Enhancing cognitive governance, lifelong-learning, and indoor air problem-solving competency through mass-balance models

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ENHANCING COGNITIVE GOVERNANCE, LIFELONG-LEARNING, AND INDOOR AIR PROBLEM-SOLVING COMPETENCY THROUGH MASS-BALANCE MODELS



The developed mass-balance models and health-risk equations provided the mental model: the relevant variables to consider, their connections, interactions and influence on outcomes of interest. The mental model, together with information gathered through walkthrough investigations, measurements, record reviews, interviews and surveys, guided questioning to enhance cognitive abilities and support continuous and self-directed learning. The resulting experience from the learning refined the mental model, which in turn guided further questioning and learning. This iterative process of developing and refining experience and the mental model supported sound judgement, informed decisions and actions for value-oriented problem diagnosis and solving.

*Experience includes knowledge, understanding and skills

1 Core Idea: Source versus Removal

$$\frac{dC}{dt} = S - KC(t)$$

- dC/dt: How quickly pollutant concentration increases or decreases at a particular moment.
- S: Pollutant source strength, representing the amount of pollutant introduced per unit room volume per unit time.
- K: Pollutant sink strength, representing how effectively pollutants are removed from the indoor air.
- C(t): Pollutant concentration at a particular time.
- KC(t): The rate of pollutant removal per unit room volume at that moment.

- If S > KC(t), pollutant concentration increases.
- If S < KC(t), pollutant concentration decreases.
- If S = KC(t), concentration remains unchanged at that moment.
- The concentration at time t is determined by the concentration left over from the initial concentration, together with the accumulated increases or decreases caused by S and K. (See point 4 below).
- If S=KC(t), concentration does not change at the moment.

2 No source present: Decay from an initial concentration

$$C(t) = C_0 e^{-Kt}$$

- C_0 = The starting concentration (initial level at t =0).
- When no new pollutant is added and removal (K) remains active, the concentration decreases exponentially over time *t* because pollutants are continuously removed, with the amount removed per unit time depending on the concentration remaining. This assume K is constant.

3 Continuous indoor source and steady state

$$C(t) + C_{ss}e^{-Kt} = C_{ss}$$

$$C(t) = C_{ss}(1 - e^{-Kt})$$

$$C_{ss} = \frac{S}{K}$$

$$S = \frac{Source\ emission\ rate\ (G)}{Volume\ (V)}$$

$$K = K_v + K_f + K_d + K_a + K_{others}$$

- C_{ss}: The long-term steady state concentration (the level the concentration approaches).
- C(t) represented the pollutant concentration already accumulated at time t, while $C_{ss}e^{-Kt}$ represented the remaining increase needed to reach steady state, i.e., the remaining gap between the current concentration at time t and concentration at steady state C_{ss}. As C(t) increased, the remaining difference decreased, causing the concentration to increase progressively more slowly as it approached steady state.
- Indoor pollutant sources could include inanimate objects, living organisms and their activities, and chemical reactions occurring in indoor air or on indoor surfaces. K_v, K_f, K_d, K_a and K_{other} represented the coefficients associated with ventilation, filtration, deposition, adsorption and other applicable pollutant removal processes, respectively.

4 When conditions change at time t_1

$$C(t) = C_0 e^{-Kt}, \qquad 0 \le t < t_1$$

$$C_1 = C_0 e^{-Kt_1}$$

$$C(t - t_1) = C_1 e^{-K(t-t_1)} + C_{ss}\left(1 - e^{-K(t-t_1)}\right)$$

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- C_1 represented the pollutant concentration remaining at the moment the new source became active. At that instant, the newly introduced source had not yet affected the indoor pollutant concentration because pollutant generation had only just begun.
- For $t \ge t_1$, assuming constant source strength and removal conditions after introduction. This means that the contribution from the existing pollutant concentration gradually decreased due to removal processes towards zero, while the contribution from the newly activated source gradually increased towards its C_{ss}, with both contributions jointly determining the total indoor pollutant concentration over elapsed time ($t-t_1$).

5 Ventilation and filtration removal

$$K_v = \frac{Q_v}{V}$$

$$K_f = \frac{CADR}{V}$$

$$CADR = Q_f \times \varepsilon_f$$

- Q_v represented the outdoor airflow rate (m³/h), and V represented the indoor air volume (m³). CADR represented the clean air delivery rate (m³/h). All coefficients (K) were expressed in h^{-1}.
- Q_f represented the airflow rate passing through the air-cleaning device (m³/h), while ε_f represented its fractional pollutant removal efficiency (0–1).

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Note: In this training, equations support mathematical reasoning and scientific understanding without requiring computation.

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Our research findings revealed a professional competency gap associated with inadequate scientific mental models, cognitive governance and independent learning capability. Compared with equally comprehensive non-equation-guided training, mass-balance and health-risk equation-guided training produced significantly better immediate performance in scientific mental models, cognitive governance and professional competency. At six months, statistically significant advantages were evident across all four capabilities. Despite performance declines and missing-data uncertainty, the findings supported its educational value in developing sustainable and transferable competency for value-oriented diagnosis and solving of unfamiliar real-life IAQ problems across building types.

6 Indoor source and outdoor source entry

$$\frac{dC(t-t_1)}{d(t-t_1)} = S + K_v C_{out} - KC(t-t_1)$$

$$C(t-t_1) = C_1 e^{-K(t-t_1)} + \frac{S + K_v C_{\text{out}}}{K}\left(1 - e^{-K(t-t_1)}\right)$$

$$C_{ss} = \frac{S + K_v C_{\text{out}}}{K}$$

- The contribution of outdoor pollutant entry through ventilation was represented by K_vC_{out}, where K_v denotes the outdoor air-exchange coefficient and C_{out} denotes the outdoor pollutant concentration. This is scientifically correct, assuming that outdoor pollutants enter through ventilation without filtration or other removal before reaching the indoor air.
- $S + K_vC_{out}$ represents the combined pollutant input rate per unit room volume from indoor sources (S) and outdoor pollutants entering through ventilation (K_vC_{out}).
- $KC(t - t_1)$ represented the instantaneous rate at which pollutants were removed from the indoor air, based on the pollutant concentration at the elapsed time ($t - t_1$) since conditions changed at time t_1.

7 When outdoor air entry depends on ventilation and infiltration fractions

$$\frac{dC(t-t_1)}{d(t-t_1)} = S + (\rho_v K_v + \rho_i K_i)C_{out} - KC(t-t_1)$$

$$C(t-t_1) = C_1 e^{-K(t-t_1)} + \frac{S + (\rho_v K_v + \rho_i K_i)C_{out}}{K}\left(1 - e^{-K(t-t_1)}\right)$$

$$C_{ss} = \frac{S + (\rho_v K_v + \rho_i K_i)C_{out}}{K}$$

- ρ_v represented the fraction of outdoor pollutants that entered the indoor air through the ventilation system, after accounting for any filtration losses.
- ρ_i represented the fraction of outdoor pollutants that penetrated through building-envelope gaps and cracks, while K_i represented the infiltration air-exchange coefficient.
- When both ventilation and infiltration were considered, the combined outdoor pollutant input rate per unit room volume was represented by $(\rho_vK_v + \rho_iK_i)C_{out}$.
- K_vC_{out} was recovered when transmission through ventilation was complete ($\rho_v = 1$) and infiltration was negligible ($K_i = 0$).

8 From exposure dose to health-risk assessment

$$E = \sum_{i=1}^{n} C_i \times \Delta t_i \times IR$$

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$$P(Y=1) = \frac{e^{\eta}}{1+e^{\eta}}$$

$$\eta = \beta_0 + \beta_1 E + \beta_2 V + \beta_3 (E \times V) + \gamma Z$$

- E represented the total inhaled pollutant mass (μg), also referred to as the inhalation exposure dose. C_i represented the average pollutant concentration during time interval i (μg/m³), Δt_i represented the duration of that interval (h), IR represented the inhalation rate (m³/h), assumed to remain constant, and n represented the total number of time intervals.
- P(Y = 1) represented the probability of a specified health problem occurring within a defined period, expressed between 0 and 1. η its log-odds of that health problem occurring, E exposure dose, V biological vulnerability, and Z other contributing factors influencing E, V and the health outcome.
- β_0 represented the starting log-odds, while β_1, β_2, β_3 and γ described how much E, V, their combined interaction (E × V), and Z contributed to the log-odds, respectively.

Risk Rating = Likelihood (L) Rating x Severity (S) Rating

- While the L rating is determined by mapping P(Y = 1), the probability of a health problem occurring, to predefined likelihood ranges, the S rating reflects the nature and seriousness of that problem should it occur, indicating the extent to which severity acts as a drag factor pulling the affected person away from their capability to deliver value.
- In everyday industry practice, professionals mentally estimate E from measured C, possible exposure duration and occupant activities influencing IR. They assess V using a five-point vulnerability scale and identify Z through walkthrough investigations, interviews and surveys. Using these findings, they assign a five-point L rating and a five-point S rating based on the seriousness of potential health consequences. They then calculate the Risk Rating, classify the risk as low, tolerable or high, and determine whether control actions are needed and to what extent.

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Fictional Case Story (Audio – available online)– Part 1 (Preface, Ch 1 & Ch 2)

Fictional Case Story (Audio – available online)– Part 2 (Ch 3)

Fictional Case Story (Audio – available online)– Part 3 (Ch 3 cont'd)

Fictional Case Story (Audio – available online) – Part 4 (Ch 3 cont'd)

Fictional Case Story (Audio – available online) – Part 5 (Ch 4)

Fictional Case Story (Audio – available online) – Part 6 (Ch 4 cont'd)

Fictional Case Story (Audio – available online) – Part 7 (Ch 4 cont'd)

Fictional Case Story (Audio – available online) – Part 8 (Ch 5 & Ch 6)

…… Preface ……

Across education, research, professional practice and everyday life, intelligence is often considered sufficient for learning, sound judgement, informed decisions and value-oriented problem diagnosis and solving. Yet intelligent individuals may overlook important circumstances when familiar mental models, unexamined assumptions and confidence in past success discourage questioning. This highlights the need for cognitive governance: the conscious regulation of mental models through questioning to enhance cognitive abilities that guide judgements, decisions and actions towards value-oriented problem diagnosis and solving. Addressing this need requires educational designs that facilitate the development and regulation of mental models through questioning and the application of cognitive abilities, including critical and reflective thinking, logical deduction, abstract reasoning and creative imagination. These processes enable independent learning, a process of using cognitive abilities to transform information into knowledge, understanding and skills that inform judgements, decisions and actions for value-oriented problem diagnosis and solving.

For one intelligent building engineer, personal experiences and doctoral research revealed how inadequate cognitive governance could limit people's independent learning and value-oriented problem diagnosis and solving capabilities. Motivated to address this challenge, she entered academia to develop original scholarly design knowledge, principles and communication solutions aimed at strengthening these capabilities in herself and others. Her public scholarship website became a design laboratory for developing her original contributions and examining the quantity, quality and safety of her scholarly outputs. Meanwhile, her classrooms became living laboratories for assessing the value learners experienced through engagement with her solutions (outcomes) and the change in learners' capability to deliver value to themselves and others, assessed before and after engagement with her educational solutions (impacts). This path demanded intellectual rigour, professional conviction and resilience amid uncertainty. Her journey forms the subject of this fiction story.

…… Chapter 1 ……

Briana Oliveira was a remarkably intelligent young girl. At fifteen, she could understand complicated explanations faster than most of her classmates, remember information after reading it only once and confidently answer questions that others found difficult. Her parents were proud of her academic achievements, while her teachers frequently praised her intelligence. Briana had grown accustomed to being described as exceptionally bright. She believed that intelligence was the most important requirement for learning, making good decisions and solving problems. Whenever she encountered a difficulty, she

expected her intelligence to provide an answer. What she did not know was that her greatest weakness was hidden behind the very intelligence everyone admired.

Her intelligence enabled her to acquire knowledge, understand complex relationships, reason logically and develop solutions. However, cognitive governance required something different: the conscious capability to question, monitor and regulate how she applied her intelligence to particular situations, including recognising limitations in her understanding and opportunities for continuous improvement. Briana possessed the intelligence to undertake these activities but seldom exercised it independently when her conclusions appeared reasonable and received positive validation. She rarely asked herself a fundamental question: “What is it that I do not know or have not considered that could make what I know or propose inappropriate for this particular situation?” Without this questioning, she often failed to recognise the limitations of her existing mental models when confronted with the complexities of unfamiliar real-life problems.

Although Briana could think, question, learn and make decisions, she rarely examined how she arrived at her conclusions. Her intelligence enabled her to find answers quickly, particularly when dealing with familiar academic problems, but she seldom questioned her assumptions, considered alternative explanations or recognised gaps in her understanding. In many situations, her intelligence enabled her to make reasonable decisions that appeared to deliver value, even when better decisions might have been possible. However, the consequences of her decisions were seldom systematically examined to establish whether the intended value had actually been achieved or whether greater value could have been delivered.

The concern was not that her decisions were imperfect, since no human decision could be guaranteed to be perfect. Rather, Briana often regarded her decisions as sufficiently correct and appropriate to require no further questioning, especially when her intelligence and the approval of others reinforced her confidence. Unlike someone with stronger cognitive governance, who would continue questioning what might have been overlooked, examining possible unintended consequences and seeking opportunities for improvement even when a decision appeared successful, Briana seldom felt the need to do so. Because her approach often produced good academic results, she had little reason to suspect that weaknesses in how she governed her thinking were limiting her lifelong learning and problem diagnosis and solving capabilities. Furthermore, her educational experiences largely rewarded the ability to reproduce expected answers, while her everyday circumstances seldom demanded accountability for the quality and consequences of her judgements and decisions. Consequently, neither Briana nor those around her had sufficient reason to question the contextual adequacy of her thinking or recognise the weakness concealed by her intelligence and apparent success.

Briana’s weakness rarely appeared during ordinary classroom lessons. She could remember scientific definitions, apply mathematical formulas and reproduce explanations

accurately. Most classroom questions provided the information needed to arrive at expected answers, allowing her to succeed without independently questioning whether her understanding was sufficient or contextually appropriate. When confronted with unfamiliar problems, she usually selected the first explanation that appeared reasonable and proceeded towards a solution. She considered hesitation a sign of inadequate knowledge and questioning an unnecessary delay. Her teachers often rewarded correct answers without examining the assumptions behind her reasoning or whether alternative explanations had been considered.

Consequently, Briana's academic success continued to reinforce her confidence in a way of thinking that worked well for familiar questions but was less effective when the problem itself required investigation. Furthermore, because the consequences of her judgements and decisions were seldom examined beyond the correctness of expected answers, she received little feedback about what she might have overlooked or how she could improve. She was learning information and successfully applying it to familiar problems without sufficiently developing the capability to question, refine and adapt her understanding to unfamiliar, complex real-life situations.

When Briana was fifteen, her aunt operated a small neighbourhood grocery shop that had served local families for many years. Briana enjoyed helping there during school holidays, particularly when her aunt complained about the difficulties of managing customer orders, stock availability and long queues. Briana quickly recognised opportunities to improve the business. She examined sales records, identified frequently purchased products and designed a simple digital ordering system that allowed customers to reserve groceries before visiting the shop. She also recommended adjusting opening hours to concentrate staff availability during periods of greater demand. Her aunt was delighted by the improvements. Customers who used the new system spent less time waiting, unsold stock decreased and the shop became more profitable. Briana's recommendations were sensible, practical and demonstrably beneficial. Her aunt proudly told friends and neighbours that her brilliant niece had transformed the business. Briana was pleased, not merely because she had helped her aunt, but because the experience confirmed what she already believed about herself: her intelligence enabled her to recognise problems and develop effective solutions.

Over the following months, the shop continued to perform well financially. Briana occasionally examined the sales records and found further evidence that her recommendations had been successful. She did not, however, question whether the available records represented the experiences of all the people who depended on the shop. Some older customers had difficulty using the digital ordering system, while others had previously relied on the earlier opening hours to purchase groceries before attending work or fulfilling family responsibilities. A few began shopping elsewhere, sometimes at greater inconvenience or expense. These changes were not immediately apparent because the business continued attracting customers, and its financial performance

remained strong. The customers who benefited from the changes expressed their satisfaction, while those who experienced difficulties gradually disappeared from the shop's daily activities. Their absence was not recorded as a problem requiring investigation. Briana's aunt was reasonably satisfied with the improvements, and there was no established practice of examining whether the changes had created unintended difficulties for customers who no longer visited.

Briana continued helping her aunt whenever she had time. She occasionally introduced further improvements based on the information available to her, and many of these improvements delivered genuine benefits. Yet she rarely questioned whether her understanding of the business adequately represented the needs and circumstances of everyone affected by her decisions. She did not ask what information might be missing from the sales records, whose experiences remained unrepresented or whether the apparent success concealed sacrifices that others were making. Neither did she investigate whether different arrangements might preserve the financial and operational improvements while accommodating customers who had been disadvantaged. Such questions seldom occurred to her because the evidence she examined consistently confirmed that her recommendations were working. Her aunt's appreciation, customers' positive comments and the improved financial performance reinforced her confidence. Briana was not making obviously unreasonable decisions. She was making decisions that delivered real value, but she had no established habit of questioning whether that value could be improved or whether consequences outside her existing understanding were being overlooked. The experience strengthened her belief in her intelligence without revealing the limitations of the mental models through which she interpreted success.

Throughout her remaining years in secondary school, Briana continued to excel academically and help her aunt improve the grocery shop whenever she had the opportunity. Her achievements strengthened her confidence in her intelligence and problem-solving capabilities. Whenever her recommendations produced satisfactory outcomes, she regarded them as confirmation of her understanding. She rarely questioned whether something important had been overlooked or whether greater value could have been achieved. Her teachers, family and friends continued to recognise her achievements, reinforcing her belief that intelligence was sufficient for making good judgements and decisions. By the time she completed secondary school, Briana had developed a strong reputation for intelligence and practical problem solving. However, she had seldom encountered situations in which she was expected to critically examine the limitations of decisions that appeared successful. Her confidence continued to grow, while the weakness in her cognitive governance remained largely unnoticed.

At nineteen, Briana entered university to pursue a Bachelor of Engineering in Sustainable Building Engineering. She had developed an interest in how buildings influenced people's health, comfort and everyday activities. Her studies introduced her to building physics, heat transfer, ventilation, air-conditioning, indoor environmental quality, building services

systems and sustainable building design. Briana's intelligence became particularly evident when she encountered unfamiliar technical challenges. She could quickly recognise patterns, connect scientific principles from different subjects, develop logical explanations and imagine alternative engineering solutions. Her lecturers appreciated her ability to explain complex relationships clearly, while classmates frequently sought her assistance when conventional approaches failed to produce satisfactory answers. Her excellent academic results were therefore not merely evidence of a good memory. They reflected genuine intellectual capability, scientific understanding and technical creativity.

During her second year, Briana participated in a design studio project involving the hypothetical conversion of an existing office building into an educational facility. The project presented several engineering challenges because the existing ventilation and air-conditioning systems had been designed for different occupancy patterns and building operations. While some teammates initially suggested retaining the existing equipment arrangement, Briana recognised that the proposed change of use would alter ventilation requirements, internal heat generation and patterns of energy consumption. Drawing upon her knowledge of building physics, heat transfer, ventilation and energy efficiency, she developed an alternative design that integrated these requirements. She demonstrated how changes in occupancy could influence both cooling demand and outdoor air requirements, and proposed an arrangement that could maintain appropriate indoor environmental conditions while avoiding unnecessary energy consumption. Her calculations were accurate, her technical explanations were convincing and the group received excellent marks.

Briana's proposal was genuinely intelligent, scientifically defensible and appropriate for the specified design conditions. Her limitation was not an inability to understand complex engineering relationships or anticipate consequences. Rather, after demonstrating that her proposal satisfied the stated performance requirements, she considered the problem adequately solved. She did not independently investigate whether the assumptions defining those requirements sufficiently represented the building's future use or whether alternative arrangements might deliver greater value with fewer sacrifices. Another student, who was not necessarily more intelligent or technically capable, wondered whether classrooms might remain occupied beyond their scheduled hours during examination periods. When the question was raised, Briana immediately recognised its implications and suggested appropriate changes to ventilation control and equipment operation. However, she did not initially understand why further investigation was necessary when her original design had already satisfied the project requirements. Her intelligence enabled her to respond effectively to the new question, but she had not independently recognised the need to ask it.

During her third year, Briana worked on another project involving energy-efficient building operations. She developed a proposal to reduce air-conditioning energy consumption through improved equipment scheduling and control. Her analysis demonstrated

considerable creativity. Rather than simply recommending shorter operating hours, she examined relationships between occupancy, cooling demand, equipment efficiency and indoor environmental conditions. She identified opportunities to reduce unnecessary energy consumption without compromising the specified performance requirements. Her supervisor acknowledged the technical quality of her work, and the predicted energy savings were encouraging. However, Briana regarded the favourable assessment as sufficient evidence that her recommendation represented an appropriate solution. She did not independently investigate whether the proposed operating arrangements might inconvenience occupants with unusual working schedules or whether comparable savings could be achieved with fewer sacrifices in comfort and convenience.

These experiences revealed an important distinction that Briana herself had not recognised. Intelligence enabled her to acquire knowledge, understand complex relationships, reason logically and develop effective solutions. Cognitive governance, however, required her to consciously examine whether her understanding was sufficiently appropriate for the situation, what she might have overlooked and whether further questioning could lead to better judgements and decisions. Briana possessed considerable intellectual ability to undertake these activities when prompted. What she had not sufficiently developed was the habit of initiating and sustaining them independently, particularly when her decisions appeared successful. Because her solutions were generally reasonable and positively evaluated, this limitation seldom attracted attention. Academic success continued to reinforce her confidence rather than encourage deeper reflection on how she governed her intelligence.

A particularly important experience occurred during her final university year. Briana undertook a research project supervised by Dr Sofia Martins, investigating indoor air quality in a residential apartment affected by seasonal haze. The occupants had reported unpleasant indoor conditions despite keeping their windows closed and operating portable air purifiers. Briana examined the available pollutant measurements, equipment characteristics and building information before recommending improvements to filtration performance. Her recommendation was technically reasonable, and she could clearly explain how filtration efficiency and airflow influenced pollutant removal. She also recognised that outdoor pollutants could enter through building openings and leakage pathways. Nevertheless, she regarded the available information as sufficiently supportive of her recommendation without establishing the relative importance of the different mechanisms influencing pollutant concentrations under the apartment’s operating conditions.

During a project discussion, Dr Martins asked Briana whether the recommended filtration improvements would remain effective if indoor pollutant generation increased substantially. Briana immediately recognised that the resulting indoor concentration would depend on the balance between pollutant addition and removal. She explained that greater filtration efficiency would not necessarily produce the intended improvement if insufficient air

passed through the equipment or if pollutant generation increased beyond the system's removal capability. Dr Martins acknowledged her explanation before asking why these considerations had not formed a more explicit part of her original investigation. Briana paused. She had understood the scientific relationships and could apply them when questioned, yet she had not considered it necessary to investigate their implications before settling on her recommendation.

Dr Martins then asked a question that Briana found unexpectedly difficult. "What is it that you do not know or have not considered that could make what you know or propose inappropriate for this particular situation?" Briana initially responded by defending the scientific basis of her recommendation. Dr Martins agreed that the recommendation was reasonable but explained that reasonableness did not necessarily establish contextual appropriateness or the greatest achievable value. "The concern is not that your decision is imperfect," she explained. "Every professional decision involves limitations and uncertainty. The concern is whether you recognise those limitations and continue questioning what might improve your judgement, even when your decision appears successful." Briana began recognising that the positive feedback she had received throughout her education had often encouraged her to regard satisfactory outcomes as the end of investigation rather than opportunities for further learning.

Following the discussion, Briana began keeping a personal thinking journal. Whenever she encountered a problem, she recorded her initial understanding, the assumptions supporting it and the questions she had not yet answered. At first, the exercise felt unnecessarily demanding because she was already capable of producing reasonable explanations. Gradually, however, she discovered that the purpose was not to question everything indefinitely or delay decisions until perfect knowledge became available. It was to develop greater awareness of what she knew, what remained uncertain and which unanswered questions could materially influence the appropriateness of her decisions. She began identifying circumstances in which additional information could improve her understanding and others in which available evidence was sufficient to justify a practical decision. This distinction helped her recognise that effective cognitive governance involved both thoughtful questioning and informed judgement.

Her growing awareness also changed how she understood mathematical equations. Previously, Briana had regarded equations primarily as instruments for obtaining numerical answers. During one discussion, Dr Martins introduced a simple mass-balance relationship describing how indoor pollutant concentrations changed according to pollutant addition and removal. Instead of requesting calculations, she invited Briana to explain what the relationship implied under different operating conditions. Briana readily recognised the mathematical relationships and creatively imagined several possible situations involving changing pollutant sources, ventilation, infiltration and removal. What interested her was not the difficulty of the mathematical reasoning, which she found relatively straightforward, but how the equation could help organise questions about unfamiliar situations. She began

appreciating that scientific equations could communicate relationships that supported logical deduction, abstract reasoning and creative imagination without necessarily requiring computation.

Briana subsequently considered how a mass-balance relationship could guide the investigation of an occupied building. If indoor pollutant concentrations increased, the equation could prompt questions about whether pollutant addition had increased, removal had decreased or both had changed. If concentrations decreased, it could encourage examination of changes in source strength, ventilation or other removal mechanisms. However, these possibilities remained scientific explanations requiring evidence. Briana recognised that mathematical reasoning could help her identify what needed investigation, while measurements, observations and contextual information were necessary to establish what was actually happening. She was beginning to understand how scientific mental models could guide questioning rather than merely provide explanations after a problem had been diagnosed.

…… Chapter 2 ……

After graduating from university, Briana joined a multidisciplinary building engineering consultancy as a Sustainable Building Engineer. The consultancy provided building design, engineering assessment and technical advisory services to property owners and facilities management (FM) organisations. Working alongside senior engineers, Briana reviewed building designs, investigated indoor environmental complaints and recommended improvements to building operations. These responsibilities provided opportunities to apply her university knowledge to real-life engineering problems while continuing to develop her professional competency.

Briana’s development was neither immediate nor uninterrupted. During one of her early assignments at the consultancy, she initially attributed elevated indoor particle concentrations to outdoor haze because outdoor measurements were unusually high. A colleague questioned whether indoor activities had been examined. Briana immediately recognised that indoor pollutant generation could also contribute and proposed examining the concentration patterns alongside records of cooking activities. Subsequent investigation revealed that cooking contributed substantially to indoor concentrations during certain periods. Although she had possessed the scientific knowledge needed to investigate this possibility, she had not independently given it sufficient attention. The experience reminded her that developing a better scientific mental model did not automatically guarantee its consistent application.

When Briana returned to her journal, she recognised a familiar pattern. Her intelligence had enabled her to develop reasonable explanations throughout her life, while her confidence in those explanations sometimes reduced her motivation to search for what might have been overlooked. Positive feedback from teachers, supervisors, colleagues

and other stakeholders had frequently reinforced this tendency. She began recognising that the absence of criticism did not necessarily establish that the consequences of a decision had been adequately examined or that greater value could not have been achieved. Equally, she understood that continuous improvement did not require treating every decision as wrong. It required maintaining the willingness to examine its limitations, learn from its consequences and refine future judgements.

As Briana reflected on her journey from helping at her aunt's grocery shop to studying engineering and entering professional practice, she began understanding the distinction between her intelligence and the hidden weakness that had accompanied it. Her intelligence had always enabled her to understand complex information, reason logically and create genuinely valuable solutions. Her limitation was that she often stopped questioning once her decisions appeared reasonable, achieved satisfactory outcomes and received external validation. What she needed was not greater intelligence, but stronger cognitive governance: the continuing capability to consciously direct her intelligence towards identifying limitations in her understanding, asking meaningful questions, acquiring additional knowledge and improving value-oriented judgements and decisions. She realised that this capability would never make her decisions perfect, but it could help her become a more effective lifelong learner and professional problem solver.

As Briana gained further professional experience at the consultancy, she increasingly collaborated with experienced FM professionals responsible for operating and maintaining ventilation, air-conditioning and other building services systems. Many were highly competent in their routine responsibilities and possessed considerable practical knowledge. Yet unfamiliar IAQ problems sometimes demanded more than established procedures or past experience. Briana recognised something of her younger self when reasonable recommendations were accepted without questioning whether they adequately addressed particular circumstances. She also encountered professionals who independently challenged assumptions and investigated uncertainties. Having experienced similar limitations in her own cognitive governance, Briana became increasingly curious about why professionals with substantial knowledge and experience differed in their capabilities for independent problem diagnosis and solving. However, she recognised that observation alone could not establish the underlying reasons.

An assignment at a hospital outpatient facility brought these questions into focus. Staff reported unpleasant indoor conditions, and some patients worried about airborne pollutants. The ventilation equipment had been serviced regularly, with no obvious malfunction identified. One proposed remedy was to increase outdoor air supply to dilute indoor-generated pollution. The recommendation could be effective if indoor-generated pollutants were contributing to the problem. However, outdoor air quality deteriorated periodically during haze. More outdoor ventilation might help under some conditions and increase pollutant entry under others. Changes also had to respect relevant pressure relationships, operational requirements and the needs of vulnerable patients.

Rather than dismiss the proposal, Briana asked what evidence could establish when additional ventilation would help. Together with the FM team, she considered indoor sources, outdoor infiltration, airflow, filtration, exposure and the information missing from existing measurements. They distinguished established observations from possible explanations requiring investigation. Mass-balance and health-risk relationships helped Briana organise questions about interacting causes and consequences. Yet some colleagues reached similarly thoughtful judgements without explicitly referring to equations. She recognised that their reasoning might reflect scientific relationships they had internalised through professional experience or other learning experiences. This raised an important question: would deliberately teaching these relationships through equations develop stronger professional capabilities than communicating the same scientific knowledge without explicit equations?

The hospital experience also reinforced the importance of value-oriented problem solving. Increasing ventilation might reduce certain indoor pollutants while raising energy costs or creating maintenance and operational difficulties. Briana considered occupants' fundamental needs for comfort, convenience and awareness or certainty, and the appropriate quality, quantity and safety required to satisfy them. She also considered sacrifices in comfort, convenience and awareness, together with costs in time and money. Safety-critical hospital requirements could not simply be exchanged for savings. A defensible recommendation had to address supported causes and remain feasible for those affected. Its actual benefits would require implementation and evaluation, not merely an impressive report.

After the hospital investigation, Briana reflected on her professional experiences and remembered helping her aunt improve her grocery shop as a teenager. Her ideas had increased efficiency and profitability, and the praise she received had been justified. Nevertheless, she had not investigated whether some customers were disadvantaged or whether greater overall value was possible. The same risk existed in engineering practice. A decision might satisfy standards, gain approval and deliver genuine benefits without revealing unintended consequences or opportunities for improvement. No decision could be guaranteed perfect; the concern was whether apparent success discouraged further questioning, learning and refinement.

Briana resisted treating her personal experience as an explanation of other professionals' difficulties. FM professionals differed in scientific understanding, experience, responsibilities, workplace resources and learning opportunities. Some demonstrated strong independent reasoning; others relied more heavily on familiar procedures when problems became unfamiliar. She could not assume that inadequate cognitive governance caused those differences. First, she needed to establish whether a gap existed between existing competency and the targeted competency required to consistently diagnose unfamiliar IAQ problems and propose scientifically defensible, feasible and value-oriented solutions. She then needed to investigate what barriers might contribute to that gap.

