P5 Report

Smart Technology in Indoor Air Quality management

Exploratory research to help Facility managers of Dutch universities

June 2024

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COLOPHON

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ABSTRACT

Although people spend 90% of their time indoors, the issue of indoor air pollution had not gained interest as compared to outdoor until the global Covid-19 pandemic. The pandemic made people and the scientific community realise the importance of good indoor air quality in tackling such health crises. There has been heightened public awareness and stricter air quality guidelines which the facility managers are responsible to address. As a response, they are shifting to innovative approaches and utilising smart indoor air quality (IAQ) technologies available to manage the IAQ better. Various smart technologies and services are available in the market which measure, monitor and report indoor air quality solutions. This research aims to explore: How does the adoption of smart IAQ technologies help the facility managers of Dutch universities and what are the barriers to it? The context is chosen to be university buildings due to the impact of IAQ on cognitive functions and the rising demand for health and comfort in educational spaces. This exploratory research includes theoretical desk research, qualitative case studies and interviews. The current status of different smart technology service providing companies are researched and evaluated. The use and benefits of these technologies in three Dutch universities is explored through the case studies and interviews with their facility managers. The interviews add to identifying barriers to the technologies from the perspective of a facility manager. A cross case analysis is done to compare and contrast the findings. One of the case studies is further investigated to get an in-depth understanding of the barriers to adoption from a different stakeholder perspective. The results show that the adoption and utilisation of smart IAQ technologies, depending on their level, can help the facility managers of Dutch universities in maintaining and enhancing an optimum indoor air quality, ensuring occupant health & safety, and taking a proactive role by making data driven decisions. However, there are several barriers in the process such as lack of knowledge, resources and manpower, conflict of stakeholders, split incentive, security issues and active involvement of facility managers in the process. The research lastly suggests recommendations to overcome these barriers to make use of these technologies effectively and to their full potential.

Keywords: Smart technology, Indoor air quality, Facility management, Dutch universities, Barriers

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Interviewee codes

FMA: Facility manager, School of Business and Economics, Maastricht University
FMB: Facility manager, Building 28, TU Delft
FMC: Facility manager, Delft Branch, HHS
B4B1: Project associate Building 28, Brains 4 Buildings
B4B2: Project Coordinator, Brains 4 Buildings

01 INTRODUCTION

1.1 Necessity of prioritising Indoor Air Quality

1.2 Impact of Covid 19 pandemic

1.3 Being ‘smart’ is the future

1.4 Problem Statement

1.5 Scientific and Societal relevance

1.6 Research Questions

1.7 Conceptual framework

01 INTRODUCTION

1.1 Necessity of prioritising Indoor Air Quality

People spend 90% of their time indoors, in both public and private indoor environments such as home, workplace, school/university and transportation (Cincinelli & Martellini, 2017). Indoor air quality (IAQ) is one of the significant factors that impact occupants' health in an indoor environment. Hence, prioritising indoor air quality is a necessity as it directly impacts people's well being and quality of life.

Numerous scientific studies have established a direct link between poor IAQ and various health problems. Indoor air pollutants such as volatile organic compounds (VOCs), particulate matter (PM), and biological contaminants can cause respiratory conditions, trigger allergic reactions, and contribute to the development of cardiovascular diseases (Marques et al., 2020). In addition to health implications, IAQ significantly influences cognitive function and productivity. Studies have demonstrated that exposure to indoor pollutants can impair cognitive performance, decrease productivity levels, and increase absenteeism in educational and occupational settings. Poor IAQ not only affects individual well-being but also incurs substantial economic costs due to decreased productivity and increase in healthcare expenditures (Wyon, 2004).

Despite such a significant impact, the scientific community had been concerned with studies on outdoor air quality more as compared to indoor. However, recently, the impacts of indoor air quality on health have become a growing concern for the scientific community because the modern homes and offices tend to be more airtight than earlier ones due to changes in building design aimed at improving energy efficiency. Although these advancements have resulted in more energy-efficient buildings, they also create interior conditions where pollutants can easily accumulate and reach significantly higher concentrations (Marques et al., 2020). Moreover, the Covid-19 pandemic has contributed in prioritisation and research of IAQ.

1.2 Impact of Covid 19 pandemic

Awareness of IAQ issues

The Covid-19 pandemic has had so far various unconventional effects on lifestyle, the economy, and the environment in addition to health. Since this pandemic is not the first or the last of its sort, it raised a number of questions about the factors that affect it, solutions for this problem, and future preventative strategies. The solutions to these concerns are being sought for by the entire scientific community. Air quality is one such metric that corresponds with both Covid-19 pandemic and the health of occupants in an interior environment (Agarwal et al., 2021).

According to Hobeika (2023), in the aftermath of the Covid-19 pandemic, there has been a heightened awareness of IAQ concerns, reflecting a growing recognition of the role indoor environments play in public health (Hobeika et al., 2023). The pandemic has brought to light several challenges associated with IAQ in the post-pandemic era, such as issues related to ventilation, airborne virus transmission, building occupancy dynamics and the need for advanced monitoring and control systems.

According to a study by Melikov (2020) many buildings face challenges regarding ventilation with buildings that heavily rely on recirculating air and struggle to prevent the spread of airborne contaminants, necessitating the exploration of alternative ventilation strategies (Melikov, 2020). In this generation of technological advancements, an integrated system adopting smart building solutions is considered a viable option to achieve a healthier IAQ (Agarwal et al., 2021).

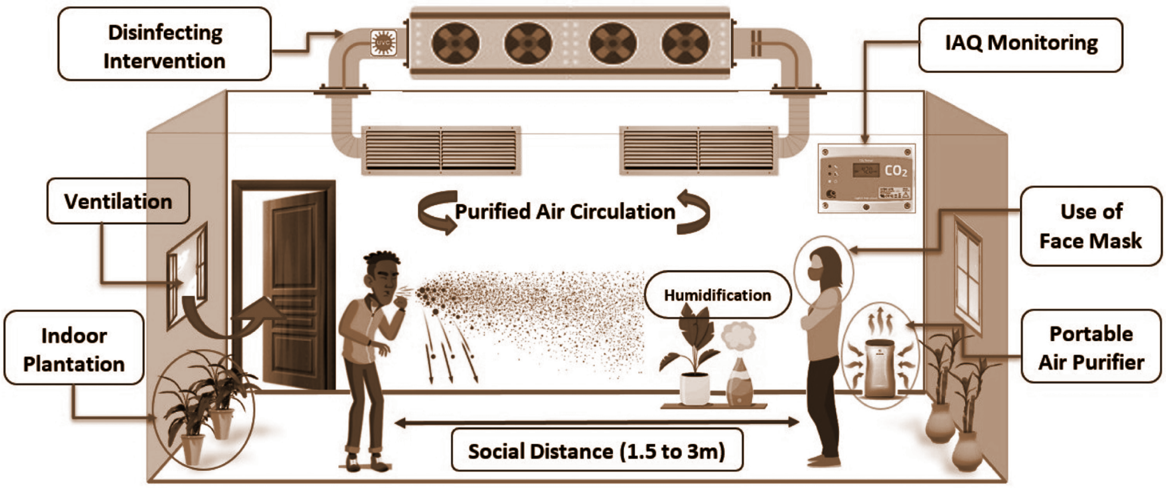

Figure 1: IAQ factors in relation to COVID-19 transmission (source: Agarwal et al., 2021)

New regulations and guidelines

In the post-pandemic era, addressing the risk of airborne disease transmission has prompted a re-evaluation of systems to reduce the spread of airborne pathogens and enhance IAQ management. Several changes and improvements are recommended to mitigate these risks and create safer indoor environments. Optimising ventilation rates is a key aspect of post-pandemic HVAC adjustments.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) is a professional association with the main aim to create a healthy built environment focusing on indoor air quality, building systems, energy efficiency and sustainability; and provides guidelines on maintaining good IAQ and HVAC systems. As a response to the outbreak of Covid-19 pandemic, ASHRAE updated new guidelines concerning the spread of aerosol transmissions through the built environment. This new document outlined the latest standards and guidelines that all facilities should follow to control the dissemination of infectious aerosols. Some of these include, new minimum outdoor airflow rates, use of air cleaners for air recirculated by HVAC systems and standalone air filters. Additionally, they recommend applying methods for real-time detection for the purpose of improved variable control of HVAC systems responsive to different levels of risks (ASHRAE, n.d.). ASHRAE continues to promote research to enhance HVAC technologies and knowledge to mitigate the risk of infection due to airborne transmission (ASHRAE, 2022).

Additionally, the World Health Organisation (WHO) has provided recommendations on ventilation in the context of Covid-19 since January 2020. The WHO Environment and Engineering Control Expert Advisory Panel (ECAP) for Covid-19 was formed early in the pandemic to assess existing scientific data and practices and revise recommendations on environmental and engineering controls. WHO contributed to recommendations on ventilation and air conditioning systems in June 2020, and specialists further improved ventilation recommendations in several technical guide items for use in healthcare institutions, residences, schools, and enterprises between 2020 and 2021 (WHO, 2021).

These new recommendations and guidelines after the COVID-19 pandemic have significant impacts on awareness of the importance of IAQ, HVAC systems, IAQ management and facility management.

Acceleration of technology in IAQ

As a response to the changes in guidelines and heightened awareness of the public, corporations are now considering innovative approaches to improve the quality of the air in their portfolios and there is a renewed interest in air quality management (Hext, 2020). According to Prof.dr.ir. Philomena Blyussen (personal communication, January 19, 2024), since the outbreak of the Covid-19 pandemic, several solutions have been sought to reduce the infection risk in indoor environments.

In the management of air quality, the majority of building managers have traditionally used low-tech remedies up to this point. However, recently, organisations are boosting the frequency with which their HVAC systems cycle fresh air into their interior spaces and opening their windows. These tactics can have trade-offs even though they are easy to use. For instance, because more heating and air movement demand power, opening windows and increasing air cycling frequently results in higher energy use and comfort suffers as well. Therefore, in order to obtain better insight into air quality, 59% of real estate executives have prepared, after the pandemic, a new investment in air quality sensors and analytics, according to the Verdantix Global Corporate Survey 2020 for efficient IAQ management. The information and data from smart technologies is used to alert residents to high-risk regions and give building managers performance statistics on HVAC systems (Hext, 2020).

Overall, there is an acceleration in adoption of technology in the field of IAQ and building management as a response to the pandemic and to make buildings smarter.

1.3 Being ‘smart’ is the future

“Smart buildings really, really matter right now. We're just coming out of the end of the global pandemic. And actually I feel more comfortable if I have more information about the environment that I'm working in. And so ultimately, the sort of building that I want to be working in is a smart building. I call COVID the great accelerator. And I think real estate, which has been manoeuvring its way through digital transformation, has been accelerated dramatically.”

- *Andy Pyle*
  Head of Real Estate, KPMG International
  (Source: Wired Score, YouTube, 2021)

Smart Buildings represent a transformative approach to the design and operation of buildings by integrating advanced technologies to enhance efficiency, sustainability, and user comfort. These buildings include interconnected systems and data analytics to optimise energy usage, improve operational performance and create a more responsive and adaptive built environment. With the ability to monitor, control and automate various building functions, smart buildings play a crucial role in enhancing occupant experience, reducing environmental impact and contributing to a more sustainable future (Dakheel et al., 2020).

Smart Buildings are characterised by a range of key features that distinguish them from traditional buildings. These buildings embrace automation, utilising automatic devices and systems to optimise functions like HVAC, lighting and security for enhanced efficiency. Adaptability is crucial, allowing these buildings to learn, predict and adjust to occupants' needs and external conditions. Interactivity is promoted, enabling users to engage with building controls and access real-time data for personalised comfort (Dakheel et al., 2020). Enabling the indoor environment with sensor technologies that routinely monitor and analyse the physical environment to ensure compliance with healthy building certification is one of the many roles of smart buildings (Banyamin, 2023).

A key goal of people-centric smart building design is occupant comfort and well-being. Measurement by sensor data, examination of the data intake to develop insights for the facility managers and working to improve indoor comfort conditions can all be achievable with smart technologies (Banyamin, 2023). One of the most important applications of such technology is in indoor air quality management as it is a critical factor which contributes to the health and well-being of the occupants of a building. Technologies such as Internet of Things (IoT) and Building management system (BMS) shape the future of smart IAQ management.

1.4 Problem Statement

Despite the fact that people spend 90% of their time in an indoor environment, the research on indoor air quality had not gained as much interest in the scientific community as compared to the outdoor air pollution. However, as a result of the COVID-19 pandemic, there has been a heightened awareness amongst people regarding the impact of indoor air quality on their health. The post-pandemic era has brought about a paradigm shift in the way indoor environments are managed, particularly with regards to IAQ (Ding et al., 2023). As the world battled the aftermath of the Covid-19 pandemic, the significance of maintaining healthy indoor spaces has become a focal point for both public health and occupational well-being. Facility managers (FM), entrusted with the responsibility of ensuring optimal building conditions, face prominent challenges in adapting their practices to the evolving demands of post-pandemic workplaces (Hounsell, 2023). In this context, exploring the potential of the rapidly developing technologies used in smart buildings as a tool for facility managers to efficiently manage IAQ emerges as a critical approach for research and innovation (Saini et al., 2020).

However, the overarching problem revolves around the existing gaps in knowledge regarding how smart technology can effectively aid FMs in their mission to create healthier indoor air quality. The study of Zhang et al. (2022) states that applications of technology in FM heavily rely on algorithms created prior to the COVID-19 pandemic, hence, new research is necessary as the historical data might not be relevant in the post-pandemic situation. Additionally, while the literature acknowledges the potential benefits of smart tools in IAQ monitoring, it has been found that there is a need for data-driven IAQ management models. According to Dai et al. (2023), the integration of data-driven algorithms into smart IAQ technologies should be considered in future research (Dai et al., 2023). The same conclusion has been reached through an exploratory interview with indoor air quality researcher Erica Ding, where she also stated that several sensors are placed in most smart buildings but the facility managers are not using the data collected by these sensors to make management decisions (Personal communication, January 18, 2024).

Therefore, this research aims to bridge this gap by first exploring the status of smart technology usage in indoor air quality management by the facility managers and secondly, identifying any barriers that exist to their adoption. Lastly, the research suggests potential recommendations to overcome these barriers and facilitate latest IAQ technology adoption.

1.5 Scientific and Societal relevance

The scientific relevance of the research is that it addresses an intersection between technological advancements and the optimisation of indoor air quality. The aim of this research is to bridge the gap regarding the utilisation of smart IAQ technologies by facility managers. This research contributes to the scientific understanding of the barriers that hinder facility managers in data driven decision making. It eventually contributes to the development of health-focused building strategies. Additionally, the findings have the potential to guide the development of future technologies aimed at creating healthier indoor environments which takes into account the perspective of building facility managers.

As a substantial segment of the global population spends a significant portion of their lives indoors, the impact of indoor air quality on well-being and health is a pressing societal concern. This research holds societal relevance by examining the potential of technological interventions to positively influence occupants' health and overall quality of life. Service providers and facility managers can use the findings of the research to implement data driven strategies that contribute to broader societal aspirations for health-focused building management.

1.6 Research Questions

Main research question

[MQ] How does the adoption of smart IAQ technologies help the facility managers of Dutch universities and what are the barriers to it?

Sub research questions:

[SQ1] What is the role of facility managers in creating healthy indoor air quality?

[SQ2] What is the current status of smart technologies available in indoor air quality management?

[SQ3] What are the benefits of smart IAQ technologies for the facility managers of Dutch universities?

[SQ4] What are the barriers encountered in adoption of smart IAQ technologies in Dutch universities and how can they be overcome?

1.7 Conceptual Framework

The main concepts included in the main research questions along with their relationships and context of research forms the conceptual framework as shown in *figure 2*. The facility management domain is responsible for managing the indoor air quality; and smart technologies help them in doing so.

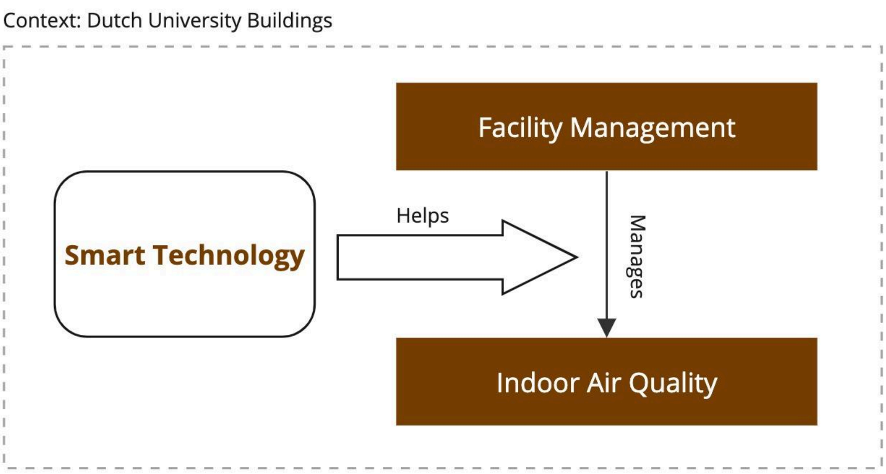

Figure 2: Conceptual framework (author)

02 RESEARCH METHODOLOGY

2.1 Research objectives

2.2 Research method

2.3 Case study design

2.4 Data collection and analysis

2.5 Research framework

2.6 Data Plan

2.7 Ethical Considerations

2.8 Personal study targets

02 RESEARCH METHODOLOGY

2.1 Research objectives

The primary objectives of this research are:

- Understand the role of facility managers in creating a healthy indoor air quality
- Evaluate the status of smart technologies in indoor air quality management
- Explore the benefits of using these technologies
- Identify barriers to the adoption of smart IAQ technologies by FMs
- Suggest recommendations to potentially overcome the barriers

2.2 Research method

The main approach undertaken for this research is theoretical desk research and qualitative case study method. Qualitative case study research method involves an in-depth exploration of particular cases within their real-life context, aiming to understand the complexity of the subject under investigation (Yin, 2003). This method emphasises detailed descriptions and analyses, by employing multiple data collection techniques such as document analysis and interviews to gather comprehensive data (Leverage Edu, 2021).

Documents and information from the internet are used as a data source by identifying phenomena where connections can be established by treating textual material qualitatively. Semi structured interviews are used to collect data in this qualitative research in which the researcher is involved in social interaction with the participants of the study (Blaike and Priest, 2019 p 216-217).

Case studies are used for various research purposes such as exploratory, descriptive and explanatory research, in order to induce theories and to commence a change. The use depends on the research questions that the study aims to answer, and the control of the researcher over the studied event (Yin, 2003; Blaike and Priest, 2019 p 195). Case study as defined by Adelman (1977) is an umbrella term for a family of research methods having in common the decision to focus on inquiry around an instance.

For this research, a multiple case study approach is used for exploratory purpose. Using multiple cases facilitates interesting comparisons and higher generalisability. Moreover, it allows for more convincing findings and adds weight to the research (Yin, 2003; Blaike and Priest, 2019 p 197). To understand the exploration of the different cases, the results are compared and contrasted by doing a cross case analysis. Furthermore, one case is developed further in depth in order to gain a better understanding of the phenomena from another perspective. The synthesis of the theoretical research, exploratory multi case study and in-depth single case study leads to the answer of the research questions posed.

2.3 Case study design

As mentioned in the previous chapter, a multiple case study approach is used for the research in which three cases are selected and analysed individually in the first step. The analysis of these cases are compared to draw conclusions from the findings to answer the research questions. The selection criteria for the cases were set as shown in *Table 1*, however, the cases were not searched for individually. In order to get connected with the cases the Brains 4 Buildings project was approached which collaborates with smart educational buildings and therefore already fulfils the most important selection criteria.

Criteria	**Why**	**Case A**	**Case B**	**Case C**
Located in the Netherlands	Geographical context of the research is specific to the location (NL) for better generalisability of the findings. Additionally, on site visit and in person social contact is possible due to this criteria	✓	✓	✓
Use of the building: University (Mainly educational and office)	Functional context is specified for the generalisability of the findings and easier comparison	✓	✓	✓
Uses smart technology to monitor/manage indoor air quality	The aim of the research is to explore the current status of smart technologies used	✓	✓	✓
A responsible facility manager is present who manages the indoor air quality	Interview will be conducted to know the perspective of facility managers	✓	✓	✓

Table 1: Selection criteria for the case studies (author)

2.4 Data collection and analysis

The data for the research is collected by two means; desk research and interviews. A literature review is done for the theoretical background. It helps in answering the SQ1 and SQ2 as the responsibilities of facility managers regarding IAQ is established and the current status of smart technology in indoor air quality management is explored. These findings are further elaborated or confirmed through the case study and interviews. The interviews with the facility managers are used to answer SQ3 and SQ4 as it is context specific and also dependent on the perspective of FM.

The data collected from the interviews are analysed manually by categorising them into different themes that arise from the sub research questions. A cross case analysis is used as a method to compare and contrast the different cases and draw conclusions. A theoretical framework is used to analyse the data collected such as the barriers identified and to provide recommendations in a timeline following the stages of the framework used.

