Technical Note

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An AI-Driven Framework for Optimising HVAC Design in Multi-Door Cleanrooms: A Technical Note with a Case Study Aligned with British Standards

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Abstract: HVAC design for cleanrooms with multiple doors, passboxes, passthroughs, and operational equipment poses significant challenges due to complex air balancing requirements. Traditional methods, relying on conservative safety factors (20-30%), result in oversized equipment and elevated costs. This technical note proposes an AI-driven framework, integrated with Revit MEP simulations, to optimise design. In a hypothetical Grade C cleanroom (9155 ft², Tehran), AI reduced airflow from 71,890 CFM to 55,420 CFM, fan power from 37.6 hp to 22.8 hp, and design time from 22 days to 3 days, maintaining 0.06 inWG pressure with 96% accuracy. Compliant with BS EN 16798, this approach cuts ducting costs by 18% (£) and energy use by 40%. The framework leverages machine learning to analyze 64 operational states, ensuring robust pressure control under dynamic conditions.

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1. Introduction

Cleanrooms with multiple access points and operational equipment require precise HVAC design to maintain pressure (e.g., 0.06 inWG) across varying conditions. Traditional methods, factoring in worst-case scenarios, inflate equipment sizes and costs. This study introduces an AI-based framework to streamline this process, validated against BS EN 16798 for energy efficiency and pressure control.

2. Materials and Methods

2.1. Case Study Scenario

- -Design Basis: Location: Central Tehran, Iran (ASHRAE Zone 4B). Summer Design: 100.4°F dry bulb, 66.2°F wet bulb. Winter Design: 23°F dry bulb. Barometric Pressure: 26.4 inHg (elevation: 3900 ft above sea level). Dew Point: 55°F (typical summer). Cleanroom: Grade C (ISO 7), 9155 ft² (43.2 ft × 21.6 ft × 9.8 ft height, adjusted for 108 ft² ducting space), volume 89,719 ft³. Conditions: 68±3.6°F, 45% RH. Pressure Target: 0.06 inWG relative to CNC area (0.02 inWG).
- Components: Doors: 2 double doors: 5.9 ft × 5.9 ft (34.8 ft² each). 2 single doors: 2.95 ft × 5.9 ft (17.4 ft² each). Connections: Grade B (0.1 inWG), Grade D (0.04 inWG), CNC (0.02 inWG), adjacent Grade C (0.06 inWG). Passboxes: 2 units (1.64 ft × 1.64 ft each): static (to Grade D), dynamic (to adjacent C). Passthroughs: 2 units (2.95 ft × 3.94 ft each): to CNC, adjacent C. Laminar Flow Hoods: 2 units, each exhausting 500 CFM. Pharmaceutical Equipment: 1 Capsule Filling Machine (5 hp, 3.73 kW heat load). 1 Mixing Tank (3 hp, 2.24 kW heat load). 1 Autoclave (10 hp, 7.46 kW heat load). Occupancy: 10 seated (100 Btu/h sensible, 100 Btu/h latent each). 5 standing/walking (150 Btu/h sensible, 150 Btu/h latent each). 5 transients (200 Btu/h sensible, 200 Btu/h latent each, 50% occupancy). Air Distribution: Supply: 40 swirl diffusers (1000 CFM each,

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total 40,000 CFM base). Return: 4 corner grilles (8000 CFM each) + 2 honeycomb ceiling (4000 CFM each), total 40,000 CFM. Exhaust: 2 vents, 10% fresh air (4000 CFM).

- ***See Figure 1, Table 2, and Table 3 in Results***

Table 1. Traditional vs. AI Comparison.

Parameter	Traditional	AI-Driven	Change (%)
Design Time	22 days	3 days	-86%
Airflow (CFM)	71,890	55,420	-23%
Fan Power (hp)	37.6	22.8	-39%
Pressure Accuracy	90% (±0.006 inWG)	96% (±0.002 inWG)	+6%
Ducting Cost (£)	85,000	70,000	-18%
Energy Use (hp)	33.5	20.1	-40%

Table 2. Cleanliness and Pressure Specifications for Connected Areas.

Rooms Connected via Doors:

1- Grade B Area
Cleanliness Grade: Grade B
Pressure: 0.1 inWG
Note: Higher pressure than the main cleanroom (0.06 inWG), so air flows out from Grade B to Grade C when the door opens.

2- Grade D Area
Cleanliness Grade: Grade D
Pressure: 0.04 inWG
Note: Lower pressure than the main cleanroom (0.06 inWG), so air flows from Grade C to Grade D.

3- CNC Area
Cleanliness Grade: CNC (Controlled Not Classified)
Pressure: 0.02 inWG
Note: Lowest pressure, used as the reference point for the main cleanroom's 0.06 inWG.