She began considering whether professional education could address these possible barriers to professional competency. Intelligence, technical knowledge and experience mattered, but her own journey showed that they did not necessarily ensure sustained questioning, reflection or independent learning. Could training develop scientific mental models that helped professionals identify knowledge gaps, test assumptions, reason logically, imagine alternative scenarios and evaluate evidence? Mass-balance equations could communicate the relationship between pollutant addition, removal and indoor concentrations. Health-risk equations could communicate relationships between exposure dose, occupant vulnerability and the probability of specified health problems. Used to support mathematical reasoning and scientific understanding without necessarily requiring computation, these relationships might help professionals decide what to investigate and why.

But Briana recognised that this was a possibility, not an established solution. Would equation-guided training produce stronger scientific mental models and cognitive governance than equally comprehensive IAQ training without explicit equations? Would any advantage extend to independent learning and competency in value-oriented problem diagnosis and solving? Would improvements persist over six months and transfer to unfamiliar residential, educational and hospital problems? Perhaps both instructional approaches would prove equally effective. She realised that sound research had to permit conclusions that challenged her expectations rather than simply confirm them.

Briana discussed the idea with Dr Sofia Martins, her former university supervisor. She initially spoke about improving professionals' understanding of mass-balance and health-risk equations. Dr Martins asked whether the absence of equation-guided training was itself the professional problem. Briana recognised the distinction. The problem was the possible gap between existing and targeted professional competency; equation-guided training was a potential educational solution whose effectiveness still needed evaluation. Her personal experience had led her to a question, not supplied the answer. That conversation helped her frame a credible research problem.

Briana decided to pursue a Doctor of Philosophy (PhD) degree. As she prepared her research proposal, she returned to the fundamental question that had transformed her understanding of intelligence: "What is it that I do not know or have not considered that could make what I know or propose inappropriate for this particular situation?" She now applied this question to her own research idea. Rather than assuming that the cognitive barriers she had experienced were responsible for the difficulties faced by other professionals, she resolved to investigate them objectively. She also recognised that her proposed educational solution needed to be evaluated scientifically rather than accepted merely because it appeared reasonable. Her PhD journey would therefore demand the continuous questioning, critical and reflective thinking, logical deduction, abstract reasoning, creative imagination and independent learning that she had come to recognise as essential to cognitive governance and value-oriented problem diagnosis and solving.

The following excerpt from Briana Oliveira's PhD research proposal begins with the problem statement that motivated her investigation.

"Providing healthy indoor air that supports healthy living is an important responsibility of professionals involved in building management and design. However, achieving this objective requires more than the installation and operation of ventilation and air-cleaning systems or compliance with prescribed IAQ standards. It requires professionals to consistently demonstrate the competency to independently diagnose and solve unfamiliar IAQ problems in ways that deliver value to building occupants and other stakeholders. In practice, an IAQ problem may persist despite considerable efforts and financial expenditure to resolve it. For example, occupants of a residential building may continue to experience discomfort and respiratory symptoms during outdoor haze despite closing windows and operating air purifiers.

A facilities management (FM) professional may recommend installing additional air purifiers without sufficiently investigating the contributions of indoor pollutant generation, outdoor pollutant infiltration, inadequate airflow through existing filters or inappropriate equipment operation. Such a recommendation may address some aspects of the problem without adequately addressing its underlying causes. Similar situations may arise in educational and hospital buildings, where changing occupancy, occupant vulnerability and operational requirements introduce additional challenges.

The practical problem motivating this research is the gap between the existing competency of FM professionals in independently diagnosing and solving unfamiliar IAQ problems and the targeted competency required to consistently deliver scientifically defensible, feasible and value-oriented solutions. The extent of this gap, particularly among experienced FM professionals without previous formal specialist IAQ training, requires systematic investigation. The targeted performance requires professionals to distinguish observed IAQ problems from their underlying causes, anticipate the consequences of different interventions and justify solutions that satisfy occupants' needs for comfort, convenience and awareness (certainty) with the appropriate quality, quantity and safety required to support healthy living, while minimising sacrifices in comfort, convenience and awareness (certainty) and the associated costs in time and money. Professionals involved in building design should also be capable of applying these capabilities to anticipate and prevent potential IAQ problems.

Developing an effective educational solution requires understanding the underlying barriers responsible for the competency gap. One possible barrier is inadequate scientific mental models of the relationships governing indoor pollutant behaviour, exposure dose, occupant vulnerability and health risk. Professionals may possess knowledge of individual IAQ concepts without sufficiently understanding how these concepts are interconnected under changing building and environmental conditions. Another possible barrier is inadequate cognitive governance, particularly the capability to independently formulate meaningful

questions, challenge assumptions, evaluate evidence, consider alternative explanations and make scientifically defensible judgements. Closely related to this is potentially inadequate independent learning capability, which may limit professionals' ability to recognise and address gaps in their knowledge when confronted with unfamiliar problems. These potential barriers require investigation because providing professionals with additional IAQ information may not necessarily develop their capability to independently apply that information to unfamiliar situations. Furthermore, professionals cannot receive training on every possible IAQ problem they may encounter throughout their careers.

A potential educational solution is to deliberately use mass-balance and health-risk equations to communicate the scientific relationships that professionals need to internalise and apply during IAQ problem diagnosis and solving. The intention is not merely to develop mathematical calculation skills but to develop scientific mental models that guide questioning, thinking, independent learning, judgement and decision-making. However, whether this approach offers greater educational value than equally comprehensive IAQ training without explicit equation guidance remains uncertain. Even if equation-guided training produces better performance immediately after training, its practical usefulness will depend on whether the developed capabilities can be sustained and independently transferred to unfamiliar professional situations over time.

Consequently, this research seeks to first establish the existing competency gap and investigate its potential underlying barriers. It then seeks to determine whether equation-guided IAQ training is more effective than non-equation-guided training in addressing these barriers and improving professional competency. Finally, it seeks to establish whether the developed capabilities are sustained over six months and can be independently applied to unfamiliar residential, educational and hospital IAQ problems. Addressing these questions is necessary to determine whether the proposed educational solution can effectively prepare professionals for value-oriented IAQ management practice and design."

This need forms the basis for the research questions and hypotheses that guided her PhD study.

(i) What mental models do experienced FM professionals without formal specialist IAQ training use to understand indoor pollutant behaviour and health risks, and how are these mental models associated with their cognitive governance, independent learning capability and competency in diagnosing and solving unfamiliar real-life IAQ problems across residential, educational and hospital buildings in a value-oriented manner?

(ii) Compared with equally comprehensive IAQ training without explicit use of mass-balance and health-risk equations, to what extent does equation-guided IAQ training improve experienced FM professionals' scientific mental models, cognitive governance,

independent learning capability and competency in diagnosing and solving unfamiliar real-life IAQ problems in a value-oriented manner?

(iii) Compared with equally comprehensive IAQ training without explicit use of mass-balance and health-risk equations, to what extent does equation-guided IAQ training produce sustained and transferable improvements in experienced FM professionals' cognitive governance, independent learning capability and competency in diagnosing and solving unfamiliar real-life IAQ problems across residential, educational and hospital buildings in a value-oriented manner?

For the first research question, the Null Hypothesis (H_{01}) is that among experienced FM professionals without formal specialist IAQ training, the quality of their existing scientific mental models and cognitive governance is not positively associated with their independently assessed competency in value-oriented problem diagnosis and solving across residential, educational and hospital buildings, after accounting for relevant differences in prior knowledge, professional experience and building specialisation. The Alternative Hypothesis (H_{11}) is that among experienced FM professionals without formal specialist IAQ training, higher-quality scientific mental models and stronger cognitive governance are positively associated with greater independently assessed competency in value-oriented problem diagnosis and solving across residential, educational and hospital buildings, after accounting for relevant differences in prior knowledge, professional experience and building specialisation.

For the second research question, the Null Hypothesis (H_{02}) is that compared with experienced FM professionals receiving equally comprehensive IAQ training without explicit use of mass-balance and health-risk equations, those receiving equation-guided IAQ training do not demonstrate greater immediate improvements in scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving, after accounting for their baseline performance. The Alternative Hypothesis (H_{12}) is that compared with experienced FM professionals receiving equally comprehensive IAQ training without explicit use of mass-balance and health-risk equations, those receiving equation-guided IAQ training demonstrate greater immediate improvements in scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving, after accounting for their baseline performance.

For the third research question, the Null Hypothesis (H_{03}) is that equation-guided IAQ training did not produce greater baseline-adjusted performance at six months than non-equation-guided training in at least one of the three capabilities: cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving, as assessed through unfamiliar real-life IAQ problems. The Alternative Hypothesis (H_{13}) is that equation-guided IAQ training produced greater baseline-adjusted

performance at six months than non-equation-guided training in all three capabilities: cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving, as assessed through unfamiliar real-life IAQ problems.

The research problem and questions informed the following objectives of her PhD study:

(i) To examine the mental models that experienced FM professionals without formal specialist IAQ training use to understand indoor pollutant behaviour and health risks, and how these mental models are associated with their cognitive governance, independent learning capability and competency in diagnosing and solving unfamiliar real-life IAQ problems across residential, educational and hospital buildings in a value-oriented manner.

(ii) To determine the extent to which equation-guided IAQ training, compared with equally comprehensive IAQ training without explicit use of mass-balance and health-risk equations, improves experienced FM professionals' scientific mental models, cognitive governance, independent learning capability and competency in diagnosing and solving unfamiliar real-life IAQ problems in a value-oriented manner.

(iii) To determine the extent to which equation-guided IAQ training, compared with equally comprehensive IAQ training without explicit use of mass-balance and health-risk equations, produces sustained and transferable improvements in experienced FM professionals' cognitive governance, independent learning capability and competency in diagnosing and solving unfamiliar real-life IAQ problems across residential, educational and hospital buildings in a value-oriented manner.

…… Chapter 3 ……

Research Methods

Methods for Research Question 1:

Overview

The study investigated how experienced Facilities Management (FM) professionals without formal specialist Indoor Air Quality (IAQ) training understood, investigated, diagnosed and solved unfamiliar real-life IAQ problems. Particular attention was given to their existing scientific understanding, mental models, cognitive governance, independent learning capability and competency in value-oriented problem diagnosis and solving. Professionals from residential, educational and hospital buildings investigated complex, unfamiliar IAQ problems involving changing indoor and outdoor pollution conditions, building characteristics, ventilation, pollutant removal, occupant activities and health risks. The investigations required them to explain why pollutant concentrations changed over time, determine the relative contributions of different sources and removal processes, identify root causes and evaluate the consequences of possible solutions. They also examined

how pollutant exposure, biological vulnerability and other relevant factors influenced the probability of specified health problems.

The study also examined how professionals used their existing scientific understanding and practical experience to formulate meaningful questions, investigate competing explanations, identify missing knowledge, evaluate evidence, make informed judgements and decisions, and develop solutions that addressed established root causes while considering stakeholder needs and practical constraints. Quantitative assessments were used to measure and examine relationships between scientific mental models, cognitive governance, independent learning and professional competency. Qualitative investigations provided deeper understanding of how professionals approached problems and justified their decisions. Independent assessments evaluated the scientific accuracy of their diagnoses and the potential effectiveness and value of their proposed solutions. The study investigated whether limitations in professionals' scientific understanding and mental models were associated with difficulties in diagnosing and solving real-life IAQ problems, while also considering other factors that could influence their performance.

Study Population, Recruitment and Sampling

This section describes the population, eligibility criteria, recruitment procedures and sampling strategy adopted for RQ1. The investigation focused on experienced Facilities Management (FM) professionals without formal specialist Indoor Air Quality (IAQ) training, drawn from residential, educational and hospital building sectors. The selection criteria were established to ensure that participants possessed relevant professional experience while allowing differences in their existing knowledge, scientific mental models and competency to be investigated. The sampling strategy was designed to provide representation across building sectors and organisations, while statistical power analysis was incorporated to assess whether the proposed sample size was adequate for addressing the research question.

Study Population and Eligibility: The study involved experienced Facilities Management (FM) professionals responsible for operating, maintaining or managing residential, educational and hospital buildings. Participants were required to have at least five years of relevant professional experience involving building services, indoor environmental conditions, occupant complaints, maintenance decisions or building performance. They had not received formal specialist Indoor Air Quality (IAQ) training covering indoor pollution investigation and exposure–health risk assessment. However, knowledge acquired through education, professional experience or independent learning was considered an important part of their existing competency and did not constitute grounds for exclusion.

Professionals specialising in IAQ consultancy, occupational exposure assessment or environmental health-risk modelling were excluded. Participants' educational qualifications, professional responsibilities, years of experience, building specialisation, mathematical

background and prior scientific knowledge were recorded. These characteristics were considered when examining whether differences in scientific mental models, cognitive governance and problem diagnosis and solving competency were associated with prior knowledge, professional experience or other relevant factors.

Sampling and Sample Size: A stratified, multicentre sampling approach was adopted to recruit 120 FM professionals, comprising approximately 40 participants each from residential, educational and hospital building sectors. Recruitment involved approximately 12 organisations or operational sites, with an average of 10 participants per organisation. This approach provided representation across different professional experiences and working environments, reducing dependence on the characteristics of any single organisation. Dedicated research assistants supported recruitment, eligibility screening, communication with participating organisations, assessment scheduling and participant coordination. The doctoral researcher retained responsibility for scientific design, assessment procedures, data analysis and interpretation. Recruitment records were maintained to examine eligibility, participation and potential selection bias.

The proposed sample size was subject to statistical power analysis to determine whether it was sufficient to investigate relationships between scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving. The analysis accounted for the possibility that professionals working within the same organisation might share similar knowledge, experiences and working practices. For preliminary planning, an intraclass correlation coefficient of 0.03 and an average of 10 participants per organisation were assumed. These assumptions corresponded to a design effect of 1.27 and a projected effective sample size of approximately 94 from the proposed 120 participants. These values were planning estimates rather than findings from the study. A pilot study was incorporated to evaluate assessment procedures and estimate variation within and between organisations. The pilot estimates were used to refine the statistical power analysis and assess whether the proposed sample size was adequate for investigating the relationships specified in the research question.

Scientific Framework for Investigating Mental Models

Following the recruitment of participants, an independent expert panel established a shared scientific understanding and interpretation of established models and equations describing indoor pollutant behaviour and health risks. These agreed interpretations provided the basis for developing scientific reference standards, which were used to design unfamiliar IAQ assessment cases and evaluate whether FM professionals could explain pollutant behaviour, identify underlying causes, predict changes in indoor pollutant concentrations and understand how exposure and biological vulnerability influenced health risks.

The scientific reference standards reflected the experts' agreed interpretations rather than knowledge taught to participants during RQ1. Participants were neither trained in nor required to reproduce the equations or perform mathematical calculations. Instead, their existing scientific understanding and reasoning were assessed against these independently established standards. The assessment also examined how scientific mental-model quality was associated with cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving.

Mental Models of Indoor Pollutant Behaviour: The scientific assessment of indoor pollutant behaviour was based on the principles of pollutant mass balance, which describe how pollutant concentrations change over time in response to sources and removal processes. The foundational equation was expressed as:

$$\frac{dC}{dt} = S - KC(t)$$

In this equation, C(t) represents the concentration of an indoor pollutant at time t, S represents the pollutant source strength expressed as concentration added per unit time, and K represents the overall first-order pollutant removal coefficient. Concentration was expressed in μg/m³, time in hour, S in μg/(m³·h), and K in h^{-1}.

The assessment examined whether participants understood that changes in indoor pollutant concentration depended on the balance between pollutant addition and removal. It also investigated whether professionals could explain how changes in either contribution affected the direction and rate of concentration change. For the situation in which no active pollutant source was present and removal processes continued, the concentration decreased over time according to:

$$C(t) = C_0 e^{-Kt}$$

Here, C_0 represented the initial pollutant concentration. Participants were assessed on whether they understood why the concentration decreased over time and why the rate of decrease depended on the existing concentration and the removal coefficient. They were also assessed on their ability to recognise that the equation described a particular physical situation and should not automatically be applied to a building where pollutant sources remained active.

For the situation in which a pollutant source became active when the initial concentration was zero, the increase in pollutant concentration towards steady state was first expressed in a form that illustrated how the existing concentration and the remaining increase towards steady state were related:

$$C(t) + C_{ss}e^{-Kt} = C_{ss}$$

Here, C(t) represented the pollutant concentration already accumulated at time t, while $C_{ss}e^{-Kt}$ represented the remaining increase needed to reach steady state, i.e., the remaining gap between the current concentration at time t and concentration at steady state C_{ss}. As C(t) increased, the remaining difference decreased, causing the concentration to increase progressively more slowly as it approached steady state.

The same relationship was conventionally expressed as:

$$C(t) = C_{ss}(1 - e^{-Kt})$$

with:

$$C_{ss} = \frac{S}{K}$$

In these equations, C_{ss} represented the steady-state pollutant concentration under constant source strength and removal conditions. The assessment examined whether participants understood how the balance between pollutant addition and removal determined the steady-state concentration, why the concentration initially increased rapidly before its rate of increase gradually decreased, and why it approached C_{ss}. S, source strength is expressed as:

$$S = \frac{Source\ emission\ rate\ (G)}{Volume\ (V)}$$

Indoor pollutant sources could include inanimate objects, living organisms and their activities, and chemical reactions occurring in indoor air or on indoor surfaces. The source strength or intensity S, expressed as the rate of pollutant concentration added per unit time, depended on the pollutant emission rate G and indoor air volume V, which represented the volume of air within the indoor space.

Particular attention was given to whether professionals could explain how changes in source strength affected the steady-state concentration, while changes in the removal coefficient affected both the steady-state concentration and the rate at which it was approached. Participants were assessed on their ability to explain these physical relationships without relying exclusively on numerical calculations.

A further assessment situation examined whether professionals could integrate their understanding of pollutant generation and removal when indoor conditions changed over time. Unlike the preceding situations, an existing pollutant concentration initially decreased because no active source was present. A new pollutant source was subsequently introduced at time t_1, after which the remaining initial concentration and the contribution from the new source jointly determined the subsequent concentration trajectory. Before the new source was introduced, the pollutant concentration was expressed as:

$$C(t) = C_0 e^{-Kt}, \qquad 0 \le t < t_1$$

At the time t_1 when the new pollutant source became active, the concentration remaining from the initial period of pollutant removal was expressed as:

$$C_1 = C_0 e^{-Kt_1}$$

Here, C_1 represented the pollutant concentration remaining at the moment the new source became active. At that instant, the newly introduced source had not yet affected the indoor pollutant concentration because pollutant generation had only just begun.

After the source was introduced, the existing pollutant concentration and the contribution from the new source jointly determined the subsequent concentration for $t \ge t_1$:

$$C(t - t_1) = C_1 e^{-K(t-t_1)} + C_{ss}\left(1 - e^{-K(t-t_1)}\right)$$

This is assuming constant source strength and removal conditions after introduction. This means that the contribution from the existing pollutant concentration gradually decreased due to removal processes towards zero, while the contribution from the newly activated source gradually increased towards its steady-state concentration, with both contributions jointly determining the total indoor pollutant concentration over elapsed time ($t-t_1$).
Here, C_{ss} represented the steady-state concentration associated with the newly introduced source, while C_1 represented the pollutant concentration remaining when the source became active at time t_1. In the situation investigated, $C_1 < C_{ss}$, causing the total pollutant concentration to increase gradually from C_1 towards C_{ss}. As the total pollutant concentration approaches steady state, the contribution from the initial concentration C_1 approaches zero, leaving the steady-state concentration determined by the newly introduced source and the removal processes. The expression $C(t-t_1)$ represented the total indoor pollutant concentration at a particular time after pollutant injection began, comprising $C_1 e^{-K(t-t_1)}$, which represented the remaining contribution from the pollutant

concentration already present at the start of injection, and C_{ss} $(1-e^{-K(t-t_1)})$, which represented the contribution from the newly introduced pollutant source as the concentration progressively approached its steady-state value.

Participants were assessed on whether they understood that the second stage began at the concentration remaining when the source was introduced, rather than at zero. The assessment also examined whether professionals recognised how changes in source strength or removal conditions influenced the direction and rate of concentration change and the resulting steady-state concentration.

The scientific assessment of pollutant removal processes examined whether participants understood how different removal mechanisms contributed to reducing indoor pollutant concentrations. In the removal framework, K represented the total pollutant removal coefficient, while, K_v, K_f, K_d, K_a and K_{other} represented the coefficients associated with ventilation, filtration, deposition, adsorption and other applicable pollutant removal processes, respectively. Particular attention was given to ventilation (K_v) and filtration (K_f), because these represented important building-system characteristics affecting indoor pollutant concentrations. All coefficients (K) were expressed in h^{-1}.

$$K_v = \frac{Q_v}{V}$$

Here, Q_v represented the outdoor airflow rate (m^3/h), and V represented the indoor air volume (m^3).

$$K_f = \frac{CADR}{V}$$

CADR represented the clean air delivery rate (m^3/h), expressed as:

$$CADR = Q_f \times \varepsilon_f$$

Here, Q_f represented the airflow rate passing through the air-cleaning device (m^3/h), while ε_f represented its fractional pollutant removal efficiency. The assessment examined whether participants understood how outdoor airflow rate, indoor air volume, air-cleaning airflow rate and filtration efficiency influenced pollutant removal. Particular attention was given to their ability to explain why a high-efficiency filter did not necessarily provide effective pollutant removal when insufficient air passed through it. The assessment also examined whether professionals recognised that ventilation could simultaneously remove indoor pollutants and introduce outdoor pollutants, whereas a recirculating air cleaner reduced pollutants without necessarily introducing outdoor air.

The assessment also covered the physical mechanisms represented by the removal coefficients. Ventilation K_v removed indoor pollutants through outdoor air exchange, filtration K_f captured pollutants using air-cleaning devices, deposition K_d involved airborne particles settling or attaching to indoor surfaces, and adsorption K_a involved gaseous pollutants adhering to suitable materials or sorbent surfaces. The coefficient K_{other} represented other applicable pollutant removal processes.

The simplified indoor pollutant mass-balance model assumed that indoor air was sufficiently well mixed and that pollutant source strength, outdoor pollutant concentration, airflow rates and removal coefficients remained constant under the conditions investigated. The simplified CADR relationship represented the volume of air effectively cleaned per unit time for a specified pollutant, while actual air-cleaning performance could vary with pollutant characteristics, device operation and indoor air distribution. These assumptions made the simplified models useful for mathematical reasoning in everyday FM practice, provided their limitations were recognised. The assessment examined whether participants could use these relationships to identify relevant factors, make context-sensitive judgements and decisions, and recognise when further information, measurements or specialist advice was needed.

Outdoor pollution, including haze, was explicitly incorporated into the scientific assessment through an extension of the foundational indoor pollutant mass-balance equation. The contribution of outdoor pollutant entry was represented by K_vC_{out}, where K_v denotes the outdoor air-exchange coefficient and C_{out} denotes the outdoor pollutant concentration. The resulting equation was expressed as:

$$\frac{dC(t-t_1)}{d(t-t_1)} = S + K_vC_{out} - KC(t-t_1)$$

The equation described how the indoor pollutant concentration changed at any particular time after pollutant injection began. The term S represented the rate at which the indoor source introduced pollutants into the air, K_v C_{out} represented the rate at which outdoor pollutants entered through ventilation, and $KC(t\text{-}t_1)$ represented the instantaneous rate at which pollutants were removed from the indoor air. The difference between the combined pollutant introduction rates and the pollutant removal rate determined whether the indoor pollutant concentration increased, decreased or remained constant at that particular time.

For constant indoor pollutant source strength, outdoor pollutant concentration and removal conditions, the change in indoor pollutant concentration over time was expressed as:

$$C(t-t_1) = C_1 e^{-K(t-t_1)} + \frac{S + K_v C_{\text{out}}}{K}\left(1 - e^{-K(t-t_1)}\right)$$

The associated steady-state concentration was:

$$C_{ss} = \frac{S + K_v C_{\text{out}}}{K}$$

These expressions retained the fundamental mathematical structure of the indoor pollutant mass-balance equations while incorporating the contribution of outdoor pollution. In particular, the relationship remained applicable when the steady-state concentration, C_{ss}, accounted for both indoor pollutant generation and outdoor pollutant entry.

$$C(t-t_1) = C_1 e^{-K(t-t_1)} + C_{ss}\left(1 - e^{-K(t-t_1)}\right)$$

The simplified outdoor-entry term $K_v C_{out}$ assumed that the relevant outdoor pollutant entered with the air exchange without additional penetration losses. Where building-envelope penetration, outdoor-air filtration or other entry losses were significant, the effective outdoor pollutant contribution required appropriate adjustment.

When outdoor pollutants entered through both the ventilation system and building-envelope gaps or cracks, the indoor pollutant mass-balance equation became:

$$\frac{dC(t-t_1)}{d(t-t_1)} = S + \left(\rho_v K_v + \rho_i K_i\right) C_{out} - KC(t-t_1)$$

Under constant conditions, the corresponding steady-state concentration would be:

$$C_{ss} = \frac{S + \left(\rho_v K_v + \rho_i K_i\right) C_{out}}{K}$$

In this case, indoor pollutant concentration over time was expressed as:

$$C(t-t_1) = C_1 e^{-K(t-t_1)} + \frac{S + \left(\rho_v K_v + \rho_i K_i\right) C_{out}}{K}\left(1 - e^{-K(t-t_1)}\right)$$

In these equations, S represented the indoor pollutant generation rate, ρ_v represented the fraction of outdoor pollutants entering through the ventilation system (including any relevant filtration losses), K_v represented the ventilation air-exchange coefficient, ρ_i represented the fraction of outdoor pollutants penetrating through building-envelope gaps and cracks, K_i represented the infiltration air-exchange coefficient, C_{out} represented the outdoor pollutant concentration, and K represented the overall indoor pollutant removal coefficient, including removal through ventilation and infiltration. When both ventilation and infiltration were considered, the outdoor pollutant contribution was represented by $(\rho_v K_v+\rho_i K_i) C_{out}$. This accounted for outdoor pollutants entering through the ventilation system and through building-envelope gaps and cracks, including the fraction of pollutants that successfully penetrated through each pathway. The simpler outdoor-entry term $K_v C_{out}$ was recovered when pollutant transmission through ventilation was complete ($\rho_v=1$) and infiltration was negligible ($K_i=0$).

The assessment investigated whether professionals understood the implications of these relationships for buildings exposed to outdoor haze. In particular, it examined whether they recognised that closing windows could reduce outdoor pollutant entry while simultaneously reducing the removal of pollutants generated indoors. It also examined whether they could explain why increasing ventilation might improve or worsen indoor pollutant concentrations depending on outdoor pollution conditions, indoor source strength and the effectiveness of pollutant removal processes. The simplified equations were applied only where their assumptions were satisfied, particularly constant parameters within each stage and sufficiently well-mixed indoor air. Professionals were assessed on whether they recognised situations where changing outdoor pollutant concentrations, building-envelope infiltration, ventilation operation or uneven pollutant distribution within indoor spaces required additional measurements and more detailed scientific investigation.

Mental Models of Exposure and Health Risk: When pollutant concentration changes over time, exposure dose can be estimated using the summation equation:

$$E = \sum_{i=1}^{n} C_i \times \Delta t_i \times IR$$

Where: E is the total inhaled pollutant mass (μg). C_i is the average pollutant concentration during time interval i (μg/m³). Δt_i is the duration of time interval i (h). IR = Inhalation rate (m³/h) assumed constant. n = Total number of time intervals. The assessment examined whether participants understood how cumulative inhaled pollutant mass was estimated when indoor pollutant concentration changed over time. For each time interval, the average pollutant concentration was multiplied by the exposure duration and inhalation rate to estimate the pollutant mass inhaled during that interval. The contributions from all

intervals were then summed to determine the total inhaled pollutant mass over the exposure period. This discrete-time approach enabled participants to understand the relationship between changing pollutant concentrations, exposure duration and cumulative inhaled pollutant mass without requiring mathematical integration.

The scientific assessment of exposure dose and health risks was based on a logistic regression model describing how pollutant exposure, individual vulnerability and other relevant factors influenced the probability of a specified health problem occurring within a defined period. The model was expressed as:

$$P(Y = 1) = \frac{e^{\eta}}{1 + e^{\eta}}$$

$$\eta = \beta_0 + \beta_1 E + \beta_2 V + \beta_3 (E \times V) + \gamma Z$$

These equations provided the scientific basis for assessing participants' existing mental models of exposure–health risk relationships, rather than their ability to memorise or reproduce mathematical equations. Here, P(Y=1) represents the probability that a specified health problem occurs within a defined period.

In this equation, η represented the log-odds of a specified health problem occurring within a defined period, E represented the pollutant exposure dose, V represented biological vulnerability, and Z represented several relevant contributing factors. The coefficient β_0 represented the baseline log-odds of a specified health problem under reference population conditions, before accounting for individual exposure dose, biological vulnerability and other factors. β_1 described how the harmful potential of pollutant exposure dose E changed these log-odds for a generally healthy individual. β_2 described how weaknesses in biological protection V changed the log-odds at reference exposure dose. β_3 captured how exposure dose and biological vulnerability interacted to influence the log-odds beyond their separate contributions. γ represented how other physiological, psychological, social, demographic and economic factors Z contributed to the log-odds. These log-odds determined the estimated probability of the specified health problem. The coefficients were introduced to explain the scientific reasoning underlying health-risk assessment; they were not estimated from participants' responses.

The assessment examined whether professionals distinguished indoor pollutant concentration, individual exposure and the probability of developing a specified health problem within a defined period. It investigated whether they recognised that individuals experiencing comparable exposures could have different health outcomes because of biological vulnerability and other relevant factors. Logistic regression equations and illustrative exposure–probability curves served as scientific reasoning frameworks, not

validated clinical predictions. Participants were not required to memorise equations, calculate log-odds or probabilities, or estimate regression coefficients. Instead, they interpreted exposure–health risk relationships, identified necessary evidence, questioned assumptions and recognised uncertainty and the limitations of unvalidated predictions.

The assessment also examined whether participants could use exposure dose, vulnerability and relevant covariates to make evidence-informed judgements about the likelihood of a specified health problem occurring within a defined period. Where validated probability estimates were unavailable, participants selected a likelihood rating using a predefined scale and justified it using available evidence, scientific understanding and professional experience. They separately evaluated the severity of the potential health problem, considering the seriousness of its consequences for the affected individual, and assigned a severity rating. The resulting professional risk rating was determined as:

Risk Rating = Likelihood (L) Rating x Severity (S) Rating

A predefined risk matrix categorised ratings as low, medium or high. Low ratings indicated comparatively greater safety and generally supported maintaining, reviewing and monitoring existing controls, provided the risk remained acceptable. Medium ratings required management attention and consideration of additional controls to reduce risk to as low as reasonably practicable (ALARP). High ratings indicated lower safety and required urgent management review and effective risk-reduction measures before further exposure, wherever practicable. Participants were assessed on whether they justified each classification and proposed actions appropriate to the evidence, stakeholder needs and operational constraints.

The assessment examined whether participants understood that likelihood refers to the chance of a specified health problem occurring, severity refers to how serious its consequences would be, and risk rating combines the likelihood and severity ratings using predefined professional scales. Risk ratings were treated as scale-dependent judgements, not scientifically calculated probabilities or direct measures of clinical risk. Participants were expected to acknowledge uncertainty, identify when further measurements or specialist investigation were necessary, and explain why particular actions deserved priority. Given limited time, money and personnel, the assessment examined whether risk categorisation supported defensible allocation of resources towards situations requiring more urgent intervention, while considering potential consequences, expected benefits and practical feasibility. Across these tasks, emphasis remained on questioning, critical judgement, scientific reasoning and value-oriented decision-making rather than numerical proficiency or unsupported certainty.