2.5 Research framework

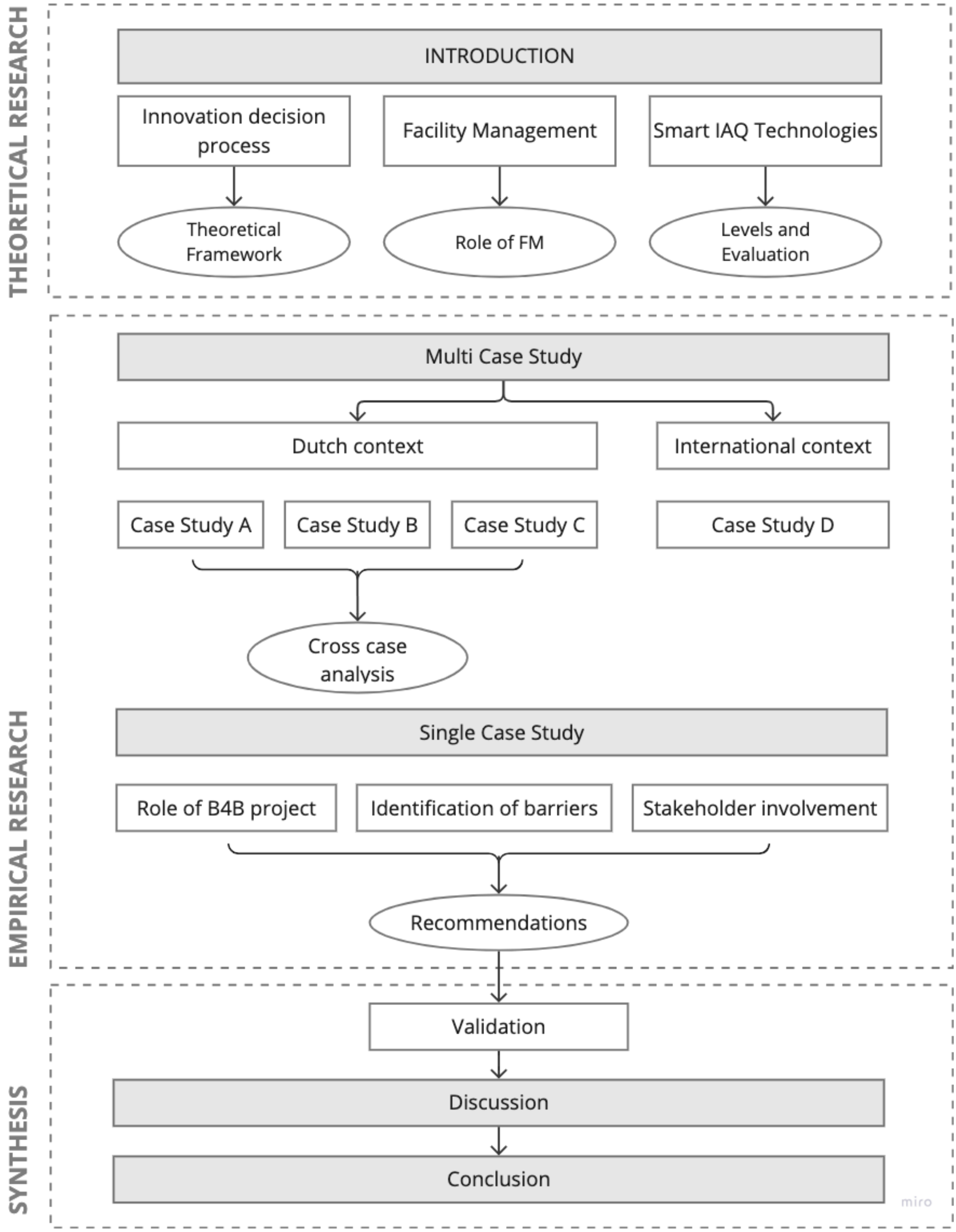

Figure 3: Research framework (author)

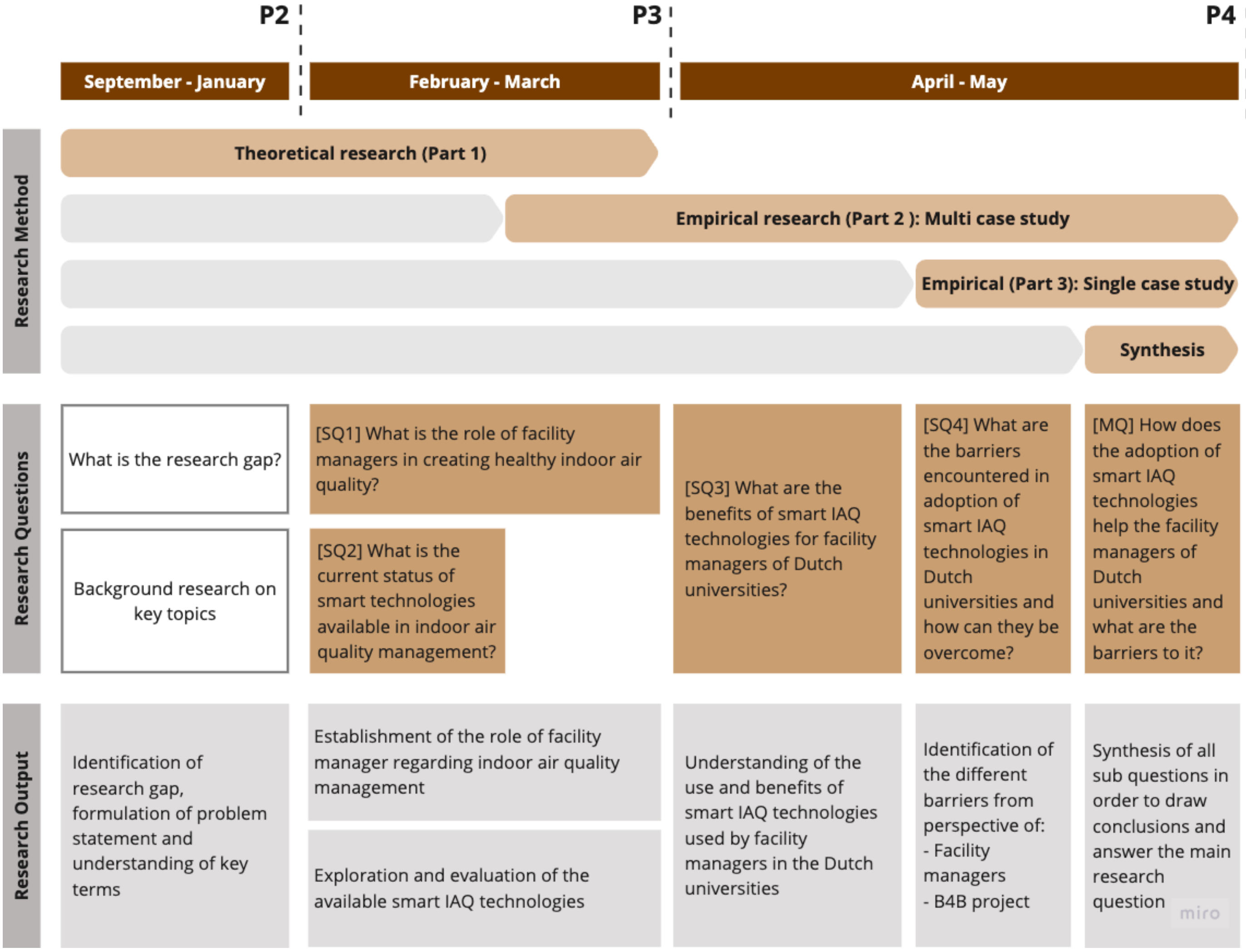

Figure 4: Research Framework with research method, questions and output (author)

2.6 Data Plan

This thesis adheres to the measurable set of principles referred as FAIR (Findable, Accessible, Interoperable and Reusable) Data Principles which enhances the reusability of the data (Wilkinson et al., 2016). The final thesis is uploaded on the TU Delft repository, with relevant keywords to ease the navigation. This will make the work findable and accessible. Additionally, the methodology will be explained in detail so that the future researchers can reuse data research to further explore the topic. The in text references and a reference list in APA makes it easy to trace all the secondary data used in the research. Furthermore, a data management plan is made using dmp online and consulted with the faculty data steward. An elaboration of the data management plan can be found in *Appendix C*.

2.7 Ethical Considerations

According to Blaike and Priest (2019), the ethical considerations of a research mostly focus on the researcher who is conducting the research, particularly how they treat their participants. However, some issues go beyond and relate to the research itself. This research involves human participants who are interviewed, hence a number of ethical issues had to be considered. It was made sure that the participation was voluntary and no kind of pressure was given. The informed consent form was signed, where the participants are fully and accurately informed about the nature of the research, the person conducting it and their involvement duration. The interview protocol with the information along with consent forms provided for the participants to sign which can be found in *Appendix A* and *Appendix B* respectively. Additionally, participants were given the freedom to withdraw and protection from harm and risk. Their right to privacy is protected by pseudo anonymisation and maintaining confidentiality. Regarding the research itself, no scientific misconduct is conducted and methodological standards are maintained (Blaike and Priest, 2019 p 66).

2.8 Personal study targets

Completing an entire research project independently and producing outcomes that are beneficial for further research is an achievement that comes with its challenges. A personal study target set to achieve through this research was to gain better insight into the field of facility management and to explore how present day smart technologies can impact user's health and comfort in buildings. The research is taken as an opportunity to explore two fields of personal interest; health and smart technology. During the process, the aim was to improve skills such as organisation, time management, communication and critical thinking. The main goal was to be persistent throughout the process and successfully produce an inspiring final result.

03 THEORETICAL RESEARCH

3.1 Context: Universities

3.2 Theoretical framework

3.3 Facility Management

3.4 Smart IAQ Technologies

03 THEORETICAL RESEARCH

3.1 Context: Universities

3.1.1 Why university?

Indoor air quality in educational buildings directly affects not only the health but also the cognitive functions of its occupants. The study conducted by Brink et al. (2019) in university classrooms in the Netherlands revealed significant findings regarding the relationship between indoor air quality and the performance/productivity of students. It was observed that carbon dioxide concentrations exceeded minimum Dutch guidelines in a considerable percentage of the classrooms, leading to poor indoor air quality that can affect the attention levels of both teachers and students, and increase the prevalence of building-related symptoms. This research highlighted a significant correlation between CO2 concentrations and perceived indoor air quality (PIAQ), as well as between PIAQ and factors such as the ability to concentrate, tiredness, and dry skin. It emphasised that increased CO2 concentrations can impact students' perceived indoor air quality, resulting in an inability to concentrate and increased tiredness, which in turn can lead to distraction and negatively affect academic performance and productivity. These findings underscore the importance of improving indoor air quality in university classrooms to enhance students' well-being, concentration, and overall academic performance (Brink et al., 2019).

Additionally, the study by Lan et al. (2009) showcased that office workers, and by extension students, exhibit changes in neurobehavioral functions such as perception, learning, memory, thinking, and executive functions in response to variations in indoor environment quality. These effects evidently underline the importance of optimal air quality in university settings for maintaining high levels of cognitive performance and productivity (Lan et al., 2009).

Therefore, due to the well-documented impact of IAQ on cognitive functions and the rising demand for health and comfort in educational spaces, the context of Dutch universities is chosen for this research, with an aim to contribute to a healthier and productive learning environment for students.

Dutch universities

Dutch universities are unique due to the combination of education, research and innovation. The experts in these organisations are working to address contemporary social concerns in the domains of sustainability, technology, safety, education, and health by utilising the results of their groundbreaking research. Moreover, universities can and want to play a role in these times of changes such as digitalisation and advancement of technology (Van Wetenschap, 2023).

According to the PhD research of Den Heijer (2011) titled ‘Managing the University Campus’, the Dutch university real estate consists of 1200 buildings covering an area of 4.5 million m^2, out of which only 3% is rented; meaning majority of it is owned and managed by the universities themselves. Since 2016, the number of university students in the Netherlands has been growing, reaching 340,000 in October 2022 as shown in *Figure 5*.

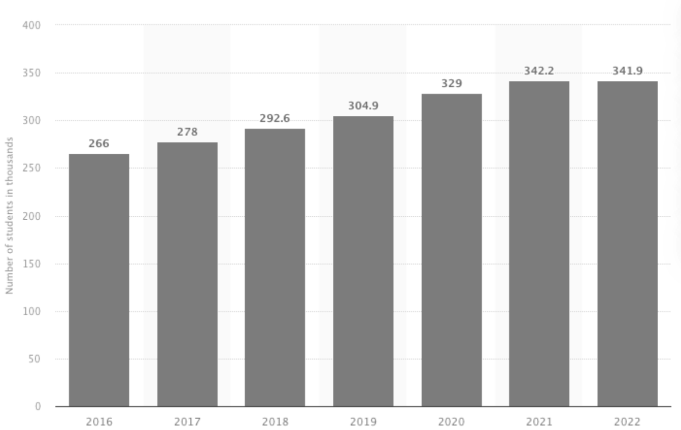

Figure 5: Number of students in Dutch universities from 2016 to 2022 (Statisca.com)

The Dutch university buildings serve various functions apart from education, extending to retail, leisure, residential and infrastructure. However, for this research, the focus is on the different types of work and educational spaces. Den Heijer (2011) identifies the following functional spaces within this context as shown in *Figure 6*.

functions	who manages / own / uses?		
	university	municipality	3rd party
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class rooms and studio spaces (small groups)	x		
lecture halls (large groups)	x		
office space academic staff	x		
office space support staff	x		
laboratories	x		x
study places for individual use / small groups	x		
library	x		
special places for ceremonies (graduation)	x	x	
special conference facilities	x		x
special educational facilities (dance, media, arts)	x	x	
academic hospital			x
medical school			x

Figure 6: Functions within education and research in Dutch universities (Den Heijer, 2011)

3.1.2 CREM and FM

CREM, originally defined as activities aimed at optimally attuning corporate real estate to corporate performance, has evolved to encompass a broader range of activities as the term corporate can exclusively refer to the sole goal of financial profit. However, for semi-profit and non-profit organisations like government buildings agencies, hospitals, and educational institutions, the broader definition of CREM has been developed to fit Public Real Estate Management (PREM) referring to the activities conducted to attune institution's accommodation to organisational performance, which does not only focus on economic but societal and political ambitions (Den Heijer, 2011). For university campuses, both CREM and PREM theories apply.

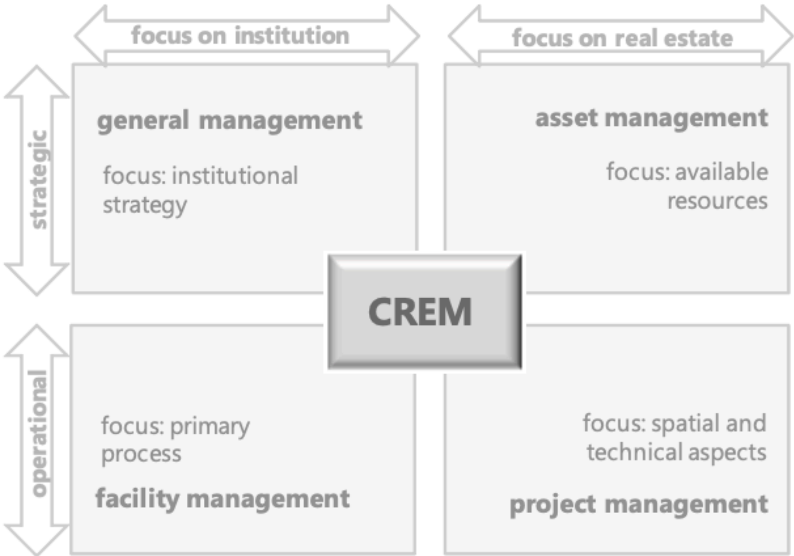

Figure 7: CREM theory (De Jonge, 1997; Krumm, 1999; Den Heijer, 2011)

As seen in *Figure 7*, CREM has its foundation on integrating general management, asset management, facility management and project management. Facility Management is a domain within CREM which focuses on the institution and has an operational character. FM primarily focuses on non-core business services, workplaces and management of the workplaces. However, FM and CREM share several key similarities and differences. Both disciplines aim to align physical resources with organisational strategies to enhance performance and add value. They focus on supporting primary business processes efficiently and effectively. However, FM typically emphasises the management of facilities and services, including aspects like maintenance, operations, and workplace management. In contrast, CREM centres on the strategic management of buildings and real estate portfolios, focusing on asset management, cost control, and aligning real estate with general management objectives. One significant difference between FM and CREM lies in their temporal and spatial considerations. FM often operates on a shorter time frame, with a focus on high flexibility in facilities to meet changing organisational needs. In contrast, CREM deals with the long life cycle of buildings and real estate assets, which are relatively static in nature (Van der Voordt, 2017).

Despite these differences, there is an increasing expectation that FM and CREM will become more integrated in the future. This integration is driven by the recognition of their shared goal of contributing to organisational success through the strategic management of physical resources. By leveraging their common objectives and expertise, FM and CREM can work together to optimise the use of real estate assets, enhance workplace productivity, and create value for the organisation as a whole (Van der Voordt, 2017).

3.1.3 Campus Management

As defined by Den Heijer (2011), campus management refers to the range of activities undertaken to optimally attune the university's performance. In her dissertation, she has applied the CREM theory to campus management which integrates the four perspectives namely; physical perspective, functional perspective, financial perspective and strategic perspective.

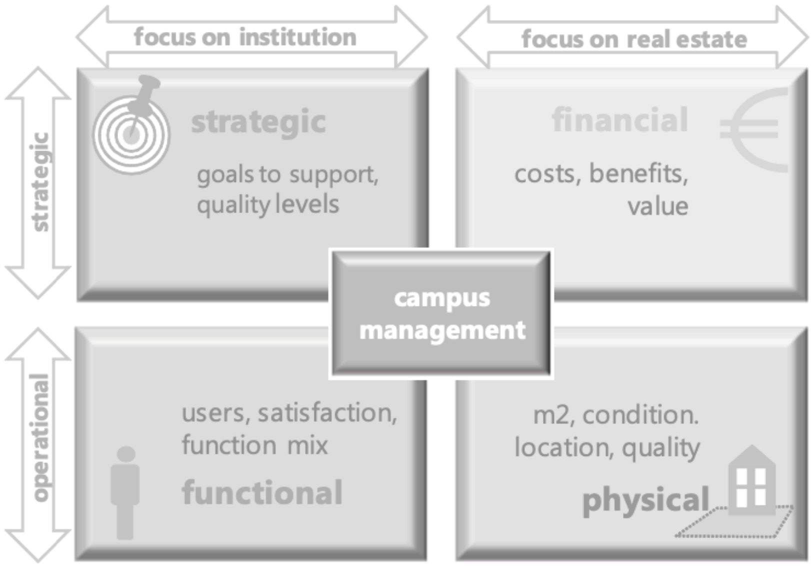

Figure 8: Basic framework for campus management, connecting four perspectives and various aspects (Den Heijer, 2011)

Campus management can also be interchanged with the term campus manager who has the responsibility of connecting the perspectives of all stakeholders in the management process. The perspective of the technical managers and controllers, who emphasise on real estate are in relation to the users and policy maker's perspective regarding the university's primary processes. The campus managers are confronted with varying ambitions from policy makers and different demands of the occupants along with the physical campus, finances, values and resources (Den Heijer, 2011).

perspective	focus	stakeholder (in general)	representatives (specific)
physical	the physical campus: land and buildings, their technical condition and legal requirements	technical managers	project managers technical campus staff (campus) architect
functional	fitness for use: quantitative and qualitative, space use, user demands and user satisfaction	users	students faculty / academic staff support staff visitors
financial	value, resources, costs (€): impact on the university resources, opportunity costs, current replacement costs	controllers	planning & control dept.
strategic	adding value to institutional goals: for education, research, attracting students and staff, human resource management and knowledge valorisation	policy makers	board of executives deans policy makers within the university policy makers outside the university (other) decision makers • on education, research, HRM and valuation of knowledge • on the role of the university (campus) in the regional economy (knowledge city & region) • on sustainability: green campus

Figure 9: Four perspectives on the university campus (Den Heijer, 2011)

Since this research focuses on the use of smart IAQ technologies by facility managers to create healthy indoor air quality, the framework of Den Heijer can be adapted as shown in *Figure 10*. The facility manager in this case is responsible for not only maintaining the quality of indoor air (physical) but their responsibilities also extend to ensure the users, meet the air quality ambitions, finding a balance between the costs and benefits.

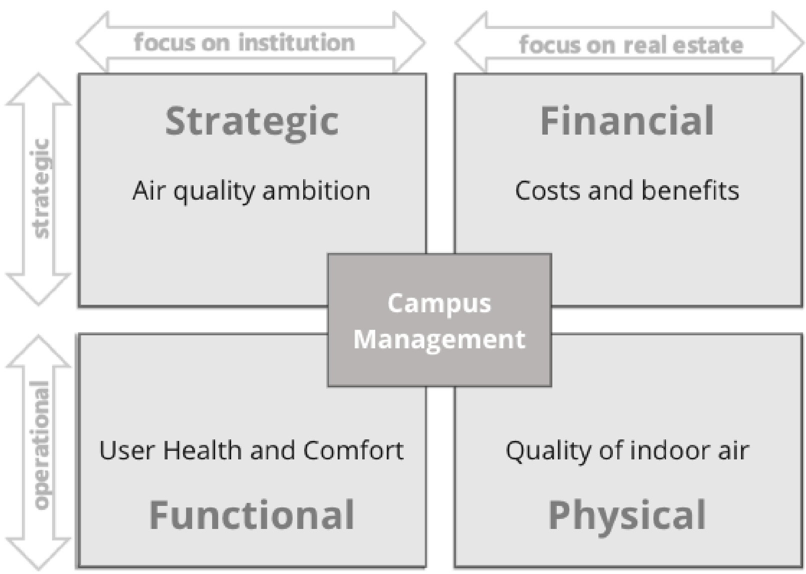

Figure 10: Campus management framework adapted for IAQ management (author)

3.2 Theoretical framework

3.2.1 Exploring theoretical frameworks

Campus Management framework (Den Heijer, 2011)

As mentioned in the previous chapter, the Campus management framework was explored as a possible theoretical framework for analysing the findings of this research. This framework focuses on creating a comprehensive approach to managing university campuses, integrating strategic, operational, and academic elements to enhance their overall performance and sustainability. This framework aligns campus management strategies with the university's mission and vision, ensuring that the physical environment supports academic goals and institutional priorities through long-term planning. It emphasises operational efficiency by optimising space usage, implementing sustainable practices, and maintaining well-functioning facilities. The framework also focuses on academic integration, designing learning environments that foster student engagement and support innovative teaching and research. Additionally, performance measurement through key performance indicators (KPIs) and benchmarking against peer institutions helps track progress and identify areas for improvement. Den Heijer's framework promotes a holistic approach to campus management, addressing immediate needs while anticipating future challenges and opportunities, ultimately creating vibrant, sustainable, and adaptable campus environments (Den Heijer, 2011). However, using this as a theoretical framework for researching the adoption and use of smart indoor air quality technology by facility managers presents certain drawbacks. First, the theory is primarily focused on strategic and managerial aspects of campus planning and operations, which might not fully capture the technical and user-specific implications of smart technology adoption. This focus could lead to an overemphasis on organisational and policy-level factors at the expense of understanding the practical and day-to-day challenges faced by facility managers. Additionally, the theory is designed to address broader campus management issues and may not provide the detailed guidance needed to explore specific technological innovations like indoor air quality systems. Therefore, these drawbacks suggest that while Den Heijer's Campus Management framework can offer valuable strategic perspectives, it might not be the most effective framework for the technology-specific research in this context.

Activity theory (Engeström, 2001)

Activity Theory is another potential framework explored to be used as a theoretical framework for this research which analyses human behaviour and consciousness through the lens of social, cultural, and historical contexts. It puts forward that activities are driven by an interplay between the subject (individual or group), the object (goal or purpose), and mediating artefacts (tools and signs). The framework also considers the broader community, rules, and division of labour that influence the activity. By focusing on the entire activity system, including its internal contradictions and developmental processes, Activity Theory provides a comprehensive understanding of how individuals interact with their environment. It is widely applied in fields such as education, organisational studies, and human-computer interaction to study how people use tools and technologies, adopt new practices, and are influenced by their social and cultural surroundings (Hasim and Jones, 2014). However, it also has drawbacks due to its complexity and multifaceted focus on the interactions between individuals, their communities, and the tools they use. The theory emphasises the social and cultural context of activities, which may overshadow individual factors that significantly influence technology adoption decisions. Especially, since this research aims to focus primarily on the perspective of facility managers rather than taking into account the complete ecosystem, these drawbacks can complicate the application of the theory in the context of this research that aims to provide clear, actionable insights into the adoption of new technologies by facility managers.

