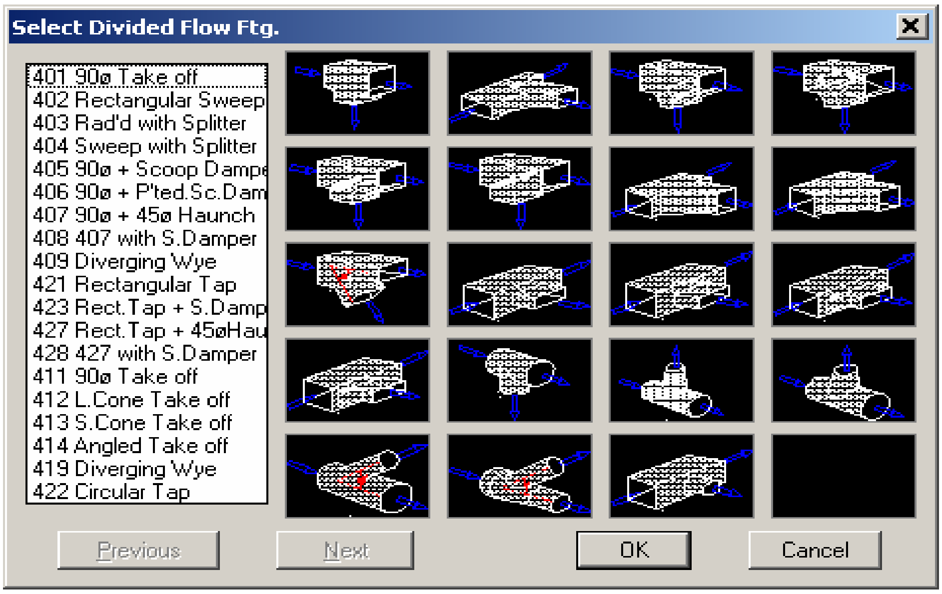

Figure 4: *Terminal summary Page Sample*

Identifying Code	segment no.	terminal no.	terminal type	air quant l/s	NR level	neck velocity m/s	total PD Pa	Damper OBP Pa
STERM	16		REG	475	34	1.5	32	12
STERM	17		REG	139	17	1.5	15	5
STERM	12		REG	139	29	1.5	33	23
STERM	18		REG	139	14	1.5	10	0
STERM	14		REG	139	14	1.5	11	1

Identifying	segment	Lw due to terminal						
Code	no.	63	125	250	500	1000	2000	4000
STERM	16	36	39	41	41	33	25	17
STERM	17	26	28	30	25	17	10	2
STERM	12	31	34	36	36	28	20	12
STERM	18	23	25	27	20	12	4	0
STERM	14	23	25	27	20	12	4	0

Identifying	segment	Lw due to fan						
Code	no.	63	125	250	500	1000	2000	4000
STERM	16	21	0	0	0	0	0	0
STERM	17	18	0	0	0	0	0	0
STERM	12	25	4	0	0	0	0	0
STERM	18	27	0	0	0	0	0	0
STERM	14	25	0	0	0	0	0	0

Identifying	segment	Lw without terminal						
Code	no.	63	125	250	500	1000	2000	4000
STERM	16	40	31	0	0	0	0	0
STERM	17	35	21	3	2	2	0	0
STERM	12	39	36	20	0	0	2	12
STERM	18	36	26	5	0	0	0	0
STERM	14	35	30	12	0	0	0	10

Figure 5: *COGEN Output Summary*

Job:	Theatres on the Bay, Singapore		MARSHALL DAY ACOUSTICS
Title:		Date:	
		Initials PRH	
Job No:	0016		
Filename:	ahuchpll.amx	Cogen: V1.9.8	Detailed analysis - Supply terminal 18