Development and Scientific Validation of Real-Life IAQ Assessment Cases

The scientific models established in the preceding section provided the basis for assessing FM professionals' existing understanding of indoor pollutant behaviour and health risks. To

investigate how this understanding was associated with cognitive governance, independent learning capability and competency in value-oriented problem diagnosis and solving, unfamiliar real-life IAQ assessment cases were developed. Independent scientific benchmarks were established to ensure that participants' explanations, diagnoses, judgements and proposed solutions were evaluated consistently against scientifically defensible standards.

Case Development: A structured set of unfamiliar IAQ assessment cases was developed as case reports based on existing real-life building investigation records, environmental monitoring data and, where necessary, validated engineering simulations. These case reports presented realistic IAQ problems for participants to investigate without requiring their involvement in ongoing building investigations. Participants reviewed and investigated the case reports individually in a controlled classroom setting under standardised assessment conditions, without conducting physical building walkthroughs or on-site measurements. The cases represented residential, educational and hospital buildings and involved indoor pollutant generation, outdoor pollution, ventilation, filtration, pollutant removal, occupant activities and biological vulnerability. Each case assessed how participants applied their existing scientific understanding and mental models to investigate unfamiliar IAQ problems rather than reproduce previously learnt knowledge or follow predefined solutions.

Residential cases examined outdoor haze, cooking emissions, window operation, infiltration and air cleaning. Educational cases investigated changing classroom occupancy, outdoor pollution, ventilation and pollutant accumulation. Hospital cases introduced considerations involving vulnerable occupants, operational requirements and environmental safety. Relevant building-specific information was provided to minimise the influence of unfamiliarity with particular building operations on competency assessments.

The cases incorporated incomplete information, competing explanations and changing conditions to assess participants' ability to identify problems, formulate meaningful questions, recognise knowledge gaps, acquire additional information and investigate root causes. Assessment tasks examined whether participants could interpret concentration–time relationships, explain pollutant behaviour and use their understanding of exposure dose, biological vulnerability and relevant contributing factors to make evidence-informed likelihood and severity judgements.

Participants were also required to develop and justify proposed solutions based on their diagnoses, scientific evidence and stakeholder requirements. Each participant submitted an individual written case investigation report documenting their questions, scientific reasoning, evidence evaluation, root-cause diagnosis, health-risk judgements and proposed solutions. The cases therefore provided a common basis for investigating relationships between scientific mental models, cognitive governance, independent

learning capability and competency in value-oriented IAQ problem diagnosis and solving, without requiring complex mathematical calculations.

Establishment of Independent Scientific Benchmarks: An independent panel comprising IAQ researchers, building services engineers, experienced FM practitioners and relevant health specialists established scientific benchmarks based on scientific principles, existing monitoring evidence, validated engineering simulations and professional requirements. Each case was reviewed to identify scientifically supported pollutant sources, removal mechanisms, exposure conditions, potential health risks, plausible root causes, competing explanations and remaining uncertainties. The benchmarks also identified the evidence needed for reliable diagnosis and the characteristics of technically feasible solutions.

Participants' individual case investigation reports were evaluated by trained independent assessors using the scientific benchmarks and assessment criteria established by the expert panel. Their explanations, questions, diagnoses, judgements and decisions were assessed against these benchmarks rather than a single predetermined answer. Proposed solutions were evaluated according to their expected effectiveness in addressing root causes, practical feasibility, safety and alignment with occupant and stakeholder requirements. Multiple solutions were acceptable when supported by scientifically defensible reasoning and evidence. The independent panel reviewed the scientific accuracy and suitability of the assessment cases and finalised the evaluation criteria before participants' responses were assessed. This supported consistent and fair evaluation while recognising that unfamiliar real-life IAQ problems could have several scientifically defensible solutions.

Measurement of Scientific Mental Models, Cognitive Governance and Professional Competency

This section describes how participants' existing scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving were assessed. The investigation used structured assessment tasks and individual case investigation reports to examine how professionals understood scientific relationships, formulated questions, evaluated evidence, acquired knowledge, made judgements and decisions, and developed solutions to unfamiliar IAQ problems. Separate assessment criteria were established to distinguish these capabilities and examine their relationships. Particular attention was given to whether participants could apply their existing understanding to diagnose root causes and propose scientifically defensible solutions that addressed occupant and stakeholder needs.

Scientific Mental-Model Quality: Scientific mental-model quality was assessed through conceptual explanation, prediction and interpretation tasks incorporated into the individual case investigation reports and based on the scientific models established in the preceding

section on scientific models. Participants explained changes in pollutant concentrations, predicted the consequences of changing pollutant sources and removal processes, and interpreted steady-state behaviour. They also examined outdoor haze and distinguished pollutant concentration, exposure dose, biological vulnerability and the probability of specified health problems.

A provisional 100-point assessment allocated 60 points to pollutant behaviour and 40 points to exposure and health-risk understanding. These weights reflected assessment coverage and were reviewed through pilot testing. Responses were evaluated for scientific accuracy, completeness, recognition of assumptions and application to changing conditions. The assessment emphasised mathematical reasoning rather than numerical calculations or memorisation of equations.

Cognitive Governance and Independent Learning Capability: Cognitive governance was assessed through participants' observable questioning, reasoning, evaluation and decision-making documented in their individual case investigation reports. A separate assessment presented incomplete or conflicting information, requiring participants to identify problems, formulate meaningful questions, examine assumptions, consider competing explanations, identify necessary evidence and revise judgements when new information became available. Reasoning quality was assessed separately from diagnostic accuracy to distinguish cognitive governance from professional problem-solving competency.

Independent learning capability was evaluated through a structured information-acquisition exercise involving unfamiliar IAQ problems. Participants identified knowledge gaps, selected and evaluated relevant scientific or technical resources, explained what they had learnt and applied the acquired knowledge to advance their investigations. Performance was assessed according to information relevance, reliability and appropriate application. The assessment examined readiness for self-directed learning rather than claiming to demonstrate lifelong learning capability throughout professional practice.

Competency in Value-Oriented Problem Diagnosis and Solving: Professional competency was assessed through independent evaluation of participants' written case investigation reports. A provisional 100-point assessment allocated 40 points to root-cause diagnosis, 20 points to scientific interpretation and prediction, 25 points to solution effectiveness and feasibility, and 15 points to stakeholder requirements and anticipated value. These criteria were refined through pilot testing, with attention to distinguishing professional competency from the separate mental-model and cognitive governance assessments.

Value orientation was evaluated by examining whether proposed solutions addressed identified root causes while considering benefits, sacrifices and resources relevant to occupants and other stakeholders. These included healthy indoor air, comfort,

convenience, safety, operational reliability, energy use, affordability and maintenance requirements, where applicable. The assessment examined whether participants justified their solutions using scientific evidence and stakeholder needs rather than proposing technically plausible interventions without considering their usefulness. Because RQ1 investigated existing professional competency through case-based assessments rather than actual building interventions, value delivery was evaluated through the independently assessed potential effectiveness and feasibility of proposed solutions. Actual improvements in occupant health or building performance were not inferred without supporting implementation evidence.

Instrument Validation, Reliability and Pilot Investigation

The assessment instruments underwent systematic validation before the main investigation. An interdisciplinary expert panel evaluated the scientific accuracy, clarity, relevance and suitability of the assessment cases and scoring criteria. Pilot cognitive interviews involving approximately 10–15 eligible FM professionals were conducted to examine whether the assessment instructions and questions were clearly understood and interpreted as intended. A separate pilot investigation involving approximately 20 professionals evaluated assessment difficulty, response variability, administration time, scoring consistency and possible floor or ceiling effects. Pilot participants were excluded from the main study sample of 120 professionals.

The instruments were evaluated to establish whether they appropriately measured scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving. Particular attention was given to distinguishing the assessment of scientific understanding, reasoning processes, independent knowledge acquisition and demonstrated professional competency. Where assessment criteria overlapped excessively or failed to capture the intended capabilities, the instruments were revised before the main investigation. Participants' individual written case investigation reports were evaluated independently by two trained assessors using the scientific benchmarks and scoring criteria established by the expert panel. An intraclass correlation coefficient of at least 0.75 was adopted as the provisional minimum target for inter-rater reliability. Assessment consistency across participants, building cases and assessors was also examined. Instruments demonstrating inadequate reliability or validity were revised and retested before the main investigation.

Data Collection and Research Procedure

The investigation began with a structured background questionnaire documenting participants' educational qualifications, professional experience, building specialisation, previous IAQ knowledge and mathematical background. Participants subsequently completed assessments of scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving.

The assessments were conducted individually in a controlled classroom setting using the standardised case reports developed for residential, educational and hospital buildings. Participants investigated unfamiliar IAQ problems using the available evidence and information resources without conducting physical building walkthroughs or on-site measurements. They documented their questions, scientific reasoning, evidence evaluation, judgements, decisions, root-cause diagnoses and proposed solutions in individual written case investigation reports.

The assessment was organised into two sessions lasting approximately three hours in total, subject to pilot validation. Assessment order and case allocation were controlled to minimise fatigue, unintended learning and differences associated with building contexts. All participants received comparable instructions, information resources and assessment conditions. No instructional feedback was provided during the investigation. A purposively selected subsample of approximately 20–24 participants, representing the three building sectors and different levels of scientific understanding and professional competency, participated in detailed reasoning interviews. These interviews examined how professionals interpreted unfamiliar problems, formulated questions, selected relevant knowledge, evaluated evidence, developed explanations and justified their decisions. Quantitative assessment results and qualitative interview findings were examined together to understand how professionals' existing scientific mental models, cognitive governance and independent learning capability were associated with their competency in diagnosing and solving unfamiliar real-life IAQ problems. These relationships were interpreted without assuming that the observed associations established causation.

Statistical Analysis and Hypothesis Testing

The primary statistical analysis investigated the relationships between scientific mental-model quality, cognitive governance and independently assessed competency in value-oriented IAQ problem diagnosis and solving. A multilevel regression model was adopted to account for repeated case assessments within participants and similarities among professionals working within the same organisation. Scientific mental-model quality and cognitive governance were included as separate primary explanatory variables, while prior IAQ knowledge, professional experience, educational background and building specialisation were considered. Differences in assessment-case complexity and building contexts were also accounted for.The null hypothesis (H_{01}) stated that scientific mental-model quality and cognitive governance were not both positively associated with professionals' competency in value-oriented IAQ problem diagnosis and solving, after accounting for relevant factors. In contrast, the alternative hypothesis (H_{11}) stated that both scientific mental-model quality and cognitive governance were positively associated with this competency. These hypotheses were tested by examining the adjusted relationships between each explanatory variable and professional competency. Support for H_{11} required statistically supported positive associations for both variables, rather than only one. Effect

sizes, 95% confidence intervals and statistical significance were reported, with attention to the strength, precision and practical importance of the relationships.

Secondary analyses examined whether these relationships differed across residential, educational and hospital buildings and whether independent learning capability provided additional explanatory information. Sensitivity analyses assessed the influence of prior knowledge, professional experience, organisational similarities, assessment reliability and alternative scoring approaches. Missing data were examined, and appropriate statistical methods were considered according to their characteristics and underlying assumptions. Qualitative interview data were analysed using a structured framework covering scientific mental models, questioning, evidence evaluation, assumptions, reasoning, judgement and decision-making. Unexpected findings were also considered. Quantitative assessment results and qualitative interview findings were integrated to examine why professionals with similar scientific understanding might demonstrate different levels of cognitive governance, independent learning capability and problem-solving competency. Because RQ1 was an observational investigation, the analysis examined relationships without assuming that scientific mental models or cognitive governance directly caused differences in professional competency.

Ethical Considerations, Scientific Limitations and Expected Contribution

The RQ1 methodology incorporated ethical safeguards for recruitment, informed consent, confidentiality, assessment fairness and responsible use of building information. Ethical approval preceded recruitment and data collection, and organisational permission covered historical building investigation records and environmental data. Assessment cases excluded identifiable building, occupant, organisational and patient information. Participation was voluntary, with informed consent covering study purpose, procedures, time commitment, confidentiality and withdrawal without professional consequences. Employer-mediated recruitment minimised perceived pressure, and individual competency results were neither disclosed to employers nor used for employment evaluation.

Assessment procedures minimised psychological discomfort arising from unfamiliar scientific concepts or mathematical relationships. Participants understood that assessments examined existing professional reasoning, not mathematical calculation skills. Standardised instructions, conditions and resources supported fairness. De-identified case reports, questionnaires and interviews were securely stored with access restricted to authorised researchers. Audio recording required separate consent; identity protection, retention and disposal followed institutional ethical and data-protection requirements.

The cross-sectional observational design investigated associations among scientific mental models, cognitive governance, independent learning capability and professional competency, without establishing causation. Prior education, professional experience,

organisational practices and other factors could influence performance; statistical adjustments, sensitivity analyses and cautious interpretation addressed these limitations. Historical case reports assessed under controlled classroom conditions demonstrated reasoning and potential solution effectiveness, not improvements in occupied buildings or observed professional practice. Interpretation remained limited to the participating FM population and investigated building contexts.

The methodology integrated established scientific models, unfamiliar real-life IAQ case reports, independent scientific benchmarks and structured professional competency assessments to investigate experienced FM professionals without formal specialist IAQ training. Mathematical equations provided scientific reasoning frameworks, not numerical calculation requirements. This approach examined whether existing scientific understanding and cognitive governance were associated with independent investigation of unfamiliar IAQ problems, root-cause diagnosis, informed judgements and decisions, and scientifically defensible solutions offering potential value to occupants and stakeholders. Crucially, RQ1 methodology distinguished possessing scientific knowledge from demonstrating its application in unfamiliar professional situations.

Methods for Research Question 2

Overview

A multicentre, two-arm, assessor-blinded, cluster-randomised educational trial compared equation-guided indoor air quality (IAQ) training with equally comprehensive non-equation training among experienced facilities management (FM) professionals following their RQ1 baseline assessment. Both groups studied indoor and outdoor pollution, including haze; pollutant sources and removal; ventilation, infiltration and filtration; concentration changes; exposure dose; biological vulnerability; and health-risk interpretation. The intervention used mass-balance and health-risk equations as scientific reasoning frameworks to strengthen mental models, cognitive governance and value-oriented IAQ problem diagnosis and solving. The control communicated equivalent scientific relationships through qualitative explanations, graphs, diagrams and case investigations without explicitly teaching equations. Training duration, learning objectives, instructional support, questioning, reflection and problem-solving opportunities were matched. Neither group was required to reproduce equations or perform mathematical calculations.

RQ1 established baseline scientific mental models, cognitive governance, independent learning capability and professional competency. Immediately after training, both groups independently investigated unfamiliar real-life IAQ problems presented through structured historical case reports. These reports differed from those used in RQ1 but were comparable in scientific complexity, evidence requirements and assessment difficulty, minimising familiarity and recall effects. Both groups received identical assessment cases, evaluated against the scientific benchmarks and competency framework established in

RQ1. The primary comparison examined adjusted between-group differences in post-training competency, while secondary analyses examined differences in mental models, cognitive governance, independent learning capability and their associations with problem-solving performance. Organisations or operational sites were randomised to minimise contamination from shared workplace practices, while individual FM professionals were assessed. Participants were analysed according to their assigned groups, accommodating realistic attendance patterns. Neither training approach was presumed superior. RQ2 informed RQ3's investigation of sustained and transferable capabilities across unfamiliar residential, educational and hospital IAQ problems.

Experimental Design and Comparison of the Intervention and Control Groups

This section described how the educational trial was organised to provide a fair and scientifically defensible comparison of equation-guided and non-equation IAQ training. It first explained the trial structure, assessment schedule and use of comparable unfamiliar historical case reports to examine participants' capabilities before and after instruction. It then outlined how participating organisations were randomly allocated, how baseline differences were documented and how the comparability of the groups was protected. Finally, it clarified the instructional distinction between the two approaches and the basis for comparing their immediate educational effects, while recognising practical constraints arising from organisational clustering and participant availability.

***Trial Structure and Assessment Schedule*:** The study used a parallel-group design with a baseline assessment obtained during RQ1 and an immediate post-training assessment administered within seven calendar days after instruction. Each group attended four three-hour sessions over two weeks, totalling 12 hours. The assessments involved unfamiliar real-life IAQ problems presented through structured historical case reports. The post-training cases differed from those used in RQ1 but were comparable in scientific complexity, evidence requirements and assessment difficulty to minimise familiarity and recall effects. Both groups received identical post-training assessment cases, evaluated using the scientific benchmarks and competency assessment framework established in RQ1. Participants independently investigated the cases and demonstrated their reasoning through individual written case investigation reports. No case-specific corrective feedback on the baseline assessments was provided before post-training assessment. The immediate outcomes were distinguished from the sustained learning and cross-context transfer investigated subsequently in RQ3.

Random Allocation and Group Comparability: Randomisation occurred at the organisation or operational-site level to reduce contamination through workplace sharing of teaching materials. The 120 FM professionals assessed during RQ1 constituted the initial recruitment pool for RQ2. A majority continued into RQ2, while additional eligible professionals were recruited to replace those unable or unwilling to participate, maintaining the target sample of 120 participants. Newly recruited participants completed equivalent

baseline assessments before randomisation, using the scientific benchmarks and assessment criteria established in RQ1. Approximately 12 organisations or operational sites, contributing an average of 10 professionals each, were targeted. Six organisational clusters were assigned to the intervention group and six to the control group in a 1:1 ratio, targeting approximately 60 participants per group. Allocation was stratified by principal building sector—residential, educational or hospital—and generated by an independent statistician following completion of recruitment and baseline measurement. Allocation was concealed until clusters and participants were enrolled. The intended sequence prevented participant preference, existing mathematical competence or anticipated learning response from influencing assignment.

Baseline distributions of professional experience, education, mathematical preparation, prior IAQ exposure, building specialisation and the four outcome scores were described separately by group. Baseline characteristics and assessment scores were also compared between continuing RQ1 participants and newly recruited professionals to identify potential differences that could influence the experimental comparison. Baseline significance testing was not used to judge the success of randomisation. Participant clustering within organisations was accounted for in estimation and uncertainty intervals, and the primary analysis followed assigned allocation irrespective of training attendance. Any departures from allocation or intervention delivery were documented.

Where clusters contained professionals working across more than one building category, each participant's principal professional responsibility was recorded, while the organisation's predominant sector informed cluster-level stratification. Sector-specific case performance was recorded independently. Randomisation was constrained to maintain reasonable balance in sector representation and cluster size across groups. The intended representation remained approximately 40 professionals from each building sector across the 120 participants. The numbers of continuing and newly recruited participants, their organisational affiliations and their baseline assessment dates were documented to support interpretation of potential recruitment-related differences. The allocation and timing of enrolment were recorded so that exclusions or withdrawals occurring after assignment could be distinguished from exclusions established before randomisation.

Experimental Contrast: Both instructional conditions covered identical scientific content concerning indoor and outdoor pollution, including haze; pollutant sources and removal; ventilation, infiltration and filtration; concentration changes; exposure dose; biological vulnerability; and health-risk interpretation. Both groups received comparable opportunities for questioning, reflection, evidence interpretation, independent learning and value-oriented IAQ problem diagnosis and solving. The intervention explicitly integrated mass-balance and health-risk equations as scientific reasoning frameworks to support the development and application of scientific mental models and cognitive governance. The control communicated the same scientific relationships through qualitative explanations, graphs, diagrams and case investigations without explicitly teaching mathematical

equations. Training duration, learning objectives, instructional support and problem-solving opportunities were matched. Neither group was required to reproduce equations or perform mathematical calculations.

The primary experimental comparison examined the baseline-adjusted between-group difference in immediate post-training competency, rather than improvements within either group alone. Secondary analyses examined differences in scientific mental models, cognitive governance and independent learning capability, including their associations with problem-solving performance. The experimental contrast therefore investigated the additional educational contribution of equation-guided scientific reasoning without presuming its superiority or equating mathematical proficiency with professional competency. Given the relatively small number of organisational clusters, statistical analyses accounted for within-organisation correlation, with appropriate caution in interpreting estimates and uncertainty intervals.

Participants, Recruitment and Training Governance

This section explained how participants were selected and prepared for a fair comparison of the two IAQ instructional approaches. It first described the eligibility criteria, baseline assessment arrangements and professional development opportunities intended to encourage voluntary participation. It then explained how training was organised and delivered consistently, including measures to minimise differences arising from instructors, learning resources and opportunities for engagement. Together, these procedures established how participants' existing capabilities were documented and how instructional delivery was managed to support a scientifically defensible comparison of the educational effects of equation-guided and non-equation training on professional learning and competency.

Eligibility and Baseline Characterisation: Eligibility followed the criteria established in RQ1. Participants had at least five years of relevant FM experience in residential, educational or hospital facilities and no prior formal specialist IAQ training. Experience involving ventilation, maintenance, occupant complaints and environmental performance was permissible and recorded. Specialist IAQ consultants, exposure assessors and health-risk modellers were excluded. Previous informal scientific or mathematical knowledge was assessed rather than used as an exclusion criterion, recognising participants' diverse professional backgrounds.

Baseline characterisation covered professional experience, qualifications, building sector, mathematical preparation, previous IAQ learning and assessment scores for scientific mental models, cognitive governance, independent learning capability and professional competency. Existing RQ1 assessment results were used for continuing participants, while equivalent baseline measurements were obtained from newly recruited professionals. This

provided a consistent basis for examining participants' starting capabilities before exposure to either instructional approach.

Participation was encouraged through complimentary professional development training designed to strengthen scientific understanding and competency in diagnosing and solving real-life IAQ problems. Both programmes offered practical learning opportunities relevant to participants' professional responsibilities. Participating organisations were encouraged to support attendance through appropriate work-release arrangements, while reasonable participation expenses could be reimbursed where applicable. Incentives were independent of assessment performance, and participation remained voluntary. Individual assessment results were not disclosed to employers. Control participants were offered access to equation-guided learning materials after completion of the study assessments.

Training Delivery and Instructor Equivalence: Standardised manuals specified matched learning objectives, scientific content, instructional duration, support, questioning, reflection and problem-solving opportunities. Qualified IAQ educators delivered both approaches, with instructor assignments balanced where feasible. Sessions were monitored for adherence. Both groups attended four three-hour sessions over two weeks, covering indoor and outdoor pollution, including haze; pollutant sources and removal; ventilation, infiltration and filtration; concentration changes; exposure dose; biological vulnerability; health-risk interpretation; and value-oriented IAQ investigation.

The intervention used mass-balance and health-risk equations as scientific reasoning frameworks to strengthen scientific mental models and cognitive governance. The control communicated equivalent relationships through qualitative explanations, graphs, diagrams and case investigations without explicitly teaching equations. Neither group was required to reproduce equations or perform mathematical calculations. Both groups received comparable instructional cases, datasets and stakeholder requirements. Within seven days after training, participants independently investigated identical unfamiliar real-life IAQ problems presented through structured historical case reports. These differed from RQ1 and instructional cases but were comparable in scientific complexity, evidence requirements and assessment difficulty. Individual written case investigation reports were submitted for blinded assessment. Analyses followed assigned groups, accounting for organisational clustering, missing outcomes and differences between continuing and newly recruited participants.

Scientific Content and Educational Intervention

This section described the scientific content and instructional approaches used to investigate whether explicit equations provided additional educational value in IAQ training. It first outlined the common scientific knowledge, real-life problems and professional competencies addressed by both groups, establishing a fair basis for comparison. It then explained how the intervention group used mass-balance and health-risk equations to

guide scientific reasoning, questioning and evidence-based decisions without requiring mathematical calculations. Finally, it described how the control group investigated the same scientific relationships through qualitative explanations and visual representations. Together, these subsections clarified the instructional differences and their intended educational contributions.

***Common Scientific Content Delivered to Both Groups*:** Both groups investigated the scientific principles governing indoor air quality (IAQ), including indoor and outdoor pollutant sources; pollutant accumulation and removal; ventilation, infiltration, filtration, deposition and adsorption; changing pollutant concentrations; exposure dose; biological vulnerability; and health risks. Instructional cases incorporated haze, cooking and cleaning emissions, air-cleaner performance and competing stakeholder needs involving health, privacy, comfort, safety, energy use, maintenance and affordability. Participants examined the underlying causes of IAQ problems and developed scientifically defensible solutions rather than relying solely on routine operating procedures. The scientific content and expected professional competencies were identical, while the approaches used to communicate and apply scientific knowledge differed.

Equation-Guided IAQ Training for the Intervention Group: The intervention used the mass-balance and logistic health-risk equations established in the RQ1 methodology as scientific reasoning frameworks for developing mental models, formulating questions, interpreting evidence, predicting outcomes and making informed judgements and decisions. The emphasis was on understanding and applying mathematical relationships rather than memorising equations or performing calculations. For example, the mass-balance equation helped participants reason about why opening windows during haze could simultaneously increase outdoor pollutant entry and increase the removal of pollutants generated indoors, requiring them to investigate which process was more influential under the prevailing conditions.

Instruction examined three pollutant concentration scenarios: the decay of an existing concentration without an active source; accumulation towards steady state under an active source; and initial decay followed by concentration changes after introducing a new source. Participants investigated how source strength, removal processes and building operating conditions influenced pollutant behaviour. They also examined limitations of well-mixed and constant-parameter assumptions and distinguished pollutant removal from air mixing. The health-risk component examined how exposure dose, biological vulnerability, their interaction and other contributing factors influenced the probability of a specified health problem within a defined period. For example, participants examined why two occupants exposed to similar pollutant doses could have different probabilities of developing the same health problem because of differences in biological vulnerability and other contributing factors. Participants considered the adequacy of available evidence, uncertainty and the distinction between statistical association and causation. Mathematical relationships supported scientific reasoning rather than numerical probability estimation.

Scientific-model-guided questioning encouraged participants to identify knowledge gaps, challenge assumptions, compare competing explanations and determine what additional evidence was needed. Where existing understanding was insufficient, participants independently identified credible technical sources, evaluated new information and refined their diagnoses. Integrated investigations required them to connect pollutant behaviour, occupant health risks and stakeholder requirements to justify practical solutions. The educational objective was to develop transferable scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving.

Non-Equation-Guided IAQ Training for the Control Group: The control group learnt the same scientific relationships through qualitative explanations, process diagrams, concentration–time graphs, environmental observations and evidence-based causal reasoning, without explicitly introducing the governing mathematical equations. For example, participants investigated the competing effects of outdoor pollutant entry and indoor pollutant removal during haze by examining concentration trends, building operating conditions and scientific explanations rather than using mass-balance equations.

Participants interpreted pollutant behaviour, examined health-risk factors, predicted possible consequences of changing conditions and justified engineering interventions using scientific understanding. The absence of explicit equations did not imply incomplete scientific instruction or reduced expectations concerning reasoning and professional competency. Both groups received equivalent opportunities to question assumptions, investigate evidence, reflect on judgements, learn independently and develop solutions. Facilitators used matched prompts addressing problem definition, underlying causes, information gaps, stakeholder requirements and unintended consequences. The experimental distinction therefore concerned whether explicitly integrating scientific equations into IAQ instruction provided additional educational value beyond equally comprehensive qualitative scientific instruction.

Assessment and Direct Comparison of Both Groups

Both groups were assessed on four outcomes: scientific mental-model quality, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving. The assessments followed the scientific benchmarks, instruments and scoring criteria established in RQ1. The primary comparison examined baseline-adjusted differences in post-training professional competency between groups, while secondary comparisons examined the other three outcomes and their associations with competency. Statistical analyses accounted for organisational clustering. Scientific mental-model quality was assessed using a 100-point scale, provisionally allocating 60 points to pollutant behaviour and 40 to exposure and health-risk understanding. Participants explained source–sink relationships, changing pollutant concentrations, steady-state conditions, scientific assumptions, exposure dose, biological vulnerability and

health-risk relationships. Scoring emphasised scientific understanding, causal explanations and predictions rather than mathematical calculations or reproduction of equations. For example, participants were assessed on whether they could explain why indoor pollutant concentrations might increase despite closed windows, considering indoor sources, outdoor infiltration and pollutant removal processes. This demonstrated whether their existing mental models could explain observed conditions and predict possible changes.

Cognitive governance was evaluated on a separate 100-point scale through participants' ability to identify and formulate problems, generate meaningful questions, examine assumptions, compare competing explanations, evaluate evidence and uncertainty, and revise judgements when necessary. The assessment focused on how participants independently governed their investigation and reasoning, rather than the correctness of their final diagnoses alone. For example, when elevated indoor pollutant concentrations had several plausible causes, participants were assessed on how they formulated questions, distinguished competing explanations and determined which available evidence could support or challenge their judgements. Independent learning capability was assessed through an information-acquisition exercise involving an unfamiliar IAQ issue and standardised resources. The 100-point scale evaluated participants' ability to recognise knowledge gaps, identify credible information, develop scientific understanding and apply newly acquired knowledge to their investigations. Performance was determined by demonstrated self-directed learning rather than information retrieval or self-reported confidence. For example, participants who lacked sufficient understanding of a pollutant removal mechanism were assessed on how they recognised this limitation, selected relevant scientific information and used what they learnt to improve their explanations or proposed solutions.

Professional competency was assessed using a provisional 100-point rubric allocating 40 points to root-cause diagnosis, 20 to scientific interpretation and prediction, 25 to feasible and effective solutions, and 15 to stakeholder alignment and anticipated value. Participants were evaluated on their ability to distinguish established causes from plausible explanations, interpret available evidence, identify information requirements and justify solutions addressing underlying problems. Multiple solutions could receive high scores when scientifically defensible and responsive to occupant needs, operational constraints, safety and affordability. For example, participants were assessed on whether they could justify an appropriate combination of source control, ventilation and air cleaning based on the diagnosed causes, anticipated effectiveness, practical constraints and potential benefits to occupants. The assessment established the potential effectiveness and value of proposed solutions rather than verified improvements in occupied buildings.

Two trained, independent assessors evaluated participants' responses using predetermined rubrics while remaining blinded to instructional allocation. An intraclass correlation coefficient of at least 0.75 served as the provisional reliability criterion, with scoring disagreements resolved without revealing group assignments. Content, response-

process and construct validity were examined to establish whether the four outcomes represented distinguishable capabilities. Assessment criteria were designed to minimise overlap between constructs and avoid favouring the instructional approach used by either group.

Intervention Fidelity and Prevention of Contamination

The implementation of both training programmes was monitored to establish whether participants received the intended instruction and whether differences in training delivery could influence the study outcomes. At least 20% of training sessions in each group were independently observed, with observations distributed across instructors and different stages of training. Standardised checklists were used to examine whether the planned scientific content, instructional activities, teaching duration and opportunities for participant engagement were delivered appropriately. Particular attention was given to whether mathematical equations were used to guide scientific reasoning in the intervention group but were not explicitly taught in the control group. Any departures from these requirements were documented, including situations where equations were unintentionally introduced during control sessions or inadequately explained during intervention sessions. Selected observation records were independently reviewed by two assessors to examine the consistency of their evaluations.

The investigation also examined whether participants obtained instructional materials or scientific information intended for the other group. Such situations could reduce the differences between the two instructional approaches and make their educational effects more difficult to distinguish. Confidential participant reports and training records were used to identify the sources, timing and extent of information sharing. Knowledge acquired before training was distinguished from additional information obtained during the investigation. Participants' mathematical anxiety, engagement, perceived learning difficulty and experiences with instructors were also examined to determine whether these factors could help explain differences in assessment performance. The documented findings were considered during sensitivity analyses to investigate whether departures from the intended training arrangements or unintended sharing of information influenced the experimental results. This provided additional evidence for interpreting whether differences in learning outcomes, or the absence of such differences, could reasonably be attributed to the instructional approaches being compared.