Innovation decision framework (Rogers, 2003)

The final framework explored is the Innovation decision process framework developed by Rogers (2003). It has been found to be used to explore several technology adoptions such as nurses' adoption of a computerised care plan system (Lee, 2004), diffusion of online games in Taiwan (Cheng, 2004), mobile device use in nursing education (Doyle et al., 2014), mobile learning adoption process by teachers after the Covid-19 pandemic (Frei-Landau et al., 2022). This theory offers substantial benefits as a theoretical framework for this research as it mentions five sequential stages through which individuals and organisations typically progress when adopting innovations: knowledge, persuasion, decision, implementation, and confirmation. This structured approach provides a clear roadmap to understand how facility managers become aware of new technologies, evaluate their potential benefits, make adoption decisions, implement the technology, and confirm its effectiveness. By applying this framework, researchers can systematically investigate each stage, identifying influential factors such as the perceived advantages of the technology, compatibility with existing systems, complexity in implementation, trialability options, and observable outcomes. This comprehensive understanding enables researchers to tailor strategies to address specific barriers and facilitators encountered by facility managers during the adoption process. Therefore, this theory is chosen due to its ability to provide actionable insights that support informed decision-making, effective implementation, and successful integration of new technologies by facility managers.

3.2.2 Innovation decision process

According to Rogers, the innovation decision-making process is an information seeking and information processing activity to decrease the uncertainty about the benefits of a certain technological innovation. The process consists of five steps that an individual or an organisation must go through before determining whether or not to utilise an innovation: Knowledge, Persuasion, Decision, Implementation and Confirmation. The characteristics of both the adopter and the innovation are critical in deciding whether diffusion will be effective. There are several communication channels that contribute to information flow in the process (Rogers, 2003).

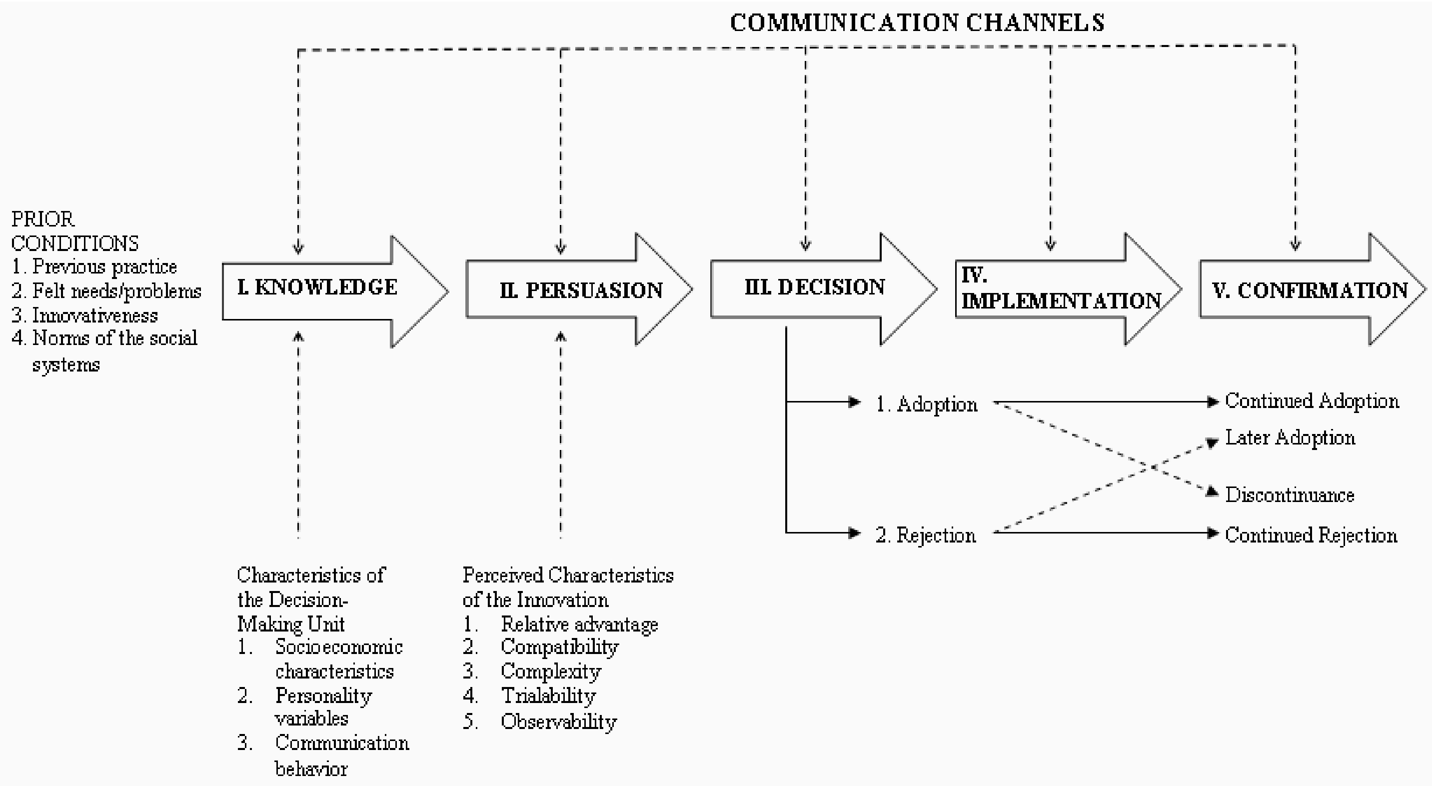

Figure 11: The innovation decision process model (Rogers, 2003)

Prior conditions

The knowledge stage is affected by certain prior conditions which refer to the contextual factors and circumstances that exist in association with the adopter. This includes: previous practice, felt needs and problems, innovativeness, and norms of the social system. These prior conditions set the stage for how individuals or organisations will move through the subsequent stages of the innovation decision process.

Stage 1: Knowledge

The first stage of the innovation decision process in the knowledge stage. During the knowledge stage, the potential adopter becomes aware of an innovation. Knowing about a new technology makes the potential adopters curious about it. It raises questions like, how can it solve the felt needs and problems? How does the innovation work? What are the consequences of the innovation in different levels? To answer these questions about the uncertainty of the innovation, the potential adopters collect information to gain understanding of how the innovation works. The communication channel that contributes to the input of the information necessary in the knowledge stage is mass media channels. Rogers mentions it to be newspapers, radio and television, however in this current generation, the most significant contribution would be of the internet.

Stage 2: Persuasion

During the persuasion stage, the potential adopter forms an opinion about the invention, which might be positive or negative. The potential adopter seeks information that can evaluate the innovation to gain certainly about the innovation's expected benefits. They want to know the advantages and disadvantages of the technological innovation for their personal situation. In this stage, interpersonal communication channels play a more important role than the mass media; because the information of mass media is general but the adopter wants to know specific information which is tailored to his/her use and benefits.

Rogers found that the persuasion stage is heavily impacted by five perceived attributes of the innovation that impact the adoption: Relative advantage, Compatibility, Complexity, Trialability and Observability.

Relative advantage: It refers to the degree to which the innovation is better than the current practice or alternative ways (Rogers, 2003; Genné-Bacon et al., 2020). The subjective perceived advantage matters rather than the objective advantage. The benefits are measured in economic terms, convenience, satisfaction and social prestige factors. Higher relative advantage is positively associated with the rapid adoption of the innovation.

Compatibility: The compatibility is tested as the consistency and usefulness of the innovation in relation to the prior conditions such as the existing values, needs of the adopter and social norms. The more compatible a technological innovation is, the higher the chances are of its adoption.

Complexity: Innovations that are complex in nature are less likely to be accepted by the adopters. Factors such as the amount of time of effort required to learn how to use the innovation effectively, technical expertise and knowledge required, have an impact on the adoption of the technological innovation. The more complex an innovation is perceived to be, the less likely it is to be adopted. Therefore, simplicity and user-friendliness enhance the adoption rates.

Trialability: Trialability refers to the degree to which an innovation can be experimented with on a limited basis before making a full-scale adoption decision. Trialable innovations imply less uncertainty to the potential adopters. Opportunities to test the innovation through pilot projects and gaining practical insights and feedback from initial use allow potential adopters to evaluate their benefits and feasibility in a controlled manner before full commitment.

Observability: It refers to the degree to which the outcomes of implementing the technology is visible to the individual and to others. Observability can be demonstrated by seeing the results of case studies and success stories where the innovation is already implemented. Innovations with high observability are more likely to be adopted because potential adopters can clearly see their positive impacts and effectiveness.

Stage 3: Decision

Following the Persuasion stage, comes the Decision stage where the prospective adopter actively decides adoption or rejection of the innovation. A positive view of the new technology acquired according to the attributes of innovation during the persuasion stage is typically required for a decision to embrace the innovation. Information evaluation occurs in this stage, where the innovation is thoroughly evaluated in terms of its advantages and disadvantages to the adopter. A cost benefit analysis is a tool used to evaluate the expense versus the benefits of the adoption. Benefits on economic terms such as Return on Investment (ROI) is calculated. All this information contributes to the decision of adopting or rejecting the new technology. The communication channel of interpersonal communication has been identified to contribute in the decision stage. Subjective evaluations from the communications with other individuals or organisations on the same level and values are likely to influence the decision of adopters.

Stage 4: Implementation

The implementation phase follows the decision-making phase, during which the individual uses the innovation for the first time. Adopters may make changes while using the innovation and continue to learn about it. This stage involves detailed planning, resource allocation, training, overcoming challenges, and continuous monitoring and adjustment. Successful implementation requires careful management, stakeholder engagement, effective training, and ongoing support to ensure that the innovation is integrated smoothly and delivers the expected benefits.

Stage 5: Confirmation

In the final Confirmation stage, the adopter's decision to embrace the innovation is either reinforced and maintained, or the innovation is discontinued. It is a continual process in which the individual or organisation seeks confirmation that the decision to adopt was correct. This can come from positive outcomes, peer validation, or ongoing support. If the innovation does not continue to meet expectations or better alternatives emerge, there may be a decision to discontinue its use (Rogers, 2003).

3.2.3 Theoretical Framework

This research aims to use the theory of Rogers (2003) as a framework to answer the research questions. This framework will be used to identify the areas of theoretical research and to design the empirical research of case studies as well.

The theoretical research (Part 1) and Multi case studies (Part 2) focus only on the Knowledge and Persuasion stage of the innovation decision process because it aims to provide inputs to the different components of these two phases so that during the decision phase, the adopter is well informed to make the decision of adoption or rejection. In this case, the adopter is defined to be the facility manager as this research focuses mainly from their perspective. Hence, by taking these steps, the research aims to influence their decision of adopting a new technology. It has to be noted that the facility managers may not have the authority to make the decision of adopting the new technology and implementing it. Hence, the term “making the decision” in this case refers to the decision of the facility manager that they want to adopt the technology; their willingness and acceptance that the technology will help them in their tasks, before an actual decision is made where various other stakeholders are also involved.

To understand the Prior conditions and the Knowledge phase, an in-depth understanding of facility management practice in general and in the context of universities is explored. Moreover, the characteristics of facility management related to two main domains of the research; indoor air quality and smart technology has to be explored as a part of this stage. This will be done by theoretical research on the topic Facility Management as presented in section 3.3. The knowledge in the case of this research is defined as the awareness of facility managers regarding the smart technologies that can be used to manage indoor air quality. The theoretical research on: Smart IAQ technology will provide the knowledge to the facility managers on what is available and how do they work? In the persuasion stage, five perceived attributes of the innovation will be explored. Hence, the available smart IAQ technologies will be researched and evaluated by theoretical research in section 3.4. These findings will be used later to analyse the case studies.

With all the aforementioned information, the innovation decision making process model of Rogers is adapted as shown in *Figure 12* to form the theoretical framework for this research.

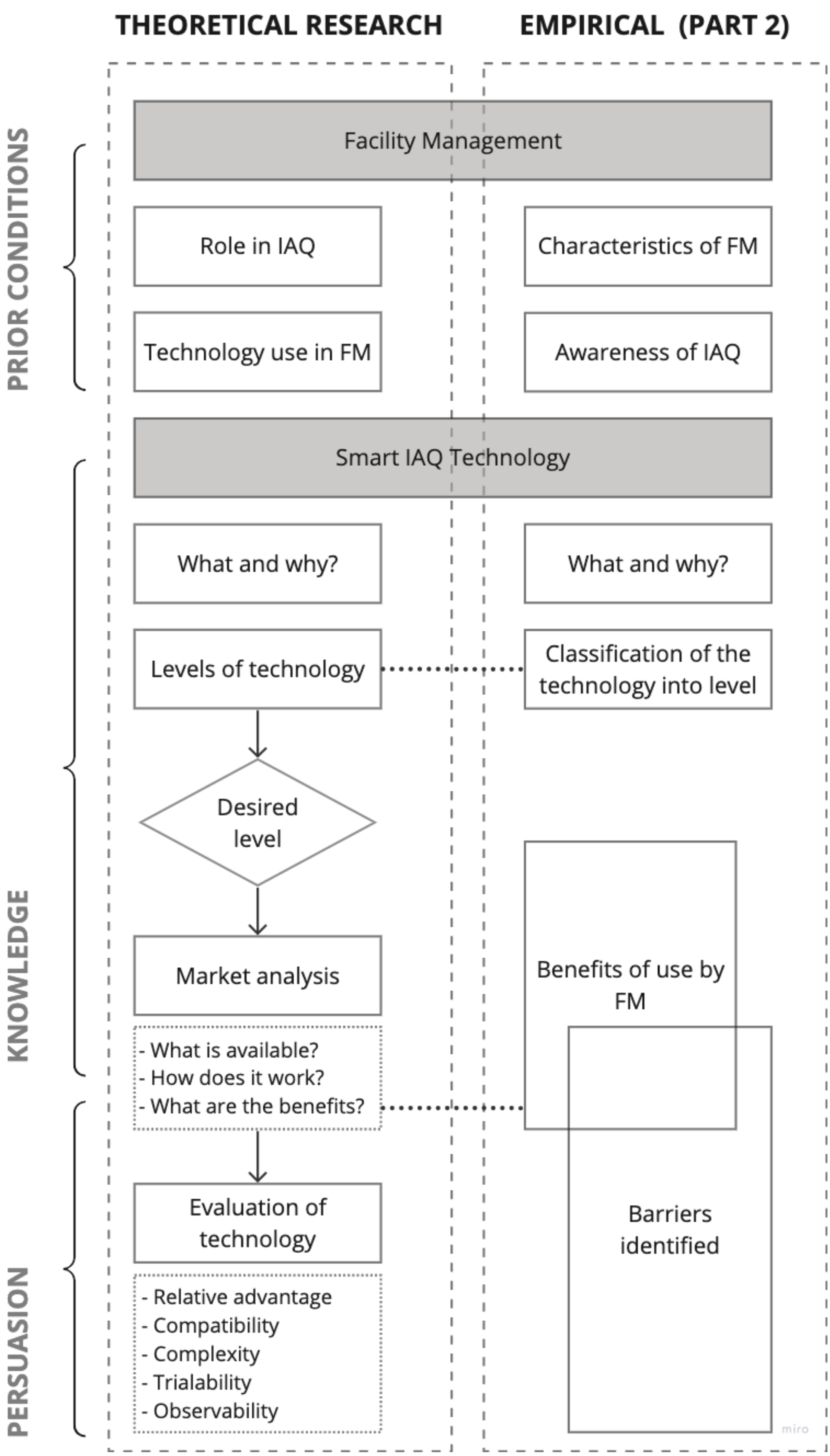

Figure 12: Theoretical framework adapted from Rogers (author)

3.3 Facility Management

3.3.1 Introduction

According to the definition by International Facility Management Association (IFMA); facility management is an organisational function which integrates people, place and process within the built environment with the purpose of improving the quality of life of people. It guarantees the built environment's efficiency, sustainability, safety and comfort (IFMA, n.d.). Similarly as defined by Becker (1990), the facility management domain is in charge of organising all activities related to the planning, design and management of buildings, as well as their systems and equipment, with the goal of enhancing the organisation's capacity to successfully compete in a fast changing atmosphere (Becker, 1990). FM plays an important role in ensuring that the buildings serve their intended objectives, the occupants are healthy and productive, and systems within the built environment function as they should (Zhang et al., 2022). The responsibilities of FMs can range from strategic planning and daily operations to safeguarding occupants' health and safety (Anderson, 2021). In the context of this research, the two roles of facility management in universities that have been emphasised are; safeguarding occupants' health and adapting to new technologies.

The term facility management was first introduced in the 1970s, starting with the development of hard FM. It was a modern concept that depicted the places used by an organisation and the condition of those places, as well as how to maintain them for further use and the best ways to utilise them. In the 1980s, the focus shifted towards the global expansion of facility management, introducing a new concept of quality of life in the work environment (Opoku & Lee, 2022). This marked the beginning of integrated real estate management, which employed strategies to improve quality of life for better productivity, while also considering the cost of place utilisation and services. This shift also involved a move from compartmentalised service activity to broad service management. The emergence of service providers allowed for the outsourcing of services to companies that provided expertise and value-added services. This trend continues today, where facility management is a professional practice and academic discipline, where latest technologies are available to manage entire buildings (Zapotoczky, 2024). It is the management of an institution which focuses on the effective functionality of the built environment. Facility management is the integration of place, system, people, and technology, encompassing both hard and soft services that are essential for achieving better health and productivity at an optimum cost which aligns with strategic planning, core business, and support. Core business involves the exact primary objectives and goals of an organisation, while support functions enable the core business to achieve its objectives and goals (Geerdink, 2020).

3.3.2 Responsibility in IAQ

As mentioned earlier, facility managers are responsible for occupant's health and safety. As one of the key determinants of occupant health in indoor environments is the indoor air quality, facility management plays an essential role in IAQ management. Facility managers are responsible for making sure ventilation rates adhere to the set requirements and HVAC systems are properly maintained. They also have to make sure that building occupants understand IAQ problems and how to report them. To guarantee that IAQ is given high priority, facility managers must collaborate closely with the service providers, maintenance personnel and the building occupants (Zannoun, 2023).

As the person in charge of effectively integrating the user with his physical surroundings, the facility manager is tasked with recognising and resolving IAQ issues. The role of FM in this context ranges from recognition of IAQ hazards, ensuring adequate level of IAQ parameters, scheduled maintenance of HVAC systems, solving current problems and preventing future ones (Bas, 2004).

In recent years, the Covid-19 pandemic has advanced facility management modifications by placing a greater emphasis on health and safety procedures. Ensuring environments that are safe, clean, and flexible was an emerging challenge for FMs during the pandemic. This covers crisis response planning, ventilation enhancements and technology integration (Burrell, 2023). The pandemic has forced organisations to follow government guidelines and make changes to ensure their survival. Facility management departments have been crucial in combating Covid-19 in university settings, ensuring a safe, productive, and sanitary environment. It is now seen as a primary source of information for implementing strategic space planning and virus control policies. Prior to the pandemic, contemporary IAQ indicators were not considered critical components of the Corporate real estate (CRE) environment. However, the CRE industry has seen a significant growth in interest and demand for real-time IAQ visualisations (Attune, n.d.). Additionally, the pandemic has presented new challenges for facility managers, who must address issues to maintain comfortable building conditions. The safety of employees was essential during this difficult time, as they faced various health risks. Organisations faced rapid changes in response to the pandemic, and FM teams dealt with new responsibilities in adjusting infrastructures to the "new normal" (Amran et al., 2022).

3.3.3 Technology use in FM

As a response to the need for adapting to the new normal after the pandemic, modern FMs are embracing adaptable strategies that include expanded roles and responsibilities with integration of technology. These tools are needed for them to succeed in their increasingly complex duties and responsibilities post pandemic, as it makes it possible to make decisions based on data and use this to manage facilities more effectively (Burrell, 2023).

In an effort to improve efficiency, accuracy, and precision, new technologies have revolutionised various established industry procedures and changed the daily lives of many people. The acceleration of this evolution can be attributed to technological advancements such as cloud computing, big data, cyber-physical systems, and IoT (Mannino et al., 2021). The development of the new paradigms for the IoT and big data management, coupled with advancements in information and communication technologies, is creating new possibilities for the cognitive and decision-making processes involved in the management of the built environment. These digital technologies' have the capacity to provide information that aid in the development of methods meant to lower management expenses while enhancing building functionality and service quality (Atta & Talamo, 2020).

Systems including lighting, security, HVAC, and ventilation all play a part in how a structure functions. Any building can be turned into a smart building by using automated procedures to manage its functions. As a result of the widespread usage of sensors, actuators, microchips, data collection, and cloud computing, smart buildings are becoming increasingly commonplace. When comparing the usefulness of new technologies such as IoT in facility management to conventional building management systems, the key differences are in real-time monitoring and the ability to make modifications (Sarkar, 2021). On a business level, one could claim that IoT makes decision-making, management, and productivity easier. Additionally, it opens up a plethora of possibilities for innovative uses that will prove beneficial to people's health and quality of life (Sarkar, 2021).

As a service driven industry, the facility management industry has incorporated innovation and technology in order to enhance management, operations and comfort. Smart technologies such as IoT have a great potential for facilitating FM activities and processes such as operations management, managing inventory, improved building component tracking, cost-effective and efficient logistics, and building energy controls (Araszkiewicz, 2017). In order to improve facility management, innovative technologies are included in the building system which provides FMs with real time monitoring data. Hence, the concept of smart facility management has arised, which is defined as "the integration of systems, processes, technologies and personnel to enhance the management of a building's facilities. It is about doing better with technology, using it as a means to an end" (SIFMA, n.d.). In the context of managing IAQ, FMs can monitor air quality at all times with the help of the latest technologies, which offers various benefits. On a periodic basis, it offers helpful information and insights about the state of interior environments. When air quality falls below predetermined criteria, building owners are notified and given the opportunity to take corrective measures. They can take proactive measures to remedy issues before they have a detrimental influence on air quality by completing predictive maintenance chores, such as identifying underperforming equipment and replacing air filters on HVAC systems. FMs may monitor temperature, humidity, carbon dioxide levels, and pollutants more intelligently and maintain an optimal air quality using the IoT air quality sensors installed in a building (Saini et al., 2020).

3.4 Smart IAQ Technologies

3.4.1 What and why

Smart indoor air quality technologies refer to interconnected and automated systems that integrate sensors, data analytics, and control mechanisms to maintain optimal air parameters within indoor environments. These systems are often part of a broader intelligent building system, addressing various pollutants, including volatile organic compounds, particulate matter, carbon dioxide and others (Sansyzbay, 2020). They have various advantages in sectors like; health and well-being, energy efficiency and financial benefits.

Health and well-being

The most important benefit of using smart IAQ solutions is to create healthy and comfortable spaces for the occupants. According to data published by Environment Health Perspectives, healthy workplaces can increase productivity by 61% and the report by The World Green Building Council, it can reduce absenteeism by 58% (EPH, 2015; 2018). Real time monitoring and presentation of actionable insights enabled by smart technologies contribute to improved air quality and eventually better health and well-being of occupants.

Energy efficiency

Smart technologies that enable real time monitoring of spaces integrated with other information such as occupancy can inform or automatically adjust the ventilation rates, HVAC systems according to the needs of people. This ensures that the energy is not wasted where it is not necessary (Banyamin, 2023). Moreover, a significant amount of energy is also lost by inefficient equipment in buildings, this energy can also be saved by the use of smart technology which can detect faults (Brains4Buildings, n.d.).

Financial benefits

Improved health of occupants and energy efficiency results in financial benefits as well. Respiratory illnesses like flu and common cold cost the economy $19.4 billion annually in lost productivity; and allergies and asthma $29 billion annually The present data demonstrates that improved IAQ management can save organisations up to $800 per employee annually (Johnson Controls, 2022). The yearly electricity expenditure of an ordinary building is impacted financially by even a 1% improvement in air quality. Optimising HVAC systems according to the needs can reduce the energy expenditure by 21% (EPA.gov, 2023).