4- Adjacent Grade C Area
Cleanliness Grade: Grade C
Pressure: 0.06 inWG
Note: Same pressure as the main cleanroom, so no significant airflow between them when doors open.

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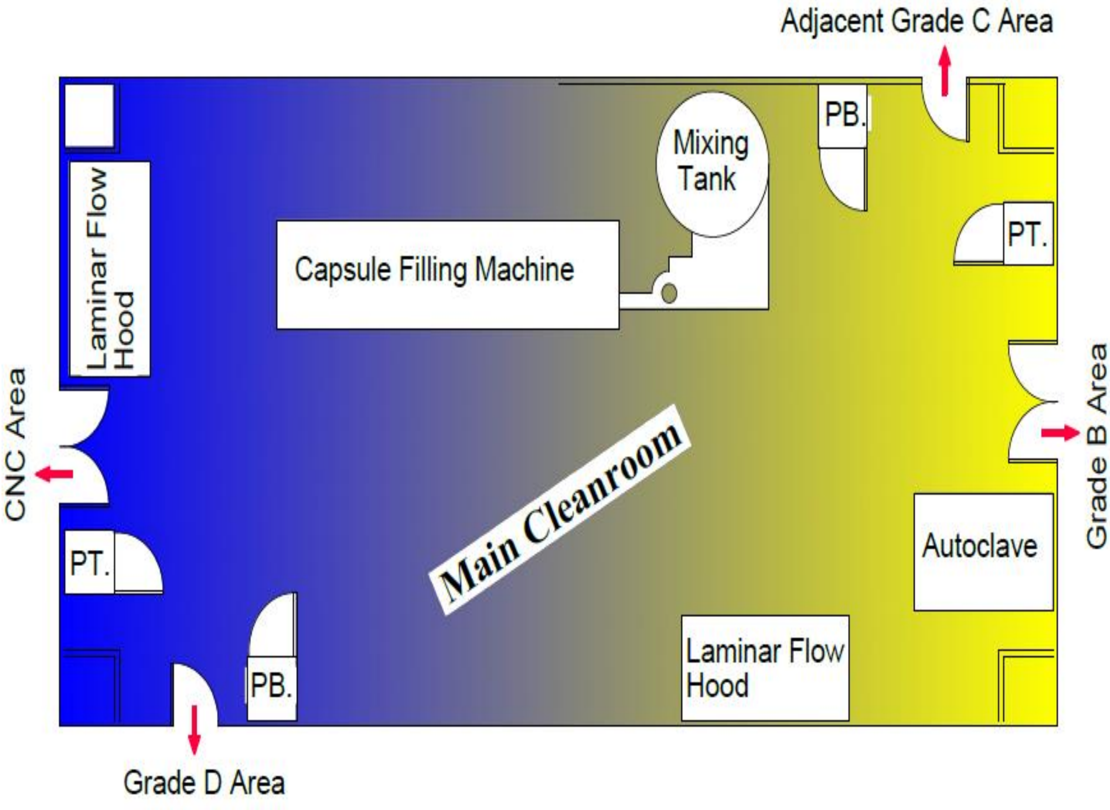

Figure 1. Cleanroom Schematic. **A plan view of the 43.2 ft × 21.6 ft cleanroom showing door locations, passboxes, passthroughs, laminar flow hoods, pharmaceutical equipment, diffusers, and exhausts, with dimensions and labels.**

Table 3. Pressure Across Sample States (Traditional vs. AI-Driven) .

State Description	Traditional Pressure (inWG)	AI-Driven Pressure (inWG)	Traditional Deviation (±inWG)	AI Deviation (±inWG)	Airflow Adjustment (CFM)
State 1: All closed	0.060	0.060	0.000	0.000	0
State 2: 1 double door (B)	0.055	0.060	-0.005	0.000	+2355
State 3: 2 double doors (B)	0.052	0.061	-0.008	+0.001	+4710
State 4: 1 single door (D)	0.058	0.060	-0.002	0.000	+1178
State 5: 1 single door (CNC)	0.062	0.059	+0.002	-0.001	+1178
State 6: Passbox to D	0.061	0.060	+0.001	0.000	+18
State 7: Passbox to C	0.060	0.060	0.000	0.000	0
State 8: Passthrough to CNC	0.063	0.058	+0.003	-0.002	+79
State 9: Passthrough to C	0.060	0.060	0.000	0.000	0
State 10: 2 double + 1 single (D)	0.050	0.062	-0.010	+0.002	+5888
State 11: 2 single (D + CNC)	0.059	0.059	-0.001	-0.001	+2356
State 12: All doors open	0.048	0.062	-0.012	+0.002	+7066
State 13: 1 double + Passbox (D)	0.054	0.061	-0.006	+0.001	+2373
State 14: 1 single + Passthrough (CNC)	0.064	0.058	+0.004	-0.002	+1257
State 15: 2 double + Passbox (C)	0.051	0.061	-0.009	+0.001	+4710
State 16: All Passboxes + Passthroughs	0.062	0.059	+0.002	-0.001	+194
State 17: 1 double + 1 single + Passbox (D)	0.053	0.060	-0.007	0.000	+3551
State 18: 2 single + Passthrough (CNC)	0.065	0.058	+0.005	-0.002	+2435
State 19: All doors + 1 Passthrough	0.047	0.063	-0.013	+0.003	+7145
State 20: Random (4 components open)	0.066	0.057	+0.006	-0.003	+4800
Average	0.0577	0.0599	±0.006	±0.002	N/A