Sample Size, Data Collection and Data Management

This section explained how the study addressed sample size adequacy, systematic data collection and reliable data management to support a scientifically defensible comparison of the two instructional approaches. It first described how the proposed sample size, organisational clustering, statistical power and potential participant withdrawal were considered when assessing the study's ability to detect educational effects. It then

explained how assessment data were collected, documented and linked across participants while accounting for possible differences in assessment conditions. Finally, it outlined the procedures used to verify data accuracy, manage missing information, protect confidentiality and ensure transparency and reproducibility of the statistical analysis.

Sample Size and Statistical Power: The provisional sample of 120 FM professionals across approximately 12 organisational clusters was evaluated to determine whether it could provide sufficient statistical evidence for comparing the two instructional approaches. An assumed intraclass correlation coefficient of 0.03 produced a preliminary design effect of 1.27, recognising that professionals within the same organisation might share similar knowledge, experiences and working practices. Consequently, 120 participants did not necessarily provide the same statistical information as 120 independently recruited individuals. With an anticipated 15% loss of post-training assessment data, approximately 102 participants were expected to provide complete outcome data. These figures represented planning assumptions rather than actual findings.

Statistical power was examined through simulation-based calculations considering organisational clustering, baseline–post-training correlations, unequal cluster sizes, missing data and standardised intervention effects of 0.30, 0.40 and 0.50. The simulations examined whether the available sample could reliably detect differences in professional competency between the intervention and control groups, using 80% statistical power as a planning benchmark. A smaller educational effect would generally require more participants or organisations to detect reliably than a larger effect. Given the limited number of organisational clusters, statistical models incorporated appropriate small-sample adjustments to reduce the risk of misleading conclusions. The findings were interpreted using estimated effect sizes, confidence intervals and statistical uncertainty. A statistically non-significant difference was not automatically interpreted as evidence that the two instructional approaches were equally effective, particularly where the available sample lacked sufficient power to detect modest differences.

Data Collection and Assessment Sequence: Data collection followed the experimental procedures established in the preceding sections. Each participant received a unique coded identifier linking baseline characteristics, training participation and assessment responses. Organisational identifiers were retained to account for similarities among professionals from the same workplace. Assessment administration followed standardised procedures to minimise differences arising from instructions, assessment environments, task order and participant fatigue. The dates, durations and completion status of assessments were documented. This enabled the researchers to examine whether differences in testing conditions could have influenced participants' performance independently of their instructional allocation.

Particular attention was given to the time elapsed between baseline assessment and training. Continuing RQ1 participants might have completed their baseline assessments

earlier than newly recruited participants. These differences were recorded because a longer interval could influence how much participants remembered about the assessment experience or whether they independently acquired additional IAQ knowledge before training. Such information supported appropriate statistical adjustments and sensitivity analyses. Incomplete assessments, withdrawals and procedural deviations were documented alongside their available explanations. This provided a basis for distinguishing missing information arising from professional commitments or logistical difficulties from missing information potentially associated with participant experiences or assessment performance.

Data Management and Quality Assurance: Before finalising the research database, records were systematically examined for incorrect identifiers, duplicate entries, missing responses, inconsistent scores and values outside permitted ranges. These checks were conducted without access to group-specific outcome summaries to minimise the possibility of unintentionally favouring either instructional approach. A standardised data dictionary documented variable definitions, outcome scales, organisational identifiers, assessment cases and scoring procedures. Research instruments, instructional materials and assessment rubrics were securely archived using version control. Any corrections to the database were recorded with their reasons, enabling researchers to trace how the original information was processed into the final analytical dataset.

Identifiable information was stored separately from coded research data, with access restricted to authorised personnel. Missing assessment data were addressed through prespecified statistical procedures rather than automatically excluding affected participants. Sensitivity analyses examined whether alternative assumptions about missing information materially changed the findings, recognising that participants who withdrew or failed to complete assessments might differ systematically from those who remained. Together, these procedures supported the reliability, transparency and reproducibility of the experimental comparison while recognising the practical limitations of educational research involving working FM professionals.

Statistical Analysis and Hypothesis Testing

The statistical analysis investigated whether FM professionals who received equation-guided IAQ training demonstrated higher baseline-adjusted post-training performance in scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving than those who received equally comprehensive training without explicit equations.

To distinguish the educational effects of the two instructional approaches from differences in participants' starting capabilities, the statistical analysis first calculated the difference between the two groups' average post-training scores. It then estimated how participants' baseline scores were related to their post-training performance using statistical regression.

This estimated relationship (b_{ANCOVA}) was multiplied by the difference between the groups' average baseline scores to determine how much of the post-training difference could be associated with their starting capabilities. The resulting value was subtracted from the original post-training difference to obtain the baseline-adjusted difference (Δadj), providing a fairer comparison of the educational effects of the two training approaches.

$$\Delta_{\text{adj}} = \left(\overline{Y}_I - \overline{Y}_C\right) - \hat{b}_{\text{ANCOVA}}\left(\overline{X}_I - \overline{X}_C\right)$$

In this equation, (Y_I-Y_C) represented the difference in average post-training scores; (X_I-X_C) represented the difference in average baseline scores; b_{ANCOVA} represented the regression-estimated relationship between baseline and post-training scores after accounting for training allocation; and Δadj represented the resulting baseline-adjusted difference.

For example, if the intervention and control groups achieved estimated baseline-adjusted average post-training professional competency scores of 75 and 68 points, respectively, the intervention advantage would be seven points. A positive difference favoured equation-guided training, while a negative difference favoured non-equation training. This comparison was more informative than examining improvement within either group separately because both groups could benefit from training, even when one instructional approach provided no additional educational advantage over the other.

Mixed-effects analysis of covariance was used to estimate the adjusted differences for each of the four outcomes, accounting for baseline performance, building sector, mathematical preparation and similarities among professionals within the same organisation. The equation above illustrated the basic adjustment; the full statistical model estimated the instructional effect while accounting for these additional factors. Given the approximately 12 organisational clusters, appropriate small-sample statistical adjustments were applied. Results were reported using adjusted score differences, standardised effect sizes and 95% confidence intervals to communicate the magnitude, direction and uncertainty of the educational effects.

The null hypothesis (H_{02}) stated that equation-guided training did not produce greater baseline-adjusted post-training performance in at least one of the four outcomes compared with non-equation training. The alternative hypothesis (H_{12}) stated that equation-guided training produced greater performance in all four outcomes. The alternative hypothesis would be supported only when the intervention demonstrated statistically significant positive effects in every domain. An intersection–union testing procedure was applied, requiring each outcome to meet the prespecified one-sided significance threshold of 0.05. Individual outcome conclusions were also subject to appropriate multiple-testing controls.

Professional competency remained the primary outcome, while the combined four-outcome hypothesis examined whether equation-guided training demonstrated comprehensive superiority across scientific mental models, cognitive governance, independent learning capability and professional competency. A provisional difference of five points on each 100-point scale was considered potentially meaningful, subject to assessment calibration. However, statistical significance did not automatically imply practical educational importance. Similarly, failure to establish superiority did not mean that both approaches were equally effective, particularly given the limited sample size.

Secondary analyses examined whether participants who developed stronger scientific mental models and cognitive governance also demonstrated improvements in independent learning and professional competency. These analyses investigated the relationships among capability development, independent investigation, root-cause diagnosis and scientifically defensible solutions. However, such relationships were interpreted as associations rather than proof that changes in one capability caused improvements in another. Differences associated with professional experience, mathematical preparation and building sector were also examined cautiously.

Missing assessment data, training attendance and departures from instructional arrangements were examined to determine whether they could influence the findings. Sensitivity analyses investigated whether alternative assumptions concerning missing information, contamination, training fidelity and organisational differences materially changed the results. Participants remained in their assigned groups for the primary comparison. The findings were interpreted by considering the direction, magnitude, statistical uncertainty and practical importance of the observed differences. This enabled an evidence-based judgement about whether equation-guided scientific reasoning provided additional educational value beyond equally comprehensive non-equation instruction, without presuming its superiority.

Ethical Considerations, Methodological Limitations and Scientific Contribution

The RQ2 educational trial incorporated ethical safeguards concerning voluntary participation, informed consent, confidentiality, assessment fairness and responsible use of professional information. Institutional ethical approval was required before recruitment and data collection. Participation was encouraged through complimentary professional development training designed to strengthen FM professionals' scientific understanding and competency in diagnosing and solving real-life IAQ problems. Participants were informed about the study objectives, instructional approaches, assessment requirements, expected time commitments, potential benefits and their right to withdraw without professional consequences. Participating organisations were encouraged to support attendance without pressuring employees to participate. Research participation remained voluntary and was distinguished from access to professional development opportunities.

Individual competency results were not disclosed to employers or used for employment appraisal.

Both groups received scientifically accurate IAQ instruction, ensuring that neither was disadvantaged through incomplete scientific knowledge. Potential psychological discomfort, particularly mathematical anxiety and embarrassment arising from unfamiliar scientific concepts, was addressed through supportive learning environments and clear communication that mathematical calculations were not required. Participants could discontinue research activities without penalty. Training involved historical IAQ cases rather than hazardous pollutant exposure or experimental modifications to occupied buildings. Organisational permission was required for confidential building information, while identifiable occupant, patient and organisational details were removed. Assessment records were coded, securely stored and accessible only to authorised researchers. Separate consent was required for audio-recorded interviews where applicable, and data retention and disposal followed institutional ethical requirements.

Scientific limitations were recognised when interpreting the experimental findings. Participants and instructors could not be blinded to the instructional approaches, potentially influencing expectations, engagement and learning behaviour. Differences in mathematical preparation, instructor delivery and unintended information sharing could influence performance despite equivalent instructional content and duration. The equation-guided intervention combined mathematical relationships with their deliberate application to scientific reasoning; consequently, its educational effects could not be attributed solely to mathematical notation.

The limited number of organisational clusters could reduce statistical power, particularly when detecting modest educational differences. Participant withdrawal, missing assessment data and differences between continuing RQ1 participants and newly recruited professionals could introduce additional uncertainty. Mathematical equations could strengthen scientific reasoning for some participants while increasing cognitive demands for others. These possibilities were considered without assuming that equation-guided instruction was universally beneficial. Furthermore, immediate assessments using historical case reports demonstrated reasoning and potential professional competency rather than verified improvements in occupied buildings or sustained professional performance.

The expected methodological contribution involved establishing a controlled approach for investigating whether equation-guided scientific reasoning provided additional educational value beyond equally comprehensive non-equation instruction. By integrating scientific mental models, cognitive governance, independent learning capability and value-oriented IAQ problem diagnosis and solving within independently assessed unfamiliar professional cases, the methodology distinguished scientific knowledge acquisition from its application to unfamiliar real-life problems. The baseline-adjusted, cluster-aware experimental

comparison provided a framework for evaluating educational interventions while considering participant differences, implementation challenges and statistical uncertainty. The methodological contribution therefore concerned the systematic investigation of how different scientific instructional approaches influenced the development and application of transferable reasoning capabilities in professional engineering education, without presuming the superiority of either approach.

Methods for Research Question 3

Overview

A multicentre, prospective, assessor-blinded longitudinal investigation examined whether the educational effects of equation-guided IAQ training were sustained over time and transferable to unfamiliar real-life IAQ problems. Continuing the cluster-randomised trial conducted under RQ2, RQ3 retained the original intervention and control group allocations. Only RQ2 participants were eligible for follow-up, preserving the assessment history required to investigate individual changes in competency.

The three research questions differed in their purposes and assessment timing. RQ1 established participants' existing scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving. RQ2 compared the immediate educational effects of equation-guided and equally comprehensive non-equation-guided training. RQ3 investigated whether these capabilities were sustained and transferred to unfamiliar problems involving different pollutant sources, building operations, occupant vulnerabilities and stakeholder requirements. Participants completed assessments three and six months after training. At each occasion, both groups independently investigated three unfamiliar historical IAQ cases covering residential, educational and hospital buildings. The established RQ1 scientific benchmarks and assessment criteria were retained. Participants demonstrated competency through questioning, root-cause diagnosis, scientific interpretation, informed judgements and decisions, and justification of value-oriented solutions. The three-month assessment provided intermediate evidence, while the six-month assessment served as the primary hypothesis-testing endpoint.

The null hypothesis (H_{03}) stated that equation-guided IAQ training did not produce greater baseline-adjusted performance at six months than non-equation-guided training in at least one of three capabilities: cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving, as assessed through unfamiliar real-life IAQ problems. The alternative hypothesis (H_{13}) stated that equation-guided training produced greater baseline-adjusted six-month performance across all three capabilities. Scientific mental-model quality remained a secondary outcome. Sustainability was evaluated through changes in performance from immediately after training to three and six months, while transferability was evaluated through independent application of

capabilities to unfamiliar IAQ problems. The primary comparison accounted for baseline differences and organisational clustering, while considering participant withdrawal, missing assessments and additional professional learning experiences. Six-month superiority was not automatically interpreted as sustained competency. The findings concerned demonstrated professional capability and potential stakeholder value rather than verified improvements in occupied buildings or occupant health.

Longitudinal Design and Continuity of the Experimental Groups

This section explained how RQ3 preserved the experimental comparison established in RQ2 while extending the investigation across the longitudinal follow-up period. The first subsection described retention of the original cohort, continuity of group allocation, and documentation of professional experiences that could influence follow-up performance. The second specified the assessment schedule and the distinction between sustained competency and comparative superiority at three and six months. The third explained how unfamiliar IAQ problems were used to examine transfer of scientific reasoning and value-oriented problem diagnosis and solving across residential, educational and hospital contexts, while maintaining scientific comparability and independent assessment during follow-up.

Cohort Retention and Allocation: RQ3 followed the FM professionals who had entered the RQ2 educational trial, rather than recruiting a new cohort. The RQ2 target was 120 professionals across approximately 12 organisations, including a majority continuing from RQ1 and additional eligible recruits who completed equivalent baseline assessments. The enrolled RQ2 cohort formed the RQ3 follow-up pool, although some participants might withdraw or miss assessments. Actual numbers retained at three and six months were documented. No replacement participants were introduced, because newcomers would lack the earlier training and assessment history needed to examine sustained performance. Flexible scheduling supported follow-up while preserving assessment requirements.The original equation-guided and non-equation group allocations remained unchanged; organisations were not randomised again. This preserved the comparison established in RQ2 and prevented higher-performing participants from being selectively reassigned. Participants who changed employer were followed where feasible and analysed according to their original allocation.

Withdrawal, changes in employment and differences between retained and non-retained participants were recorded to assess whether loss to follow-up could distort the comparison. Baseline and immediate scores were compared between participants who completed follow-up and those who did not. No further researcher-delivered IAQ training was provided before the six-month assessment, and control participants were offered the equation-guided materials after that assessment. Ordinary workplace experience and independent learning were not restricted, because these were part of real professional practice. Relevant professional courses, IAQ investigations, changing responsibilities and

exposure to materials from the other training group were documented. Such experiences informed interpretation and supplementary analyses; they were not automatically controlled for in the main comparison, since some could themselves have resulted from the earlier training.

Assessment Schedule and Sustainability: Four assessment occasions informed the longitudinal analysis: baseline before training, immediately after training, three months and six months after training. RQ3 contributed the two delayed assessments. The three-month assessment showed whether performance appeared to consolidate, remain stable or decline; the six-month assessment was designated in advance as the principal endpoint. Prespecifying this endpoint prevented selective choice of favourable results. Actual assessment dates were recorded, and reasonable assessment windows were set in advance so that variations in professional availability did not create inconsistent follow-up periods. Sustainability meant that participants continued demonstrating scientifically defensible cognitive governance, independent learning and value-oriented IAQ problem diagnosis and solving months after instruction. Performance at three and six months was considered alongside immediate post-training results, using comparable scoring standards.

The investigation distinguished two different findings: whether participants maintained their demonstrated capabilities over time and whether the equation-guided group outperformed the control group at the follow-up assessments. A higher six-month score in the intervention group did not, by itself, establish sustainability, because both groups could have experienced substantial declines from their immediate post-training performance. Retention of capability was judged against prespecified competency criteria and the size and uncertainty of changes, not merely the absence of a statistically significant decline. The primary comparison examined baseline-adjusted differences between the originally assigned groups at six months, accounting for organisational clustering and missing assessments. Consistent performance across several cases provided stronger evidence of reliable competency than success on one task. Conclusions concerning sustainability therefore considered individual performance trajectories, the extent of competency retention and the intervention–control differences at both follow-up occasions.

Transfer Across Unfamiliar IAQ Problems: Transferability concerned whether participants could apply their understanding and reasoning independently when confronted with problems they had not previously investigated. New historical case reports therefore introduced unfamiliar combinations of pollutant sources, outdoor haze, building operations, exposure information, occupant vulnerabilities and stakeholder requirements. Participants needed to identify relevant principles, test assumptions, distinguish evidence from speculation, recognise knowledge gaps and justify solutions appropriate to the new circumstances.

Because both RQ2 groups had already studied residential, educational and hospital examples, RQ3 did not claim transfer to entirely untrained building sectors. Instead, it

examined transfer to new problems within and across these familiar sectors. Less demanding tasks involved changed circumstances with recognisable mechanisms; more demanding tasks introduced conflicting or incomplete evidence and unfamiliar combinations of constraints. These distinctions and case-difficulty criteria were established before assessment. Expert review and pilot testing supported comparability of the different case sets, reducing the risk that apparent changes in performance merely reflected easier or harder cases. Both groups received identical cases at each occasion, but different cases across occasions, with no corrective case-specific feedback. Independent assessors remained blinded to original training allocation and used the established RQ1 competency benchmarks to evaluate each report. Independently assessed case performance established potential professional value, not proven improvements in buildings or occupants' health.

Development and Scientific Validation of Transfer Cases

This section described how the unfamiliar IAQ cases used in RQ3 were developed, balanced and scientifically validated to support credible assessment of sustained and transferable competency. The first subsection explained the construction of six historical case reports from building investigations, environmental records and engineering simulations, including how evidence gaps prompted independent reasoning. The second outlined the residential, educational and hospital contexts and the procedures used to maintain scientific comparability across the three- and six-month assessments. The third described the independent expert benchmarks and value criteria used to evaluate root-cause diagnoses and proposed solutions against scientific evidence and stakeholder requirements involved.

Case Construction: A battery of longitudinal assessment cases was developed from authentic building investigations, de-identified environmental records and validated engineering simulations. Six distinct historical IAQ case reports were developed, comprising three cases for the three-month assessment and three different but comparable cases for the six-month assessment. Each assessment included one residential, one educational and one hospital case. This arrangement enabled investigation of sustained and transferable capabilities across the three building contexts while minimising familiarity with previously encountered problems. Each case presented a credible but incompletely defined IAQ problem requiring participants to investigate causes and consequences before proposing solutions. Materials included time-varying pollutant concentrations, building characteristics, source and removal conditions, occupant information and practical constraints. A case-development matrix specified the building context, scientific mechanisms, available evidence, intended knowledge gaps, stakeholder requirements and expected difficulty. This provided a systematic basis for developing and comparing the six cases.

The six cases differed from those encountered during RQ1, RQ2 and instructional activities. Scientific information was provided consistently to both groups. Missing or conflicting information was deliberately included to examine whether participants formulated meaningful questions, recognised uncertainty and identified evidence needed to distinguish competing explanations. Because the cases concerned historical investigations, participants explained what further evidence would have been useful rather than undertaking new building inspections or measurements. Cases drew upon the pollutant source–sink, changing-concentration, steady-state, outdoor pollutant entry, exposure and vulnerability relationships established in RQ1. Participants were assessed on their scientific understanding and application of these relationships rather than equation reproduction or mathematical calculations. Some cases satisfied simplified well-mixed assumptions, while others required recognition of limitations arising from changing conditions, filtration effectiveness or spatial variations. Unsupported application of scientific models was not rewarded.

Building Contexts and Scientific Comparability: Residential cases addressed haze, cooking and cleaning emissions, window operation, infiltration, air cleaning, privacy and affordability. Educational cases examined changing occupancy, classroom ventilation, outdoor pollution, equipment operation and occupant needs. Hospital cases introduced vulnerable populations, specialised ventilation and operational restrictions. Building-specific technical requirements were provided to prevent unfamiliarity with specialist practices from being mistaken for inadequate scientific reasoning. Clinical decisions remained outside participants' professional responsibilities. At three months, participants independently investigated three unfamiliar IAQ cases, one from each building context. At six months, they investigated another three cases involving different pollutant sources, operating conditions, scientific evidence and stakeholder requirements. Both instructional groups received identical cases at each assessment occasion, ensuring that differences in performance were not attributable to different assessment problems.

The cases incorporated varying levels of transfer difficulty. Less demanding problems involved familiar scientific mechanisms under changed conditions, while more demanding problems introduced unfamiliar combinations of pollutant behaviour, incomplete evidence and competing stakeholder requirements. The distribution of these difficulties was balanced across assessment occasions to distinguish changes in participants' capabilities from differences in case complexity. Expert reviewers examined scientific accuracy, evidence sufficiency, difficulty and comparability before assessment. Independent pilot participants, excluded from the main longitudinal cohort, examined instructions, completion time, reading demands, unintended clues and the adequacy of available evidence. The pilot also evaluated whether completing three investigations at each assessment occasion was manageable without excessive fatigue. Cases were revised where necessary, and their final versions were documented. Common scoring criteria and reference examples supported comparison across the six cases, while case presentation order was balanced

to minimise order effects. Participants received no answer-specific feedback that could influence subsequent assessments.

Independent Benchmarks and Value Criteria: An interdisciplinary panel comprising IAQ researchers, building services engineers, experienced FM practitioners and relevant health specialists established scientific reference diagnoses and acceptable solution criteria before participant responses were evaluated. Monitoring evidence and validated simulations supported causal explanations and predictions where available. The panel documented supported causes, scientific uncertainties and competing plausible explanations. For each case, the benchmark identified the minimum evidence needed for reliable diagnosis, acceptable scientific reasoning, relevant assumptions and practical limitations on proposed interventions.

Value-oriented performance was assessed by examining whether participants' solutions addressed supported root causes while considering occupant health, comfort, convenience, privacy, safety, energy use, operational reliability, affordability and maintenance. Stakeholder requirements were specified within each case to ensure that proposed solutions were evaluated against relevant needs rather than assessors' personal preferences. Safety-critical requirements were treated as essential constraints rather than benefits that could automatically be sacrificed for lower costs. Multiple solutions could receive high scores when their expected effectiveness, limitations and consequences were scientifically justified. Two trained independent assessors applied the predetermined benchmarks to participants' individual written case investigation reports while remaining blinded to their instructional allocation. Comparisons across the six cases examined both performance consistency and the ability to apply scientific reasoning under unfamiliar conditions. The assessments established the scientific defensibility and potential stakeholder value of proposed solutions rather than verified improvements in occupied buildings or occupant health.

Measurement of Sustained and Transferable Competency

This section explained how the RQ3 methodology measured sustained and transferable competency using the assessment framework established in RQ1 and applied in RQ2. The first subsection identified the primary outcomes, their operational definitions and the aggregation of scores from residential, educational and hospital cases at three and six months. The second described how independent assessment, scoring reliability and case comparability supported valid longitudinal interpretation. The third explained how proposed IAQ solutions were evaluated for scientific defensibility, feasibility and potential stakeholder value, while distinguishing assessed professional competency from verified implementation outcomes. Together, these procedures supported consistent interpretation of competency changes and transfer across unfamiliar problems.

Primary Outcomes and Operational Definitions: The methodology for RQ3 retained the assessment framework established in RQ1 and applied in RQ2, including the instruments, scientific benchmarks, operational definitions and scoring criteria. The methodological difference concerned the timing and purpose of their application. While RQ2 assessed immediate post-training performance, RQ3 applied the same assessment procedures three and six months after training to investigate sustainability and transferability. Three co-primary outcomes were examined: cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving. Scientific mental-model quality remained a secondary outcome. The established 100-point assessment scales were retained to maintain consistency across the research questions.

At each follow-up occasion, participants completed three unfamiliar IAQ cases, representing residential, educational and hospital buildings. The established assessment instruments were applied to each case to produce separate scores for cognitive governance, independent learning capability and professional competency. Each case therefore contributed one score on the established 0–100 scale for each co-primary outcome. For each participant, the three case scores for a given outcome were combined using an equally weighted arithmetic mean to obtain the overall outcome score at that assessment occasion. Thus, the residential, educational and hospital cases each contributed one-third of the overall score. The same procedure was applied at three and six months. The aggregation of case scores and their interpretation followed the same assessment principles established in RQ2, with case calibration supporting comparability of competency scores across assessment occasions. Incomplete case assessments were identified and addressed through the prespecified missing-data procedures rather than being treated automatically as equivalent to complete three-case assessments. Individual case scores were also retained for examining transferability and performance consistency across building contexts. This prevented an overall average from concealing substantial difficulties in particular types of unfamiliar problems.

Sustainability was evaluated by examining whether the capabilities demonstrated immediately after training were maintained, strengthened or weakened at three and six months. Transferability was evaluated by examining whether participants independently applied those capabilities to unfamiliar IAQ problems involving changed building conditions, pollutant sources, occupant vulnerabilities and stakeholder requirements. Consequently, transferability was established through demonstrated performance on unfamiliar assessment problems, rather than inferred simply because participants completed assessments several months after training. The six-month assessment served as the primary endpoint, while the three-month assessment provided additional evidence of changes in performance over time. The originally assigned intervention and control groups were compared to determine whether equation-guided training demonstrated greater sustained and transferable educational benefits.

Assessment Independence, Reliability and Comparability: The independent assessment procedures, blinded scoring arrangements and reliability criteria established in RQ1 and applied in RQ2 were retained without modification. The principal difference concerned the assessment materials. Six new historical IAQ case reports were used, comprising three at the three-month assessment and three different but comparable cases at six months. Each occasion included residential, educational and hospital problems. The scientific validation and case-calibration procedures described in the preceding section supported comparability across assessment occasions. Differences in case difficulty, participant withdrawal and missing assessment data were considered when interpreting the findings. Performance consistency across building contexts was also examined because strong reasoning in one unfamiliar case did not necessarily establish reliable competency across different professional situations.

Practical Value and Implementation Evidence: The value-oriented assessment procedures established in RQ1 and RQ2 were retained. Proposed solutions were evaluated against the existing scientific benchmarks, including their potential effectiveness, feasibility, safety and value to occupants and other stakeholders. RQ3 extended this evaluation by examining whether participants continued to demonstrate these capabilities when confronting new problems several months after training. This provided evidence of whether the application of scientific understanding and cognitive governance remained dependable beyond immediate instruction. Where suitable technical evidence was available, the predicted effectiveness of proposed solutions was examined using existing measurements, validated simulations or engineering appraisal. As in RQ2, the assessments distinguished scientifically defensible proposed solutions from verified improvements following actual implementation. The findings therefore concerned sustained and transferable professional competency, rather than demonstrated reductions in pollutant exposure or improvements in occupant health.

Follow-Up Procedures and Professional Experience

RQ3 applied the assessment procedures established in RQ1 and RQ2 at three and six months after training. This section describes the practical administration of the follow-up assessments, documentation of participants' professional experiences and collection of supplementary interview evidence. The assessment outcomes, scoring procedures and scientific validation of the cases were addressed in the preceding sections. Both instructional groups completed their follow-up assessments under equivalent conditions. Assessment sessions were provisionally organised into approximately three hours across two sittings, subject to pilot confirmation of the time required to complete the investigations. Assessment dates, completion times and deviations from the standardised procedures were recorded. Reasonable scheduling flexibility accommodated professional commitments without changing assessment requirements. Coded participant and organisational identifiers enabled follow-up results to be linked with baseline and immediate post-training records while protecting confidentiality. Individual assessment

results were not disclosed to employers. No corrective case-specific feedback or researcher-delivered refresher training was provided before the six-month assessment.

Professional experiences occurring between the immediate post-training assessment and the three- and six-month follow-ups were documented to support interpretation of longitudinal changes in competency. Structured activity records captured relevant IAQ investigations, additional professional training, independent learning activities, changes in responsibilities and exposure to instructional materials associated with the alternative group. Participants completed these records at both follow-up occasions, supplemented by available attendance and contact records. Where relevant, participants described the nature and extent of their involvement in these activities, allowing researchers to distinguish occasional exposure from substantial professional engagement. Reported experiences were treated as contextual evidence rather than substitutes for independently assessed competency. Participants who changed employers, professional responsibilities or building sectors remained in their originally assigned instructional groups and were invited to complete the scheduled assessments. Changes in employment circumstances, difficulties attending assessments and reasons for withdrawal were documented to examine whether professional circumstances contributed to differences in follow-up participation. Participants could also report challenges encountered when applying scientific understanding to unfamiliar IAQ problems, including uncertainty, difficulty interpreting scientific information and mathematical anxiety. These experiences informed the interpretation of assessment findings but did not alter participants' competency scores.

Following completion of the six-month assessments, a purposive subsample was invited to participate in interviews. Selection sought variation in instructional allocation, building specialisation, baseline preparation and observed performance. A common semi-structured interview guide was used to explore participants' professional experiences since training, the circumstances in which they applied their learning and the difficulties they encountered. Participants were asked how they recognised relevant scientific principles, identified knowledge gaps, obtained additional information, addressed uncertainty and justified professional decisions. Interviews were conducted only after the primary assessment to prevent interview questions from inadvertently coaching participants before their competency was evaluated. Interview findings were examined alongside the longitudinal assessment results and documented professional experiences to help explain patterns of sustained or changing performance. They provided supplementary insight into how participants perceived and applied their learning in professional practice, without replacing the controlled comparison between the original intervention and control groups.

Statistical Analysis and Hypothesis Testing

This section explained the statistical procedures used to evaluate RQ3 outcomes and test whether equation-guided training produced greater sustained and transferable competency than non-equation-guided training. The first subsection addressed sample size, statistical

power, participant retention and missing data. The second described baseline-adjusted comparisons between the original groups at three and six months. The third explained joint hypothesis testing and the distinction between six-month superiority and sustained competency. The fourth outlined analyses of transferability, explanatory factors and sensitivity to alternative assumptions. The fifth described how qualitative interview findings were analysed and integrated with longitudinal results to support interpretation without overstating causality.

Sample Size, Power and Missing Data: Methodology for RQ3 followed the cohort enrolled in RQ2, which targeted 120 FM professionals across approximately 12 organisations, with six organisational clusters allocated to each instructional group. No additional participants were recruited, preserving individual training and assessment histories. Assuming 25% attrition by six months, approximately 90 participants were expected to complete the primary assessment. Retention at three months was also recorded, with actual participant numbers reported separately at both follow-ups. These figures were planning assumptions, not observed results.

Power was evaluated through simulations reflecting the original cluster randomisation, repeated observations and three co-primary outcomes. Scenarios considered intraclass correlations of 0.01–0.08, baseline–follow-up relationships, correlations among outcomes, unequal cluster sizes, 15%–30% attrition and standardised intervention effects of 0.30–0.50. The desired 80% power for joint superiority was a planning benchmark rather than an assumed property of the available sample. The limited number of organisational clusters constrained statistical precision, particularly for modest effects. Missing outcomes and reasons for non-completion were recorded by instructional group, organisation and assessment occasion, including both three and six months. Baseline and immediate post-training characteristics of retained and lost participants were compared descriptively. No replacement participants were introduced. Loss of an entire organisation was distinguished from isolated individual non-response because it affected the available independent clusters.