3.4.2 Classification

In order to systematically classify the smartness of the various technologies used in indoor air quality management, a literature review was conducted. This review presents the architecture and use of the different technologies and at the end classifies them into 3 levels. This classification process helps to answer [SQ2] by presenting the evolution leading to the current status of the latest technology available in IAQ. Furthermore, this classification table also serves as a theoretical framework to identify the current status of technologies used in the context of Dutch universities from the case study and interviews.

Level 1: Sensors

The first level of using technology for IAQ is the sole use of sensors. Sensors are devices that detect and respond to a stimulus in the physical environment and generate a signal that is transferred to a human readable display at the sensor location (Sheldon, 2022). The sensor system as defined in the WMO report refers to integrated devices consisting of one or more sensing elements and supporting complements which create a fully autonomous and functional monitoring and detection system (Lewis et al., 2018).

From the literature review, it is found that most of the studies conducted during the emergence of sensors for air quality were focused on outdoor air pollution. The application of sensors was firstly done in outdoor conditions then it shifted to indoor when the due importance of indoor air quality was acknowledged. The need for developing better sensor technologies was identified when the conventional instruments were incapable of providing real time data. The conventional monitoring took place during a longer period of time could not inform about the peak level of pollutant exposure when it occurred in real time. Additionally, it could not address the temporal and spatial heterogeneity of indoor air pollution (Kumar et al., 2016).

In order to achieve efficient use and result of the sensors, the devices should exhibit a quick response time, quality performance, robustness and durability (Mead et al., 2013). Due to the advances in technology, numerous hi-tech sensors for indoor air have emerged which are capable of measuring different indoor air pollution parameters such as CO2, VOC, PM2.5, PM10, O3 etc (Snyder et al., 2013). Air sensing devices feature microelectromechanical systems (MEMS) made using micro-fabrication techniques. These transducers interface with microprocessors and electronic circuitry, responding to environmental changes with physicochemical changes. They generate electrical pulses, processed into signals and converted to digital data. MEMS transducers come in various chemical compositions, shapes, and sizes, including microfluidic, optical, gas, or nanomaterial-based materials (Snyder et al., 2013; Kumar et al., 2016).

A lot of the sensors are battery operated, mobile and contain communication protocols within them. They have been improved in technical and performance features in terms of efficiency, power consumption and light-weight. Additionally, there has been development of portable low cost sensors which is changing the conventional approach, enabled due to the continuous technological advancements. Since the innovation of wireless networks, the use of sensors has risen as it has allowed information access and communication across wide networks and the web services (Snyder et al., 2013). Moreover, wireless communication has played a significant role in this as they have been proven to be relatively cheaper in terms of initial investment as well as the operating costs (Kumar et al., 2015).

Level 2: IOT (Internet of Things)

The second level of technology is classified as the indoor air quality systems that use the Internet of Things (IoT) technology. The term 'Internet of Things' was first coined by Kevin Ashton in 1999 with respect to Radio-frequency identification (RFIB). Currently the term IoT is taken as the presence of RFID tags, sensors, actuators, mobiles and computers. The contribution of IoT has been significant in terms of changing the monitoring strategies as it allows for cost effective, long-term and real time and comprehensive information on the status of IAQ as a data monitoring solution which benefits all the stakeholders involved, including the building managers (Sun et al., 2019). Several internet of things-based initiatives aiming to monitor indoor air quality employ microsensors for quick access to collected data via mobile computing and an open source technology for data processing and transmission (Marques et al., 2020).

The communication mechanism of the IoT involves a multi-layered approach that facilitates seamless interaction between various interconnected devices. At the core of this mechanism are sensors and actuators that collect and transmit data over a network. IoT devices typically communicate through protocols such as MQTT (Message Queuing Telemetry Transport), CoAP (Constrained Application Protocol), and HTTP/HTTPS, which are designed for lightweight and efficient data exchange. These devices connect via various network technologies, including Wi-Fi, Bluetooth, Zigbee, and cellular networks, depending on their range, power consumption, and data rate requirements. The data gathered by these devices is often transmitted to cloud-based platforms where it is processed, analysed, and stored. This enables real-time monitoring, automation, and intelligent decision-making. Security measures, such as encryption and authentication, are crucial in the IoT communication process to ensure data integrity and privacy. Therefore, the IoT communication mechanism is a complex but highly efficient system that enables a wide range of applications from smart homes and healthcare to industrial automation and smart cities (Al-Sarawi et al., 2017; Ovsthus & Kristensen, 2014).

A prototype of an Internet of Things (IoT) architecture-based IAQ monitoring system was developed by Marques for ambient data collection, using open-source technologies like ThingSpeak (a cloud platform for IoT) (Marques et al., 2017). The architecture of an IoT-based monitoring system includes two components: hardware and software. These domains collaborate to offer rapid information on pollution levels. Selecting the appropriate hardware of sensors, microcontrollers (MCUs), and gateways is critical. Similarly, for the software, communication technologies such as Wi-Fi, ZigBee, Bluetooth, and Ethernet are utilised to provide real-time updates on pollution concentrations (Saini et al., 2020).

Figure 13 visualises the typical architecture of IoT-based IAQ monitoring systems. The structure is separated into four sections: monitoring system, data storage, data analytics services, and data presentation. The monitoring system consists of several IAQ sensors, MCUs, and communication devices. Data acquired by a sensing unit is then saved in a data storage system, which can be either online or physically stored. Data analytics services may be used to assess the effects of the indoor air pollutants. The presentation of data further enables end users to receive information on IAQ levels (Saini et al., 2020).

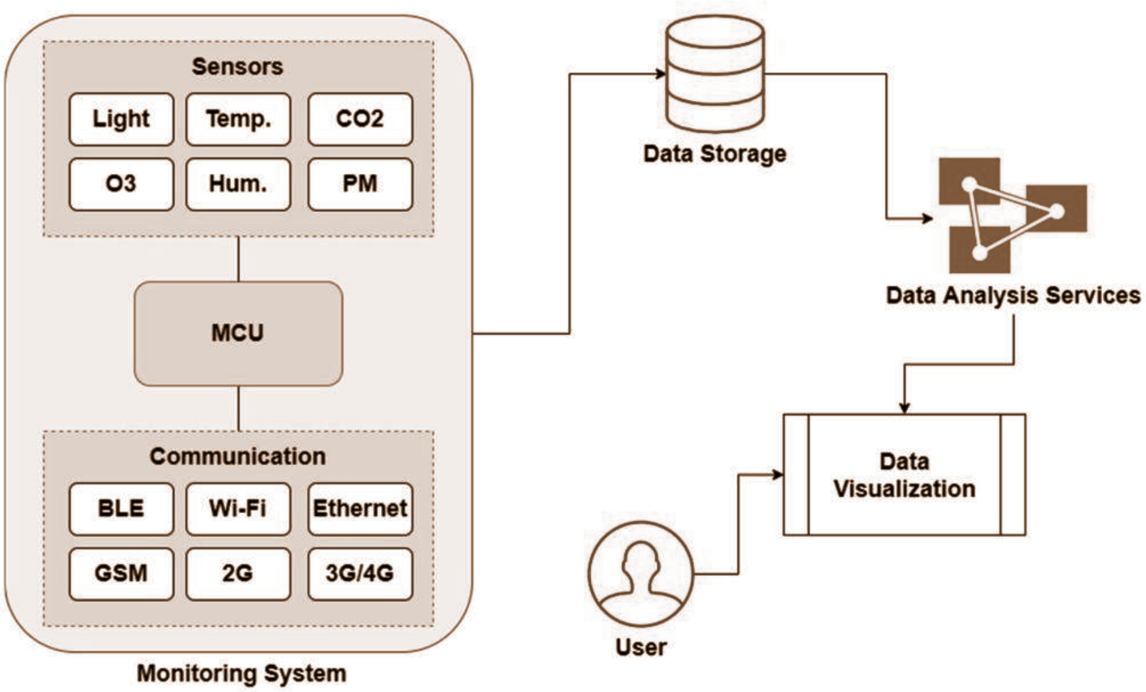

Figure 13: Typical architecture of IoT based IAQ monitoring system (Saini et al., 2020)

Level 3: Software as a solution (SaaS)

The third level of IAQ technology classified for this research is the use of software as a platform which is mainly associated with the visualisation of the collected and analysed air quality data. Therefore, SaaS is an addition to sensors and IoT which plays a role in the later stage of the data usage, but is used to directly communicate with the users. There has been an increase in the interest and demand of visualisations of the real time IAQ data and as a result SaaS application services that consist of real time IAQ data have arisen in the market (Attune, n.d.).

Nowadays, most of the service companies that work in the field of IAQ technology have integrated the provision of providing SaaS in addition to the products that help in IAQ management. SaaS acts as a potential solution to one of the research gaps identified in this study. The gap that the facility managers are not utilising the data to make decisions and strategies because the data is not readable and understandable, can be improved by the use of SaaS since it has various benefits to the facility managers due to its user interface. SaaS presents and visualises complex data into an interpretable format. Additionally, there is no need to install or maintain complex software systems due to the provision of SaaS since the provider handles updates, patches and other maintenance tasks. These solutions are accessible from any device with internet access, which offers flexibility and convenience. SaaS solutions are typically deployed in scalable cloud settings with connections to other SaaS products which makes it possible to scale its usage up and down based on individual requirements. Moreover, managers can track IAQ across various locations in a centralised manner, making it easier to oversee large or multiple facilities (IBM Cloud, 2020).

SaaS can also include visualisation of IAQ data on floor plans of different buildings in a single platform. It can provide alerts and recommendations on air quality and ventilation systems (Spacewell, n.d.). Another beneficial feature of SaaS is the production of smart reports which contains the data on IAQ which allows to identify areas of concern and plan a long term vision (Inbiot, n.d.). With real-time data and analytics, managers can make informed decisions promptly to maintain or improve IAQ. SaaS platforms can help ensure that facilities comply with IAQ standards and regulations by keeping accurate records and facilitating easy reporting. Additionally, they often allow for customization to meet the specific needs of a facility or company, whether it's integrating with existing systems or focusing on particular IAQ parameters. They also provide scalability as when the needs of the facility change, the SaaS solution can scale accordingly, adding or reducing features and services (TSI, 2023).

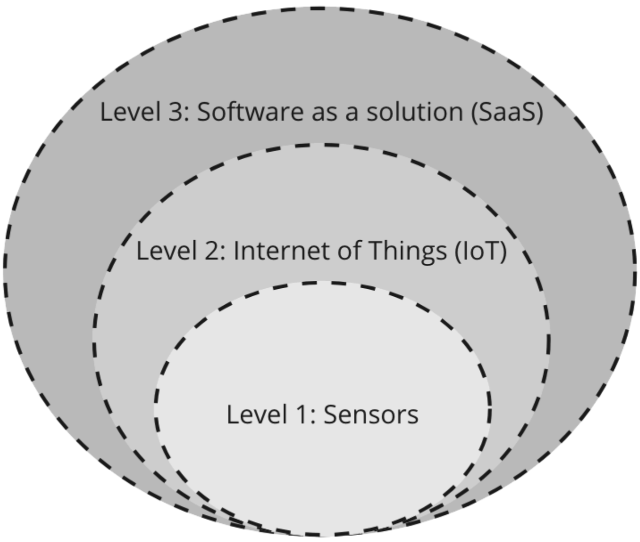

Figure 14: Overview of the level of smart technology used in IAQ (author)

After identifying all the smart IAQ technologies, Level 3 (SaaS) was chosen as the desired level which is to be further elaborated in this research. It was chosen because a lot of literature is already available on the topic of sensors and IoT in IAQ management, however, there is not much research on SaaS, especially in relation to IAQ management used by facility managers. Moreover, online platforms can be directly used by the facility managers without involvement of any data or technical experts, therefore, this direct use is beneficial to identify the benefits solely from the perspective of FMs which is the aim of this research. Lastly, as these software solutions provide graphical easy to understand data interpretations, it seems most relevant in filling the research gap of data not being efficiently used by FMs.

3.4.3 Service providing companies

The purpose of this section is to do a market analysis of the latest smart IAQ technologies available to provide information to the facility managers of the Dutch universities. Various service providing companies are available globally which provide different smart products and services for indoor air quality monitoring, management and solutions. Three such companies are selected to know the current status of technologies available and evaluation; namely: Johnson Controls, Spacewell and Inbiot. The first company Johnson Controls was selected on the basis that they provide service to the Case study B (TU Delft). Hence, it was interesting to know what are the latest technologies they provide and if they are up to date with their services. The second company Spacewell is selected based on the association with researcher's contact and the third company Inbiot was connected by the same contact person. The information is collected through desk research and one interview with the sales manager of Inbiot.

Johnson Controls

Company introduction

Johnson Controls is a multinational company that supports smart buildings and designs environments that are sustainable, safe and healthy. It has improved buildings for almost 140 years, and with its award-winning digital technology and services, it is currently transforming the future. With operations in 150 countries, Johnson Controls provides the broadest range of building technology, software, and services globally, enabling its clients to fulfil their missions and realise their ambitions (Johnson Controls, n.d.).

SaaS: Open Blue Enterprise Manager

The new SaaS provided by Johnson controls is called 'The OpenBlue Enterprise Manager', and was launched in 2020. It enhances the performance of the building and provides real-time data visibility across assets, people and processes. It provides building automation and control service that enables automated control of all building systems including HVAC in a single platform. Air quality parameters such as CO2, PM, ventilation are actively monitored. The platform combines smart edge computing to process and enrich data before sending it to the cloud for analytics. OpenBlue platform enables management of operations more systematically, resulting in buildings with memory, intelligence, and a distinct identity. The platform enhances the OpenBlue array of products and services with award-winning artificial intelligence (AI), incorporating data from both inside and outside buildings. The comprehensive suite of apps available through the platform pulls data from OT and IT systems and from external sources such as weather forecasts and utilities. Enterprise Manager continuously scans these data streams for opportunities to save energy, reduce carbon emissions, improve indoor air quality, and enhance occupant comfort and productivity while managing cost. Integration of all these functions in a single platform makes it easy for the facilities team to make operational choices that match the priorities or can have the system make decisions automatically (Johnson Controls, n.d.).

In addition to SaaS, Johnson Controls provides IAQ audits services, which are tailored recommendations to make improvements in the facility. The process includes gathering necessary data for two weeks as measurement only at a particular time is not accurate due to factors such as outdoor air quality, weather, occupancy and time of the day impact the data. Their team of WELL AP engineers then provide recommendations, personalised to the need of the facility. As a result, it provides a clear direction to the building managers regarding where to focus their time, effort and resources to improve the air quality (Johnson Controls, n.d.).

Case study

Case Study	Challenge	Solution	Result
Richmond School District, Sussex, Wisconsin	As an impact of the global pandemic of Covid-19, the main challenge of the school was their concern regarding unhealthy IAQ leading to the risk of virus spread, which would lead to absenteeism and have an adverse impact on students' progress. Their primary requirement was the risk mitigation of virus transmission.	Johnson Controls places air quality sensors to measure CO2, CO, PM2.5, temperature and relative humidity over several days to gain an accurate vision of the baseline performance of the building under several conditions and provided a comprehensive report which presented data and identified critical concern areas.	This assessment and report identified specific areas for immediate IAQ action like addition of an in-zone filter to clear art class air and uncovered energy saving opportunities.
School District of Lacaster, PA	Safeguard health of school occupants and improve air quality exceeding merely virus mitigation and extending to healthier, comfortable learning environments for focused and successful students.	Installation of 1500 HEPA filters and implementation of Metasys (Building Automation System) controls. Johnson control will be assisting the school operating personnels with the servicing and maintenance of the installations.	Lesser Covid-19 cases amongst the occupants with attendance reaching pre-Covid times. Improved IAQ, insight into occupancy data and gained confidence of occupants. Supported the school's healthy, smart and connected learning environment vision.

Table 2: Case study of company Johnson Controls (Johnson controls, n.d.; author)

Figure 15: Open Blue Enterprise Manager dashboard (Johnson controls, n.d.)

Spacewell

Company introduction

Spacewell is a technology and consulting firm founded in 1989 which focuses on digital solutions for building management. The company developed a product for CAD designs for constructed assets, allowing non-specialists to convert designs into data. Over time, an Integrated Workplace Management System (IWMS) was created, integrating workplace, real estate, and facility management applications powered by a single database. Spacewell's PropTech solutions integrate IWMS, mobile tools, and the Internet of Things, enabling facility managers to monitor comfort, air quality, energy efficiency, and space usage.

SaaS: Spacewell workplace and Dexma

Workplace solutions offered by Spacewell monitors air quality (VOCs, CO2 concentration), temperature and relative humidity on a continual basis using IoT sensors. The interplay of variables temperature, CO2, and relative humidity offers crucial insights into viral risk prevention. Additionally, the data is visualised on floor plans and offers guidance on risk management and reduction strategies, such as modifying ventilation systems or imposing occupancy restrictions on particular rooms. The indoor air quality data can be seen on the app which gives workers access to real-time information and they can search for and reserve spaces according to their comfort preferences, avoiding areas with poor air quality. It also provides data insights on a dashboard which provides a dynamic picture of all the information. Moreover, it allows flexibility in using the organisation's own analytic tools.

Spacewell energy platform (Dexma) provides real time IAQ alerts, which can be set according to legal thresholds or own operative thresholds. The system sends an email if the threshold is exceeded. HVAC correlation analysis can be done which adjusts the ventilation to achieve energy efficiency. It also provides bespoke dashboards and custom IAQ reports which shows the status and levels of the different IAQ parameters (Spacewell, n.d.).

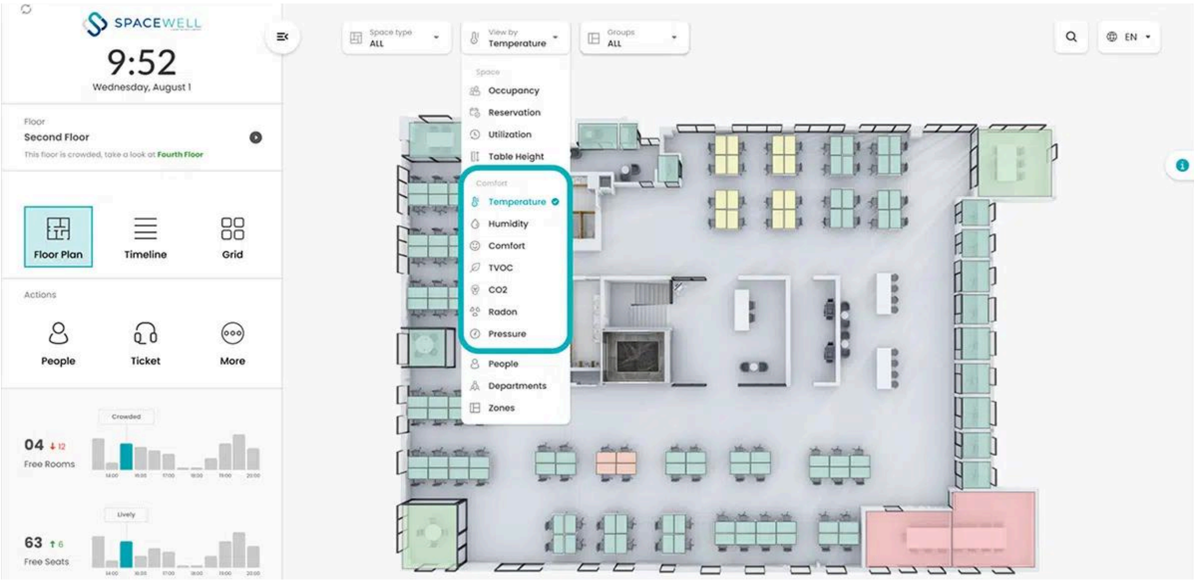

Figure 16: Spacewell Workplace solution (Spacewell, n.d.)

Case Study

Case Study	Challenge	Solution	Result
Polytechnic University of Catalonia (UPC)	The circumstances during the Covid-19 epidemic emphasised the necessity of ensuring the interior air quality of universities. Apart from enhancing ventilation to prevent infections, indoor air quality was perceived as a crucial element impacting the well-being, productivity, and comfort of the academic community. The university was in need of an automated monitoring system for IAQ which measures CO_2 concentration in order to enable a system that manages space and informs the occupants about the status of the various rooms.	A total of 850 sensors were installed across the university which gathered data openly accessible to the entire community. This created awareness amongst the occupants as well as the ventilation needs were detected. This monitoring network contributed to the UPC Energy Emergency Programme as it provided information regarding air-conditioning system functioning and energy saving opportunities. The University also encouraged conducting research on their own buildings. Hence, the data collected was useful for researchers, students and teachers as the facilities and buildings were transformed into a living lab for experimentation and learning.	As a consequence, by optimising the ventilation and air exchange systems, the interior areas' air quality was greatly enhanced. As part of the energy-saving initiatives, it also made the application of new temperature regulations easier. Along with the monitoring feature, having alarms and an accessible, transparent system in place made it simpler for the community to comprehend the goal and participate in the process. A trial test of the solution was introduced during the university admission exams. The result shows that it worked well and gave the occupants a great degree of security during the pandemic.

Table 3: Case study of company Spacewell (Spacewell, n.d.; author)

InBiot

Company introduction

Inbiot is a technology company founded in 2018 with its headquarters in Spain. They are solely focused on providing digital technology to control the air quality of buildings. With their products and services, they help in creating a balance amongst healthy, safe and sustainable spaces. The company values innovation and has commitment in continuous updating of technological advancements. Inbiot has been awarded one of the 10 best companies for indoor air quality solutions in Europe by Construction Tech review magazine.

SaaS: My inbiot platform and Inbiot business intelligence

Inbiot provides a comprehensive ecosystem of solutions for indoor air quality management. Their precise sensors measure all the necessary air quality parameters with multiple connectivity and integration options. The connectivity can be integrated with building management systems or industrial automation systems. Apart from these, Inbiot provides different cloud services.

My Inbiot platform has up-to-date functionalities to analyse and interpret data, manage IAQ, alert systems and sharing of data with the public. It can be easily accessed in any browser, provides visual representation of real time IAQ data to take action and its easy to use interface allows for quick and efficient management. The data history within a given time period can be downloaded for further analysis and certification processes can be tracked. Smart reports can also be downloaded to know about the status of IAQ which allows to identify specific areas for improvement and effective measures (John Oliver, P.C., 2024). Inbiot business intelligence develops custom panels for the data management to control the air quality of all spaces. It provides graphical representation of data and real time monitoring and control of all devices (Inbiot, n.d.).