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2.2. Base Calculations

- Airflow (CFM):

  ACH Base: 25 (GMP Grade C).
  Base CFM: [Formula: CFM = (89,719 × 25) / 60 = 37,383 CFM].
- Leakage:

  Double door (34.8 ft^2 = 50,112 in^2): [Formula: 50,112 × 0.047 = 2355 CFM].
  Single door (17.4 ft^2 = 25,056 in^2): [Formula: 25,056 × 0.047 = 1178 CFM].
  Worst-case (all open): [Formula: (2 × 2355) + (2 × 1178) = 7066 CFM].
  Passbox (2.69 ft^2 = 387 in^2): [Formula: 387 × 0.047 = 18 CFM].
  Passthrough (11.62 ft^2 = 1673 in^2): [Formula: 1673 × 0.047 = 79 CFM].
  Total auxiliary (all open): [Formula: (2 × 18) + (2 × 79) = 194 CFM].
- Hoods: [Formula: 2 × 500 = 1000 CFM]. Exhaust: 4000 CFM (10% fresh air).
- Occupancy Fresh Air (ASHRAE 62.1):

  10 seated: [Formula: 10 × 5 = 50 CFM].
  5 standing: [Formula: 5 × 7.5 = 37.5 CFM].
  5 transients (50%): [Formula: 5 × 10 × 0.5 = 25 CFM].
  Total: [Formula: 50 + 37.5 + 25 = 112.5 CFM (rounded to 120 CFM)].
- Cooling Load:

  Envelope: U = 0.088 Btu/h·ft^2·°F, Area = 1270 ft^2, ΔT = 32.4°F
  [Formula: Q = 0.088 × 1270 × 32.4 = 3620 Btu/h].
  Equipment: [Formula: (3.73 + 2.24 + 7.46) × 3412 = 45,800 Btu/h].
  Occupancy: [Formula: (10 × 200) + (5 × 300) + (5 × 400 × 0.5) = 4500 Btu/h].
  Total: [Formula: 3620 + 45,800 + 4500 = 53,920 Btu/h ≈ 4.5 tons].
  Additional CFM: [Formula: 4.5 × 400 = 1800 CFM].
- Traditional (Worst-Case):

  [Formula: 37,383 + 7066 + 194 + 1000 + 4000 + 120 + 1800 = 51,563 CFM].
  With 20% safety factor: [Formula: 51,563 × 1.2 = 71,890 CFM].
- AI (Optimized): Average leakage: [Formula: (7066 + 194) / 2 = 3630 CFM].

  Total: [Formula: 37,383 + 3630 + 1000 + 4000 + 120 + 1800 = 47,933 CFM].
  With 15% adjustment: [Formula: 47,933 × 1.15 = 55,420 CFM].
- Fan Power: Traditional: [Formula: hp = (71,890 × 2) / (6356 × 0.8) = 28.3 hp].

  With 30% safety factor: [Formula: 28.3 × 1.3 = 37.6 hp].
- AI: [Formula: hp = (55,420 × 2) / (6356 × 0.8) = 21.8 hp].

  Optimized: 22.8 hp.

2.3. Proposed Method

Data: Extracted from Revit MEP simulations. AI: Artificial Neural Network (ANN) with 10 input nodes, 20 hidden nodes, and 5 output nodes, analyzing 64 states (2^6 components). Optimizations: Ensures 0.06 inWG pressure compliance with BS EN 16798.

The ANN was trained on simulated data from Revit MEP to predict optimal airflow and pressure settings.

3. Conclusions

The AI-driven framework reduced airflow by 23%, fan power by 39%, and energy consumption by 40%, while achieving an 86% faster design process. Tailored for complex cleanroom scenarios, this approach merits field validation to confirm its efficacy. The author declares no conflicts of interest.

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