Primary Three- and Six-Month Comparisons: The analysis estimated baseline-adjusted intervention–control differences at both three and six months for cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving. The three-month comparison assessed the earlier follow-up advantage, whereas the six-month comparison evaluated longer-term performance and constituted the primary endpoint for hypothesis testing. For each outcome, the primary analysis used the participant's overall follow-up score derived from the three equally weighted building-context cases, as specified in the measurement procedures. Case-level scores were retained for supplementary analyses of performance variation across building contexts.

The mixed-effects approach established in RQ2 was extended to analyse immediate post-training, three-month and six-month observations, with corresponding baseline scores

included as covariates. The model included instructional allocation, assessment occasion, their interaction, prespecified randomisation strata and random effects addressing repeated measurements within participants and clustering within organisations. Case-difficulty effects were considered where supported by validation evidence. Separate adjusted differences were estimated at three and six months. Changes from immediate post-training to three months, from three to six months, and across the entire follow-up period were also examined. These analyses distinguished retention or decline within each group from superiority between groups. Immediate post-training scores were used to describe trajectories, not as adjustment covariates in the primary six-month contrast, because training had already influenced them. Adjusted differences, standardised effects, 95% confidence intervals and model diagnostics were reported, with small-sample corrections and cluster-level sensitivity checks.

Joint Hypothesis Testing and Sustainability: The RQ3 null hypothesis (H_{03}) stated that equation-guided training did not outperform non-equation-guided training at six months in at least one of the three co-primary outcomes. The alternative hypothesis (H_{13}) required superiority in all three. An intersection–union procedure used a one-sided significance level of 0.05 for each component; the joint claim was supported only when all three adjusted six-month contrasts were positive and met their inferential criteria. Three-month group contrasts were reported as prespecified secondary comparisons, with effect estimates and confidence intervals. Separate confirmatory claims for individual outcomes or additional time points were subject to appropriate multiplicity control. Failure to demonstrate joint superiority did not establish equivalence. A provisional five-point difference on the 100-point scales was considered for practical significance, subject to validation of its professional meaning. Sustainability was judged from the size and uncertainty of changes across the immediate, three-month and six-month assessments, together with consistency across unfamiliar cases. A non-significant decline alone was not considered proof that competency had been maintained.

The six-month hypothesis test established whether equation-guided training produced superior performance across the three capabilities when participants investigated unfamiliar IAQ problems. Sustainability was evaluated separately through participants' performance trajectories from immediately after training to three and six months, considering prespecified competency criteria and the magnitude and uncertainty of changes. Transferability was evaluated through the application of these capabilities to unfamiliar assessment cases at both follow-ups. Consequently, evidence of six-month superiority was interpreted together with evidence of competency retention and transfer, rather than being treated as sufficient proof of both. Where the intervention group retained a six-month advantage despite substantial deterioration in its own performance, the findings were interpreted as evidence of comparative superiority but not necessarily successful maintenance of competency. Similarly, improvements in individual performance

did not establish superiority unless supported by the direct intervention–control comparison.

Transferability, Explanatory and Sensitivity Analyses: Transferability was assessed at both follow-ups through performance on the three new residential, educational and hospital cases administered at each occasion. Secondary analyses explored whether instructional effects varied by building context or problem novelty; these comparisons remained exploratory because the study was not powered separately for every case type. Scientific mental-model quality was retained as a secondary outcome. Associations between follow-up performance and baseline preparation, mathematical confidence, earlier mental-model development and subsequent professional learning opportunities were explored without interpreting post-randomisation associations as causal effects.

Sensitivity analyses examined alternative clustering assumptions, case-difficulty adjustment and missing-data mechanisms. Likelihood-based methods or multiple imputation were used where their missing-at-random assumptions were defensible, with sensitivity analyses exploring plausible departures. Differential attrition at three and six months, contamination and unequal professional learning opportunities informed interpretation but did not replace the primary analysis by original randomised allocation.

Qualitative Analysis and Integration: The post-six-month interviews described in the follow-up procedures were analysed using a theory-informed coding framework addressing scientific understanding, questioning, independent learning, diagnosis and value-oriented decisions. The framework accommodated unexpected explanations and contradictory evidence. A subset of transcripts was independently coded, and disagreements were documented. Interview findings were examined alongside individual trajectories across the immediate, three-month and six-month assessments and adjusted group comparisons to explore why performance persisted, improved or weakened, including contrasting patterns across building contexts. Interviews supplied contextual explanations, not independent causal evidence that the instructional intervention produced the observed differences.

Ethical Considerations, Limitations and Scientific Contribution

RQ3 methodology followed the ethical approval and safeguards established for RQ1 and RQ2 methodologies, with additional provisions for repeated contact and longitudinal data linkage. Participants received clear information about the three- and six-month assessments, activity records and optional interviews, and provided informed consent for these activities. Participation remained voluntary, independent of employment appraisal, and withdrawal carried no professional penalty. Recruitment and follow-up communications avoided employer pressure; managers neither selected participants on the basis of performance nor received individual scores. Identifiable contact details and the code linking participants' records across assessment occasions were stored separately from scored reports, with access restricted to authorised researchers. Electronic records were

secured using institutionally approved storage, access controls and retention procedures. Publications reported aggregated findings, suppressing potentially identifiable combinations of organisation, role and building sector. Interview quotations were reviewed for indirect identification risks. Participants were informed of the limits of withdrawing data already irreversibly anonymised or included in completed analyses.

Historical building records were de-identified before assessment, including information potentially identifying occupants, patients, staff and facilities. Hospital cases excluded identifiable clinical records. Organisational permission was required for any supplementary access to facility information, with no disclosure of confidential operational or security details. No pollutant exposure was deliberately induced, and researchers did not implement participants' proposed interventions in occupied buildings. Any immediate safety concern identified from genuine records was handled through the institutionally approved reporting procedure rather than treated solely as assessment material. Both groups received substantive IAQ training; equation-guided materials were offered to the control group after the six-month assessment. Standardised assessment conditions reduced unfair differences, while reasonable scheduling accommodated employment responsibilities. Participants could decline interviews and report discomfort, including mathematical anxiety, without adverse consequences.

The approximately 12 organisational clusters limited statistical power, particularly after attrition. Differential withdrawal, cross-group sharing of instructional materials and unequal workplace learning opportunities could influence observed differences. Neither participants nor instructors had been blinded to instructional format, although assessors remained blinded. Case calibration reduced, but could not eliminate, differences in difficulty. Written investigations represented potential capability under structured conditions, not guaranteed performance in workplaces. Since all three building sectors appeared in training, transfer concerned unfamiliar problems within those sectors, not wholly new domains. Observed performance through six months could not establish lifelong learning or verified improvements in occupant health. RQ3 extended RQ2's immediate comparison into a cluster-aware longitudinal evaluation with matched assessment procedures and distinct unfamiliar cases at three and six months. It distinguished changes within participants from intervention–control differences, and retained competency from transfer across cases. The primary causal inference concerned assignment to the instructional approach, not equations in isolation; proposed psychological mechanisms remained exploratory. Positive, null or adverse results could therefore refine how sustained, value-oriented IAQ professional competency was investigated.

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Research Findings

Findings for Research Question 1

Overview

The investigation examined the existing scientific mental models, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving among experienced Facilities Management (FM) professionals without formal specialist IAQ training. Scientific mental models described how professionals understood pollutant behaviour, while cognitive governance described how they formulated questions, evaluated evidence and guided their reasoning. The investigation considered whether these capabilities helped explain differences in professional competency when participants encountered unfamiliar IAQ problems. The study involved 120 FM professionals from 12 organisations, equally representing residential, educational and hospital buildings, with 40 participants from each sector. Each professional investigated three historical IAQ cases involving indoor and outdoor pollution, ventilation, filtration, pollutant exposure, biological vulnerability and health risks. Each of the 120 FM professionals was expected to investigate three unfamiliar IAQ cases, comprising one residential, one educational and one hospital building case. Of the 360 expected case investigations, 357 were completed (99.2%). All 120 professionals provided assessment data, although three completed only two cases.

The results showed differences in participants' existing capabilities. Scientific mental-model quality averaged 58.3 out of 100, cognitive governance 55.3, independent learning capability 54.8, and competency in value-oriented IAQ problem diagnosis and solving 57.8. These scores reflected performance against established assessment criteria rather than percentages of correct answers. Without validated competency thresholds, they did not establish whether individual professionals were competent or incompetent. The primary analysis found that both scientific mental-model quality and cognitive governance were positively associated with professional competency after accounting for participant characteristics, organisational similarities and differences in assessment cases. Examination of the case reports also revealed that understanding individual scientific principles did not always translate into the ability to connect them when indoor conditions changed. Some professionals recognised possible pollutant sources but did not sufficiently investigate competing explanations or justify their proposed solutions. The results therefore highlighted a distinction between possessing scientific knowledge and applying it through questioning, evidence evaluation, sound judgement and informed decision-making. Because the study was observational, these associations did not establish causation.

Participant Characteristics and Assessment Reliability

The 120 simulated participants had an average of 11.1 years of relevant FM experience, with a standard deviation of 3.6 years. This meant that participants typically had around 11 years of experience, although individual experience varied. All satisfied the minimum five-year experience requirement. Thirty-four participants (28.3%) reported prior IAQ knowledge acquired outside formal specialist training, while 68 (56.7%) held tertiary

qualifications. Their responsibilities included building operation, maintenance, indoor environmental conditions, occupant complaints and building-performance management. These details mattered because experience, education and prior exposure to IAQ problems could influence assessment performance. Recruitment included 40 professionals each from residential, educational and hospital buildings. This allowed the investigation to consider all three sectors without one sector dominating the results. However, equal representation did not mean that the sample represented all FM professionals. People whose employers supported participation, or whose schedules permitted it, might differ from those who did not participate.

Assessment reliability concerned whether two independent assessors gave similar scores when evaluating the same written case investigations. This mattered because an apparent difference between participants could reflect inconsistent marking rather than a genuine difference in capability. The final assessment score was determined by averaging the two independent assessors' scores, with substantial scoring disagreements resolved through a predefined adjudication procedure. Inter-rater intraclass correlation coefficients (ICCs) were 0.84 for scientific mental models, 0.77 for cognitive governance, 0.83 for independent learning and 0.81 for professional competency. ICC values closer to 1 generally indicate stronger agreement. All four estimates exceeded the provisional target of 0.75. The corresponding 95% confidence intervals were 0.77–0.88, 0.70–0.83, 0.77–0.87 and 0.75–0.86, respectively. These intervals indicated the uncertainty surrounding the estimated agreement. In particular, cognitive governance could have reliability below the target because its interval included values below 0.75. Furthermore, agreement between assessors did not prove that the four capabilities were measured accurately. Independent scientific benchmarks and distinct scoring criteria remained necessary to prevent overlapping marks from making the relationships between mental models, cognitive governance and professional competency appear stronger than they were.

Existing Scientific Mental Models of Indoor Pollutant Behaviour

The assessment examined whether experienced FM professionals understood how indoor pollutant concentrations changed in response to pollutant sources and removal processes. Importantly, participants were neither exposed to nor trained in the mathematical equations during RQ1. The expert panel's agreed scientific understanding and interpretation of the established equations provided the basis for developing scientific reference standards, which were used to design the assessment cases and evaluate participants' existing understanding and reasoning. Participants were not required to reproduce mass-balance equations or perform advanced mathematical calculations. Instead, they were assessed on whether they could interpret the physical relationships represented by those equations and use them to explain unfamiliar building conditions. The equations described why concentration rose when pollutant addition exceeded removal, fell when removal exceeded addition, and remained unchanged when the rates were equal. They also described how quickly concentration changed.

Of the 120 professionals assessed, 83 (69.2%) correctly explained that indoor pollutant concentrations increased when pollutant addition exceeded removal and decreased when removal exceeded addition. A larger proportion, 93 (77.5%), correctly explained the gradual reduction in concentration when no active pollutant source was present and removal continued. This reflected the concentration-decay equation: as less pollutant remained, its removal slowed. The explanation assumed no new pollutant entry. These percentages represented the proportions of participants whose explanations satisfied the established scientific assessment criteria. Understanding was less consistent when active sources and changing conditions were introduced. Seventy-three participants (60.8%) correctly explained why concentration progressively approached a steady-state value under constant source strength and removal conditions. At steady state, pollutant addition and removal continued at equal rates, leaving concentration unchanged. Only 57 participants (47.5%) satisfactorily explained the more complex situation in which an existing pollutant concentration initially decreased before a new source became active.

This connected the decay and accumulation equations provided in the methodology. Participants needed to recognise that, after source introduction, the concentration left over from the earlier period continued to decrease while the new source made a growing contribution towards its own steady-state level. Both contributions determined the total concentration at each subsequent time. The total could initially rise or fall, depending on the remaining concentration and the new source–removal balance. The lower proportion of satisfactory responses therefore suggested greater difficulty combining scientific mechanisms than describing them separately. In everyday terms, about seven in ten professionals understood the basic addition–removal relationship, but fewer than half could explain the more complex situation involving a newly introduced pollutant source.

Similar differences emerged in the interpretation of building-system characteristics. Sixty-two participants (51.7%) satisfactorily explained why a filter with high pollutant removal efficiency might still provide inadequate air cleaning when insufficient airflow passed through it. This reflected the relationship between airflow rate, pollutant-specific filtration efficiency and clean air delivery rate: high filtration efficiency alone did not guarantee effective pollutant removal. Seventy-one participants (59.2%) recognised that increasing outdoor ventilation could remove indoor pollutants while simultaneously introducing outdoor pollution, while 69 (57.5%) considered pollutant entry through building-envelope gaps and cracks. These findings related to the extended mass-balance equations, which accounted for outdoor pollutant entry alongside indoor pollutant generation and removal. During haze, the resulting indoor concentration depended on the interacting effects of indoor and outdoor pollution, airflow rates and pollutant penetration.

Overall, more participants explained individual physical processes than the combined consequences of several interacting processes under changing conditions. This distinction was important for professional competency: knowing the function of a ventilation system or filter was insufficient to establish why pollutant concentrations were elevated in a particular

building. These findings helped explain the average scientific mental-model quality score of 58.3 out of 100 reported in the overview. However, the assessment results alone could not establish how participants organised scientific knowledge in their minds or identify the cognitive processes responsible for their performance.

Existing Mental Models of Exposure and Health Risk

The investigation also examined professionals' understanding of the relationships between indoor pollutant concentration, cumulative inhaled pollutant mass, biological vulnerability and the probability of developing a specified health problem within a defined period. As with the pollutant behaviour assessment, participants were not taught or required to use the exposure and health-risk equations. These equations served as scientific reference standards for assessing their existing understanding. This followed the scientific relationship between the concentration of pollutants in indoor air, the amount inhaled by an occupant and the probability of a particular health problem occurring. These were related but distinct concepts.

Eighty-one participants (67.5%) correctly recognised that cumulative inhaled pollutant mass could be estimated by multiplying the average concentration during each time interval by its duration and the inhalation rate, then summing the contributions. This reflected the exposure summation equation in the methodology, which accounted for changing pollutant concentrations over time. The resulting value represented the total pollutant mass inhaled, rather than necessarily the amount absorbed by the body. Seventy-three participants (60.8%) satisfactorily distinguished pollutant concentration, individual exposure and health-risk probability. A high pollutant concentration at a particular moment did not, by itself, establish how much pollutant an occupant inhaled over time or the probability of developing a health problem.

Ninety-two participants (76.7%) recognised that people experiencing comparable pollutant exposures could have different probabilities of developing the same health problem because of differences in biological vulnerability and other contributing factors. This reflected the logistic health-risk model, which considered exposure dose, biological vulnerability, their interaction and other relevant factors in estimating the probability of a specified health problem within a defined period. The model provided a framework for scientific reasoning rather than validated clinical predictions. The higher proportion recognising vulnerability, compared with the proportion distinguishing concentration, exposure and health-risk probability, suggested that understanding a general health-risk principle was more common than explaining the complete scientific relationships involved. However, these aggregate results did not identify which individual participants demonstrated both capabilities.

In the professional risk-assessment tasks, 78 participants (65.0%) adequately distinguished the likelihood of a specified health problem occurring from the severity of its

potential consequences. However, only 72 participants (60.0%) satisfactorily justified their resulting risk classifications using the available evidence and predefined likelihood and severity rating scales. Likelihood concerned the chance of a health problem occurring, while severity concerned how serious its consequences would be. Their ratings were combined using the professional risk matrix to support intervention prioritisation. However, the resulting risk rating was not a scientifically calculated probability of illness. A participant might therefore recognise that vulnerable occupants required attention but still provide insufficient justification for the likelihood rating, severity rating or priority assigned to an intervention. Taken together, these findings suggested that recognising individual scientific concepts was generally easier than connecting several concepts to support evidence-based judgement and informed decision-making under uncertainty. They represented performance in unfamiliar case-based assessments, not evidence that participants accurately predicted actual disease occurrence or delivered verified health benefits.

Cognitive Governance in Unfamiliar IAQ Investigations

While the preceding section examined what professionals understood about pollutant behaviour and health risks, cognitive governance examined how they used their existing understanding to guide their investigations, reasoning, judgements and decisions. Cognitive governance was assessed through participants' ability to independently formulate meaningful questions, investigate alternative explanations, evaluate evidence, recognise uncertainty and justify their judgements and decisions. The average cognitive governance score was 55.3 out of 100, with a standard deviation of 12.0. This meant that the average participant achieved 55.3 points against the established assessment criteria, although individual scores varied. The standard deviation indicated how widely participants' scores differed around that average. The score did not represent the percentage of questions answered correctly or automatically indicate professional incompetence.

Seventy participants (58.3%) satisfactorily formulated questions that could guide their investigations. However, only 59 participants (49.2%) adequately examined competing explanations, while 65 (54.2%) explicitly recognised important uncertainties affecting their diagnoses. These percentages represented the proportions of the 120 professionals whose responses satisfied the relevant assessment criteria. The results indicated that formulating relevant questions was not necessarily accompanied by systematic examination of alternative causes. For example, a professional investigating elevated indoor $PM_{2.5}$ concentrations might correctly question whether cooking emissions were responsible but fail to investigate outdoor infiltration, ventilation operation or inadequate filtration as competing explanations.

The distinction concerned whether professionals could govern their thinking beyond their initial assumptions. Effective cognitive governance required questions that helped distinguish plausible explanations, identify missing information and support reliable judgements. Recognising uncertainty was also important because reaching a confident

conclusion without sufficient evidence could lead to an inappropriate intervention. The findings suggested that differences in cognitive governance could help explain why professionals possessing comparable scientific knowledge might demonstrate different levels of diagnostic competency. However, these descriptive results did not establish such a relationship independently of other factors. The primary statistical analysis was required to examine whether cognitive governance remained associated with professional competency after accounting for scientific mental-model quality and other relevant characteristics.

Independent Learning Capability

Independent learning capability differed from scientific mental models and cognitive governance. Scientific mental models concerned existing understanding, while cognitive governance concerned how professionals guided their reasoning. Independent learning examined what professionals did when their existing knowledge was insufficient to investigate a problem. Independent learning capability was assessed through participants' ability to recognise missing knowledge, identify appropriate information resources, evaluate their credibility and apply newly acquired understanding to unfamiliar IAQ investigations. The average independent learning score was 54.8 out of 100, with a standard deviation of 12.8. This indicated an average performance of 54.8 points against the independent learning assessment criteria, with considerable differences among participants. Sixty-six participants (55.0%) satisfactorily identified and evaluated relevant scientific or technical information resources. However, only 62 participants (51.7%) demonstrated adequate application of the acquired information to advance their investigations.

These results showed that slightly more professionals could identify credible information than demonstrate its appropriate application. However, the aggregate percentages did not establish that the same individuals succeeded or struggled with both activities. For example, identifying the need for filtration performance information demonstrated awareness of a knowledge gap. However, independently obtaining relevant airflow and pollutant removal efficiency information, evaluating its reliability and explaining its implications for indoor pollutant concentration demonstrated a more complete application of independent learning capability. The findings therefore distinguished access to information from the ability to transform newly acquired information into useful scientific understanding that could improve problem diagnosis, judgement and decision-making. Nevertheless, performance in the structured assessment was interpreted as evidence of readiness for independent learning under the investigated conditions. It did not establish that participants consistently demonstrated lifelong learning capability throughout their professional practice.

Competency in Value-Oriented IAQ Problem Diagnosis and Solving

Professional competency represented a further distinction. While scientific mental models examined what participants understood, cognitive governance examined how they governed their investigations, and independent learning examined how they addressed knowledge gaps, professional competency assessed how effectively and consistently participants brought these capabilities together to diagnose unfamiliar IAQ problems and propose scientifically defensible, feasible solutions of potential value to stakeholders. Professional competency was evaluated through independently assessed written case investigation reports covering root-cause diagnosis, scientific interpretation and prediction, intervention effectiveness and feasibility, and anticipated value to occupants and other stakeholders.

The overall competency score averaged 57.8 out of 100, with a standard deviation of 10.1. The score reflected overall performance against four weighted competency requirements, not a percentage of correct answers. Root-cause diagnosis averaged 23.0 out of 40, scientific interpretation and prediction 11.6 out of 20, intervention effectiveness and feasibility 14.5 out of 25, and stakeholder alignment and anticipated value 8.8 out of 15. The different maximum scores reflected the importance assigned to each competency component. For example, root-cause diagnosis contributed 40% of the overall score because identifying why an IAQ problem occurred was fundamental to proposing an appropriate solution. Differences between component scores could not establish which capability was strongest without considering their scoring criteria and reliability. Fifty-eight participants (48.3%) demonstrated sufficiently supported root-cause diagnoses, while 71 (59.2%) proposed technically justified interventions. Only 53 (44.2%) satisfactorily incorporated stakeholder requirements into their solution justifications.

These findings suggested that proposing a technically plausible intervention was more common than providing a sufficiently supported root-cause diagnosis or addressing stakeholder requirements. For example, recommending additional air cleaning could be reasonable, but its effectiveness depended on pollutant characteristics, source strength, clean air delivery rate and existing ventilation conditions. Its value also depended on occupant needs, safety, affordability, energy use, maintenance and operational constraints. The distinction was important because a technically reasonable solution might fail to address the actual causes of a problem or impose unacceptable sacrifices on stakeholders. Value-oriented competency therefore required evidence-based diagnosis, feasible interventions and justification of their expected usefulness. Although these capabilities were related, their separate assessment criteria were intended to minimise overlapping scores that could exaggerate their statistical associations. Importantly, the findings concerned the scientific defensibility and anticipated value of proposed solutions, not verified improvements in building performance or occupant health.

To examine the extent to which professional competency was demonstrated consistently across different building contexts, participants' performance was also investigated in relation to their professional specialisation and the characteristics of the residential,

educational and hospital assessment problems. Two distinctions were important: the building sector in which professionals worked and the building type represented in the assessment cases. Since participants investigated unfamiliar residential, educational and hospital cases, these comparisons addressed different questions. The mean competency scores were 56.5 out of 100 among professionals employed in residential buildings, 60.0 among those from educational buildings and 56.9 among those from hospitals. These scores represented the average competency of 40 professionals from each employment sector, rather than their performance on a particular building case.

Although educational-sector professionals scored 3.5 points higher than residential-sector professionals on average, this difference alone did not establish that they possessed greater competency. After adjusting for scientific mental-model quality, cognitive governance, prior knowledge, education and professional experience, the associations between employment sector and competency were not statistically distinguishable from zero. This meant that the analysis did not establish a reliable difference in competency associated with employment sector after considering these other factors. It did not prove that the sectors were equivalent. When performance was examined according to the building types represented in the assessment cases, mean scores were 58.8 for residential problems, 58.8 for educational problems and 55.7 for hospital problems. These scores described how participants performed when investigating each type of building, regardless of their employment sector.

The adjusted analysis indicated that performance on the hospital case was approximately 2.95 points lower than on the educational case (95% confidence interval: −4.71 to −1.20; $p = 0.001$). The confidence interval indicated the range of differences compatible with the statistical model and data, while the small p-value provided evidence that the difference was unlikely to be explained by random sampling variation alone under the model assumptions. However, this did not establish that hospital IAQ problems were generally more difficult. Hospital cases involved vulnerable occupants, specialised operational requirements and additional safety constraints. Because each building context was represented by a particular assessment case, differences in case difficulty could have influenced performance. More independently calibrated cases would be needed to establish whether the finding extended beyond the problems investigated. Furthermore, differences in average competency scores between building contexts did not, by themselves, establish how consistently individual professionals performed across the three contexts. Such consistency required examining the variation in each participant’s performance across the unfamiliar residential, educational and hospital cases, while accounting for potential differences in case difficulty and assessment reliability.

Relationships Between Scientific Mental Models, Cognitive Governance and Professional Competency

While the preceding findings described participants' existing capabilities, the primary statistical analysis examined how these capabilities were related. Specifically, it investigated whether professionals with stronger scientific mental models and cognitive governance also demonstrated greater competency in diagnosing and solving unfamiliar IAQ problems. The multilevel analysis incorporated 357 case investigations from 120 professionals across 12 organisations. Because each professional investigated multiple cases, and professionals within the same organisation could share similar experiences, the investigations were not treated as completely independent observations. The analysis accounted for repeated case assessments, organisational similarities, differences between cases, educational background, prior IAQ knowledge, years of professional experience and employment sector.

The adjusted results showed that a 10-point higher scientific mental-model score was associated with an average 3.50-point higher professional competency score on the 100-point scale (95% confidence interval: 2.67–4.34; $p < 0.001$), after accounting for cognitive governance and other relevant factors. For example, professionals scoring 70 rather than 60 in scientific mental-model quality were estimated to score approximately 3.50 points higher in professional competency, assuming other measured factors were comparable. This represented an average statistical relationship, not a prediction that every professional would achieve the same difference. Similarly, a 10-point higher cognitive governance score was associated with an average 3.93-point higher professional competency score (95% confidence interval: 3.04–4.83; $p < 0.001$), after accounting for scientific mental-model quality and other factors. This meant that professionals who demonstrated stronger questioning, evidence evaluation and justification of judgements and decisions tended to achieve higher competency scores, even when their scientific understanding was considered. The confidence intervals indicated the precision of these estimated relationships, while the p-values provided statistical evidence against the absence of an association.

The findings therefore indicated that scientific mental-model quality and cognitive governance provided distinct but related information about professional competency. Possessing scientific understanding was not equivalent to effectively governing an investigation, although both capabilities were positively associated with competency. The associations remained positive in a supplementary analysis accounting for similarities among professionals within the same organisation and the relatively small number of organisations. The corresponding estimates were 3.59 points per 10-point increase in scientific mental-model quality (95% confidence interval: 2.73–4.45) and 4.20 points for cognitive governance (95% confidence interval: 3.68–4.73). The similar results strengthened confidence that the associations were not dependent on one statistical approach, although they could not eliminate unmeasured influences. Both associations satisfied the positive-association requirements of the RQ1 alternative hypothesis (H_{11}). Consequently, the null hypothesis (H_{01}) was rejected in the hypothetical analysis. However,

because RQ1 was observational, these findings established statistical associations rather than demonstrating that stronger mental models or cognitive governance caused greater professional competency.

Additional Contribution of Independent Learning Capability

Secondary analysis examined whether independent learning capability provided explanatory information beyond scientific mental-model quality and cognitive governance. This was important because professionals could possess scientific understanding and formulate relevant questions but still require additional knowledge to investigate unfamiliar problems reliably. A 10-point higher independent learning score was associated with an additional 0.98-point higher professional competency score (95% confidence interval: 0.16–1.80; $p = 0.019$), after adjusting for the other explanatory variables and participant characteristics. For example, professionals scoring 70 rather than 60 in independent learning were estimated to achieve approximately one additional competency point, assuming other measured characteristics were comparable.

Although smaller than the other estimated associations, this positive relationship indicated that independent learning provided additional statistical information about competency. Including independent learning reduced the estimated mental-model association from 3.50 to 3.38 points per 10-point increase and the cognitive governance association from 3.93 to 3.53 points. Both remained positive and statistically supported. These findings suggested that independent learning contributed additional explanatory information without eliminating the relationships involving scientific mental models and cognitive governance. Together, the three capabilities were positively associated with professional competency. However, the analysis could not establish which capability influenced another or whether other unmeasured factors contributed to their relationships.

Statistical Robustness and Scientific Limitations

The findings showed that FM professionals with stronger scientific mental models and cognitive governance generally demonstrated greater competency in diagnosing and solving unfamiliar IAQ problems. However, an important question remained: could these relationships be explained by factors other than the capabilities being investigated? The statistical analysis therefore examined whether the findings remained reliable after considering differences between organisations, participants and assessment methods. One concern was that professionals working in the same organisation might have similar knowledge, experiences and approaches to problem solving. For example, professionals from an organisation that regularly investigated occupant complaints might have developed similar investigation practices. Their assessment performances could therefore be more alike than those of professionals working in different organisations.

The statistical analysis estimated an organisational intraclass correlation of approximately 0.13 for professional competency, compared with the initial planning assumption of 0.03.

This meant that approximately 13% of the remaining differences in competency scores, after accounting for the factors included in the model, were associated with differences between organisations. The original planning assumption had anticipated approximately 3%. The higher value demonstrated that organisational differences were more important than initially anticipated. Why did this matter? The investigation involved 120 professionals from approximately 12 organisations. If professionals from the same organisation performed similarly, their assessment results could not be treated as though they came from entirely unrelated individuals. Doing so could make the statistical findings appear more certain than they actually were. The analysis therefore accounted for organisational similarities. The positive relationships between scientific mental models, cognitive governance and professional competency remained supported when an alternative statistical approach was used to account for these similarities. This increased confidence that the findings were not simply consequences of the way professionals were grouped within organisations. Nevertheless, the relatively small number of organisations limited how precisely some relationships could be estimated, particularly when differences were small.

A second concern was whether the assessment genuinely distinguished the capabilities being investigated. Scientific mental models concerned what professionals understood. Cognitive governance concerned how they guided their investigations, questioned assumptions and made judgements. Independent learning concerned how they addressed missing knowledge. Professional competency concerned how effectively and consistently they applied these capabilities to diagnose problems and propose solutions of value to stakeholders. Although these capabilities were assessed using different criteria, participants demonstrated them through written investigations of related IAQ problems. A professional who was particularly effective at explaining scientific ideas in writing might receive higher scores in several assessment areas. This could create the appearance of stronger relationships between capabilities, even when part of the relationship reflected the participant’s ability to communicate clearly. Independent assessors evaluated the written reports using predefined criteria. Their scoring agreement helped establish that the assessment results were reasonably consistent between assessors. However, two assessors agreeing on a score did not necessarily mean that the assessment measured exactly what it was intended to measure. The possibility of some overlap between the capabilities therefore remained a scientific limitation.

A third concern was whether the findings demonstrated cause and effect. The statistical results showed that professionals with stronger scientific mental models and cognitive governance tended to demonstrate greater professional competency. However, they did not establish that strengthening these capabilities would automatically improve competency. For example, professionals who had frequently investigated complex IAQ problems might have developed stronger scientific understanding, better questioning practices and greater diagnostic competency through their professional experience. Their experience could therefore contribute to all three capabilities, rather than one capability

necessarily causing another to improve. Although the analysis considered professional experience, education and other measured factors, it could not exclude every possible explanation. These limitations were important because identifying a relationship was not the same as explaining how that relationship developed. The statistical findings showed which capabilities tended to occur together, but did not fully explain how professionals actually thought when confronted with unfamiliar IAQ problems.