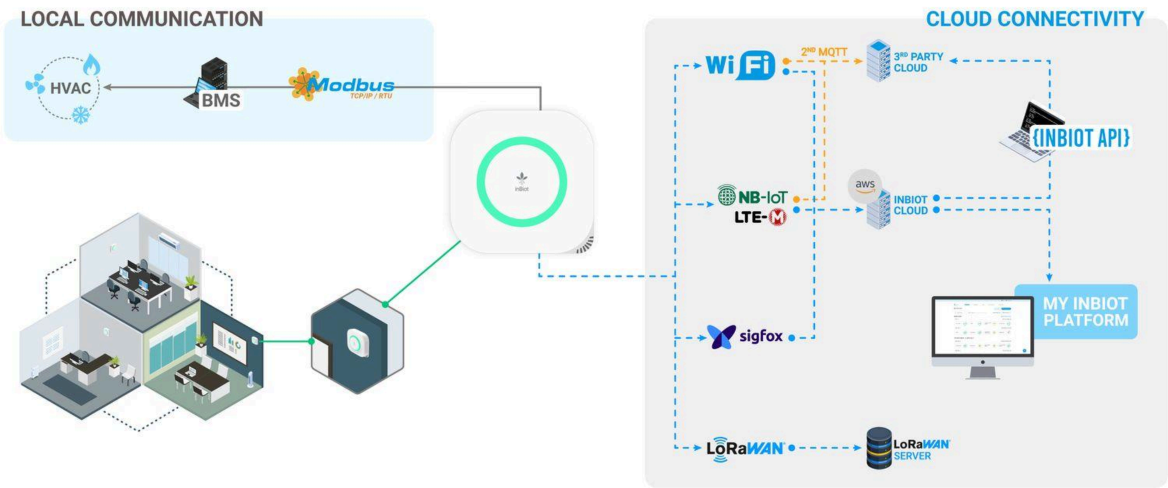

Figure 17: My Inbiot platform architecture (Inbiot, n.d.)

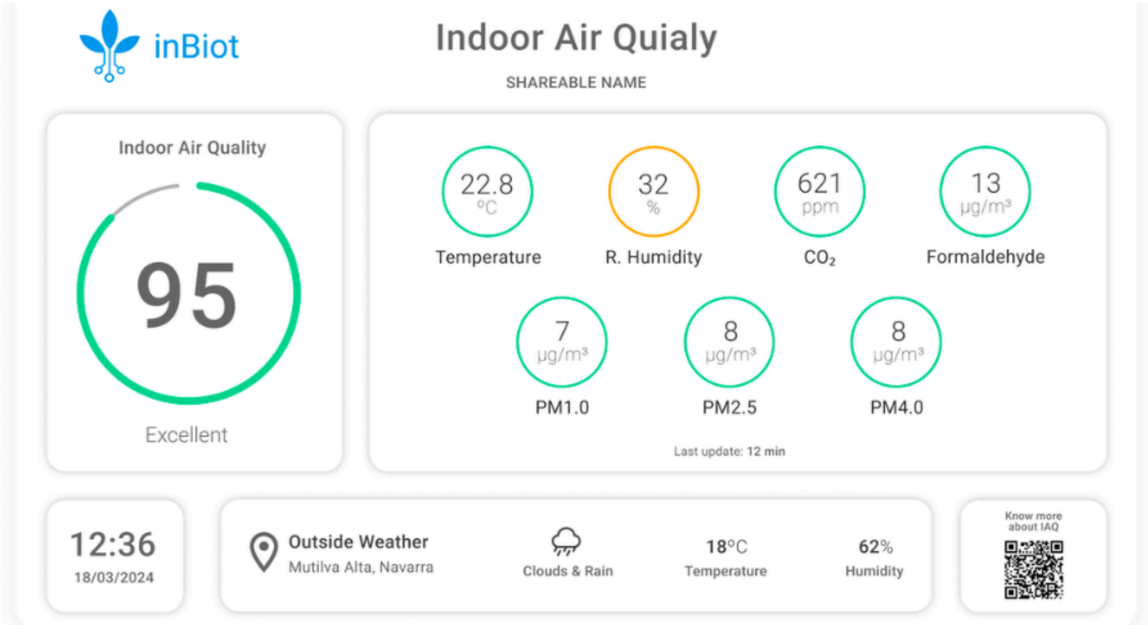

Figure 18: My Inbiot platform dashboard (Inbiot, n.d.)

Case Study

Case Study	Challenge	Solution	Result
NTT Data, Spain	NTT Data was in need of a complete solution to monitor and improve the indoor air quality of their Data centres and offices. Furthermore, they aimed to collect reliable data to get the WELL building certificate.	Inbiot presented a wide variety of products and services to overcome these challenges. They installed MICA sensors to track air quality parameters and real time information for ventilation. Devices that ensure compliance with building certifications and cloud connectivity devices were also installed. Additionally, My Inbiot app, customised control panel and personalised assistance was provided for analysis and reporting.	Improved well-being and comfort: There was enhancement of well-being, productivity and job satisfaction of the occupants was increased due to the creation of an optimal indoor environment by better ventilation, temperature and humidity control. WELL certification: Due to Inbiot's special devices, the necessary data to fulfil the requirements to earn the WELL certificate was collected and the company's reputation has been impacted positively. Optimised HVAC system: The IAQ monitoring enabled ventilation rates to be adjusted depending on the real time needs which promoted energy efficiency while safeguarding occupant health and comfort. Data-driven decision making: My Inbiot business platform provided NTT Data with a comprehensive overview of air quality across all their offices which could be interpreted to make informed and proactive data driven-decision making to enhance indoor environments and operation efficiency in all their offices.

Table 4: Case study of company Inbiot (Inbiot, n.d.; author)

Multi criteria analysis

The smart technology services provided by the aforementioned companies are evaluated using a multi criteria analysis as shown in *Table 5*. The criteria are set through the findings of the desk research and are categorised primarily into three types: Measurement, monitoring and reports; and others.

Criteria	Johnson C.	Spacewell	Inbiot
Measurement			
Reliable and certified sensors	✓	✓	✓
Ease of installation	✓	✓	✓
Integration with other building systems	✓	✓	✓
Monitoring			
Real time monitoring	✓	✓	✓
Alert system via alarm	✓	✓	✓
Alert system via email		✓	
Remote access and control	✓	✓	✓
Historical data storage	✓	✓	✓
Reporting			
Digital platform	✓	✓	✓
Visualisation of real time data	✓	✓	✓
Air quality displayed on floor plans		✓	
Mobile application		✓	
Automated decision making	✓	✓	✓
Others			
In depth audit services	✓		
Certification guidance		✓	✓
Flexibility by public API		✓	✓

Table 5: Multi criteria analysis of smart technology services (author)

The desk research of the services provided by the selected three companies shows they are very advanced and up-to-date with technological advancements of the current generation. The different case studies additionally highlight their effectiveness and positive results. Moreover, they already identified the problem of facility managers not being able to interpret the data produced by the smart sensors and devices. So they have tailored their solutions for the ease of use by the facility managers. All companies provide services and digital platforms where the collected data is analysed and visually represented to provide the managers with easily understandable smart reports and useful insights to take effective air quality measures.

The results of the evaluation of these technological services by a multi criteria analysis approach shows that they mostly align with each other. All of them are on the same page regarding the measurement. For monitoring, Spacewell provides email alerts, however, it is not a major advantage. Spacewell also performs well in reporting by displaying air quality on floor plans and enabling a mobile application. Johnson control provides an in depth audit facility but lacks on providing certification guidance and having an open public API.

3.4.4 Evaluation of SaaS

With the general information on SaaS and the SaaS services provided by the three selected companies, this section evaluates SaaS as a technology using the attributes of innovation (Relative advantage, compatibility, complexity, trialability and observability) of the persuasion stage from Rogers' theory as explained in section 3.1. This allows us to understand the benefits of SaaS platforms over traditional IAQ technologies and its likelihood of adoption by the facility managers.

Relative Advantage

The relative advantage of SaaS platforms for facility managers lies in their ability to deliver cost-effective, scalable, and easily accessible solutions for indoor air quality management. Compared to traditional on-premises systems, SaaS platforms require lower upfront investments and offer predictable subscription-based pricing, reducing financial barriers. They can be rapidly scaled to accommodate growing needs without significant infrastructure changes, and their cloud-based nature allows facility managers to access real-time data and analytics from any location. Additionally, automated updates and maintenance handled by the SaaS provider ensure that the system remains current and secure, minimising the burden on internal IT resources. These benefits collectively enhance operational efficiency and decision-making, making SaaS a highly advantageous option for managing IAQ.

Compatibility

The compatibility of SaaS platforms for facility managers is a significant advantage, as these systems seamlessly integrate with existing building management systems and other IoT devices. SaaS solutions are designed to work within the current technological infrastructure of most facilities, reducing the need for extensive modifications or new hardware. They support a variety of data formats and communication protocols, making it easy to incorporate IAQ monitoring into broader facility management practices. Additionally, the user-friendly interfaces and customizable dashboards of SaaS platforms align well with the operational workflows of facility managers, facilitating easy adoption and efficient use in monitoring and improving indoor air quality.

Complexity

The complexity of SaaS platforms for facility managers is generally lower compared to traditional on-premises systems, but there are still some considerations to manage. SaaS platforms are designed to be user-friendly and intuitive, often requiring minimal technical expertise for day-to-day operations. The initial setup and integration with existing systems might require some technical support, but once configured, these platforms streamline processes through automated updates and maintenance handled by the provider. Despite their sophisticated capabilities, such as advanced analytics and real-time monitoring, the complexity is mitigated by comprehensive customer support, training resources, and detailed documentation, ensuring that facility managers can effectively leverage the technology with relative ease.

Trialability

The trialability of SaaS platforms is a key benefit for facility managers, as these solutions often offer free trials and demos that allow managers to evaluate their effectiveness before committing to a full deployment. This ability to test the software in a real-world setting helps facility managers understand how the SaaS platform integrates with existing systems and meets their specific IAQ monitoring needs. During the trial period, facility managers can assess the user interface, functionality, and overall performance without a significant financial investment. This hands-on experience reduces the perceived risk and uncertainty associated with adopting new technology, enabling informed decision-making and smoother transitions to full-scale implementation.

Observability

The observability of SaaS platforms provides a distinct advantage for facility managers, as these systems typically offer comprehensive dashboards and real-time analytics that make it easy to monitor and visualise indoor air quality (IAQ) data. With clear, intuitive interfaces, facility managers can quickly observe the impact of environmental adjustments and identify trends or anomalies in air quality. This high level of transparency and immediate feedback not only aids in timely decision-making but also enhances the ability to demonstrate improvements and compliance with health standards to stakeholders. The ability to readily observe and share IAQ metrics fosters accountability and supports proactive facility management practices.

04 MULTI CASE STUDY

4.1 Brains 4 Buildings Projects

4.2 Case Study A: SBE, Maastricht University

4.3 Case Study B: Building 28, TU Delft

4.4 Case Study C: Delft Branch, The Hague University

4.5 International Case Study D: University of Richmond

4.6 Cross Case Analysis

04 MULTI CASE STUDY

4.1 Brains 4 Buildings Project

Introduction

The Brains4Buildings project is a multi-year project which aims to give "brains" to buildings, as in, it aims to make the buildings smart and intelligent by generating big data from technologies such as building management systems (BMS) and Internet of Things. Lower energy consumption, improved comfort, and saving costs associated with installation and maintenance will be accomplished by creating artificial intelligence and machine learning models and algorithms that are quicker and more effective. The project is intended for utility buildings, which include institutional and commercial structures. The Brains4Buildings initiative was created under the leadership of TKI Bouw & Techniek, an alliance of several construction industry players formerly known as the Building and Technological Innovation Centre, or BTIC. TKI Bouw & Techniek wants to make sure that multi-year, open knowledge and open innovation programmes are carried out in a way that ensures the outcomes are shared as broadly as possible and that the content of the various projects is linked. The project is coordinated by TU Delft, however, it has 39 collaborating partners which include knowledge institutions, installation companies, energy consultancies, platform/interface developers, building owners and managers, technology suppliers, industry associations and other subject matter experts (Brains4building.org, n.d.).

Project Mission

As even the most modern utility buildings waste 30% of energy due to malfunctioning equipment, as well as the facility managers have to face complaints of users regarding comfort and high operational costs, Brains4Buildings project aims to solve these challenges by empowering these utility buildings through the use of smart technologies. The mission of the project is in line with the purpose of this research, which is to aid facility managers in maintaining a healthy indoor environment (Brains4building.org, n.d.).

The ambition of the project mainly constitute of the following:

- The development of control and control systems that intelligently manage non-residential buildings in order to: (1) reduce energy waste and reduce CO2 emissions (2) take user behaviour into consideration to ensure the comfort, health, and well-being of users (Han.nl, n.d.).
- Put open-source prototypes (living labs, use cases) through testing and validation so that businesses, building owners, and facility managers may see their market value.
- Quick scan and the Standardised Smart Readiness Indicator (SRI)
- Data integration techniques, standards, and guidelines for smart building infrastructure, together with a corresponding open data platform
- A learning community to exchange information about self-learning smart building software and its connection to the smart grid (Brains4building.org, n.d.)

Living labs

Prototypes of algorithms and methodologies are tested and validated in a range of consortium partner buildings used by the B4B study. A distinction is made between validation & use cases and living labs.

Living labs are structures where algorithms and techniques are tested in order to provide open-source prototypes of techniques and intelligent plug-ins. In order to do this, building/facility management should: (1) give adequate historical and real-time data from the BMS, energy metre, sensors, etc.; and (2) permit experiments in a safe setting by, for example, causing faults or tampering with the control systems.

Living Labs, use and demonstration cases

For the use cases and validation cases, buildings are utilised to test particular strategies or duplicate and validate discoveries and outcomes from the living labs (Brains4building.org, n.d.). Two of the living labs will be used as case study for this research.

The provisional list of all the buildings used within the B4B project are:

1. HHS (Haagse Hogeschool) Education building

2. TU Delft Building 28: Wiskunde en Informatica

3. TU Delft Building 33a: Pulse

4. Kropman Breda Building

5. Avans LA Breda

6. TNO

7. Hogeschool Windesheim

8. TU Eindhoven: Atlas Living Lab building

9. BAM Office Bunnik: Building F

10. DWA Office

11. TNO: Next Delft

12. Spie Office building

4.2 Case Study A: SBE, Maastricht University

4.2.1 Context

Maastricht University is a public research university located in The Netherlands and founded in 1976. In 2021, the total number of students was recorded to be 22,383 and the number of staff members to be over 4,000. The School of Business (SBE) is a faculty of the university founded in 1984 and hosts 4,200 students. It is the most international institution in the Netherlands which differentiates itself via its unique educational model, worldwide focus, and multidisciplinary approach to research and education. In collaboration with the Province of Limburg and APG, they have founded the Brightlands Smart Services Campus, which consists of a campus site, an enabling campus management and development organisation, and a knowledge pillar around which a complete ecosystem is formed around digital technologies and data. The Brightlands Institute for Smart Society (BISS) is located on the campus site of Maastricht university. For this case study, the facility manager who is responsible for six of the SBE buildings was questioned regarding the smart IAQ technologies used in those buildings.

4.2.2 Smart IAQ technology used

The buildings under the responsibility of FMA include mechanically and non-mechanically ventilated buildings. Rooms with mechanical ventilation are connected to a building management system, which measures and controls the amount of fresh air blown into the rooms. Rooms with non-mechanically ventilation have CO2-sensors in the rooms which display the acute air quality in the room and alert users to ventilate (e.g. by opening windows) when ppm levels are exceeded.

4.2.3 Facility Manager Perspective

Facility manager A (FMA), mentions that the technologies used in the buildings certainly help him in maintaining a good indoor air quality. The CO2-sensors in the rooms display the acute air quality in the room and alert users to ventilate when thresholds are exceeded. The data from the BMS system has also been useful in monitoring and controlling ventilation in the buildings. During the Covid-19 crisis he experienced how much more difficult office work and the implementation of education becomes when new government regulations are imposed and he has to improvise accordingly. The management of indoor air quality using sensors and BMS has helped to overcome the difficulties of the pandemic and meet the standards set by Bouwbesluit-2012 (Dutch Building Decree 2012).

"During the Covid-crisis we have experienced how much more difficult office work and the implementation of education becomes when new (government) measures are constantly coming up and you constantly have to improvise.…We can conclude that the used technology is certainly helping us in maintaining a good indoor air quality."

- FMA, Facility manager, School of Business and Economics, Maastricht University

Regarding the barriers, the FM sees the unforeseen defects of the systems as an issue, where he believes that the wear and tear of the ventilation systems result in the prevention of achieving optimum air quality in the rooms. The most important factor that is considered regarding the technological installations is the cost, so systems that are out of budget are not installed in the buildings. Hence, unaffordability is another barrier encountered. Besides these, Maastricht university owns multiple monumental buildings in the old inner city of Maastricht. Monumental buildings have several restrictions regarding transformation and hence this results in the adoption of new technology or new systems, a complex situation and in some cases even impossible.

"Yes, cost is important. Besides, UM is owner of multiple monumental buildings in the (old) inner-city of Maastricht which means that adopting to new technology or new systems is a complex situation, in cases even impossible."

- FMA, Facility manager, School of Business and Economics, Maastricht University

In terms of the decision making regarding the adoption of new technologies, the Facility Services department is the owner of all buildings and is responsible for the managerial control of all technical installations within the buildings and decides in collaboration with the Executive Board of the university about adopting new technologies or systems.

4.2.4 Summary and discussion

Themes	Findings	Discussion
Smart IAQ Technology	Sensors + Building Management System (BMS)	The smart technology used is Level 1 and 2. It is not advanced as some buildings are non mechanically ventilated which is not efficient
Benefits of use for FM	Informing and alerting the rise in CO2 levels in rooms	Historical data is not used to make proactive decisions by the FM, reactive use of technology. The BMS system could be used more efficiently to collect the sensor data and identify trends
Barriers identified	Reliability, Costs, Complexity, Regulations regarding monumental buildings	Certified installations and allocation of budget can solve the barrier of reliability and cost. Barrier of monumental building is more complex which requires change of regulation and involvement of many stakeholders
Improvements desired	Not answered	-
Decision making process	The decision is made by the Facilities Service department in collaboration with the Executive board	The facility manager does not have the decision making authority.

Table 6: Summary and discussion case study A (author)

4.3 Case Study B: Building 28, TU Delft

4.3.1 Context

Building 28 is at the south of TU Delft campus at Van Mourik Broekmanweg 6, and houses the Mathematics and Computer science department of the university. The building consists of 9 floors from the basement to the 7th floor. It was constructed in the year 2002 and renovation work was done in the building in 2018/2019. The total floor area GFA is 10,827m^2. The functional use of the building mostly consists of office and educational space. A more detailed distribution of the usage function can be seen in *Figure 8*.

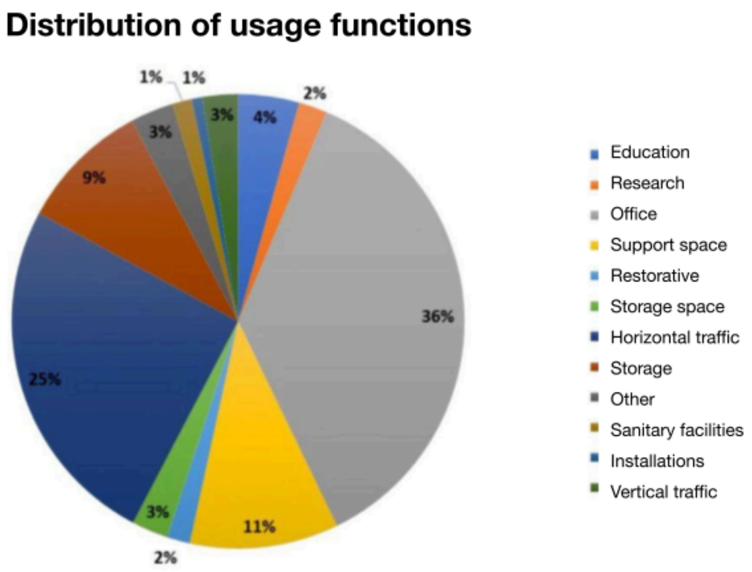

Figure 8: Distribution of usage functions (TOPdesk TU Delft, 2020)

Regarding the sustainability aspect, the energy label of the building has expired. It had an energy label A in September 2009, but this certificate is only valid for ten years. Additionally, the building does not have a sustainability classification such as BREEM, EPC or LEED.

Air quality requirements

The quality requirements of the building are set by the CRE TU Delft in the TU Delft Space Matrix which contains the ambition levels with different quality requirements. For this research, the set quality requirements of the indoor environment with a focus on factors which impact the air quality is of importance. This is presented in *Table 7* below:

Quality requirements based on Space Matrix TU Delft		**Level**
Air	CO2 max, office	1.200 ppm
	CO2 max, lecture hall	1.200 ppm
	CO2 max, project rooms	1.200 ppm
	CO2 max, restaurant	1.400 ppm
	CO2 max, conference room	
	Ventilation min, office	23,4 m^3/h.pp
	Ventilation min, lecture hall	21,6 m^3/h.pp
	Ventilation min, project rooms	4 $m^3/h.m^2$
	Ventilation min, restaurant	8,7 $m^3/h.m^2$
	Ventilation min, conference room	25,2 m^3/h.pp
Temperature and Relative Humidity (RH)*	Winter temperature	19-25 ℃
	Winter RH	> 30%
	Summer Temperature	22-27 ℃
	Summer RH	< 70%

Table 7: Quality requirements based on TU Delft Space Matrix, 2020

*RH requirements are not always binding as TU Delft has a policy not to use air humidification due to energy consumption.

HVAC Installations

The building includes facilities for Heating, Ventilation and Air Conditioning. For heating, two natural gas boilers are used which are located on the 7th floor of the building. The primary centre of distribution is located in the technical room which is located on the roof of the building. The heat is delivered to the air handling units (AHU), radiators, underfloor heating and air curtains. There is also a cooling machine for comfortable cool temperature during the summer which is also located on the roof. For ventilation and air treatment, AHUs and extraction systems are in use which supplies the building with fresh conditioned air. This ensures a pleasant air quality in the building and comfort of the users. The air treatment includes filtering, heat recovery with a heat wheel and cooling; and are equipped with frequency controlled fans. The AHUs are included in the BMS. Several rooms, such as the kitchen and restrooms, have exhaust fans installed but are not linked to the AHU. A fan is used to expel the extracted air above the roof. The building has about 7 exhaust fans, some of which are part of the BMS. A shaft distributes supply air from the AHUs throughout the floors. Supply grilles allow the air to enter the space locally. In certain rooms, the return air is removed both locally and centrally. Through the central shaft, the extracted air is brought back to the AHU.

4.3.2 Smart IAQ technology used

The type of smart technology used in Building 28 is Building Management System (BMS). The service provider of this technology is manufacturer Johnson Control. The mechanical systems of HVAC are connected to the BMS. The usage of the BMS currently includes reporting of malfunctions, viewing installation status, operating the installations centrally and to change the control setting. This implies that a reactive approach is taken rather than a proactive one. The system is not used for predictive models or fault detections which could be beneficial in cost saving and better strategic decisions.

4.3.3 Facility Manager perspective

Questionnaire 1

In order to gain insight into the use and effectiveness of the smart technology services at Building 28, a questionnaire was answered by the facility manager B (FMB). His role within the B&O department of CREFM involves cooperating with various departments from CREFM to manage and maintain the buildings that are allocated to his responsibility. From his role, it is important to coordinate all work within the building, which includes corrective, preventive and inspection work. He also deals with specific maintenance requirements from the users. He believes that in order to ensure that building users can get to work comfortably, it is extremely important to maintain good indoor air quality.