Identifying Code	Segment Number	Length	63	125	250	500	1000	2000	4000	8000	Type	PD (Pa)	Vel m/s	Quant l/s	Fitting Type
FAN			86	86	90	88	84	80	76	76		106		1031	
SFITT	1		0	0	0	0	0	0	0	0	GEN	1			331- Plane symmetric diffuser at fan
			0	0	0	0	0	0	0	0	ATT				
			86	86	90	88	84	80	76	76	ACC				
SDUCT	1	7.5	0	0	0	0	0	0	0	0	ATT	4	4.3	1031	600x400mm duct
SFITT	2		0	0	0	0	0	0	0	0	GEN	2			1- Rectangular radius bend
			0	1	6	15	17	17	19	19	ATT				
			76	70	44	0	0	24	40	40	ACC				
SDUCT	2	2.8	0	0	0	0	0	0	0	0	ATT	3	4.3	1031	600x400mm duct
SFITT	3		0	0	0	0	0	0	0	0	GEN	2			1- Rectangular radius bend
			1	3	10	19	20	20	18	18	ATT				
			71	61	19	0	0	0	16	16	ACC				
SDUCT	3	4.4	0	0	0	0	0	0	0	0	ATT	4	4.3	1031	600x400mm duct
SFITT	4		0	0	0	0	0	0	0	0	GEN	3			1- Rectangular radius bend
			1	3	9	19	22	19	16	16	ATT				
			64	49	1	0	0	0	0	0	ACC				
SDUCT	4	3.9	0	0	0	0	0	0	0	0	ATT	6	5.7	1031	600x300mm duct
SFITT	5		1	0	0	0	0	0	0	0	GEN	3			1- Rectangular radius bend
			1	3	9	19	21	18	15	15	ATT				
			58	37	9	0	0	0	0	0	ACC				
SDUCT	5	0.7	0	0	0	0	0	0	0	0	ATT	3	5.7	1031	600x300mm duct
SFITT	6		0	0	0	0	0	0	0	0	GEN	0			4- Rect radius - two splitters
			3	3	10	28	17	8	4	4	ATT				
			54	36	9	0	0	3	5	5	ACC				
SFITT	6		22	22	20	12	4	0	0	0	GEN	1			324- Single blade fire damper
			0	0	0	0	0	0	0	0	ATT				
			55	41	24	12	4	3	7	7	ACC				
SDUCT	6	3.2	0	0	0	0	0	0	0	0	ATT	1	3.4	1031	600x500mm duct
SFITT	10		53	49	45	40	34	28	28	28	GEN	22			401- Rect 90° take-off
			0	2	6	16	22	20	15	15	ATT				
			58	51	45	40	34	28	28	28	ACC				
SDUCT	10	0.3	0	0	0	0	0	0	0	0	ATT	23	4.6	278	400x150mm duct
SFITT	11		21	14	8	5	8	11	14	14	GEN	0			401- Rect 90° take-off
			0	0	0	0	0	0	0	0	ATT				
			50	44	38	26	16	16	21	21	ACC				
SDUCT	11	0.5	0	0	0	0	0	0	0	0	ATT	1	2.3	139	400x150mm duct
SFITT	13		0	0	0	0	0	0	0	0	GEN	0			1- Rectangular radius bend
			0	2	4	12	17	13	8	8	ATT				
			49	40	28	0	0	0	5	5	ACC				
SDUCT	13	0.4	0	0	0	0	0	0	0	0	ATT	1	2.3	139	400x150mm duct
SFITT	18		0	0	0	0	0	0	0	0	GEN	0			1- Rectangular radius bend
			0	2	5	14	19	16	10	10	ATT				
			49	36	19	0	0	0	0	0	ACC				
SDUCT	18	1.0	0	0	0	0	0	0	0	0	ATT	11	2.3	139	400x150mm duct
STERM	18		23	25	27	20	12	4	0	0		10	1.5	139	Sound power from terminal
			27	0	0	0	0	0	0	0					Sound power from fan
			36	26	5	0	0	0	0	0					Sound power excluding terminal
			36	**29**	**27**	**20**	**12**	**4**	**0**	**0**					Total sound power from terminal

	63	125	250	500	1000	2000	4000	8000
Distance to listener	-11	-11	-11	-11	-11	-11	-11	-11
Directivity	3	4	5	6	7	8	8	0
Direct sound pressure level	28	22	21	15	8	1	-3	-11
Room correction	-28	-28	-28	-28	-28	-28	-28	-28
Number of terminals - 5	7	7	7	7	7	7	7	7
Reverberant sound pressure level	15	8	6	-1	-9	-17	-21	-21
Noise criteria	36	22	13	8	5	3	3	3
Total sound pressure level	28	22	21	15	8	1	-3	-11

1031	Total air quantity
139	Terminal air quantity
57	Total pressure drop
106	Total fan pressure
0.093	Terminal area
1	Distance to listener
M	Directivity
5	Number of terminals
2415	Room constant
N-1	Noise criteria