To investigate this further, the RQ1 methodology specified detailed reasoning interviews with approximately 20–24 selected professionals. The purpose of these interviews was to understand the thinking behind participants' assessment performances, rather than relying solely on their numerical scores. For example, some participants correctly explained how individual pollutant sources and removal processes affected indoor air but struggled when several processes interacted. Interviews could help establish whether they failed to recognise the interactions, overlooked important information or relied on assumptions that were inappropriate for the problem. Similarly, some participants proposed technically reasonable interventions without sufficiently establishing the underlying causes of the problems. Interviews could examine how they arrived at their proposed solutions, whether they considered alternative explanations and why certain evidence or stakeholder requirements received insufficient attention. Another issue concerned professionals who recognised gaps in their knowledge but struggled to apply additional information. Interviews could investigate whether the difficulty involved selecting appropriate information, understanding its scientific meaning or incorporating it into subsequent judgements and decisions. These examples represented questions for qualitative investigation, not established explanations of participants' behaviour. Because interview findings were not available for the present analysis, no conclusions about the actual reasoning processes revealed by those interviews could be established.

Overall, the statistical findings provided evidence that scientific mental-model quality and cognitive governance were positively associated with professional competency, while independent learning provided additional explanatory information. However, the findings could not establish precisely how these capabilities influenced one another or whether improving them through training would improve professional competency. This distinction provided the basis for RQ2, which examined the effects of deliberate IAQ training on these capabilities and participants' subsequent competency in unfamiliar problem diagnosis and solving.

Integrated Interpretation of the Findings

The findings indicated that scientific mental-model quality, cognitive governance and independent learning capability provided related but distinguishable information about professional competency in unfamiliar IAQ investigations. For professional practice, this meant that possessing technical knowledge or years of experience did not necessarily establish how effectively and consistently an FM professional could diagnose and solve

unfamiliar IAQ problems. The results suggested that difficulties in professional diagnosis and solving could not be adequately understood merely by determining whether professionals possessed individual pieces of scientific knowledge. The more important consideration was whether they could connect relevant variables, formulate meaningful questions, evaluate evidence, recognise uncertainty and use their knowledge to justify decisions and solutions offering value to occupants and other stakeholders.

Three distinctions emerged from the findings. First, knowledge of individual scientific principles was not equivalent to the capability to integrate them into a coherent explanation of changing real-life conditions. Second, recognising a plausible explanation was not equivalent to demonstrating cognitive governance through systematic investigation of alternative causes. Third, proposing a technically reasonable intervention was not equivalent to establishing its expected effectiveness, feasibility and usefulness to stakeholders. These distinctions had practical implications. For example, when occupants complained about elevated indoor $PM_{2.5}$ concentrations during haze, an FM professional needed to investigate possible indoor sources, outdoor pollutant entry, ventilation, filtration and occupant activities. Focusing on one suspected cause without examining alternatives could result in an inappropriate intervention. Similarly, recommending additional air cleaning without considering pollutant characteristics, airflow, maintenance and operating costs might not provide adequate value to occupants.

The assessment results reinforced these concerns. Although 69.2% of professionals explained the basic relationship between pollutant addition and removal, only 47.5% satisfactorily explained a more complex situation involving a newly introduced source. Furthermore, only 48.3% demonstrated sufficiently supported root-cause diagnoses, while 44.2% adequately incorporated stakeholder requirements into their solution justifications. These percentages reflected performance against predefined assessment criteria, rather than the proportion of professionals considered competent or incompetent in their employment. For FM organisations, these findings suggested that professional development and competency assessment should extend beyond knowledge of building systems, equipment operation and established procedures. Professionals could be presented with unfamiliar building problems requiring them to formulate investigative questions, examine competing explanations, identify missing evidence, justify their conclusions and evaluate the anticipated value of proposed solutions. Their performance across different building contexts could also be examined to establish how consistently they demonstrated these capabilities.

The statistical results supported a positive association between scientific mental-model quality and professional competency, together with a separate positive association between cognitive governance and competency. Independent learning capability provided additional explanatory information, although the analysis did not establish causal relationships among these capabilities. Consequently, the findings supported giving

attention to all three capabilities in professional assessment, but did not establish that improving any one of them would necessarily improve competency. The scientific and practical contribution of RQ1 was therefore to establish evidence about existing professional capabilities, their limitations and their relationships before formal specialist IAQ training. The findings identified opportunities for strengthening value-oriented professional education without establishing the effectiveness of any particular teaching method. This provided the foundation for RQ2, which investigated whether equation-guided IAQ instruction produced greater immediate improvements in these capabilities and professional competency than equally comprehensive instruction without explicit equations.

Findings for Research Question 2:

Overview

The RQ2 findings showed that both approaches to IAQ training—one guided by mass-balance and health-risk equations and the other without explicit equations— improved participants' scientific mental-model quality, cognitive governance, independent learning capability and competency in value-oriented IAQ problem diagnosis and solving. However, the extent of improvement differed between the two training approaches. For scientific mental-model quality, RQ1 established an overall pre-training average score of 58.3 out of 100. In RQ2, the equation-guided group's average increased from 56.9 before training to 76.9 after training, compared with an increase from 58.0 before training to 67.7 after training in the non-equation-guided group. These results showed improvements in both groups relative to their respective starting scores. The equation-guided group therefore achieved statistically supported higher post-training performance after accounting for baseline differences.

For cognitive governance, the average score of all 120 participants assessed before specialist IAQ training was 55.3 out of 100 in RQ1. Following RQ2 training, the equation-guided group's average increased from 55.9 before training to 71.8 after training, compared with an increase from 54.8 to 64.0 in the non-equation-guided group. This indicated greater improvement in participants' ability to govern their investigations, reasoning, judgements and decisions under equation-guided training, with a statistically supported advantage after accounting for baseline differences. For independent learning capability, RQ1 established an overall pre-training average score of 54.8 out of 100. The equation-guided group's average increased from 54.0 before training to 69.4 after training, compared with an increase from 55.9 to 66.5 in the non-equation-guided group. Although both groups improved, the difference in post-training performance was not statistically conclusive after accounting for baseline differences. Therefore, the findings did not establish that equation-guided training was more effective in developing independent learning capability.

For professional competency, RQ1 established an overall pre-training average score of 57.8 out of 100. Among RQ2 participants who completed the post-training assessments, the equation-guided group's average increased from 56.5 before training to 74.4 after training, compared with an increase from 60.6 to 69.3 in the non-equation-guided group. The adjusted analysis confirmed a statistically supported advantage for equation-guided training. This indicated that participants receiving equation-guided instruction demonstrated greater immediate competency in diagnosing unfamiliar IAQ problems and proposing scientifically defensible, feasible solutions of potential value to stakeholders. Overall, equation-guided training demonstrated statistically supported advantages in three of the four assessed capabilities. However, because superiority in independent learning capability was not established, the findings did not satisfy the RQ2 alternative hypothesis requiring superiority across all four outcomes.

Participants, Allocation and Assessment Completion

This section presented the characteristics and starting capabilities of the professionals who participated in RQ2 and the extent to which they completed assessments after IAQ training. The first subsection reported the allocation of participants to the two training groups, their recruitment history and pre-training capabilities. The second examined assessment completion and differences in starting competency between participants with and without complete post-training results, providing context for interpreting the findings on the effectiveness of the training approaches.

Recruitment and Starting Capabilities: The RQ2 investigation involved 120 experienced Facilities Management (FM) professionals from 12 organisations or operational sites covering residential, educational and hospital buildings. Six organisations, comprising 60 professionals, were allocated to mass-balance and health-risk equation-guided IAQ training, while the remaining six organisations, also comprising 60 professionals, received equally comprehensive non-equation-guided training. Of the 120 participants, 96 (80.0%) continued from RQ1, while 24 (20.0%) were newly recruited. Each training group comprised 48 continuing and 12 newly recruited professionals. The existing RQ1 assessment results provided the pre-training scores for the 96 continuing participants, while the 24 newly recruited professionals completed equivalent assessments before training. Consequently, the RQ2 baseline combined previously established RQ1 results with the assessment results of newly recruited participants.

Across all 120 RQ2 participants, the overall pre-training average scores were 57.8 out of 100 for scientific mental-model quality, 55.3 for cognitive governance, 54.8 for independent learning capability and 57.8 for professional competency. These results established the existing capabilities of the complete RQ2 cohort before either training approach was introduced. The overall scores differed slightly from those reported in RQ1 because the RQ2 cohort included 24 newly recruited professionals. Participants in the equation-guided group averaged 11.8 years of FM experience, compared with 10.6 years in the non-

equation-guided group. Differences in education, mathematical preparation, prior informal IAQ knowledge and building responsibilities were also documented. These differences showed why participants' starting characteristics needed to be considered when interpreting subsequent differences in learning outcomes.

Retention and Missing Outcomes: Of the 120 professionals, 102 (85.0%) completed the assessments conducted after IAQ training, comprising 51 of 60 participants in each group. The remaining 18 participants, nine from each group, had incomplete or unavailable assessment results. The post-training assessments were completed within seven days after training, with a median interval of five days. They established participants' immediate performance in the same four capabilities assessed before training, using different unfamiliar IAQ problems. The findings therefore concerned the capabilities demonstrated shortly after training, rather than whether improvements were sustained over time.

Among the 102 participants who completed the post-training assessments, 84 had continued from RQ1 and 18 were newly recruited. This represented completion rates of 87.5% among returning participants and 75.0% among newly recruited participants. Although both training groups recorded identical overall completion rates, newly recruited professionals were less likely to complete their post-training assessments. The average pre-training professional competency scores were 56.5 out of 100 for participants who completed the later assessment in the equation-guided group and 60.6 for those in the non-equation-guided group. In comparison, participants who did not complete the later assessment had lower pre-training average scores of 52.4 and 54.9, respectively. These findings showed that participants with missing post-training results had lower initial professional competency scores than those who completed the assessments. The differences were 4.1 points in the equation-guided group and 5.7 points in the non-equation-guided group. Consequently, the available post-training results required careful interpretation because participants with weaker starting competency were less fully represented in the completed assessments.

Instructional Fidelity and Assessment Credibility

This section presented findings on the comparability of the two training approaches and the credibility of participants' assessment scores. The first subsection examined training attendance and the extent to which comparable instructional conditions were maintained, identifying limitations that could influence the interpretation of learning outcomes. The second examined agreement between independent assessors and whether the four professional capabilities were adequately distinguished during assessment, providing context for judging the reliability of comparisons between the training groups.

Comparable Training Conditions: Both training groups received four three-hour sessions over two weeks, totalling 12 hours of IAQ instruction. The training covered the same scientific content, learning objectives and opportunities for questioning, evidence

evaluation and value-oriented problem diagnosis and solving. The principal difference was that the equation-guided group used mass-balance and health-risk equations to understand scientific relationships, while the non-equation-guided group learnt equivalent relationships through graphs, diagrams and qualitative explanations. Attendance records showed that 48 of the 60 equation-guided participants (80.0%) attended all four sessions, compared with 46 of the 60 non-equation-guided participants (76.7%). At least three sessions were attended by 55 participants (91.7%) in the equation-guided group and 57 participants (95.0%) in the non-equation-guided group. These findings showed that most participants in both groups received at least nine of the twelve scheduled hours of training. The difference in full attendance was relatively small, at 3.3 percentage points in favour of the equation-guided group. However, slightly more participants in the non-equation-guided group attended at least three sessions. These patterns suggested broadly comparable attendance across the two training approaches.

This was important when interpreting the better post-training performance demonstrated by the equation-guided group in scientific mental-model quality, cognitive governance and professional competency. The attendance findings did not indicate a substantial difference in participation between groups that would readily explain these outcomes. Nevertheless, attendance alone could not establish how effectively participants engaged with the instruction or how much they learnt during individual sessions. The instructional fidelity audit covered two of eight scheduled sessions (25.0%), exceeding the planned minimum observation coverage of 20%. This established the extent of direct observation but did not demonstrate that instructional delivery was equivalent across every session. The reported findings also did not establish whether instructional materials were exchanged between groups or whether the intended distinction between the two approaches was consistently maintained.

Reliability and Distinctness of Outcomes: An important question was whether participants' assessment scores could be trusted. To examine this, two independent assessors evaluated the same written IAQ case investigation reports. If the assessors gave substantially different marks for the same work, the resulting scores would be less reliable for comparing participants' capabilities and the effectiveness of the two training approaches. The level of agreement between assessors was examined using a statistical measure called the intraclass correlation coefficient (ICC). An ICC closer to 1 generally indicates stronger scoring reliability. It considers differences between participants' scores alongside differences arising from the assessors' marking. The ICC values were 0.83 for scientific mental-model quality, 0.79 for cognitive governance, 0.89 for independent learning capability and 0.85 for professional competency. The corresponding 95% confidence intervals were 0.77–0.88, 0.72–0.85, 0.84–0.93 and 0.79–0.89, respectively.

All four ICC values exceeded the established reliability target of 0.75. This indicated relatively strong agreement between the two assessors across the four assessed capabilities. However, the confidence interval for cognitive governance extended below

0.75, indicating greater uncertainty about whether its scoring reliability met the target. These ICC values did not represent the percentage of identical marks awarded by the assessors. A second question concerned whether the assessments genuinely distinguished the four capabilities. Agreement between assessors did not automatically establish this. For example, a participant who correctly explained how indoor pollutant concentrations changed could receive a high scientific mental-model score. However, that explanation alone should not justify a high cognitive governance score unless the participant also demonstrated meaningful questioning, examination of alternative causes, evaluation of evidence and sound judgement. Similarly, professional competency required evidence of effective and consistent problem diagnosis and scientifically defensible solutions of potential value to stakeholders. Although separate assessment criteria were used, some overlap between the capabilities could remain. Therefore, strong agreement between assessors supported confidence in the reliability of the scores but did not, by itself, prove that the four capabilities were measured as entirely distinct constructs.

Overall, the findings provided reasonable confidence that the two assessors evaluated participants' performances consistently. This strengthened the credibility of comparisons between the training groups, while recognising that scoring reliability and the accurate distinction between capabilities were separate scientific considerations.

Immediate Effects on Scientific Mental Models

This section presented findings on how equation-guided and non-equation-guided IAQ training influenced participants' scientific understanding of indoor pollution and its health implications. The first subsection examined improvements in participants' understanding of pollutant sources, removal processes and changing indoor pollutant concentrations. The second examined their understanding of the relationships between pollutant concentration, exposure dose, biological vulnerability and health risks. Together, the findings highlighted the additional educational value of equations in helping professionals understand interconnected scientific relationships.

Pollutant Sources, Removal and Changing Concentrations: Scientific mental-model quality assessed whether professionals understood why indoor pollutant concentrations changed, rather than whether they could reproduce equations or perform calculations. It therefore concerned their ability to explain unfamiliar IAQ conditions using scientific reasoning. In RQ1, the overall pre-training average was 58.3 out of 100. Among RQ2 participants who completed the assessments after training, the equation-guided group's average increased from 56.9 before training to 76.9 afterwards, an improvement of 20.0 points. The non-equation-guided group's average increased from 58.0 to 67.7, an improvement of 9.7 points. Both groups improved, but the equation-guided group achieved higher post-training performance.

After accounting for differences in starting capabilities and similarities among professionals from the same organisation, the estimated equation-guided advantage was 9.32 points (95% confidence interval: 4.25–14.38; one-sided p = 0.001). This was the estimated difference between groups after adjustment, not a score of 9.32 out of 100. The confidence interval indicated the uncertainty surrounding that advantage, while the small p-value provided statistical evidence in favour of equation-guided training. What did these findings mean for understanding pollutant behaviour? Consider a room containing particles from earlier cooking. Without an active source, the existing concentration would gradually decrease as particles were removed. If cooking resumed, new particles would be added while removal continued. The total concentration would depend on the balance between these processes. Similarly, ventilation during outdoor haze could remove indoor-generated pollutants while introducing outdoor pollution.

These situations required professionals to connect pollutant sources, removal and changing conditions, not merely describe each process separately. The mass-balance equations used during equation-guided training made those relationships explicit. The higher overall scores were consistent with better understanding of interacting mechanisms. However, the results did not establish a statistically significant advantage for every individual pollutant scenario. Exposure, Vulnerability and Health-Risk Reasoning: Scientific mental models also concerned how indoor pollution could affect occupants. Three concepts were important: the concentration of pollutants in the air, the cumulative pollutant mass inhaled over time, and the probability of a specified health problem occurring within a defined period. A concentration reading alone could not establish how much an occupant inhaled or their probability of illness.

After training, the equation-guided group averaged 45.8 out of 60 points for pollutant behaviour and 31.1 out of 40 for exposure and health-risk understanding. The non-equation-guided group averaged 40.5 out of 60 and 27.2 out of 40, respectively. Together, these component scores accounted for the overall post-training averages of 76.9 and 67.7. The higher equation-guided performance was therefore evident in both parts of the mental-model assessment, although these component averages alone did not establish statistical significance for each part. For example, two occupants exposed to similar air concentrations could inhale different pollutant masses because their exposure durations or inhalation rates differed. Even with comparable inhaled doses, their probabilities of a particular health problem could differ because of biological vulnerability and other contributing factors. The health-risk equations helped participants reason about these distinctions without requiring clinical probability calculations. Overall, the findings indicated stronger immediate scientific understanding in the equation-guided group, not proven ability to predict actual illness or verified health benefits for occupants.

Immediate Effects on Cognitive Governance

This section presented findings on how equation-guided and non-equation-guided IAQ training influenced participants' ability to govern their thinking and learning during unfamiliar IAQ investigations. The first subsection examined meaningful questioning, evidence evaluation and consideration of competing explanations. The second addressed the recognition of uncertainty and revision of judgements when evidence was insufficient. The third examined independent learning capability, particularly participants' ability to recognise knowledge gaps, acquire credible information and apply newly acquired understanding during investigations.

Questioning and Evaluation of Competing Explanations: Scientific mental-model findings concerned what participants understood about indoor pollution. Cognitive governance examined how they used that understanding to ask questions, examine evidence and justify decisions. Knowing why pollutant concentrations change was not enough; participants also needed to investigate what caused those changes in an unfamiliar building. In RQ1, the average cognitive-governance score across all 120 participants was 55.3 out of 100. Among RQ2 participants who completed the assessments after training, the equation-guided group's average increased from 55.9 before training to 71.8 afterwards, an improvement of 15.9 points. The non-equation-guided group's average increased from 54.8 to 64.0, an improvement of 9.2 points. Both groups performed better following training, but the equation-guided group demonstrated a larger increase.

After accounting for differences in starting scores and similarities among participants from the same organisation, the equation-guided group had an estimated advantage of 7.01 points (95% confidence interval: 0.47–13.54; one-sided $p = 0.019$). This was an adjusted difference between groups, not a score out of 100. The confidence interval showed uncertainty about its size; the statistical test supported an equation-guided advantage. What did better cognitive governance mean in practice? Consider an office where occupants reported discomfort and high $PM_{2.5}$ concentrations were measured. Asking whether cooking caused the pollution would be a reasonable first question. Concluding that cooking was responsible without checking alternatives would be premature. A stronger investigation would consider outdoor haze, ventilation, filtration and occupants' activities, then determine what evidence could distinguish these explanations.

The findings were consistent with equation-guided training helping participants organise this questioning around relevant scientific relationships. However, they did not establish which particular activity—formulating questions, comparing explanations or evaluating evidence—accounted for the higher overall score. Cognitive governance was assessed separately from whether the final diagnosis was correct.

Managing Uncertainty and Revising Judgements: Cognitive governance also involved recognising insufficient evidence. For example, an elevated $PM_{2.5}$ reading could show that pollution was present without revealing its main source. A professional might need outdoor

measurements, information about occupant activities or evidence of air-cleaner performance before deciding on an intervention. A stronger cognitive-governance score therefore reflected better overall performance in recognising assumptions, identifying missing evidence and explaining when conclusions should be reconsidered. It did not mean that participants could identify the correct cause in every case. Sometimes, withholding a firm conclusion until more evidence became available was the more scientifically defensible decision.

Immediate Effects on Independent Learning Capability: Independent learning concerned a further capability: what professionals did when they recognised that they lacked knowledge needed to continue an investigation. It went beyond asking good questions to finding trustworthy information, understanding it and using it to make progress. In RQ1, the overall average independent-learning score was 54.8 out of 100. In RQ2, the equation-guided group's average rose from 54.0 before training to 69.4 afterwards, an improvement of 15.4 points. The non-equation-guided group's average increased from 55.9 to 66.5, an improvement of 10.6 points. Both groups therefore improved, and the equation-guided group achieved a higher average post-training score.

After accounting for baseline differences, the estimated advantage for equation-guided training was 4.26 points (95% confidence interval: −2.47 to 10.99; one-sided $p = 0.094$). Although the equation-guided group achieved a higher average score, the statistical evidence was insufficient to establish with confidence that equation-guided training was more effective than non-equation-guided training in developing independent learning capability. Understanding the practical meaning of this finding required considering what participants were expected to demonstrate when learning independently. For example, a professional might recognise that an air cleaner's filtration efficiency was unknown. Independent learning required more than finding a manufacturer's specification. The professional also needed to judge whether the information was reliable and relevant, establish how much air actually passed through the filter and use that understanding to assess the proposed intervention.

Both approaches included opportunities to identify knowledge gaps and use information, possibly contributing to improvements in both groups. However, the results did not establish why the additional equation-guided advantage was uncertain. Nor did they prove that the approaches were equally effective. The assessments demonstrated independent learning during unfamiliar case investigations, not lifelong learning behaviour throughout professional practice.

Immediate Effects on Value-Oriented Professional Competency

This section presented findings on how equation-guided and non-equation-guided IAQ training influenced participants' competency in value-oriented problem diagnosis and solving. The first subsection compared overall professional competency while accounting

for differences in starting capabilities. The second examined participants' ability to identify underlying causes, explain pollutant behaviour and predict changes in indoor conditions. The third examined their ability to propose effective and feasible solutions and justify their anticipated value to occupants and other stakeholders.

Overall Competency and Baseline-Adjusted Comparison: Professional competency was the main outcome investigated in RQ2. Unlike scientific mental models, which concerned what participants understood, cognitive governance, which concerned how they governed their investigations, and independent learning, which concerned how they addressed knowledge gaps, professional competency examined how effectively and consistently participants brought these capabilities together to diagnose unfamiliar IAQ problems and propose scientifically defensible, feasible solutions of potential value to stakeholders. In RQ1, the overall average professional competency score was 57.8 out of 100. Among RQ2 participants who completed the assessments after training, the equation-guided group's average increased from 56.5 before training to 74.4 afterwards, an improvement of 17.9 points. The non-equation-guided group's average increased from 60.6 to 69.3, an improvement of 8.7 points. These findings showed that both groups improved, but the equation-guided group achieved greater improvement despite starting with a lower average competency score.

After accounting for differences in starting capabilities, professional backgrounds and similarities among participants from the same organisation, the estimated advantage for equation-guided training was 6.37 points (95% confidence interval: 1.60–11.13; one-sided $p = 0.007$). This meant that the equation-guided group demonstrated statistically supported higher professional competency after training. The confidence interval indicated uncertainty about the size of the advantage, but its values supported a positive difference between groups. The estimated advantage also exceeded the five-point difference previously identified as potentially meaningful for professional education. However, the statistical uncertainty meant that the findings could not establish with sufficient confidence that the actual advantage exceeded five points. Thus, the evidence supported better immediate competency under equation-guided training, without establishing precisely how substantial that advantage would be in professional practice.

Root-Cause Diagnosis and Scientific Interpretation: Professional competency was assessed through four requirements: root-cause diagnosis (40 points), scientific interpretation and prediction (20 points), intervention effectiveness and feasibility (25 points), and stakeholder alignment and anticipated value (15 points). For root-cause diagnosis, the equation-guided group averaged 30.3 out of 40, compared with 27.4 in the non-equation-guided group. For scientific interpretation and prediction, the corresponding averages were 14.4 out of 20 and 14.0. These results suggested that the equation-guided group performed better in identifying and explaining the underlying causes of IAQ problems, with a smaller difference in scientific interpretation and prediction. However,

these component differences were descriptive and did not independently establish statistically supported advantages.

What did this mean for professional practice? Consider occupants experiencing unhealthy indoor air despite keeping their windows closed during haze. A professional might immediately suspect inadequate filtration. However, the problem could also involve indoor pollutant sources, haze-related outdoor pollutants entering through building-envelope gaps, inadequate ventilation or several interacting causes. A competent investigation required determining which explanations were supported by the available evidence, rather than simply selecting a familiar engineering solution. The assessment therefore examined whether participants could establish scientifically defensible causes using historical case evidence, not whether they had conducted actual building investigations.

Feasible Solutions and Anticipated Stakeholder Value: This part of the professional competency assessment examined two important questions. First, could participants propose engineering solutions that were likely to address the identified causes of IAQ problems and were feasible to implement? Second, could they explain how those solutions would benefit occupants and other stakeholders while considering possible disadvantages? For intervention effectiveness and feasibility, the equation-guided group averaged 18.6 out of 25, compared with 17.5 in the non-equation-guided group. This meant that the equation-guided group scored, on average, 1.1 points higher in explaining why their proposed solutions were expected to work and whether they could reasonably be implemented. For stakeholder alignment and anticipated value, the equation-guided group averaged 11.1 out of 15, compared with 10.4 in the non-equation-guided group. This represented an average difference of 0.7 points in favour of the equation-guided group. It indicated slightly better performance in explaining how proposed solutions addressed the needs of occupants and other stakeholders. However, the statistical analysis did not separately establish whether these differences in the two assessment components represented reliable advantages of equation-guided training.

What did these findings mean for professional practice? Consider occupants experiencing unhealthy indoor air despite keeping their windows closed during haze. Suppose an investigation identified both indoor pollutant sources and outdoor pollution entering the building. Increasing ventilation might help remove indoor-generated pollutants but could also introduce more haze-related pollution if the incoming air was inadequately filtered. Installing an air cleaner might reduce pollutant concentrations, but its effectiveness would depend on whether sufficient air passed through an appropriate filter. Therefore, recommending ventilation improvements or installing an air cleaner was not enough. Professionals needed to explain how their proposed solutions would address the identified causes, whether the solutions were technically and financially feasible, and how their effectiveness might change under different operating conditions. The value of a proposed solution also depended on its anticipated benefits and disadvantages for occupants and other stakeholders. For example, an air-cleaning system might improve indoor air quality

but introduce additional noise, energy costs or maintenance requirements. A valuable solution therefore needed to provide appropriate health protection, comfort, convenience and safety while keeping the sacrifices required from stakeholders acceptable.

Overall, the findings indicated better immediate professional competency in the equation-guided group when all four competency components were considered together. However, the results demonstrated participants' ability to diagnose problems and justify proposed solutions, rather than proving that those solutions had been implemented or had improved actual building conditions or occupants' health.

Building Contexts, Mathematical Preparation and Robustness

The preceding findings showed that mass-balance and health-risk equation-guided IAQ training produced better immediate outcomes in three of the four assessed capabilities. However, two important questions remained: Did the training benefit professionals from different backgrounds, and were the findings sufficiently reliable to support these conclusions? This section examined these questions. The estimated advantage of equation-guided training in professional competency was 8.59 points for residential FM professionals, 6.89 for educational building professionals and 4.62 for hospital FM professionals. These results suggested that the advantage might differ across building sectors. However, the differences were not sufficiently established statistically to conclude that equation-guided training was more effective for residential professionals than for hospital professionals. Only four organisations represented each sector, with two receiving each training approach. This limited the certainty of comparisons between sectors.

Participants' mathematical backgrounds were also considered. Professionals with stronger mathematical preparation might find equations easier to understand, while those less comfortable with mathematics might experience greater learning difficulties. The overall advantage of equation-guided training remained supported after accounting for mathematical background. However, the findings did not establish whether professionals with different mathematical abilities benefited equally. Another concern was whether the conclusions depended on the particular statistical approach used. Professionals working in the same organisation might share similar knowledge, experiences and working practices. These similarities could influence their assessment scores. An alternative statistical analysis that considered the allocation of organisations produced results consistent with the primary findings. The corresponding one-sided p-values were 0.009 for scientific mental-model quality, 0.023 for cognitive governance, 0.093 for independent learning and 0.014 for professional competency.

This confirmed the same overall pattern: statistically supported advantages for equation-guided training in three capabilities, but insufficient evidence of an advantage in independent learning. The agreement between analyses strengthened confidence in the findings, although the small number of participating organisations remained a limitation.

Among the 84 continuing RQ1 participants who completed their post-training assessments, the estimated advantages were 10.37 points for scientific mental models, 8.22 for cognitive governance, 4.63 for independent learning and 6.49 for professional competency. These findings followed a similar pattern, suggesting that the overall results were not explained solely by the inclusion of newly recruited participants. However, differences between participants who completed assessments and those who did not remained a possible source of uncertainty.

A final question concerned why equation-guided training produced better professional competency. The findings suggested that stronger scientific mental models and cognitive governance might have supported participants' ability to diagnose problems and justify solutions. However, the results did not establish that improvements in these two capabilities directly caused the improvement in professional competency. Other aspects of learning, engagement and investigative practice might also have contributed. Overall, the additional analyses strengthened confidence in the immediate educational advantages of equation-guided training while identifying uncertainties about differences between professionals and the reasons for the observed improvements.

Interpretation of the Educational Value of Equation-Guided IAQ Training

The findings showed that mass-balance and health-risk equation-guided IAQ training produced better immediate outcomes in scientific mental-model quality, cognitive governance and professional competency than equally comprehensive non-equation-guided training. A possible explanation was that the equations helped participants connect different pieces of scientific knowledge into a more organised way of thinking, rather than considering each scientific principle separately. For example, both groups learnt that indoor pollutant concentrations were influenced by pollutant sources, ventilation, infiltration and filtration. However, the mass-balance equations explicitly connected these factors by showing how pollutant addition and removal jointly determined changes in concentration over time. This provided a common scientific framework for examining unfamiliar situations, including circumstances in which several processes occurred simultaneously.

Consider a building where occupants experienced unhealthy indoor air despite keeping their windows closed during haze. A professional relying on individual scientific principles might recognise several possible causes without adequately connecting them. In contrast, a professional reasoning through the mass-balance relationships could systematically ask which pollutants were entering the building, which were generated indoors, how quickly they were being removed and how changing building conditions affected these processes. These questions could help distinguish competing explanations and identify the evidence needed to establish the underlying causes. The health-risk equations provided a similar framework for connecting pollutant concentration, exposure dose, biological vulnerability and other contributing factors to the probability of a specified health problem. Rather than assuming that a higher pollutant concentration automatically meant the same health risk

for every occupant, participants could examine how exposure duration, inhalation rate and individual vulnerability influenced the potential consequences. These connections offered a possible explanation for the stronger scientific mental-model and cognitive-governance scores. The equations may have helped participants organise their existing understanding, formulate more purposeful questions, examine competing causes and justify their judgements using relevant scientific relationships.

The advantage in professional competency could also be understood through this reasoning process. When participants connected pollutant behaviour, exposure, health risks and stakeholder requirements, they had a clearer scientific basis for diagnosing problems and proposing solutions expected to be effective, feasible and valuable to occupants. However, equation-guided training did not demonstrate a statistically supported advantage in independent learning capability. Both training approaches provided comparable opportunities to recognise knowledge gaps, find information and apply newly acquired knowledge. This might help explain why both groups improved without a conclusive difference between them. Importantly, these explanations represented scientifically plausible reasons for the observed differences, not independently established mechanisms. The assessments demonstrated stronger performance under equation-guided training but did not directly establish which aspects of participants' thinking accounted for the advantage. The central scientific interpretation is therefore that the potential additional educational value of the equations lay in providing an explicit, connected framework for scientific reasoning, not in requiring participants to memorise formulas or perform mathematical calculations.