“To ensure that the "users" of the building can get to work in a comfortable manner, it is extremely important to maintain good indoor air quality.”

- FMB, Facility manager, Building 28, TU Delft

The smart technology of sensors in combination with a BMS system as mentioned earlier is used for an alarm that is generated the moment specific threshold values are exceeded. The technology is only as a measuring point to see if the system meets the set requirements. Van Dorp is the installation company of the BMS system which gets the notification of the alarm and they are the ones who act on it to solve the issue. The facility manager gets a report of the incident later. Additionally, when there is a user complaint regarding the indoor environment, the facility manager checks the system for the data on the condition and works together with Van Dorp to solve the issue.

One of the barriers to the use of smart technologies identified from the facility manager perspective is that he does not fully trust the system. The issue he encountered is the reliability of the device as he believes that the alert cannot be blindly assumed because the transducer can also be faulty. The questionnaire also included a question where he was asked about what improvement he wants to see in the future regarding the smart IAQ technology. The response was that he would like to have a single system which links different components allowing the system to be used for more sustainable control of the entire building. However, from the desk research on the available smart IAQ technologies, it is known that this kind of platform which incorporates different components in a single platform already exists and is in use by many organisations as well. Hence, the main barriers identified from the interview is that the facility manager is unaware about the state of the art of the advanced technologies available and the reliability of the system is also another barrier that is hindering their adoption by the university.

4.3.4 Summary and discussion

Themes	Findings	Discussion
Smart IAQ Technology	Building Management System (BMS)	The smart technology used is of Level 2 identified from the theoretical research as the BMS system is used independently without a SaaS
Benefits of use for FM	Resolve issues regarding user complaint and equipment malfunction	The FM has a reactive role as the data produced and collected by the sensors are not used for long term vision and strategy implementation
Barriers identified	Reliability, Lack of awareness	The barrier of reliability can be improved by using the latest better quality systems which are certified and provide guarantee from the manufacturer.
Improvements desired	A single platform that integrates different components	Such a platform already exists which is provided by many service providing companies which indeed makes the task of an FM easier
Decision making process	The FM is not able to make the decision. The request is communicated with Team GBS	Decision making of the FM is low, justified by their reactive role

Table 8: Summary and discussion case study B (author)

4.4 Case Study C: Delft Branch, The Hague University

4.4.1 Context

The Delft Branch of The Hague University of Applied Science (THUAS) is also a building listed on the living lab of Brains4Buildings located in Delft, The Netherlands. The building was opened in 2009 within the premises of TU Delft. Seven courses are offered in the Delft branch and the faculty has a high reputation in the field of higher technical education.

4.4.2 Smart technology used for IAQ

The smart technology used in this building of THUAS is an IoT based BMS and SaaS. Both these systems help the facility manager in the management of indoor air quality along with other aspects of building facilities and management.

IoT based BMS and SaaS from Priva:
The integrated BMS system is used for indoor air quality monitoring and management along with other building maintenance and management tasks. The BMS system is from the company Priva. With the Priva BMS, the manager can control the parameters of indoor air quality such as CO2, temperature, humidity and airflow in the building. It integrates, monitors, and controls complex building systems for comfort and energy optimization. With the system, all air quality parameters can be monitored 24/7 and as the system also operates in cloud, the overview of the building performance can be accessed at all times through computers or mobiles, as well as receive push notifications and alerts. Additionally, in order to overcome the expensive maintenance of wear and tear of installations, Priva uses the latest smart technology to switch on the systems only when and where it is necessary (P.C. FMC, 2024, Priva.com, n.d).

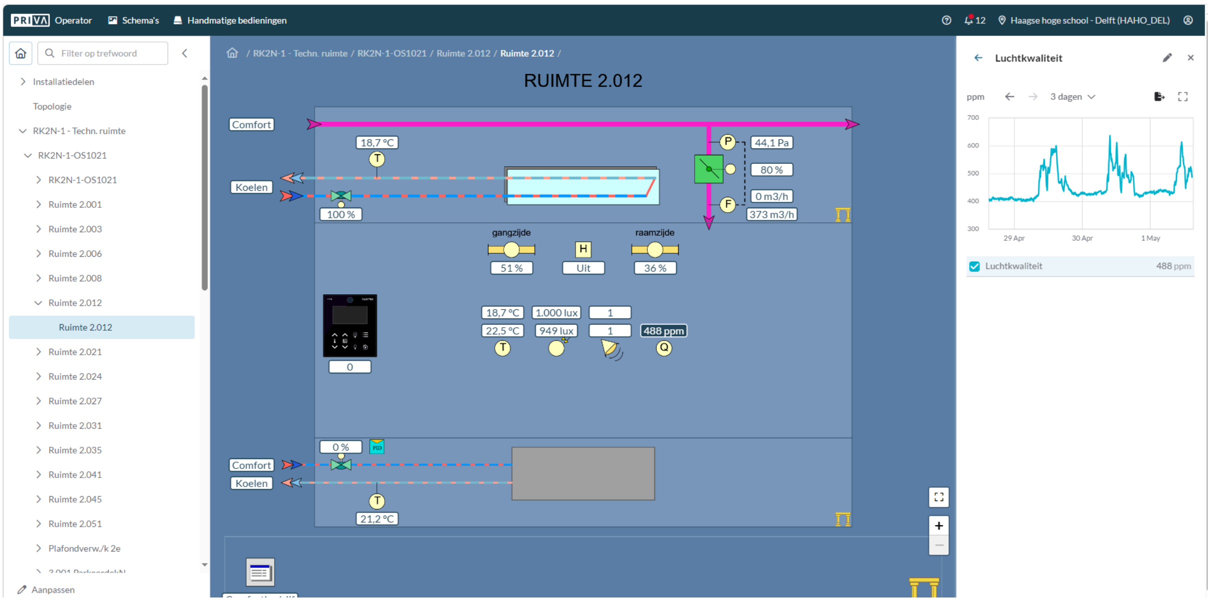

Figure 19: Screenshot of Priva BMS accessed by the facility manager (P.C. FMC, 2024)

SaaS from Unica:

Another SaaS platform used in THAUS is Building Insight from the company Unica. Unica is a technical service provider and innovator of sustainable technologies in the built environment based in the Netherlands which implements solutions in the fields of installation technology, ICT, internet of things, and smart buildings to create effective, healthy, and safe living and work environments. It transforms consumers' preferences and demands into high-quality, tailored solutions. The Unica Innovation Centre created Building Insight, which is a digital data platform that collects and organises all essential building information. The open system gathers pertinent information from building management systems, sensors, smart metres, access systems, weather data, and smartphone apps. Clear dashboards and real-time models enable the facility managers to adapt to anticipated changes in use, allowing for pleasant, efficient, and safe building management (P.C. FMC, 2024; Unica.nl, n.d.).

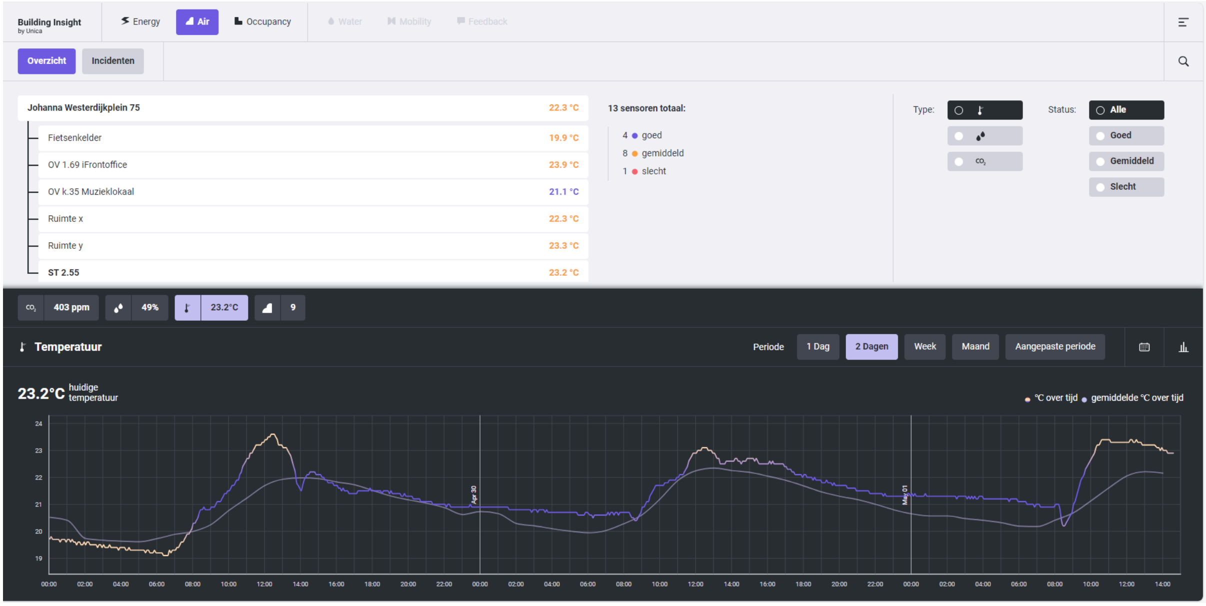

Figure 20: Screenshot of Unica SaaS accessed by the facility manager (P.C. FMC, 2024)

4.4.3 Facility Manager perspective

In order to understand how the smart technologies are used and how helpful the tools are in their tasks, an interview was conducted with FMC, the facility manager of the Hague university. He has a background in mechanical engineering with 27 years of experience as the manager of the building maintenance department, hence it is found that he has great knowledge and understanding of the building installation systems.

Moreover, he mentioned his concern and importance regarding indoor air quality. IAQ is a priority for him because of the impact it has on the concentration level of the students.

"…at HBO half of the students don't make it to the finish, the half of it. So we have to do anything to let them concentrate good, to get a very good environment to study at their best. So that's very important for us. So, yes, the air quality is very important for us."

- FMC, Facility manager, Delft Branch, HHS

The FM in this case, uses the technologies in his daily tasks and considers it very helpful in achieving his ambitions. The ambitions or role of facility manager identified in this case were:

- The university wants to comply with the Paris accord by 2030 regarding sustainability and energy of the buildings. The building installations are responsible for a significant amount of energy consumption, hence, It is a part of the FM's job to make the installations energy efficient
- Make long term plans and a timeline in order to achieve the sustainability requirements, for example, maintenance of HVAC installations and changing the radiators in 2029
- Maintain a comfortable indoor air quality where the students can concentrate and learn better to reduce the dropout rate of HBO students

- Provide a healthy and safe indoor air quality for the occupants, as well as be transparent about communicating the air quality by providing measurement data to the occupants and gain their trust
- Reduce costs by using resources only when and where necessary, hence, use data from occupancy to optimise ventilation, lighting, cleaning etc.
- Optimise the use of real estate of all buildings within the university

FM plays a proactive role in implementing strategies to achieve the university's long term goals. The smart technology plays an important role in this task of his by providing historical data. He uses the Priva BMS system to check all the installations and the indoor air quality parameters such as CO2, temperature, humidity and air exchange in each room of the building. When a user complains about their comfort, then he gets into the system as shown in *Figure 19*, to set new values for the parameters and resolve the issues of the occupants.

The FM also played an active role in getting knowledge on the latest technology available, because in this case, he is the one who talked to Unica about their service and took the initiative to adopt it. Moreover, he was also very enthusiastic about adopting another new technology called "Signify" by Philips. Signify is a smart lighting system which has sensors in the LED lights which are connected to the Internet of Things. It aims to create an interactive system using cloud-based software and multi sensors. Moreover, the aim is to elevate the lighting experience and provide data-driven apps, while the data analytics and visualisations contribute to make the organisation smarter and sustainable (Signify.nl, n.d.). Hence, the FM was aware of all these benefits and took the initiative to adopt the technology.

Building Insight of Unica is used by the FM to look at the dashboard and get an overview of the building conditions as shown in *Figure 21*. Moreover, by scanning the QR code provided in the sensor installation of Unica, the occupants can get insights about the air quality. He mentions that sometimes people just have the feeling of discomfort even when the air quality is good, so this helps to assure the occupants through data proof.

"With the Building Insight, the user of the room, by a QR code can see what's happening in real time…sometimes it's a feeling that it's in the head. It's in the, and I'm going to die like that. But then I can show them now that you're not going to die."

- FMC, Facility manager, Delft Branch, HHS

The Building Insight has also allowed the FM to be transparent in his job. From the perspective of the FM, this is considered very important.

"..this is important because we can show we have no secrets. Yeah, we're trying to do our best for our job. And when it's not okay, it's not okay. We have to do something about it. So this is very helpful"

- FMC, Facility manager, Delft Branch, HHS

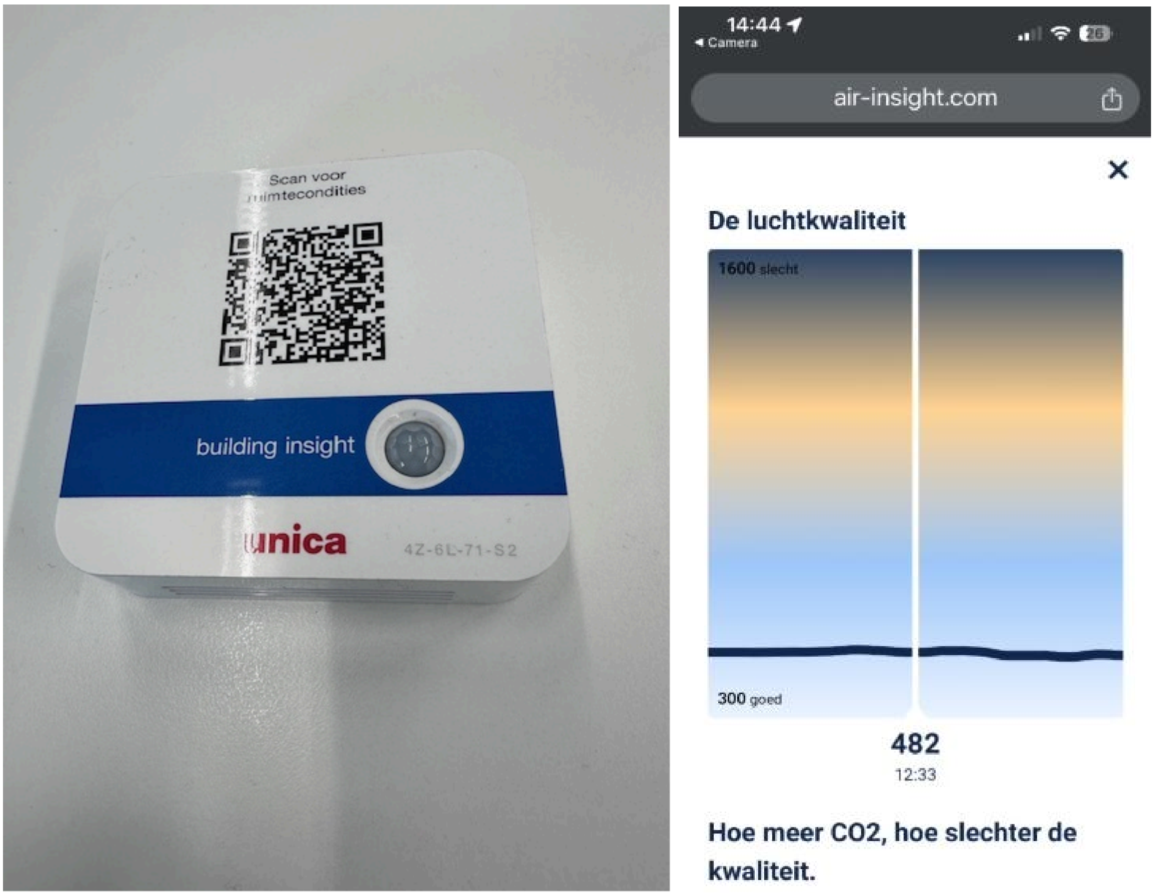

Figure 21: Unica sensor and data accessed by all occupants through the QR code (P.C. FMC, 2024)

In addition to BMS and Unica, the FM of the Hague university also has a subscription from the company "Bright Buildings (BWA)". This service can overlook the BMS system and they send a weekly report via email to the facility manager about the indoor climate of different rooms and report any faults detected as seen in *Figure 22*. The buildings are continuously monitored by Bright Buildings, so that the FM can track the performance of the installations and see what adjustments are needed for, for example, better comfort and lower energy use.

Beste Gerard Willemse,

Uw gebouwen worden continu gemonitord door Bright Building, zodat u de prestaties van uw installaties kunt volgen en kunt zien welke aanpassingen nodig zijn voor bijvoorbeeld een lager energiegebruik en een beter comfort.
Onderstaand overzicht toont de meldingen die Bright Building heeft geconstateerd. Meer informatie over de meldingen staat op .

Vriendelijke groet,
Het team van DWA Bright

Geconstateerde overschrijdingen:
Gebouw: De Haagse Hogeschool

* Comfort
- DIS: Centraal GKW: aanvoertemperatuur te hoog (37 keer)
- DIS: Centraal GKW: aanvoertemperatuur te laag (4 keer)
- DIS: Centraal CV: aanvoertemperatuur te laag (27 keer)
- DIS: Zuid GKW: drukverschil is te laag (29 keer)
- DIS: Zuid CV: drukverschil is te laag (27 keer)
- LBK Zuid: GEA Cairplus SX 280.160: gerealiseerde luchtdruk is te laag (3 keer)
- LBK Zuid: GEA Cairplus SX 280.160: inblaastemperatuur LBK te laag (1 keer)
- LBK Noord: GEA Cairplus SX 188.188: gerealiseerde luchtdruk is te laag (4 keer)

Figure 22: Email sent to the FM by Bright Buildings reporting the indoor comfort (P.C. FMC, 2024)

Furthermore, when there were complaints about inadequate ventilation in certain rooms, the FM team decided to place an additional air exchange unit which cost 250,000 euros. However, when they consulted Bright Buildings to look into the data, they detected that too much air was being ventilated where it was not necessary (places where occupancy was low). Hence, they optimised the ventilation based on real time occupancy data, due to which they could save 250,000 euros of investment.

"you can change the parameters so that the air goes where it should it and they did so, so we avoided the the costs of 250,000 euros so we were very happy"

- FMC, Facility manager, Delft Branch, HHS

The FM also mentioned the challenges he faced when he wanted to adopt a new technology. The higher level authorities, the CEOs (Deans and faculty heads) denied his request arguing that the opinions of the entire university, including the staff and students opinions are required to adopt a new technology. The process of convincing all the stakeholders involved took 2 years, but there was still no action taken. However at the end, they decided to adopt the system by themselves and this was possible because they had the money available. This money was received as a subsidy by DUMAVA as they proved that the new system is more sustainable.

As an improvement in the future the FM, along with his team of 6 other colleagues, wanted to become a directing organisation. In the current situation, the FM has to act on the complaints and reports, but, in the future, the FM wishes to order the companies themselves to fix the issues. The FM themselves want to be in control of the overview and long term strategies, but want the system to be automated or an external company in charge to act on the daily issues and maintenance tasks.

"I want data mining and smart buildings technologies to automate it and maybe I'm in between unica and the building. I call them if something is going wrong over there but they can also see it, so my job can be different….we want to be a facility management directing organisation. The others do the work and we are dictating what they have to do…"

- FMC, Facility manager, Delft Branch, HHS

4.4.4 Summary and discussion

Themes	Findings	Discussion
Smart IAQ Technology	Sensors + Building Management System (BMS) + SaaS + External service providers	The smart technology used is Level 3. The smart technologies used in HHS is advanced
Benefits of use for FM	Ensure comfort of occupants. Make long term strategies for comfort and sustainability. Gain trust of the occupants with transparency. Monitor the condition of indoor air on a weekly basis.	The FM plays a proactive role and is found to be taking initiatives in adopting latest technologies. The historical data is also utilised to achieve long term goals. Has been mentioned that the technologies help him a lot in satisfying the occupants.
Barriers identified	Higher authority stakeholders did not give a positive response, resulting in a time delay of several years.	The budget was available from a subsidy so even if the higher authority were not supportive, the FM could decide by themselves to adopt the new technology.
Improvements desired	Want to be a facility management directing organisation.	Technology companies do provide this kind of service where they fix issues of the FM for them. However, giving the control of your building to an external party is debatable in terms of data privacy and security.
Decision making process	The decision is seeked from the higher level stakeholders. However, they want everyone's opinion on it which takes a long time	The availability of budget plays an important role in the power, and in this case the subsidy enabled the FM team to make the decision even when it was not supported by the higher authority stakeholders.

Table 9: Summary and discussion case study C (author)

4.5 International Case Study D: University of Richmond

4.5.1 Context

University of Richmond is a liberal arts college located in Virginia, United States. The campus real estate covers an area of 1,400,000 m^2. It hosts 3,900 students and 1,700 staff members in its five schools (Richmond.edu, 2024). The total real estate of the university consists of seventy buildings. The university aims to make each building as comfortable and energy efficient as possible. Hence, the buildings are being updated with new technologies that help them achieve their goals.

4.5.2 Smart IAQ Technology used

The university uses the Building Automation System (BAS) to create a comfortable indoor environment for the students and staff and to be energy efficient. The improved air quality through the updated system will contribute in improving concentration levels and creating better learning environments. The Associate Director of Energy Management, Julian Morgan, has been tasked with updating 41 buildings and 1,300 equipment since 2014 by integrating the Staefa Control System to Niagara JACEs so that the front-end workstation has an improved user interface (Sait, 2020).

After evaluating the available technologies, the building management chose J2 innovations' FIN Stack solution. This service involves the provision of open market software as a solution to simplify the complex management process of campus buildings. The installation helped to integrate the campus and provided more choices for facilities management and reporting as compared to the situation when the campus was not operating with the latest technologies available in the market (J2 innovations, 2022).

Implementation of FIN Stack offered the campus with a streamlined graphical user interface which makes it easier for the facility managers to use the software. Additionally, there is a unified alarm management in the solution. Multi vendor integration is possible which refers to the process of integrating and connecting devices and controllers from different vendors or manufacturers into a single automation system. This has various benefits such as interoperability, data exchange, flexibility, scalability and vendor collaboration (Siemens, n.d.). It provides cross-vendor control structure which refers to a system or framework that allows for the centralised management and control of devices or systems from multiple vendors or manufacturers. It provides a unified interface or platform for administrators or users to monitor, configure, and control heterogeneous components within an integrated environment. Figure 23 shows how all the systems across the different campus buildings can be overviewed in the platform of FIN Stack.