Primary Statistical Findings and Hypothesis Testing

Although both training groups demonstrated improvements across the four assessed capabilities, the principal question in RQ2 was whether mass-balance and health-risk equation-guided IAQ training produced better learning outcomes than equally comprehensive non-equation-guided training. Answering this question required considering the differences in participants' capabilities before training. After accounting for these differences, the equation-guided group achieved an estimated advantage of 9.32 points in scientific mental-model quality, 7.01 points in cognitive governance, 4.26 points in independent learning capability and 6.37 points in professional competency. However, obtaining higher average scores did not automatically establish that equation-guided training was more effective. The statistical analysis also needed to determine whether the evidence was sufficiently strong to support that conclusion. A statistical measure known as the p-value was used for this purpose, with smaller values indicating stronger evidence against the hypothesis that equation-guided training offered no advantage. The threshold for establishing statistical significance was set at 0.05.

The one-sided p-values were 0.001 for scientific mental-model quality, 0.019 for cognitive governance, 0.094 for independent learning capability and 0.007 for professional

competency. Only independent learning capability had a p-value exceeding 0.05. Consequently, sufficient statistical evidence supported the advantages of equation-guided training in three of the four capabilities. To reduce the possibility of drawing incorrect conclusions when examining four capabilities separately, an additional statistical adjustment known as Holm correction was applied. The resulting p-values were 0.004, 0.038, 0.094 and 0.021, respectively. The conclusion remained unchanged: equation-guided training demonstrated statistically supported advantages in three capabilities, but not independent learning.

The RQ2 alternative hypothesis (H_{12}) proposed that equation-guided training would produce better immediate learning outcomes across all four capabilities. The null hypothesis (H_{02}) stated that equation-guided training did not provide an advantage in at least one capability. Since sufficient statistical evidence was not obtained for independent learning capability, the requirement of the alternative hypothesis was not fully satisfied. Consequently, the null hypothesis was not rejected. This did not mean that equation-guided training was ineffective or that both training approaches were equally effective. It simply meant that its superiority across all four capabilities could not be established. The most important finding for professional practice was that equation-guided training produced better immediate professional competency, the primary outcome of RQ2. It also produced better scientific mental-model quality and cognitive governance, although its additional educational value for independent learning capability remained statistically uncertain.

Integrated Interpretation of the Findings

The results suggested that explicitly incorporating mass-balance and health-risk equations as scientific reasoning frameworks could offer additional immediate educational value beyond equally comprehensive qualitative instruction. Both programmes improved assessment performance, but equation-guided instruction showed statistically supported advantages in scientific mental-model quality, cognitive governance and professional competency. The advantage in independent learning capability remained uncertain. For indoor air quality management practices, the findings suggested that professional development should extend beyond familiarising FM professionals with pollutant sources, ventilation systems, air-cleaning equipment, regulatory requirements and standard operating procedures.

Greater attention should be given to developing their ability to understand how these factors interact under changing building and environmental conditions. For example, during haze, increasing outdoor ventilation might help remove indoor-generated pollutants while introducing additional outdoor pollutants. Similarly, closing windows might reduce outdoor pollutant entry but allow pollutants generated indoors to accumulate. Equation-guided scientific reasoning could help FM professionals recognise these competing processes, formulate appropriate investigative questions, identify the measurements required and make informed decisions about building operation. This could reduce reliance on general

operating recommendations that might not be appropriate under particular circumstances. The findings also had implications for indoor air quality engineering design. Designers needed to understand not only the individual functions of building components but also how their combined characteristics influenced pollutant concentrations, occupant exposure and health risks. For example, specifying a filter with high pollutant removal efficiency would not necessarily provide adequate air cleaning if insufficient airflow passed through it. Similarly, designing a ventilation system without considering outdoor pollution, building-envelope infiltration and occupant activities could compromise indoor air quality.

Using mass-balance and health-risk equations to guide design thinking could help professionals identify the scientific relationships that needed consideration, question design assumptions, anticipate unintended consequences and evaluate alternative design solutions before implementation. However, the value of a design solution would also depend on its ability to support occupants' health, comfort, convenience, awareness and safety without imposing unacceptable financial, operational or environmental sacrifices. Several limitations constrained interpretation. Only 12 organisations participated, and differences in mathematical preparation, instructional experiences and assessment completion could have influenced the findings. Eighteen participants lacked complete post-training assessments. Possible overlap between the assessed capabilities also remained a concern. Furthermore, the findings did not directly establish which aspects of equation-guided reasoning accounted for the stronger professional competency outcomes.

Most importantly, participants investigated unfamiliar historical IAQ cases under controlled assessment conditions immediately after training. Although stronger assessment performance indicated better readiness for professional practice, it did not establish that participants subsequently made better management or design decisions in their workplaces. Neither did it establish that their proposed solutions produced measurable reductions in pollutant exposure or improvements in occupants' health. For building owners, design consultants and FM organisations, the immediate findings therefore supported considering equation-guided training as an approach to professional capability development, rather than treating it as a proven means of improving actual building performance. Its longer-term educational value depended on whether professionals retained and independently applied their developed capabilities beyond training. RQ3 therefore extended the comparison to three- and six-month assessments using further unfamiliar residential, educational and hospital IAQ problems to examine the sustainability and transferability of the capabilities developed in RQ2.

Findings for Research Question 3:

Overview

While RQ2 established the immediate educational advantages of mass-balance and health-risk equation-guided IAQ training, RQ3 examined whether these advantages were

sustained over time and whether participants could independently apply their developed capabilities to unfamiliar IAQ problems. The original training groups investigated further residential, educational and hospital IAQ problems three and six months after training, without receiving researcher-delivered refresher training. For cognitive governance, the equation-guided group's average score decreased from 71.8 immediately after training in RQ2 to 70.3 after three months and 68.9 after six months. The corresponding scores for the non-equation-guided group were 64.0, 62.3 and 60.5, respectively.

For independent learning capability, the equation-guided group's average score decreased from 69.4 immediately after training to 67.9 after three months and 65.8 after six months. The corresponding scores for the non-equation-guided group were 66.5, 62.6 and 58.4, respectively. For professional competency, the equation-guided group's average score decreased from 74.4 immediately after training in RQ2 to 72.3 after three months and 70.4 after six months. The corresponding scores for the non-equation-guided group were 69.3, 66.5 and 63.6, respectively. For scientific mental-model quality, the equation-guided group's average score decreased from 76.9 immediately after training to 74.7 after three months and 72.9 after six months. The corresponding scores for the non-equation-guided group were 67.7, 65.0 and 62.7, respectively.

Although average performance declined in both groups, the equation-guided group maintained higher average scores across all four capabilities. After accounting for differences in participants' starting capabilities, the six-month advantages were 7.8 points for cognitive governance, 8.6 for independent learning capability and 8.8 for professional competency. Unlike RQ2, where the advantage in independent learning capability was statistically uncertain, RQ3 provided statistical evidence of superior performance in all three primary outcomes at six months. Consequently, the primary analysis supported the RQ3 alternative hypothesis, although this conclusion was sensitive to certain assumptions about missing assessment results.

Overall, the findings supported partial retention and transferability of the capabilities developed through equation-guided training. However, declining average scores indicated that the immediate learning outcomes were not fully sustained. The findings demonstrated participants' ability to apply their learning to further unfamiliar IAQ problems, rather than verified improvements in actual building management, design practices or occupants' health.

Participant Retention and Longitudinal Assessment

This section examined how much confidence could be placed in the RQ3 findings on the sustainability and transferability of the professional capabilities developed through IAQ training. Three considerations were particularly important: the number of professionals who completed subsequent assessments, their performance across comparable but unfamiliar IAQ problems, and the reliability of their assessment scores. Together, these

considerations influenced the confidence with which changes in participants' capabilities over six months could be interpreted.

Continuity of the Original Experimental Groups: The RQ3 investigation followed the 120 FM professionals enrolled in RQ2, comprising 60 participants from six organisations in the mass-balance and health-risk equation-guided group and 60 participants from six organisations in the non-equation-guided group. No replacement participants were introduced, and the original training-group allocations remained unchanged. Of the original 120 participants, 102 (85.0%) completed the immediate post-training assessments in RQ2, comprising 51 participants from each group. At three months after training, 100 participants (83.3%) completed the follow-up assessments, comprising 52 participants (86.7%) from the equation-guided group and 48 participants (80.0%) from the non-equation-guided group. At six months, 90 participants (75.0%) completed the assessments, comprising 47 participants (78.3%) from the equation-guided group and 43 participants (71.7%) from the non-equation-guided group.

Despite the gradual decrease in overall assessment completion, three-quarters of the original participants completed the investigation at six months, and all 12 organisations remained represented. This provided a reasonable basis for examining longer-term educational outcomes across the original experimental groups. At six months, assessment results were incomplete or unavailable for 30 professionals, comprising 13 from the equation-guided group and 17 from the non-equation-guided group. The higher completion rate in the equation-guided group did not necessarily mean that its participants were more motivated or had retained their learning better. The reasons for this difference were not established.

The missing assessment results raised an important question: would the average scores reported in the overview have been different if all 120 professionals had completed the assessments? For example, if professionals experiencing greater difficulty retaining their learning were less likely to complete subsequent assessments, the available results might overestimate the capabilities retained after training. Therefore, the declining average scores needed to be interpreted alongside changes in assessment completion.Unfamiliar Case Assessments and Comparability: At three months, the 100 participants completed 300 case investigations involving residential, educational and hospital buildings. At six months, the 90 participants completed 270 case investigations involving the same three building contexts but different unfamiliar IAQ problems. Together, these represented 570 completed case investigations across the two follow-up periods. The equation-guided group contributed 156 case investigations at three months and 141 at six months, while the non-equation-guided group contributed 144 and 129, respectively.

The importance of these findings was that participants demonstrated their capabilities across several unfamiliar professional situations rather than repeatedly investigating the same problem. This provided evidence of transferability, while changes in their assessment

scores over time provided evidence of sustainability. Each building context contributed equally to participants' overall assessment scores. However, an overall average could conceal differences in individual performance. For example, a professional might perform well when investigating a residential IAQ problem but experience difficulty when investigating an unfamiliar hospital IAQ problem. The individual case scores therefore provided additional evidence for examining how consistently professionals applied their developed capabilities.

Another consideration was whether the declining scores reported in the overview reflected a genuine reduction in participants' capabilities. If the six-month assessment problems were more difficult than those investigated immediately after training, some of the decline could reflect differences in problem difficulty rather than loss of previously developed capabilities. Expert appraisal and pilot calibration provided a basis for establishing comparability, although they could not guarantee identical difficulty across assessment periods.

Scientific Validity and Assessment Reliability: Confidence in the reported changes in participants' capabilities also depended on whether the two independent assessors marked their work consistently. Substantial differences between assessors' marks could make changes in assessment scores difficult to interpret. The inter-rater intraclass correlation coefficients (ICCs), for which values closer to 1 generally indicated stronger scoring reliability, were 0.80 for cognitive governance, 0.82 for independent learning capability and 0.86 for professional competency. The corresponding 95% confidence intervals were 0.72–0.86, 0.75–0.88 and 0.80–0.90, respectively.All three ICC estimates exceeded the provisional reliability target of 0.75. Professional competency demonstrated the highest estimated scoring reliability, while greater uncertainty remained for cognitive governance because its confidence interval extended below the established target. Nevertheless, the findings generally supported confidence in the consistency of assessment scoring. Agreement between assessors did not necessarily establish that the assessments accurately distinguished the different capabilities. Some overlap between the assessed capabilities could remain despite separate scoring criteria.

Overall, the retention of 75% of the original participants, the completion of 570 unfamiliar IAQ case investigations and the relatively strong agreement between independent assessors provided a reasonable basis for examining sustainability and transferability. However, missing assessment results, possible differences in case difficulty and potential overlap between assessed capabilities limited the certainty with which changes in assessment scores could be attributed solely to changes in participants' capabilities.

Six-Month Effects on Cognitive Governance

This section presented the findings on the sustainability and transferability of cognitive governance and independent learning capability developed through the two IAQ training

approaches in RQ2. The first subsection examined how well professionals retained and applied their capabilities for questioning, evaluating evidence and making justified judgements. The second subsection examined how well professionals retained and applied their capabilities for recognising and addressing knowledge gaps. Both subsections compared participants' performances immediately after training, after three months and after six months.

Questioning, Evidence Evaluation and Judgement: RQ2 established that equation-guided IAQ training was more effective in developing cognitive governance immediately after training. The RQ3 findings examined whether this advantage remained evident six months later, when participants independently investigated further unfamiliar IAQ problems. The equation-guided group's average cognitive-governance score decreased from 71.8 immediately after training to 70.3 after three months and 68.9 after six months. The corresponding scores for the non-equation-guided group were 64.0, 62.3 and 60.5, respectively. Between the immediate and six-month assessments, the average score decreased by 2.9 points in the equation-guided group, compared with 3.5 points in the non-equation-guided group. Although average performance declined in both groups, the equation-guided group maintained its advantage. After accounting for differences in participants' starting capabilities and organisational characteristics, the estimated six-month advantage was 7.8 points out of 100 (95% confidence interval: 1.2–14.4; one-sided $p = 0.012$). The statistical evidence supported the conclusion that equation-guided training resulted in better cognitive-governance performance six months after training, although the exact size of the advantage remained uncertain.

The practical significance of this finding concerned how effectively professionals governed their thinking, questioning and judgement during unfamiliar IAQ investigations. For example, when investigating elevated indoor PM2.5 concentrations during outdoor haze, a professional needed to question whether the problem resulted from indoor pollutant generation, outdoor pollutant entry, inadequate pollutant removal or a combination of these factors. The professional also needed to determine what evidence was required before reaching a scientifically defensible conclusion. The higher cognitive-governance scores suggested that professionals in the equation-guided group were generally better at undertaking such reasoning activities. One possible explanation was that the scientific relationships made explicit through mass-balance and health-risk equations continued to guide what participants questioned, how they evaluated evidence and how they arrived at their judgements. However, the findings did not establish whether participants consciously recalled or used the equations during their investigations.

Six-Month Effects on Independent Learning Capability: While cognitive governance concerned how professionals governed their investigations and thinking, independent learning capability concerned how effectively they acquired and applied additional knowledge when their existing knowledge and understanding were insufficient to diagnose and solve an IAQ problem. The equation-guided group's average independent learning

score decreased from 69.4 immediately after training to 67.9 after three months and 65.8 after six months. The corresponding scores for the non-equation-guided group were 66.5, 62.6 and 58.4, respectively. Over the six-month period, the average score decreased by 3.6 points in the equation-guided group, compared with 8.1 points in the non-equation-guided group. This pattern suggested better retention of independent learning capability in the equation-guided group.

After accounting for differences in starting capabilities and organisational clustering, the estimated six-month advantage was 8.6 points out of 100 (95% confidence interval: 0.6–16.6; one-sided $p = 0.019$). This finding was particularly important because, unlike the immediate findings in RQ2, the six-month findings provided sufficient statistical evidence of an advantage for equation-guided training. However, this did not establish that the advantage had increased significantly over time. For example, a professional investigating inadequate air-cleaning performance might lack sufficient knowledge about filtration efficiency. Effective independent learning would involve recognising this knowledge gap, obtaining reliable information, developing the required understanding and applying that understanding to determine how filtration efficiency, airflow and operating conditions influenced pollutant removal. The findings suggested that equation-guided training provided a more enduring foundation for recognising and addressing knowledge gaps during unfamiliar IAQ investigations. Nevertheless, workplace learning experiences and missing assessment results could also have influenced the observed performance patterns. The findings demonstrated independent learning capability within the assessed investigations rather than establishing lifelong learning behaviour.

Six-Month Effects on Value-Oriented Professional Competency

This section presented the findings on the sustainability and transferability of competency in value-oriented IAQ problem diagnosis and solving. The first subsection examined root-cause diagnosis and scientific interpretation, while the second examined the feasibility, safety and anticipated stakeholder value of proposed solutions. The third subsection examined whether the advantages observed at six months were already evident at three months. The fourth subsection examined the extent to which the professional capabilities developed immediately after training were sustained over six months.

Root-Cause Diagnosis and Scientific Interpretation: While the preceding sections examined cognitive governance and independent learning capability separately, the professional competency findings examined how effectively participants brought these capabilities together with their scientific understanding to diagnose unfamiliar IAQ problems and propose solutions of potential value to stakeholders. The equation-guided group’s average professional competency score decreased from 74.4 immediately after training in RQ2 to 72.3 after three months and 70.4 after six months. The corresponding scores for the non-equation-guided group were 69.3, 66.5 and 63.6, respectively. After accounting for differences in participants’ starting capabilities and organisational clustering,

the equation-guided group had an estimated six-month advantage of 8.8 points over the non-equation-guided group (95% confidence interval: 1.4–16.2; one-sided p = 0.012). This finding provided statistical evidence that equation-guided training was more effective in developing professional competency that remained evident six months after training.

The estimated advantage also exceeded the provisional five-point difference considered potentially meaningful for professional performance. However, because the confidence interval included differences smaller than five points, uncertainty remained about the extent of its practical importance. The practical significance of the higher competency score concerned professionals' ability to distinguish an observed IAQ problem from its underlying causes and justify appropriate solutions. For example, observing elevated indoor PM2.5 concentrations during outdoor haze did not necessarily establish that outdoor pollution was the principal cause. Indoor pollutant generation, inadequate filtration and changing ventilation conditions could also contribute to the problem. The higher overall competency score suggested that the equation-guided group was generally more effective in bringing together scientific understanding, questioning and independent learning to undertake such investigations. However, the overall score alone did not establish that the group performed significantly better in every individual aspect of professional competency.

Feasibility, Safety and Stakeholder Value: Effective IAQ problem solving extended beyond identifying scientifically appropriate solutions. It also concerned whether the proposed solutions could address the underlying causes while satisfying the needs and requirements of occupants and other stakeholders. For example, increasing outdoor ventilation could help reduce exposure to pollutants generated indoors. However, during outdoor haze, increasing ventilation without adequate filtration could introduce additional pollutants into the building. Similarly, increasing filtration efficiency could improve pollutant removal but introduce additional energy, operational and maintenance requirements.

Value-oriented professional competency therefore involved anticipating both the benefits and sacrifices associated with proposed solutions. These included implications for occupants' health, comfort, convenience and safety, alongside financial costs, energy consumption and maintenance requirements. Safety-critical requirements could not simply be compromised to achieve financial savings. The higher competency scores in the equation-guided group provided evidence of stronger overall performance in investigations requiring such considerations. Nevertheless, the findings concerned the scientific defensibility, feasibility and anticipated value of proposed solutions. They did not establish that implementing these solutions would necessarily achieve the anticipated improvements in indoor air quality, occupants' health or building performance, because the solutions were not implemented and evaluated.

Three-Month Findings and Intermediate Performance: The three-month findings helped explain whether the advantages observed at six months were already evident during the earlier follow-up assessment. For cognitive governance, the estimated advantage for

equation-guided training at three months was 7.4 points (95% confidence interval: 0.8–14.0). For independent learning capability, the estimated advantage was 6.1 points (95% confidence interval: −1.1 to 13.3). For professional competency, the equation-guided group achieved an average score of 72.3, compared with 66.5 in the non-equation-guided group. After accounting for differences in starting capabilities and organisational clustering, the estimated advantage was 7.9 points (95% confidence interval: 0.5–15.3).

The three-month findings suggested that the advantages in cognitive governance and professional competency observed immediately after training in RQ2 remained evident three months later. However, the statistical evidence for an advantage in independent learning capability remained inconclusive at three months. It was only at six months that the primary analysis provided statistical evidence of an advantage across all three capabilities. This did not necessarily mean that the effectiveness of equation-guided training increased over time. The three-month findings primarily helped explain the progression of participants' performance towards the six-month assessment, which was the main basis for evaluating longer-term comparative effectiveness.

Sustainability of Capability After Training: An important distinction in interpreting the RQ3 findings was the difference between comparative effectiveness and sustainability. Comparative effectiveness concerned which training approach produced better performance after six months. Sustainability concerned how much of the capability developed immediately after training remained evident six months later. Between the immediate and six-month assessments, the equation-guided group's average scores decreased by 2.9 points for cognitive governance, 3.6 points for independent learning capability and 4.0 points for professional competency. The corresponding decreases in the non-equation-guided group were 3.5, 8.1 and 5.7 points, respectively. Although average performance declined in both groups, the decreases were consistently smaller in the equation-guided group. Furthermore, its six-month average scores remained approximately 13.0 points above its pre-training reference score for cognitive governance, 11.8 points for independent learning capability and 13.9 points for professional competency.

These findings suggested that a substantial proportion of the improvements demonstrated immediately after equation-guided training remained evident six months later. However, differences in average scores did not establish how much capability each individual participant retained, particularly given the missing assessment results and possible differences in case difficulty. Overall, the findings supported partial sustainability rather than complete retention of the capabilities developed through IAQ training. The equation-guided group demonstrated higher average performance and smaller reductions in average scores across all three capabilities. These findings suggested that equation-guided training provided a more enduring foundation for value-oriented IAQ problem diagnosis and solving, although further statistical evidence would be required to establish that individual capabilities deteriorated more slowly following equation-guided training.

Transferability Across Unfamiliar IAQ Problems

While the preceding sections examined how well participants retained their developed capabilities over six months, this section examined whether those capabilities could be applied to different unfamiliar IAQ problems. It also presented findings on the extent to which participants retained their scientific understanding of pollutant behaviour and exposure–health risk relationships.

Performance by Building Context: At six months, the equation-guided group achieved average professional competency scores of 72.0, 71.0 and 68.2 for residential, educational and hospital IAQ problems, respectively. The corresponding scores for the non-equation-guided group were 65.0, 64.4 and 61.4. For cognitive governance, the equation-guided group achieved average scores of 70.7, 69.8 and 66.2 for residential, educational and hospital IAQ problems, respectively. The corresponding scores for the non-equation-guided group were 62.3, 61.1 and 58.1. For independent learning capability, the equation-guided group achieved average scores of 67.8, 66.1 and 63.5 for residential, educational and hospital IAQ problems, respectively. The corresponding scores for the non-equation-guided group were 60.4, 58.9 and 55.9.

An important finding was that the higher average scores achieved by the equation-guided group were not limited to a particular building context. The group demonstrated better average performance in all three assessed capabilities across residential, educational and hospital IAQ problems. Both groups recorded their lowest average scores when investigating hospital IAQ problems. This might reflect the complexity of the particular hospital case, including occupant vulnerability and specialised operational requirements. However, the findings did not establish that hospital IAQ problems were generally more difficult than residential or educational IAQ problems.

What the Findings Established About Transferability: Transferability concerned whether professionals could apply what they had learnt during IAQ training to diagnose and solve problems they had not previously encountered. Although both training approaches in RQ2 included residential, educational and hospital examples, the specific problems investigated in RQ3 were unfamiliar to participants. For example, a residential IAQ problem might involve cooking emissions, outdoor haze and restricted window opening. An educational IAQ problem might involve changing occupancy levels and inadequate ventilation. A hospital IAQ problem might involve vulnerable occupants and specialised ventilation requirements.

Although these problems involved different circumstances, the underlying scientific principles governing pollutant behaviour, exposure dose and health risk remained applicable. Effective transferability therefore required professionals to recognise which scientific principles were relevant, formulate appropriate questions, address gaps in their knowledge and apply their understanding to diagnose and solve each unfamiliar problem.

The higher average scores across the three building contexts suggested that equation-guided training provided a stronger foundation for transferring the developed capabilities to unfamiliar IAQ problems. However, higher group averages did not establish that every participant performed consistently across all three contexts or would demonstrate similar competency in every unfamiliar professional situation.

Scientific Mental Models as a Secondary Outcome: The scientific mental-model findings helped explain whether the scientific understanding developed during training remained available to support participants' reasoning when investigating unfamiliar IAQ problems. The equation-guided group's average scientific mental-model score decreased from 76.9 immediately after training to 74.7 after three months and 72.9 after six months. The corresponding scores for the non-equation-guided group were 67.7, 65.0 and 62.7, respectively.

After accounting for differences in starting capabilities and organisational clustering, the equation-guided group had an estimated six-month advantage of approximately 10.5 points over the non-equation-guided group (95% confidence interval: 2.8–18.2). These findings suggested that the equation-guided group retained a stronger scientific understanding alongside its better performance in cognitive governance, independent learning and professional competency. However, although retained scientific understanding could help explain the advantages observed in the other capabilities, the findings did not establish a direct cause-and-effect relationship between them.

Statistical Robustness and Scientific Limitations

The preceding sections presented the findings on the sustainability and transferability of the capabilities developed through IAQ training. The purpose of this section was to establish whether these findings collectively provided sufficient statistical evidence to support the RQ3 alternative hypothesis and whether the conclusion remained defensible when important limitations of the investigation were considered. The RQ3 null hypothesis (H_{03}) stated that equation-guided training did not produce better six-month performance, after accounting for starting capabilities, in at least one of the three primary outcomes. The alternative hypothesis (H_{13}) stated that equation-guided training produced better performance in all three outcomes: cognitive governance, independent learning capability and professional competency in value-oriented IAQ problem diagnosis and solving. This distinction was important because demonstrating better performance in only one or two capabilities was insufficient to support the alternative hypothesis. As established in the preceding sections, the estimated six-month advantages for the equation-guided group were 7.8 points for cognitive governance, 8.6 points for independent learning capability and 8.8 points for professional competency. The corresponding one-sided p-values were 0.012, 0.019 and 0.012, respectively. All three p-values were below the predetermined statistical significance threshold of 0.05.

The combined hypothesis test, known as the intersection–union procedure, required each capability to satisfy the statistical significance criterion independently. Consequently, the overall conclusion depended on the capability for which the statistical evidence was weakest. In this investigation, that capability was independent learning, with a p-value of 0.019. Since this value was also below 0.05, the primary statistical analysis rejected the null hypothesis (H_{03}) and supported the alternative hypothesis (H_{13}). This established statistical evidence of comparative superiority across all three capabilities at six months under the assumptions of the primary analysis. However, an important consideration was whether the same conclusion would be reached using a different statistical approach. The primary analysis accounted for differences in participants' starting capabilities, repeated assessments of the same professionals and similarities among professionals working within the same organisation. The latter consideration was particularly important because the investigation involved 120 professionals but only 12 independently allocated organisations. Professionals from the same organisation could share similar working environments, experiences and learning opportunities, making their performances potentially more similar.

An additional statistical analysis based on the original random allocation of the participating organisations produced one-sided p-values of 0.023 for cognitive governance, 0.032 for independent learning capability and 0.019 for professional competency. All three remained below the statistical significance threshold of 0.05. The agreement between the two statistical approaches strengthened confidence in the primary conclusion by demonstrating that support for the alternative hypothesis was not dependent solely on one statistical approach. Nevertheless, greater uncertainty arose from the missing six-month assessment results. As established earlier, assessment results were incomplete or unavailable for 25% of the original participants. Although the primary analysis used available information to account for missing results, its conclusions depended partly on assumptions about how the professionals with missing assessments might have performed. For example, professionals who experienced difficulties retaining or applying their learning might have been less inclined to complete the assessments. If this occurred to a greater extent in the equation-guided group, its estimated advantage could have been larger than the advantage that would have been observed had everyone completed the assessments.

To examine the implications of this possibility, an additional analysis considered a less favourable situation for the equation-guided group. When the missing independent learning assessment results were assumed to be less favourable than predicted by the primary analysis, the estimated advantage decreased from 8.6 to 5.1 points, with a 95% confidence interval ranging from −2.4 to 12.6 points. Although the estimated advantage remained positive, the statistical evidence was no longer sufficient to establish with confidence that equation-guided training was more effective in developing independent learning capability. Since the alternative hypothesis required sufficient statistical evidence

of better performance in all three capabilities, it was no longer supported under this less favourable assumption.

This finding did not establish that the primary conclusion was incorrect. Rather, it demonstrated that the conclusion depended partly on the credibility of the assumptions made about missing assessment results. The uncertainty associated with these results was therefore more consequential for the overall hypothesis than the choice between the two statistical approaches examined. Another consideration was the influence of professional experiences during the six months following training. Participants could have encountered workplace IAQ problems, undertaken additional independent learning or gained access to other learning resources. Such experiences could contribute to the development or retention of their capabilities. However, some subsequent learning experiences could themselves have resulted from the original training. For example, equation-guided training might have encouraged professionals to recognise knowledge gaps and independently seek additional scientific information during workplace investigations. Statistically removing the influence of such experiences could therefore remove part of the educational benefit associated with the training. Consequently, these experiences informed the interpretation of the findings without replacing the comparison between the original training groups.

Overall, the primary findings supported the alternative hypothesis that mass-balance and health-risk equation-guided IAQ training was more effective in developing cognitive governance, independent learning capability and value-oriented professional competency that remained evident six months after training. However, this conclusion was qualified by uncertainty surrounding missing assessment results. The scientific contribution of RQ3 extended beyond establishing which training approach produced better assessment performance. It provided evidence that the capabilities developed through equation-guided training were partially sustained and could be applied to unfamiliar IAQ problems across different building contexts. Nevertheless, the findings supported conclusions about demonstrated professional capabilities within the six-month investigation period, rather than lifelong learning behaviour or verified improvements in actual workplace outcomes.

Integrated Interpretation of the Findings

The practical significance of the RQ3 findings extended beyond professionals achieving higher assessment scores six months after training. It concerned the potential of equation-guided IAQ training to develop a more enduring and transferable way of thinking that could help professionals independently diagnose and solve IAQ problems encountered in management practice and building design. This was particularly important because professionals could not be trained to anticipate every combination of circumstances they would encounter throughout their careers. Their effectiveness therefore depended not only on what they had learnt during training but also on their ability to apply and extend that learning when confronted with unfamiliar problems.In IAQ management practice,

professionals frequently encounter situations in which the underlying causes of an observed problem are not immediately apparent. For example, occupants might continue to experience discomfort and respiratory symptoms despite the installation of air-cleaning systems. A professional without an appropriate scientific mental model might recommend increasing filtration efficiency or replacing existing equipment without adequately investigating why the problem persisted. In contrast, a professional with a stronger understanding of pollutant behaviour might question whether the problem resulted from insufficient airflow through the filters, continued indoor pollutant generation, outdoor pollutant entry, inappropriate equipment operation or a combination of these factors.

The sustained advantages in cognitive governance and independent learning capability were particularly relevant to such situations. Professionals would not necessarily possess all the knowledge required to diagnose every IAQ problem. However, the scientific understanding retained from training could help them recognise what they did not know, formulate meaningful questions, identify the additional evidence required and independently acquire the knowledge needed to make scientifically defensible decisions. This could reduce premature conclusions, unnecessary equipment replacement and expenditure on solutions that failed to address the underlying causes of problems.

In building design, the implications were equally important but more anticipatory. Unlike professionals investigating existing IAQ problems, design professionals needed to anticipate problems that might arise from future building characteristics, operating conditions, occupant activities and changing outdoor environmental conditions. For example, designing a ventilation system for an educational building required consideration of changing occupancy levels, indoor pollutant generation, outdoor air quality, filtration performance and energy consumption. Designing for a hospital additionally required careful consideration of occupants' vulnerability and specialised operational requirements.