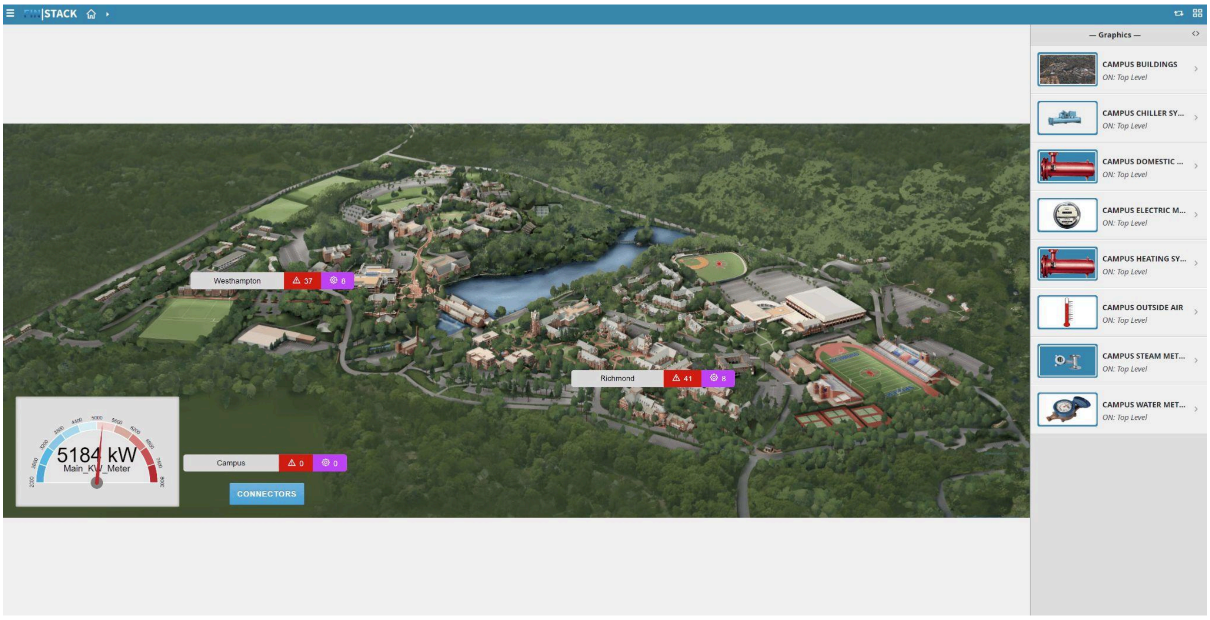

Figure 23: FIN Stack platform to view different building automation systems in a single platform (J2 innovations, 2022)

For the building managers and technicians, a mobile platform is available through which they can access the BAS of the campus whenever required in order to resolve issues as well as to monitor the HVAC system at the university. Moreover, the Historian App, provided as a service of the solution, allows the managers to browse, graph, format and download all the historical data collected. For indoor air quality, this enables them to track the status, identify trends and prepare long term visions to implement data driven strategies (J2 innovations, 2022). *Figure 24* shows how the managers can get an overview of all the air handling units and can control the set points from the system remotely. Since the integration of FIN Stack in 2014, the university has transformed 55 out of its 77 buildings, connecting 2460 equipment and 63,600 data points.

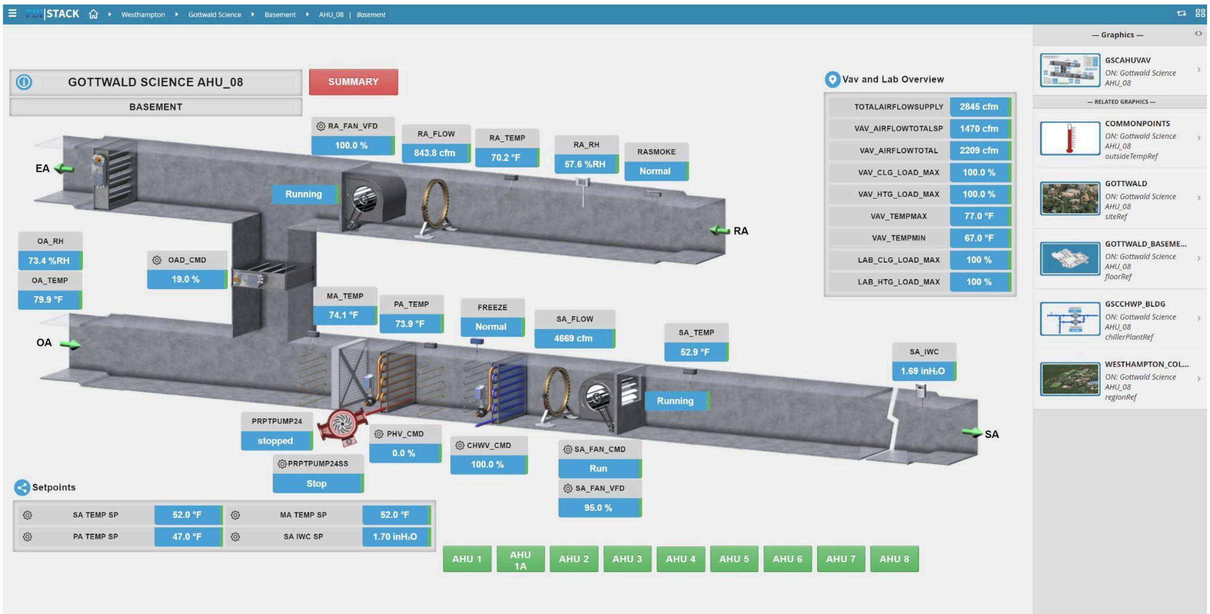

Figure 24: FIN Stack platform to view different air handling units in a single platform (J2 innovations, 2022)

4.5.3 Facility Manager Perspective

Technological solutions such as FIN Stack are mostly developed to help the building managers responsible with the task to create a comfortable environment for the occupants which includes the quality of air indoors. However, the use of such technologies is not limited to air quality but extends to all indoor environment parameters as well as energy since the world is moving towards sustainability and energy efficiency. This research aims to explore how these technologies help the facility managers in their task and decision making. Hence, it is important to evaluate the technology from the perspective of facility managers.

The facility manager in this case study (FMD) emphasises the attractiveness and usefulness of the system in terms of the collection, storage and provision of historical data in the application apart from the graphics. He therefore sees the value of the historical data in future possibilities to make long term strategies in contributing to a healthy and sustainable campus.

"When I first evaluated J2 Innovations' products for the conversion to Niagara I was only interested in the graphics. When I was shown FIN Stack, the history app was what sold me. To have that amount of data at your fingertips is invaluable – I could see so many possibilities for the campus with FIN Stack."

- FMD, Former Associate Director, Energy Management, University of Richmond

Moreover, one of the main roles of the manager in this case is troubleshooting, which refers to a systematic approach of problem solving by identifying, diagnosing and solving issues (IBM, n.d.). FIN Stack makes this task of the manager easy by the collection, analysis and reporting of historical and current data. The managers are able to make long term plans for the future of the university. Having new construction being built on campus, FIN's troubleshooting data on the current building stock has assisted the team in optimising the new structures during the commissioning phase and the new buildings will benefit more by the solution upon completion.

Focusing on the role of the technology in IAQ management, the manager mentions the ease of identifying trends to maintain optimal indoor temperature and ensure comfort of the occupants:

“At the moment, we are in ‘shoulder-season’ when we have to constantly question - are we cooling or are we heating? Having data trends at my fingertips really helps get through this as I can look at each building as an individual to get the correct temperature, save energy and keep the occupants happy.”

- FMD, Former Associate Director, Energy Management, University of Richmond

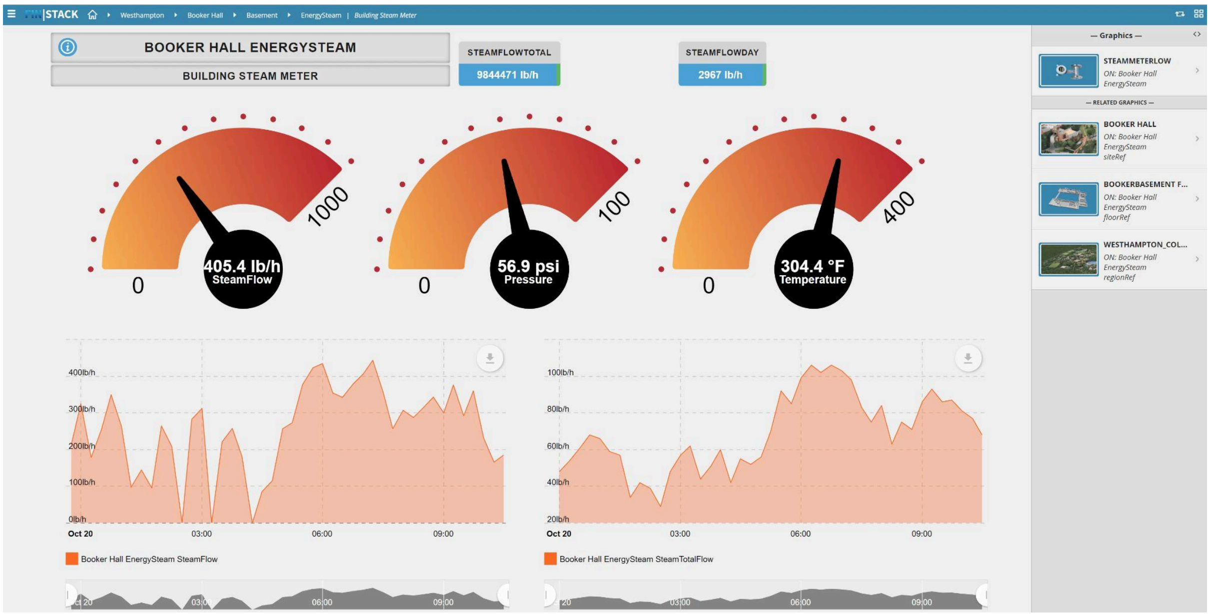

Figure 25: FIN Stack platform visualisation of data in a dashboard (J2 innovations, 2022)

“FIN Stack is not just a BAS integration system; it is facility management tool that I can customise the user interface to make my job of managing the campus easier. Set-points, sequences, and schedules – these are the bread and butter of optimising energy efficiency for facilities managers. With FIN on our side, it saves us a lot of time so we can focus on making our campus a great place to work and study.”

Overall, with this quote, the facility manager of University of Richmond expresses how helpful the solution has been in his task of managing the facilities of the campus through the set points, sequences and schedules in a customisable dashboard as shown in Figure X. It has been of great help to satisfy the needs of the campus users as well as optimise management systems, all this while being more time efficient (J2 innovations, 2022).

4.6 Cross Case Analysis

Four case studies were explored as the empirical part of this research out of which three were within the Dutch context. One case study in the United States was also explored in order to get an international perspective and to know what the latest technology use is benefitting facility manager of university outside of the Netherlands. To understand the exploration of the different cases, the results are compared and contrasted by doing a cross case analysis. The analysis is done by dividing the findings of the case study and interviews into answering the research questions. The international case is used just as an inspiring example and will not be used for the cross case analysis as the research aims to explore only in the Dutch university context.

4.6.1 Current status of use of smart technology

From the case studies, it is found that the level of smart IAQ technologies used in each university is on a different level. Maastricht university, which is not a part of the Brains4Buildings project, is still in Level 1 and Level 2 in the classification table of smart IAQ technology as some buildings are not even mechanically ventilated and use sensors to only monitor the CO2 level. These sensors are not connected to the BMS system and there the ventilation has to be done manually by opening the windows in order to maintain an optimal indoor air quality in the university building. Some buildings do use the BMS system, however the role of the facility manager regarding the use of the BMS system in managing indoor air quality has been found to be reactive as they act in case of an alert. In the case of TU Delft, the technology used is Level 2, where a BMS system is in place which is accessed by the facility manager. However, the use of it is comparable to the case of Maastricht university as the role of facility manager is rather reactive than proactive. Even though TU Delft building is a part of the Brains4Buildings project, the facility manager only checks the BMS system if an issue is raised, for example an alert by the system or complaints by the occupants. In both the cases, the historical data collected by the sensors is not utilised to identify trends, predict the outcomes or make strategies for a long term vision. In the Hague university, the situation is more advanced and the used technology is Level 3 since they use an online dashboard in addition to the BMS system. The online platform contains a dashboard which visualises the air quality data and contains information of all the building on a single platform. The international case study is also on the same level as the Hague university (Level 3) and uses the dashboard of the online platform and historical data to implement strategies regarding the comfort of occupants.

4.6.2 Use and effectiveness of the smart technology

The effectiveness of the smart technology in the case of this research is defined as its usefulness to the facility manager and the positive results that can be achieved using them. The sensors used in Case Study A have been used to measure the CO2 levels. In Case Study B, the smart technology has been useful to FM to identify the faults by an alert system, hence it has been effective to detect and fix issues in the air quality maintenance system. The technology has also been effective in solving comfort complaints of occupants which includes the parameters of indoor air quality. The use and effectiveness of smart IAQ technology is found to be most advanced in Case study C. The BMS system is not only used to fix issues when alarms go off, but it is rather used by the FM to check the status of the installations periodically. The data is used to identify the efficiency of the systems and a long term plan is made to upgrade/replace inefficient installations. This has been effective not only in ensuring comfort of occupants but also in saving energy costs and unforeseen investments. Moreover, using the technology of Unica has enabled the FM to visualise the air quality data of different parameters in graphs and use the historical data to identify trends. This has also facilitated them to gain the trust of occupants as they can show the easy to read data to the occupants in case of complaint. The system with the QR code has also allowed the occupants themselves to get insight of the real time air quality data, increasing their satisfaction.

4.6.3 Barriers identified by the facility managers

Several barriers to using new technologies are identified in the case studies which can be categorised under: Regulatory, Technological, Knowledge and Stakeholders. In Case A, several buildings of the university are listed as monumental buildings with restrictions to make changes in the interior and exterior of the buildings. Therefore, this implies that the installation of new technologies is not possible in these cases due to the government rules. Lack of knowledge is another barrier encountered where the FMs are not up to date with the availability, utilisation and the benefits of the latest technologies. In two of the cases, the FMs have been found to play a reactive role by only using the current technology to resolve issues and complaints. Moreover, there is no incentive to adopt new technologies as long as the way of working now is accepted by the university. Technological barriers such as wear and tear of installations and reliability of the sensors are also identified from the perspective of the facility managers. The decision making authority of the FMs also hampers the adoption of new technologies as they do not have the power to implement the technology they want without the financial investment and approval of the stakeholders in the higher management level. However, an interesting finding is discovered in an example of Case study C. When the initiative of adopting a new lighting (equipped with IAQ sensors) was presented to the management, the stakeholders wanted the opinion of all the other involved stakeholders including the users, due to this, the technology was not adopted even after two years of its initiation. However, the FM team had an available budget from a subsidy they received. The provision of the budget enabled them to decide on implementing the new technology even when the management was not fully convinced. They only needed the approval but no financial investment which gave them the power to go forward with their decision.

4.6.4 Overview, compare and contrast

	WHAT?	CASE A	CASE B	CASE C	COMPARE & CONTRAST
FACILITY MANAGEMENT	**Characteristics of FM**	• Facility manager in university for 22 years • Skills and specialities in Health and Safety management, Operational Management and Building Management	• Bachelor's of engineering, specialising in mechanical installation technology, industrial equipment and maintenance and repair work • Technical building co-ordinator at TU Delft since 2022	• Background in mechanical engineering. • 27 years experience in general manager of building maintenance. • Now he is a specialist in building management at HHS.	• Two FMs (Case B and C) have an educational background in the technical field of mechanical engineering • Two FMs (Case A and C) have over 20 years of working experience in the facility management sector • Education and experience contribute to the proactive role of FM in technology adoption
	Awareness on importance of good indoor air quality	• New government measures regarding IAQ after the Covid 19 pandemic has raised awareness to implement changes in office and education environment	• Good indoor air quality is considered very important by the FM for the comfort of the occupants	• Understands the role of a good indoor air quality not only in the comfort but also on the concentration level of students in the university	• There is different level of understanding amongst the FMs; from IAQ measures being taken for regulatory reasons after Covid, to being aware about the impact of good air quality on occupants comfort and students' concentration level
	Awareness regarding smart IAQ technologies	• There is little awareness about the use of smart technologies as it is currently only used by the FM for ventilation in case of alert from CO2 sensors	• Awareness of smart IAQ technology is present but limited. An online platform with all the components in a single place is wanted as improvement in the future	• The FM is aware of the latest technologies available, has talks with new companies who provide latest IAQ solutions	• Awareness of available latest IAQ technologies is only present in FM-C • The awareness comes from communication with technology service providing companies who have endorsed their products and services to the FM
SMART IAQ TECHNOLOGIES	**Smart IAQ technologies implemented**	• Use of smart IAQ technology is still in Level 1 (sensors and non mechanical ventilation) and • Level 2 (IoT based BMS)	• Level 2 (IoT based BMS) is used to control the indoor climate including air quality	• SaaS (online dashboard) is used by the FM to view historical data in addition to the BMS. • IAQ insight is gained from the digital platform of Unica • Comfort quality is updated weekly by the company Bright Buildings	• All three universities chosen for the case studies are on different levels in terms of the smart IAQ technology used • Level 3 technology of digital platform is only used by one of the cases (Case C) • Similarly, IAQ data is reported weekly only in Case C
	Benefits of use by FMs	• The CO2 sensor is used to alert about the need for ventilation • The BMS system is used to measure and automatically control the air flow in the rooms	• The alert system in the BMS is used to fix the issue with installations • User complaints about comfort are solved using the BMS	• Use the dashboard to monitor real time IAQ data • To make long term vision to upgrade or replace the HVAC system for more efficiency • Ensure the occupants about a safe indoor air quality	• The use of smart IAQ technologies have contributed in different extends in all cases, ranging from reactive use to fix issues and complaints to proactive use of using historical data for long term strategies and ensuring occupant safety with transparency
	Barriers identified by the FMs	• Legal: Monumental buildings have restrictions regarding the smart technologies and installations that can be implemented • Technological: HVAC installations and sensors are subject to wear and tear • Cost: It is an important factor to consider, hence lack of budget can be a barrier • Authority: Decision is up to different stakeholders (UM Facility Services and Executive Board)	• Technological: Reliability of the sensor is not trusted • Technological: Need a software which includes all systems in a single platform • Knowledge: Unaware of dashboards (SaaS) available • Authority: Does not have the authority of making the decision to adopt a new technology. Need to make a request to Team Energy	• Authority: Needed to consult higher authorities which resulted in a time delay, however decision could be taken due to the availability of budget through subsidy • Technological: Need for a better service from the service providing company where the FM can merely act as a directing organisation and the service providers take the necessary actions according to the order of the FM	• In all three cases, the FMs do not have the authority to make decision regarding the adoption of new technologies despite identifying the benefits of the technology in their task and comfort of users • The FMs have to approach the higher authorities on the managerial level with their request and this may often takes a longer time • However, if there is no need for the higher authorities to make financial investments and only permission is required, it can be easier to convince them. Therefore, the FMs have more power in decision making and spending the budget on new technologies

Table 10: Overview, compare and contrast of the cross case analysis (author)

05 INVESTIGATING CASE STUDY B

5.1 Research findings

5.2 Communicating findings with FM

5.3 Role of Brains 4 Buildings project

5.4 Barriers identified

5.5 Stakeholder involvement

5.6 Recommendations

5.7 Validation

05 INVESTIGATING CASE STUDY B

This chapter outlines a second layer of empirical research after the exploratory research presented in the previous chapter. This second layer of research involves an investigation into Case Study B, Building 28 of TU Delft. The first part of this chapter includes communicating the research findings of the latest technology available with the facility manager in response to the improvement he desired in the first questionnaire. After confirming the usefulness of the technology by the facility manager, the next step was taken to explore the barriers in implementing it. Since Building 28 is a living lab under the Brains4Buildings project, interviews were conducted with project members to investigate why the latest technology is not being implemented and used by the facility manager in this case. Moreover, since the facility manager of one of the living labs of the project (Hague university) uses the smart dashboards and online platforms for indoor air quality management, it was aimed to investigate why Building 28 of TU Delft does not use such technology which is more beneficial for the facility managers. With the results of these interviews, a number of barriers are identified and lastly, recommendations are suggested to overcome these barriers.

5.1 Research findings

The findings of the theoretical research presented in section 3.4 was summarised and a presentation was made to present to the facility manager of Building 28. Information collected on the technology service (SaaS) was summarised as follows:

Online platform linking different components in a single platform (including IAQ management)

- Summary of the different service providing companies
- Johnson control, Spacewell and Inbiot

Summary of the benefits included in the presentation:

- Access to data on well-being (which includes the indoor air quality), energy, equipment performance and security all in this one interface
- Not only collects the data but also provides visuals and reports
- Possible to see the trends and changes that occur which allows to make more proactive decisions instead of just acting when something goes wrong
- Possible to plan the financial aspect; to invest in maintenance or buying new equipment ahead of time. Sudden investment can be avoided in case of emergency when something already stops working
- Overview of how the platform helps all the stakeholders involved such as the facility manager, service technician, building manager, energy manager, and the occupants can also with this app they have they can directly say about their comfort and space in the same platform

- Since the FM is responsible for 4 of the buildings of TU Delft, the information of all the different buildings can be stored in the same platform
- Visualise the data and different parameters on the floor plan
- Availability of mobile apps for the occupants to use to get information and mention their complaints directly through the app to the FM

5.2 Communicating findings with FM

Interview 2

The purpose of the second interview with the facility manager of TU Delft was to discuss the findings of the research which provided valuable information regarding the improvements that he wanted to see in the future. The aim was to communicate the research findings on how the latest smart technologies can help him to make his tasks easier. With this information, it is possible for him to take a more proactive role in the building management and make data driven decisions for the future of the campus.

During the interview, a presentation was given by the researcher which presented the findings of the research regarding the latest smart IAQ technologies available which was already mentioned in the previous section of this report. In the presentation, the online platforms (SaaS) provided from different companies were shown and their benefits were mentioned. Apart from the presentation, a practical demo was given of the online platform "Spacewell workplace" to show how the software is actually used and how the different types of data are analysed, compared and visualised in the dashboard of the software.

Then the facility manager was questioned about his opinion on what he thinks about the software service and how useful it would be for him. As a response, he was positive about the usefulness of the service and considered it to be better than the level of technology currently in use. He highlighted the importance of understandability (how easy it is to interpret the data presented in the online platform), and considered this feature as an important improvement to the BMS system used at present by the university.

".....system running now from Johnson Controls, it is not that fancy as the one you showed in this presentation, so I think it will help because it gives a lot of information and it is, well as far as I can see now, understandable for everyone"

- FMB, Facility Manager, Building 28, TU Delft

Furthermore, he confirmed that the availability of historical data, analysis and visual representation of data can help him in taking a more proactive role regarding the technical management of the university building. The ease of use by having all the data in one platform without having to switch to different loggers was also an important added benefit from the perspective of the facility manager.

“I think it's much easier and I think it will give much more information in just one look in the system. The system we use now, you have to look on different tabs, different screens, different loggers to get your information”

- FMB, Facility Manager, Building 28, TU Delft

After getting the confirmation of the facility manager regarding their willingness to use the latest smart systems, the researcher aimed to understand the role of the facility manager in the decision making process of adopting the new technology in the context of TU Delft, to add information to the findings of the theoretical research. Hence, the next subject for the interview was about the steps they have to take if they want to adopt a new technology. The response concluded that the facility managers themselves do not have the authority to make big decisions on the campus but can only suggest that it will help them better in their task. The first contact department that the facility manager would reach out in order to make a request as such is the Team GBS in the context of TU Delft, however there are many other stakeholders that are involved in the later stages of the process.

“Well I can suggest this new system because it can help us better but I cannot make the final decision to use it for the whole campus. For that reason, we have too many people involved so I cannot make that decision on my own.”