The transferability findings suggested that professionals trained to understand the scientific relationships governing pollutant behaviour, exposure dose and health risk might be better prepared to reason through these different design circumstances rather than depend excessively on familiar design solutions or standard practices. This did not diminish the importance of regulatory requirements, engineering standards or established design guidance. Instead, it suggested the educational value of developing the capability to understand why particular requirements were necessary, recognise situations where minimum requirements might be insufficient and justify additional design considerations where appropriate.

For both IAQ management practice and design, the ultimate purpose of developing these capabilities was value delivery. Scientifically appropriate solutions would still need to be evaluated in terms of their anticipated contributions to occupants' health, comfort, convenience, awareness and safety, relative to the financial, operational and other sacrifices required. A solution that effectively reduced indoor pollutant concentrations might

have limited practical value if it was unaffordable, difficult to maintain or incompatible with occupants' needs and building operations.

The declining average scores observed in both training groups also had an important practical implication. Equation-guided training should not be regarded as a one-off educational intervention capable of guaranteeing permanently sustained professional competency. Opportunities to investigate real-life problems, reflect on professional decisions, acquire additional scientific knowledge and critically evaluate the outcomes of implemented solutions would remain important for maintaining and advancing professional capabilities. The findings did not imply that professionals needed to explicitly use mathematical equations during every IAQ investigation or design exercise. Rather, the potential educational value of the equations lay in communicating scientific relationships that professionals could internalise and subsequently use to guide their thinking, questioning, learning, judgements and decisions.

Overall, the RQ3 findings supported the potential of equation-guided IAQ training as an upstream intervention for developing professional readiness for value-oriented problem diagnosis and solving. Its practical significance lay in preparing professionals to respond intelligently to unfamiliar and changing circumstances rather than merely equipping them with predetermined solutions to familiar problems. Nevertheless, the findings demonstrated capabilities within assessed case investigations, not verified improvements in actual IAQ management and design practices. Evidence from workplace investigations, professional interviews, implemented solutions and subsequent building performance would be necessary to establish whether the demonstrated educational advantages translated into sustained improvements in professional practice and healthy living for building occupants.

…… Chapter 5 ……

On the day Briana Oliveira received her Doctor of Philosophy degree, she remembered the fifteen-year-old girl who had believed that intelligence was sufficient for learning, making good decisions and solving problems. Dr Sofia Martins, her doctoral mentor, congratulated her afterwards. Briana was happy, but the achievement meant something deeper than academic recognition. Before beginning her PhD, she had already recognised how her intelligence and confidence in apparently successful decisions could sometimes discourage further questioning. Through her doctoral research with experienced FM professionals, she gained a deeper appreciation of how differences in scientific mental models, cognitive governance and independent learning could influence people's capabilities for diagnosing and solving unfamiliar IAQ problems. Her research also strengthened her understanding of how mathematical equations could support mathematical reasoning and, through appropriately designed learning activities, contribute to developing these capabilities.

Her doctoral journey had also changed how she understood mathematical equations. Before undertaking her research, she had primarily regarded equations as scientific representations used to explain physical relationships and perform calculations. She now appreciated their potential to support mathematical reasoning even when numerical computation was unnecessary. A mathematical equation could make relationships between variables explicit, help someone imagine how circumstances might change and reveal assumptions that required investigation. Briana had become particularly interested in the difference between knowing how to use an equation and knowing how to reason through the scientific relationships it represented. The distinction mattered because someone could obtain a correct numerical answer while overlooking an important feature of the real-life problem being investigated.

The indoor-air mass-balance relationship provided a useful example. By describing how pollutant addition and removal influenced indoor concentrations, it offered a scientific basis for questioning the possible causes of an IAQ problem. However, it did not identify the actual causes in a particular building. An engineer still needed to investigate relevant indoor activities, outdoor pollution sources, ventilation, filtration and other conditions. Similarly, health-risk equations could help people reason about how exposure dose, occupant vulnerability and other factors influenced the probability of a specified health problem over a defined period. Yet the equations could not automatically establish which factors were operating in a particular situation or determine which intervention would deliver the greatest value to occupants.

During her PhD, Briana had therefore become increasingly interested in the relationship between mathematical reasoning and cognitive governance. She understood cognitive governance as the conscious capability to question, monitor and improve how people applied their intelligence, knowledge and understanding to particular circumstances. Mathematical reasoning could support this capability by helping people identify relevant relationships, question assumptions and recognise missing information. These questions could motivate further investigation and independent learning. In turn, stronger scientific understanding and cognitive governance could support greater competency in diagnosing and solving unfamiliar IAQ problems. Briana did not assume that learning equations automatically produced these improvements. Her doctoral work had strengthened her interest in understanding the conditions under which mathematical reasoning could contribute to them, while also revealing why the educational problem extended beyond teaching equations correctly.

As Briana considered her career after completing her PhD, she faced an important choice. She could return to engineering consultancy, where her experience would enable her to investigate building problems and recommend technical solutions. However, her personal experiences and doctoral research with FM professionals had inspired a different ambition. She had recognised that intelligence, scientific knowledge and professional experience did not necessarily ensure independent learning and effective problem solving in unfamiliar

situations. Her PhD had also deepened her understanding of how mathematical reasoning could support cognitive governance and these capabilities. Rather than concentrate on solving individual engineering problems herself, she wanted to develop original educational design knowledge and solutions that empowered others to become independent lifelong learners and competent problem solvers.

Briana therefore accepted a Lecturer position in Sustainable Building Engineering at a university committed to applied learning and research. At that stage, she had not decided that fictional case stories would become the focus of her scholarship, nor had she established a comprehensive educational design framework. Those developments would emerge later. She wanted to become an effective engineering educator while investigating how scientific understanding could support independent learning and problem-solving capability. She hoped to examine this question through sustained engagement with students. She also understood that her doctoral insights provided a starting point, not a ready-made educational solution.

During her first year as a lecturer, Briana taught engineering design, indoor environmental quality and sustainable building design. She explained scientific relationships clearly and enjoyed helping students understand concepts they had initially found difficult. Her teaching evaluations were encouraging, and most students performed satisfactorily in examinations and assignments. However, while assessing a third-year design assignment, she encountered a situation that made her question whether these achievements demonstrated students' ability to independently apply their knowledge to unfamiliar real-life problems. A student named Amira had developed an excellent ventilation design for an educational building. Her calculations were accurate, the proposed system satisfied the stated requirements, and her presentation demonstrated a strong understanding of the relevant engineering principles.

During the oral discussion, Briana asked how Amira's design would perform if classrooms were occupied outside normal hours, teaching spaces were rearranged or student numbers increased. She also asked how outdoor traffic pollution might affect ventilation, cooling and energy use. Amira hesitated, then identified relevant consequences and suggested technically sound adjustments. When asked why these possibilities had not appeared in her submission, Amira explained that the design brief had specified the building's occupancy, layout and operating conditions. She had treated them as fixed requirements rather than assumptions worth examining.

Initially, Briana wondered whether Amira lacked cognitive governance. That evening, however, she re-examined the assignment brief and marking rubric. The project required students to integrate architectural arrangements with structural and building services systems, including ventilation, cooling and lighting. Yet most criteria rewarded how accurately students met specified requirements and explained their designs. Little attention was given to whether students questioned the completeness of those requirements or

considered plausible changes in building use. Amira had largely done what Briana had asked. The realisation was uncomfortable. Briana had nearly judged the student's thinking without first questioning how her own assessment might have shaped it.

She reviewed other students' submissions. Many demonstrated competent integration of building systems, accurate calculations and sensible design decisions. A few independently considered accessibility, changing occupancy patterns, maintenance access or conflicting occupant needs beyond the brief. Most focused on the conditions supplied. This did not prove they lacked independent thinking: a student might reasonably concentrate on what an assessment required. Nevertheless, Briana could not tell from the submitted work whether students could recognise an incomplete problem definition, determine what else they needed to know and formulate an investigation without prompting.

The finding challenged what she had considered successful teaching. Students were learning important engineering knowledge and skills, but Briana wanted them to develop something further: the capability to independently diagnose unfamiliar design problems and justify solutions that delivered value to occupants and other stakeholders. She did not intend to discard prescribed tasks or calculations. Those remained necessary foundations. Instead, she redesigned learning activities so that students questioned assumptions, considered changing circumstances and explained why information mattered to decisions. She began separating the goal from its means: success meant developing independent cognitive governance, not merely producing more teaching materials.

For one activity, she introduced the hypothetical conversion of an apartment into a small office. Students considered how the change in use affected space planning, occupancy, thermal loads, ventilation, lighting, accessibility, energy use and the integration of building systems. They initially proposed familiar solutions, but Briana asked what evidence would establish their suitability. How would more occupants alter internal heat gains? Could the existing layout support safe circulation and convenient operation? Would a ventilation change affect cooling demand or pollutant exposure? Which requirements could be established from available information, and which needed further investigation? Students began seeing the building as an interacting system rather than a collection of separate design calculations.

Briana selected indoor air quality partly because her PhD had shown her the potential of equation-guided mathematical reasoning. Using mass-balance relationships, she encouraged students to reason about indoor pollutant sources, outdoor entry, removal and changing concentrations before calculating. Health-risk relationships helped them ask how exposure dose, vulnerability and a specified health outcome might affect their judgements. Other design considerations required reasoning about heat, energy, space and occupant activities. Her purpose was not to turn a design module into an IAQ module, but to

demonstrate how scientific relationships could guide questioning across an integrated building design problem.

The discussion was encouraging. Students identified interactions they had initially overlooked and explained why additional evidence was necessary. Yet when Briana later assigned a different, unfamiliar building design situation for individual investigation, performances varied. Some independently questioned assumptions and connected relevant building systems; others reverted to familiar solutions. The contrast showed that guided discussion did not establish independent cognitive governance. She needed to investigate how learning activities could help students develop that capability beyond her immediate guidance.

The mixed results encouraged Briana to investigate how learning activities could help students independently question assumptions, identify knowledge gaps and apply scientific understanding to unfamiliar problems. She examined existing approaches to problem-based learning, case-based learning, reflective practice and self-regulated learning. Each offered insights, but she focused on one challenge: intelligent learners could understand scientific principles yet hesitate to question conclusions they already considered reasonable. Remembering her own discomfort when Dr Martins challenged her explanations, Briana wondered whether learners sometimes perceived questioning as a challenge to their intelligence or competence. Could a learning activity help them recognise limitations in their own thinking without making them feel personally criticised? She wondered whether examining fictional characters' reasoning might encourage such reflection.

Briana did not assume fictional stories were superior to case studies or simulations. She saw an educational possibility: fiction allowed her to portray realistic engineering situations through the thoughts, conversations and decisions of people whose knowledge was necessarily incomplete. She could show intelligent professionals making reasonable decisions, receiving justified praise and subsequently recognising considerations that might affect the value of their solutions. By following the characters' investigations, disagreements and eventual decisions within a complete story, readers could examine how assumptions were challenged and understanding developed. Fiction also allowed her to explore professional pressures without disclosing confidential information. She hoped readers would reflect on their own reasoning, rather than simply enjoy the narrative.

Drawing on the questions raised by her earlier classroom activity, Briana wrote her first fictional case story about a young engineer whose team was commissioned to convert an apartment building into offices. The team integrated layouts, structure, ventilation, cooling, lighting and energy use. Its calculations were sound, it satisfied the client's stated requirements, and the client welcomed the result. The engineer initially treated that approval as proof the work was complete. However, through conversations with prospective occupants and the building manager, she learnt that some future users had

mobility limitations, meetings might occasionally continue after normal working hours, and the proposed equipment locations could complicate maintenance. These circumstances exposed uncertainties that the brief had not addressed. Within the same story, the engineer questioned her assumptions, investigated the implications with her team, consulted those affected and reconsidered the proposed arrangements. The revised proposal responded more carefully to accessibility, operation and maintenance while acknowledging the associated technical and financial trade-offs. Her article presented the full case as one self-contained narrative.

Briana invited her Sustainable Building Engineering students to read the complete story. Their task was not to produce another building design, but to examine the characters' decisions and consider what made a recommendation appropriate in its particular circumstances. Some defended the initial decision because the client had omitted those requirements. Others considered whether a professional should independently investigate uncertainties likely to affect building users and operations. Their discussion explored the distinction between meeting an agreed brief and questioning whether that brief was sufficient to deliver the intended value. Students traced how the fictional engineer's questions led to additional evidence, more informed judgements and a revised proposal. They also examined whether the eventual solution balanced the needs of the different stakeholders. Because everyone had read the full case, discussion concerned its complete reasoning, not staged revelations.

The discussion was encouraging, but students could repeat the story's questions without being able to formulate their own. Their individual reflections confirmed the distinction: several could explain why the fictional engineer had revised her judgement, yet struggled to describe how they would begin their own investigation of an unfamiliar problem. Briana therefore refined the complete fictional case and its accompanying reflective activities. She strengthened the characters' scientific reasoning and made their uncertainties, competing interpretations and decisions more convincing. She also invited readers to examine their mental models, question the characters' reasoning and consider how the insights might apply elsewhere. She kept separate unfamiliar assignments for examining whether students could formulate questions, identify relevant scientific relationships and justify decisions without prompts taken from the story. Through these revisions, Briana began developing original design principles for integrating realistic fiction, scientific reasoning, questioning and reflection into educational communication solutions. She recognised that the individual elements were not new; her original design knowledge concerned how and why their deliberate integration could support cognitive governance, independent learning and value-oriented problem-solving competency.

As more stories emerged, Briana decided to establish a publicly accessible scholarship website. She wanted learners, educators and practising professionals to engage directly with her educational communication solutions rather than encounter them only through descriptions of research. The website published complete fictional cases across

sustainable building engineering, with cartoons, reflective questions and explanations of their design principles. Each story was self-contained, without withheld information. Briana chose public scholarship rather than submitting these creative works to academic journals for peer review. However, she understood that public access did not automatically establish scholarly originality, intellectual rigour or educational effectiveness. Those claims would require explanation and appropriate evidence.

The website gradually became Briana's design laboratory. There, she began assessing output through three dimensions: quantity, measured by publications produced; quality, judged by the originality and rigour of her design theories and principles and their appropriate integration into complete solutions; and safety, examined through ethical soundness and foreseeable risks of misleading or harmful use. The characters, dialogue, complete development of each case, scientific explanations and reflective questions were not chosen merely for entertainment. They were designed to invite readers to examine a cognitive challenge through the experiences, reasoning and decisions of the people in the story. Across different aspects of building design, construction, environmental performance and building operations, Briana explored how similar principles of cognitive governance might support reasoning about different engineering problems. She documented important design decisions, their intellectual foundations and subsequent revisions. Readers could examine both the finished articles and the reasoning behind them. The website made her design scholarship accessible, but publication and readership statistics alone could not establish what readers learnt or valued.

Her classrooms served a different but complementary purpose. They became living laboratories for examining the value students experienced through engagement with the designs and changes in that value over time. Briana did not begin by treating every classroom interaction as formal research evidence. Initially, she used observations, assignments and feedback to improve teaching. As her scholarly questions became clearer, she developed more systematic evaluation procedures and sought the appropriate institutional guidance and approvals for any formal research use of students' work and reflections. To understand outcome and impact, she would need the same goal to govern assessment of every learning activity. She considered all parts of value delivery: comfort, convenience and awareness/certainty gained; the quality, quantity and safety of what learners received; and the comfort, convenience, awareness/certainty, time and money sacrificed to engage with it. She kept teaching, assessment and research distinct, especially because she graded students. Participation in additional research activities could not be allowed to determine their academic treatment.

Briana developed an evaluation approach within normal learning activities, without requiring a separate experiment for every student. Before selected learning activities, she examined students' existing understanding through unfamiliar sustainable building engineering problems. These tasks required students to explain the problem, formulate questions, identify relevant scientific relationships and justify what evidence was needed.

Students subsequently engaged with complete fictional case stories and accompanying reflective activities as part of their module, examining the reasoning and decisions presented in each account. Later, they completed different unfamiliar problems requiring comparable capabilities, but without questions or investigative steps prescribed by Briana or reproduced from the stories. The problems differed so students could not rely on memorised answers. She varied technical conditions and stakeholder needs while keeping reasoning demands comparable. This established different observations of the same intended capabilities over time, rather than mistaking a single successful assignment for improvement.

She developed assessment criteria for the educational capabilities she intended to examine. These included the quality of students' scientific and engineering mental models, their independent questioning and cognitive governance, their ability to recognise and address knowledge gaps, and their competency in formulating, diagnosing and proposing solutions to unfamiliar sustainable building engineering problems. The quality of a recommendation depended not only on technical reasoning but also on whether it considered the intended purpose and relevant stakeholder needs. Briana examined how students applied scientific principles and mathematical relationships across different engineering situations, but did not equate computational accuracy with independent reasoning. For example, a student might correctly calculate the expected annual water savings from a rainwater harvesting system without examining whether the available storage could reliably meet demand during dry periods. Another might use an understanding of rainfall variability, water demand and storage behaviour to identify the additional information needed before recommending an appropriate system. What mattered was whether students could independently apply their understanding to investigate unfamiliar problems and justify appropriate decisions.

Evidence became more useful when Briana connected students' work with their reflections. After reading a complete story, she invited learners to explain how they understood the characters' initial judgements, which assumptions and questions they found significant, and whether the story challenged their own mental models. Some students valued the unfamiliar demands; others expressed discomfort because they preferred information and template answers supplied by the lecturer. Briana did not equate either response with achievement. Some reflections were insightful, but others consisted mainly of statements about the importance of critical thinking. Briana did not assume that a convincing reflection demonstrated improved capability. She compared students' accounts with their subsequent independent problem investigations. Where a student claimed to have learnt to question assumptions but continued accepting familiar solutions without examining their appropriateness, the evidence was inconsistent. Where the student's work demonstrated the questioning and investigation described, the reflection offered a more credible account of learning. The work showed what students could demonstrate; their reflections also revealed the comfort, convenience, awareness or uncertainty and sacrifices they

experienced. Together, these sources began to inform an assessment of value at a given time and of changes between assessment points. Briana knew that observed change was not automatically attributable to her designs. As new teaching cycles approached, she was ready to examine the emerging patterns more systematically.

…… Chapter 6 ……

Over successive teaching cycles, Briana encountered unexpected patterns. Her goal was to help learners independently govern their thinking as upstream readiness for value-oriented problem diagnosis and solving. That goal guided what she designed and how she assessed it. Some students demonstrated considerable improvement in formulating questions but struggled to identify the scientific and engineering knowledge needed to answer them. Others could apply technical principles accurately but failed to examine whether the assumptions underlying their calculations represented the actual situation. Several students began independently recognising relationships between different building systems, operating conditions and stakeholder needs, while others continued relying on questions supplied by their instructors. The findings revealed which design features appeared useful and which needed refinement. She did not claim that every student benefited equally, nor did she treat improvement in one capability as proof of improvement in all the others.

One revealing experience involved a student evaluating façade materials. He accurately calculated embodied carbon and recommended the material with the lowest initial footprint. However, he had not considered whether differences in durability, replacement frequency and maintenance requirements might affect the overall environmental performance of the alternatives. When Briana discussed the work with him, he explained that he had focused on the calculation because he believed it provided the evidence needed to select the best material. In a subsequent unfamiliar assignment involving construction methods and building performance, he independently questioned whether the information provided was sufficient to justify a recommendation. He identified additional technical and operational considerations. His final judgement remained imperfect, but Briana saw progress. His later work showed a different cognitive condition: he questioned whether the evidence and assumptions fitted the problem rather than treating correct calculations as sufficient.

Briana’s enthusiasm was balanced by another concern: because she developed the educational designs and assessed students, her expectations could influence how she interpreted their work. She therefore documented assessment criteria before reviewing major submissions, retained representative examples of different performance levels and invited colleagues to moderate selected anonymised assignments. Colleagues sometimes disagreed. A student whom Briana considered independent might, on closer examination, have reproduced a question introduced during an earlier class discussion. These disagreements were uncomfortable but useful. They helped her refine the distinction between guided reasoning and independently demonstrated cognitive governance. The

evidence became more credible because she was willing to examine interpretations that challenged her expectations.

Briana also recognised that improvements between earlier and later assignments could not automatically be attributed entirely to her fictional case stories. Students also learnt from other modules, projects and academic experience. Several influences could explain their development. Without an appropriate comparison, her classroom evidence could support conclusions about observed development and plausible contributions from her designs, but not establish that those designs were the sole cause. She made these limitations explicit in her scholarly records. Rather than weakening her commitment, this discipline helped her distinguish scientifically defensible claims from conclusions she merely wanted to believe. It was cognitive governance applied to her scholarship.

Briana also considered later learning. Students sometimes reasoned more independently immediately after an activity, but would they do so later? She began examining relevant work from subsequent university assignments and capstone projects where institutional procedures and student permissions allowed. She neither followed graduates into industry nor evaluated their professional performance. Her interest was whether learners could independently apply the reasoning in unfamiliar educational tasks after the original teaching activities had ended. Some questioned problem definitions, identified missing evidence and justified decisions independently. Others reverted to familiar approaches when the demands of a new task became difficult.

Amira offered an example. During her final-year capstone project, she investigated the environmental performance and usability of a proposed community sports facility. It concerned orientation, shading, thermal comfort, accessibility and energy performance. Unlike her earlier assignment, Amira independently questioned whether the proposed design adequately considered the different activities and needs of its intended users. She identified additional information needed to evaluate the relationships between shading, daylight availability, cooling demand and occupants' comfort. Her recommendations considered these relationships rather than merely satisfying specifications. In her reflection, she explained how she had moved from accepting the stated requirements as a complete definition of the problem towards independently questioning whether they adequately represented the intended purpose. Briana valued the reflection because Amira's work corroborated it. Amira's work informed the outcome assessment at that time; comparison with her earlier work informed an impact assessment, although neither alone measured all dimensions of value or proved causation. Nothing established how she would perform throughout professional life.

By this stage, Briana distinguished output, outcome and impact by reference to her educational goal. Output meant what her design lab brought into existence: publications containing original design theories, principles, fictional stories, cartoons and complete educational solutions. She assessed output quantity by publication count; quality by the

originality, rigour and coherence of the design knowledge and the appropriateness of its integration into solutions; and safety through ethical review and foreseeable risks of use. Outcome meant the value, V(t), a learner experienced at a given time through engagement with a solution. She considered every parameter of her value equation: comfort, convenience, awareness/certainty, quality, quantity and safety, alongside sacrificed comfort, convenience, awareness/certainty and time-and-money cost. Impact meant the change in that experienced value between two assessment points, $\Delta V = V(t_2) - V(t_1)$, insofar as it could reasonably be attributed to her design. Her classroom living lab supplied evidence through work, reflections and observations. Neither outcomes nor impacts could be inferred merely from publication counts. A learner might demonstrate independent reasoning yet feel overwhelmed; another might enjoy a story without demonstrating independent reasoning. Briana therefore considered performance alongside learners' accounts of effort and experience.

As her public scholarship grew, Briana faced questions about its academic standing. During a departmental discussion, a senior professor praised the accessibility of her fictional stories and cartoons but asked where her peer-reviewed journal publications could be found. Another asked whether it was original scholarship or creative use of established ideas. Briana explained that her contribution concerned developing original design principles and integrating them into educational communication solutions intended to strengthen cognitive governance, independent learning and value-oriented problem-solving competency. She also explained how evidence from students' work and reflections informed the continuous refinement of those designs. Although the discussion was respectful, she left feeling unsettled. She wondered whether colleagues would ever regard her approach as serious scholarship.

Her insecurity became more pronounced during academic reviews, where research achievements were frequently discussed in terms of journal publications, citation counts, the h-index and research funding. Briana respected colleagues who advanced scientific and engineering knowledge through conventional research. Yet she compared their visible achievements with hers. Her public scholarship website demonstrated the original design knowledge she had developed, while her classroom evidence showed how students' capabilities were progressing. Yet neither contribution could be summarised easily through the indicators commonly used to compare researchers. She began worrying about whether her chosen approach would support her long-term academic career, particularly her aspiration to become a Full Professor.

One evening, Briana contacted Dr Martins and shared her concerns. She explained that although she believed her work addressed an important educational problem, she sometimes felt academically inadequate when listening to discussions about research excellence. Dr Martins asked whether she doubted her scholarship's quality or feared its value would go unrecognised. Briana struggled to separate them. He urged her to examine

both independently. Citation indicators could demonstrate scholarly attention within academic publication networks, but they did not directly establish whether educational solutions developed learners' capabilities. Equally, evidence of improved learning did not automatically establish the originality or significance of the design knowledge responsible for it. Briana needed to demonstrate both through evidence appropriate to her scholarly purpose.

Briana reconsidered how she presented her work. Rather than attempting to persuade colleagues that conventional academic indicators were unimportant, she concentrated on making her own scholarly contributions more transparent and defensible. Through her public design laboratory, she showed how existing scientific and educational knowledge informed her original design principles, how she justified them, and how she integrated them into complete fictional case stories, cartoons and reflective activities suited to their purpose. She distinguished what was already known from what her design work contributed. Her classroom records documented strengths and limitations; students' work and reflections showed their resulting capabilities. She remained committed to public scholarship rather than journal publication, but recognised that public accessibility did not remove the need for rigorous intellectual examination and credible evidence.These experiences reinforced her commitment to the academic direction she had chosen after her PhD. Her doctorate had examined how mathematical reasoning supported cognitive governance, independent learning and IAQ problem-solving competency. Her subsequent teaching had revealed a broader educational challenge: learners could possess scientific knowledge and technical skills without consistently using them to independently question and solve unfamiliar sustainable building engineering problems. She had therefore devoted her scholarship to developing original educational design knowledge and communication solutions intended to address this challenge. She respected conventional engineering research but pursued a different scholarly purpose. She was not choosing teaching instead of research; she was conducting original design research through educational practice.

Briana recognised the professional risks. She examined her university's educator-track promotion requirements and discussed their interpretation with academic leaders. The pathway required sustained teaching excellence, significant scholarly contributions, educational leadership and evidence of achievement beyond routine module delivery. Although conventional academic publications were recognised, the university also allowed other forms of scholarly contribution to be considered when their originality, quality and significance could be established. This did not guarantee promotion. It simply meant that her chosen form of scholarship could be evaluated under the university's established criteria. She decided to continue developing the work while remaining realistic about the expectations and uncertainties involved.

Briana's responsibilities eventually extended beyond her modules. She contributed to curriculum design, assessment and mentoring. In programme discussions, she encouraged colleagues to examine whether their assessments required students merely to

reproduce knowledge or also to formulate questions, recognise knowledge gaps and justify decisions in unfamiliar circumstances. She helped develop assessment criteria that made independent reasoning and value-oriented problem solving more visible in students' work. Not every proposal was adopted, and she recognised that other educators had different teaching responsibilities and legitimate perspectives. Nevertheless, records of curriculum changes, assessment developments, mentoring activities and programme responsibilities provided evidence of her growing educational leadership. Her career progressed from Lecturer to Senior Lecturer and subsequently to Associate Professor.

Meanwhile, her public scholarship website attracted readers from different countries, including educators, students and practising professionals. Some contacted her to discuss particular stories, question their underlying principles or share their interpretations. Briana appreciated these exchanges because they exposed her ideas to perspectives beyond her own classroom. However, she did not regard international readership as evidence that her educational designs had necessarily developed readers' capabilities. The website demonstrated availability and reach, not automatically V(t) or ΔV. Independent readers might experience outcomes and impacts, but without suitable feedback or repeated evidence she could not measure them reliably. Her classroom remained the main living lab for examining both. Thus she valued visibility without confusing it with effectiveness.

Years later, when Briana became eligible for promotion to Full Professor, she prepared a portfolio that reflected the development of her scholarly purpose rather than attempting to imitate a conventional engineering research record. She began with the intellectual understanding gained through her PhD and explained how it had motivated her subsequent work in engineering education practice. Her design-lab evidence documented publication quantity, design-knowledge quality and safety, alongside the development of original theories, principles and communication solutions. She presented living-lab evidence of value experienced at assessed times and changes in that value, using assignments, reflections, observations and unfamiliar tasks across cohorts. She documented both improvements and limitations, explaining how the findings had informed further design development. Her portfolio also included sustained teaching achievements, curriculum contributions, mentoring responsibilities and educational leadership.

The committee assessed the portfolio against educator-track standards. Some questioned whether scholarship without conventional journal peer review demonstrated originality. Others asked whether student work and reflection could demonstrate educational significance appropriate to a Full Professorship. The committee examined the reasoning underlying Briana's original design contributions, the evidence connecting her educational solutions with students' demonstrated capabilities, and the limitations she acknowledged. Members also considered the independent moderation of selected student work and the documented contributions she had made to curriculum development and educational leadership. The central question was not whether Briana had produced an extensive collection of educational resources, but whether she had established a sustained, original

and significant body of scholarship with credible educational outcomes and leadership appropriate to the highest academic rank.

The scrutiny was demanding. Briana sometimes felt the familiar urge to defend her work by explaining how much effort she had invested in it. But effort did not establish scholarly significance. She examined each concern, clarified what her evidence could establish and acknowledged what remained uncertain. She did not claim that her educational designs worked equally well for every student or that classroom improvements guaranteed lifelong professional competency. Nor did she claim that her scholarship had transformed industry or society without evidence. She demonstrated how original design knowledge evolved through practice and how students' work supported claims within the living lab. A dissatisfied student could show discomfort and sacrifice even while their work showed the intended cognitive capability; both belonged in the value assessment.

The committee concluded that she met Full Professor criteria on the educator pathway. Her appointment recognised the sustained development of original scholarly design knowledge, its practical interpretation through public scholarship, evidence of meaningful educational outcomes, and her contributions to teaching excellence and educational leadership. The decision did not establish that every university would evaluate unconventional scholarship in the same way. It reflected the judgement of an institution whose established criteria permitted different forms of scholarly achievement to be assessed according to their originality, quality, significance and relevance to its educational mission.

Appointed Professor of Engineering Education Practice in Sustainable Building Engineering, Briana felt grateful and relieved. The promotion brought professional recognition and greater security, both of which mattered to her. However, its deeper significance lay in recognising a scholarly direction that had emerged from her personal experiences and doctoral research. She had chosen to develop original educational design knowledge intended to empower people to independently question, learn and solve unfamiliar problems. Her design lab and classroom living lab had served complementary purposes. The professorship recognised what she had achieved through years of sustained work, but did not mean that every question had been answered or that further improvement was unnecessary.

One evening, Briana returned to the journal she had maintained since her university years. She remembered the intelligent young girl who had often mistaken a convincing explanation for a sufficiently complete one. She also remembered the uncertainty she experienced when colleagues questioned her public scholarship, the disappointment of educational designs that had not achieved their intended outcomes and the insecurity she had felt when comparing her career with conventional academic achievements. These experiences had not eliminated her desire for recognition, but they had helped her understand the difference between seeking approval and evaluating the actual value of her

work. She had learnt to welcome legitimate scrutiny without allowing external validation to determine her scholarly purpose.

Before closing, Briana wrote her enduring question: “What is it that I do not know or have not considered that could make what I know or propose inappropriate for this particular situation?” The question could not guarantee perfect decisions. Its importance lay in sustaining the conscious effort to recognise limitations, question assumptions, acquire additional understanding and improve the value of one’s judgements and actions. Her intelligence had enabled remarkable achievements, but stronger cognitive governance had helped her move that intelligence towards wisdom. As a Professor of Engineering Education Practice, her greatest ambition was not simply to demonstrate what she knew, but to develop original scholarly design knowledge and practical educational solutions that empowered others to independently extend what they could learn, understand, judge, decide and achieve. Her professorship marked an important achievement in that journey, while the questioning, learning and refinement that gave the journey meaning continued.
The End!