- FMB, Facility Manager, Building 28, TU Delft

5.3 Role of Brains 4 Buildings project

As Building 28 is a living lab under the Brains4Buildings project, two interviews were conducted with the project members. The first interview was with the project associate of Brains4Buildings responsible for Building 28 (Interviewee code: B4B1) and the second interview was with the project co-ordinator of Brains4Buildings project (Interviewee code: B4B2). The information from these interviews provided a better understanding of the role of B4B project. Additionally, several barriers along with their corresponding stakeholders were identified using the interviews. An overview of the information is presented in *Table 11:*

Data collected on	**Interview 1**	**Interview 2**
Interviewee profile	• Project associate of Brains4Buildings responsible for Building 28 • Project manager at Green Village TU Delft • Code: B4B1	• Project coordinator of Brains4Buildings project: Was responsible in acquiring the project • Works at the Impact and Innovation Centre, TU Delft • Code: B4B2

Role of Brains4Buildings project on technology used in the building	• Research on fault detection and diagnosis • Control over changing the set points to give buildings more flexibility • Used as pilot project to implement the technologies on a bigger scale • Can help in identifying the root cause of problems in the building if the required tools are available	• Conducts webinars where the findings of the research is shared with the partners • Actively share knowledge of research projects conducted at the current time • Working with project partners in the consortium to identify the actual needs of the facility managers • One project partner (Royal Haskoning DHV) working on the cost benefit analysis
Barriers identified	• Need to make an API connection to the BMS in order to collect data real time, to make this connection safe and secure is an hurdle • Another security concern when a third party has the control over the systems installed in your building • Difficult to find the right person to convince and explain the benefits of adopting a new technology • Takes a long time to get all the stakeholders together • Scale up the pilot projects in difficult as bigger investments are needed • Not enough measurements to show the benefits that the technology is providing • No cost benefit analysis of the latest technologies • The benefits on monetary terms is low because an already smart building is made smarter • Split incentive: Stakeholders not willing to invest on something that the other stakeholders will also benefit from • Brains4Buildings can only do pilots, because they are not equipped and need a professional party • Not enough trained facility managers: need to spend time to understand the systems	• Hard to find the cooperation with the facility/building managers about explaining what the project is about • Difficult to find out what people actually need in order to do their job • The dashboard developed 5 years ago is still not being used: The people responsible for the BMS system developed the dashboard but the facility/building managers were not involved • Hard to show the added value because there is only insights but no cost benefit analysis • The benefits are not proven yet with in the living labs • Difficult to convince the stakeholders in the higher level management that the technology is worth the investment • The management stakeholders do not know what to ask for • Need to have a cost benefit analysis • More academic partners in Brains4Buildings project, need more industry partners • Knowledge sharing is mostly on the academic level • Need for a handbook for the facility/building managers for data integration: Show what steps they need to take to

	• New technology is not a priority because of budget for Team Energy (who is in charge of the BMS system) • Problem of a vendor lock in when working with the third party providing the technological services • TU Delft wants to stay the owner of the data and only allow the third parties to add their plug-ins: Need for an independent data layer in between • Do not know the Return on Investment (ROI)	make building smart (adopt new technologies) • Better communication is needed with the facility/building managers about the actual data collected • Need to develop business cases • Lack of resources, lack of employees • No incentive for companies to work smarter since they already have contracts
Stakeholder involvement insights	• Campus real estate and facility management do not want to spend their budget on new technologies as the benefits are enjoyed by the deans and faculty heads • Team energy is responsible for the BMS system, has a budget of 5 million euros, aims to save 50% of energy • The sustainability coordinator is responsible for a plan for the whole campus and other stakeholders comply with it	• Campus real estate and facility management department involved in the early stage of Brains4Buildings project to identify the buildings where they want to save energy & increase comfort • Facility and building managers not involved directly (example: developing the dashboard) • High level management authorities (Dean and faculty heads) do not know what to ask for from the market (smart technology service providing companies)

Table 11: Overview of the information collected from the interview (author)

As the mission of the Brains 4 Buildings project is stated to make buildings smarter to reduce energy costs and increase comfort, it was interesting to investigate the role that the project plays in the smart technologies used in their living labs. On a broader perspective, the B4B project helps in knowledge sharing about the smart technologies amongst all its living labs by conducting webinars. The findings of the different research conducted in the living labs is actively shared in these webinars.

Building 28 was chosen as a living lab as the project coordinators of B4B came in contact with the Campus Real Estate department of TU Delft and they mentioned the list of buildings that were interesting examples and Building 28 is one of them. It is used as a pilot project by the B4B project to scale up and implement the technologies on a bigger scale. In this Building, the research on Fault detection and diagnosis is conducted. Real time data is collected for air quality parameters, comfort parameters, occupancy and energy which is used for the research purposes. Moreover, there are around 30 project partners of the B4B project and some of them (for example: Spectral) are working on identifying the actual needs of facility managers as this is lacking in the current scenario. Another project partner (Royal Haskoning DHV) is also playing an important role by conducting a cost benefit analysis of the new smart technologies available. However, these initiatives do not have any proven results yet. Furthermore, B4B can also play a role in identifying root causes of technological issues if the required tools are available.

5.4 Barriers identified

From the interview, a number of barriers are identified to answer the question of why the latest technologies such as the online dashboard are not being used by the facility manager of Building 28. These barriers mentioned in *Table 11* are categorised into Lack of knowledge, Safety and Security, Stakeholders and Lack of resources.

Lack of Knowledge

The knowledge barrier is the main barrier which was identified from the questionnaire with the facility manager as mentioned in section 4.4.3. It is an important barrier because if the facility managers are not aware of what kind of technologies are available and how it can help them, there will be no initiative taken to upgrade the technology. This research has contributed in overcoming this barrier by informing the facility manager about what technologies are available, their benefits and how to use them. Additionally, the B4B project can also play a better and active role in communicating with the FMs because in the current situation, the knowledge sharing is only at the academic level.

"...what we experience that it was quite hard to find the corporation with the with the building manager, with facility manager, that you need to explain what project is about"

- B4B-2, Project Coordinator, Brains 4 Buildings

B4B is also working on developing a handbook for facility managers for data integration which mentions what steps they need to take. There should also be better communication and involvement of the facility managers. For example, when the dashboard was being developed by the company Van Dorp Installations, the facility managers were not involved. This could have added knowledge for the FMs and helped in designing the dashboard better according to the needs of the FM.

"we share knowledge with them (facility managers) through webinars but I think we can do better…B4B project is rather academic, or a lot of academic partners involved but also the industry but I think maybe we can do a little bit of a better job in also actively involving the people from building 28 to show what we actually have achieved…"

- B4B-2, Project Coordinator, Brains 4 Buildings

Safety and Security

Safety and security is another important barrier that has been identified in this case. In order to collect real time data, an API connection to the BMS is needed. To make this API safe and secure is a barrier and is taking a long time to implement. The concern of security also arises when a third party technology company provides their service of managing the building systems. This means that a party outside of the university has control over the buildings which is not preferred. Moreover, TU Delft is also concerned about a vendor lock in which is a reason why they are not willing to adopt the technologies such as the one provided by Unica.

"the campus real estate won't buy the system of Unica, I don't think so maybe because they don't want a vendor lock in"

- B4B1, Project associate Building 28, Brains 4 Buildings

For example, if a company like Unica leaves after the contract ends, the data will be lost. TU Delft wants to stay the owner of the data collected and processed of the university buildings. To maintain this ownership and overcome this barrier, an independent data layer in between is required. Hence, B4B tries to maintain an open source platform to collect data so that the university stays the owner of the data but the other companies can add their plug-ins in the data warehouse.

"We try in Brains 4 Buildings to have an open source platform to collect the data or at least that TU Delft stays the owner of the data and then Unica can put their plug into the data warehouse, but if Unica leaves that you don't lose the whole system"

- B4B1, Project associate Building 28, Brains 4 Buildings

Stakeholders

Adopting a new technology involves various different stakeholders. In the TU Delft organisation as well, there are many stakeholders that need to be convinced regarding the benefits of adopting a new technology. It is especially difficult to convince the higher level management authorities to make the investment since it is necessary to have the budget to implement the technologies. Therefore, it takes a long time to get all these stakeholders on board.

"If we can prove that it's worth the investment then I think we convince the higher management to invest in that"

- B4B2, Project Coordinator, Brains 4 Buildings

Moreover, the problem of split incentive occurs which refers to the benefits of an investment that is not enjoyed by the one who pays but rather other stakeholders gain the advantage. So, no one is willing to invest as they expect the others to contribute financially. The Campus real estate department has to make the investment in the new technologies, but the benefits are enjoyed by the Deans and Faculty heads who save money from the efficient technologies.

“split incentive…so the Campus Real Estate has to invest and the faculties or the deans are getting the benefit because they have to pay less energy”

- B4B1, Project associate Building 28, Brains 4 Buildings

In the case of adopting a new dashboard/SaaS, it has been found that the initiative was taken five years ago, however, it has still not been implemented till now. Adoption of the dashboard not being a priority of the responsible stakeholder is also a barrier of not taking the initiative of upgrading the latest technology. However, the most important barrier is regarding the involvement of the facility managers in the process. They are an essential stakeholder as they are the end users of the dashboard. These technology services are supposed to help them in making their job easier, so it is necessary to involve them in the entire process of designing and implementing these kinds of technologies. This will result in a better product which caters to the specific needs of the FMs and will therefore be utilised in an efficient way by the end user.

“It was not actually the building manages itself that were actively involved in developing the dashboard but mainly the people that are responsible for the BMS systems”

- B4B2, Project Coordinator, Brains 4 Buildings

Additionally, the companies that provide the technology services already have a contract with the university and therefore have no incentive to work smarter, and when the university does not know what additional services to ask for, there will be no upgrading of the existing systems.

Lack of resources

Various resources; physical, financial and manpower needs to be employed when adopting and utilising new technologies. The B4B project identifies the lack of such resources as another barrier in adopting new technology in Building 28. The B4B project only does pilot projects as it requires less resources, however when they have to implement the same on a larger scale, it is hard to get the necessary investments. The project is not equipped enough to scale up on their own without the involvement of professional parties. Moreover, the project does not have any proof of benefits yet from the pilots as the experiments are still ongoing. There is no cost benefit analysis done which can be used to show the other stakeholders that the investment in the new technology will actually benefit them.

“after a pilot it is an obstacle to get it scaled up because then you have to do bigger investments, you have to have business cases, so that is now actually the hurdle”

- B4B1, Project associate Building 28, Brains 4 Buildings

Building 28, as any other living lab of B4B is an already smart building, hence, the additional investment is just making a smart building smarter. This results in the difference of added benefit and the current situation not being significant. The data of benefits in monetary terms is also lacking, there are no exact measurements on the return of investment (ROI), which is necessary to convince the investing parties. There is also a lack of manpower, employees to adopt the technology. Although a technology like the dashboard seems easy to understand, there still needs to be a certain level of knowledge on how to use it. This requires some training and time needs to be spent in better understanding of the utilisation, however, if the university does not have enough employees in this sector, they ask them to focus only on the priority things. This is the situation currently where manpower is only employed to fix big issues and problems in the building system. Hence, facility managers need to be trained in using the new systems to their full potential such as making long term vision and implementing strategies using the trends of historical data, rather than just fixing an arised issue.

"if you don't have enough people you only do the priority things and that's just fixing, there are complains you fix it…also you have to find people who can work with it so that's a complex total"

- B4B1, Project associate Building 28, Brains 4 Buildings

5.5 Stakeholder involvement

From the interviews, the most important stakeholders are also identified in the process of adopting new innovation specific to the case of Building 28. Their role, responsibilities and the barriers corresponding to them are mentioned in *Table 12* below:

Stakeholder	Role and responsibilities	Corresponding barriers
Dean and faculty heads	• High level authorities who make investments in adopting new technologies • Need cost benefit analysis before making the investments	• It is difficult to convince them to make such investments without proof of benefits • Lack of knowledge on what to ask from the market parties (for example: new features of latest smart technologies)
Campus real estate and facility management	• Responsible for the management of all the real estate and facilities of the entire university buildings • Involved in the early stage of B4B project to identify the buildings where they want to save energy & increase comfort	• Split incentive: not willing to pay for something that the other stakeholders will also benefit from
Team Energy	• Responsible for the energy consumption and efficiency of all buildings • Contact point of FM if they want a new technology • Is in control of the BMS system • Has gotten a budget of 5 million euros to save energy	• Adopting a dashboard not a priority or in the budget • Split incentive: not willing to pay for something that the other stakeholders will also benefit from

Facility Manager	• Responsible in ensuring the functionality of buildings assigned to them • Respond to the comfort complaints of occupants • Respond to faults and issues detected in the building systems by alerts • Work with external technology companies to fix the reported issues	• Lack of knowledge of the latest technologies available • Need to invest time to train them in using new technology • Scarcity of facility managers who are trained to use dashboards • Reactive role rather than a proactive role in the organisation
B4B project	• Share knowledge with in the living labs of the research findings • Bridge the gap between researchers and Campus real estate • Conduct pilot projects to scale up in the future	• Lack proof of benefits from the research projects to convince the necessary stakeholders • Not equipped to scale up the pilot projects as bigger investments are needed • Not communicating enough with and involving important stakeholder facility manager in the process
Sustainability coordinator	• Responsible to make long term sustainability vision for the whole campus • Make plans to adopt new technologies that contribute in the sustainability vision	-
Technology service providing companies	• Provide services such as the technical installations and BMS system (Johnson controls, SPIE, Van Dorp installations, Priva)	• No incentive to upgrade to smarter technologies as they are in contract and there is no demand from the client (the university) • Problems of safety and security and vendor lock in

Table 12: Stakeholders roles, responsibilities and corresponding barriers (author)

Furthermore, these barriers are categorised and their occurrence is classified under the different stages of the innovation decision process as shown in *Figure 26*.

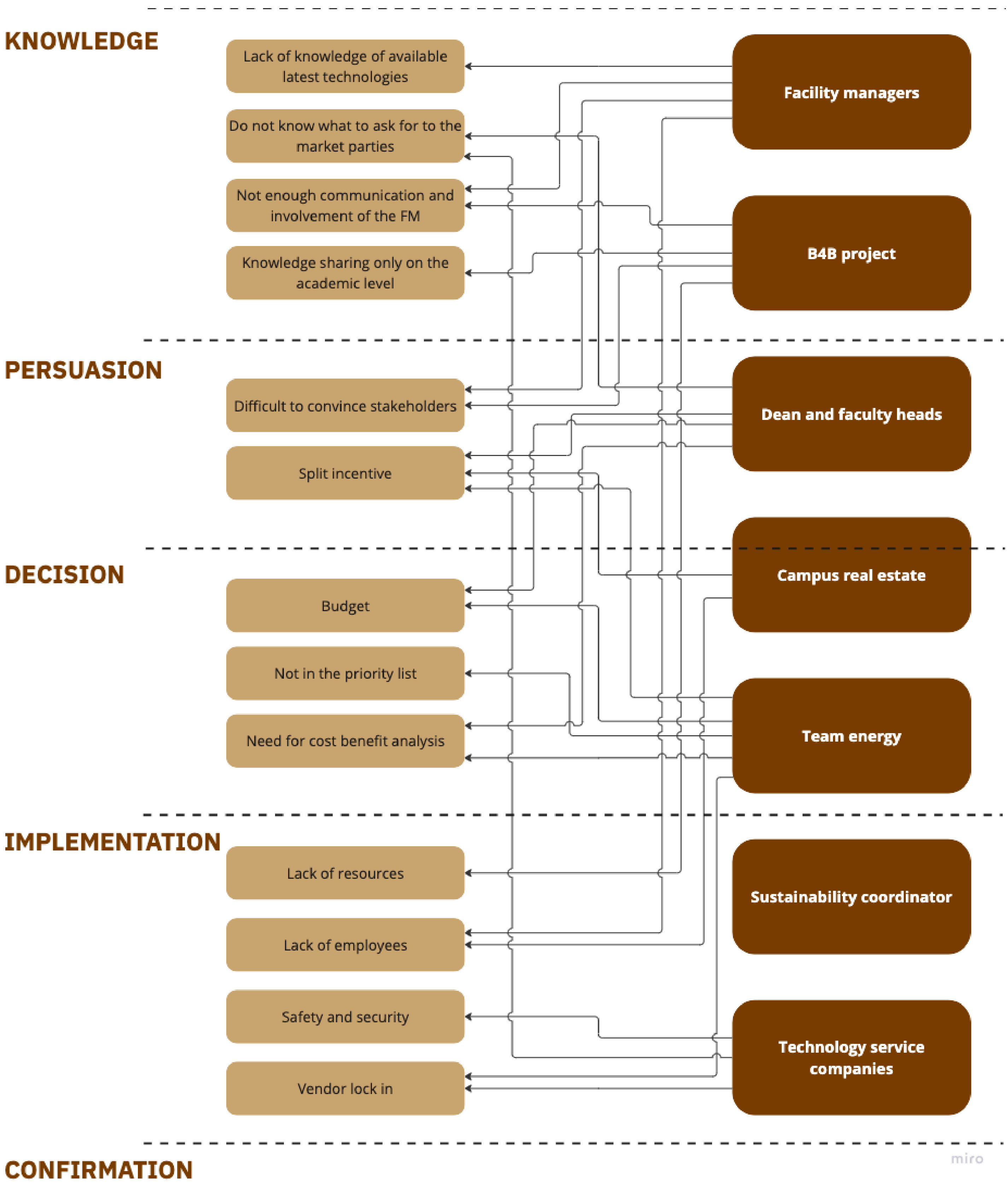

Figure 26: Barriers and the corresponding stakeholders related to them per stage (author)

5.6 Recommendations

The analysis of the interviews enabled to answer the question 'why is the latest technology not being implemented in Building 28?' The identification of the different barriers and the corresponding stakeholders associated with them and relating them to the different stages of innovation decision making, has aided in suggesting recommendations to overcome these barriers in order of time.

Phase 1: Knowledge

Do a market analysis: To resolve the barrier of lack of knowledge of facility managers and the client (the university) not knowing what to ask for from the market parties, conducting a market analysis of the emerging technologies and their benefits would be useful. Information provided in *section 3.4.3* and *section 3.4.4* can be an example of a market research which identified the usefulness of the latest technology provided as a software service. Communicating these findings of the technology and benefits of use with facility managers mitigated the barrier of lack of their knowledge. Similarly, doing such research by the university can also benefit in knowing what to ask the market parties or technology companies that are in contract with the university. This will mitigate another barrier of the contracted companies not having an incentive to work smarter, because if they are confronted with the demand of the client, they will be compelled to upgrade their technologies to their full potential.

Knowledge sharing: There should be better communication of the research findings that the B4B project does with the facility managers as the goal of the project is to help this target group in better management of buildings by increasing comfort and energy efficiency. Therefore, the knowledge sharing should be extended from the academic level to a practical level which involves communicating findings with the relevant stakeholders. B4B project is already working on making a handbook for the facility managers about data integration which includes the steps to take to work smarter and adopting the latest technologies.

Apply for subsidies: Since adopting new technologies often come with the added advantage of sustainability and benefit to the environment. In case of a private investment costs of such technology is greater than the private benefits but less than social benefits, the adoption of the technology might not be affordable privately but is socially preferable. In order to encourage the adoption of this kind of technology which benefits the society and environment, subsidies are provided by the government (Aalbers et al., 2009). The case of Hague university can be taken as an example where a subsidy from Dumava was granted which was used by the facility management team to adopt a new technology. The available budget allowed them to go for the adoption even when the high level authorities were not convinced because they did not have to rely on their financial investment. These subsidies can be used by the university authorities in implementing the new technology as well as by the B4B project in scaling up their pilot projects.

Involvement of facility managers in an early stage: The end users should be actively involved in the process of adopting a new technology from the initial stage. For example, the development of the dashboard was an initiative taken by certain members of the university, however, during the designing of the dashboard, the facility managers were not involved at all. Involving them will help in identifying what they actually need, therefore increasing the usefulness of the dashboard.

Phase 2: Persuasion

Present results to relevant stakeholders: The proof of benefits concluded from the preparation/knowledge phase should be presented to the relevant stakeholders. Different benefits should be presented to different stakeholders depending on their interests. For example, energy saving opportunities which come as an added benefit to better comfort management should be presented to Team energy. Similarly, the savings on costs allowed by better planning through historical data should be presented to the Dean and Faculty heads.

Cost sharing agreements: To overcome the barrier of split incentive which involves different stakeholders, a cost sharing agreement can be made based on the amount of savings the different parties gain from the new technology. This agreement can be binded legally into a contract signed by the stakeholder so that issues will not arise in the later stages due to conflicts.

Phase 3: Decision

Allocation of budget: Once the cost sharing is agreed by the stakeholders, the budget should be well planned and allocated. In case the applied subsidies are granted, it is easier to make decisions independently since there is no need to rely on investments, rather only the approval would be required.

Demand the market: The client (the university) should know what to ask the market in terms of the kind of technology, its benefits and how it works. The information gained during the knowledge stage by market analysis and knowledge sharing has a positive influence on this. Moreover, the involvement of the facility managers in an early stage allows them to identify the exact needs of the end users and hence, the university can present their demands more clearly to the market parties.

Cost benefit analysis: Results of the research conducted in the pilot projects should be concluded to present to the stakeholders as proof of benefits. A cost benefit analysis (CBA) should also be conducted in order to convince the relevant stakeholders to invest in the new technology. The purpose of the CBA is to evaluate the financial viability, potential benefits, and associated costs of the technology to determine if it is worth pursuing. In the CBA, the costs involved in acquiring, implementing, and maintaining the new technology and the potential benefits such as efficiency, cost savings, and improved satisfaction should be assessed. The results of the CBA can be used to make an informed decision about whether to proceed with the technology implementation. This analysis helps stakeholders understand the return on investment (ROI) and justify the expenditure (Butler, 2022; OpenCourseWare TU Delft, n.d.).

Flexible contract with the technology companies: The problem of a vendor lock occurs as the university contracts a certain company for a long period of time and is not able to switch to the services provided by another provider. Hence, the contracts with the existing partners should be made more flexible so that there is higher incentive of efficiency due to competition.

Phase 4: Implementation

Better manpower: Lack of trained facility managers was another barrier encountered in the decision stage which can be overcome by employing new trained FMs or by providing training to the existing FMs.

Implement API: Standardised APIs can promote interoperability between different systems and vendors, reducing the risk of vendor lock-in and making it easier to switch providers if necessary. By using APIs, organisations can integrate diverse services and components, allowing greater flexibility and adaptability to changing business needs (Evans, 2017).

Phase 5: Confirmation

Final cost benefit analysis: A final cost benefit analysis should be done after the implementation of the new technology as even after adoption, the innovation should be evaluated to ensure it continues to meet expectations and delivers the promised benefits. If the technology does prove to deliver the benefits the decision to confirm the adoption can be made.

Validation by facility Manager/end user: Since the use of the online platform and dashboard is a technology aimed at helping facility managers in their tasks, the confirmation should also come from them. Surveys and interviews should be conducted to ask the FMs if the use of such dashboards are actually being helpful or not. If it is confirmed by them that it is beneficial, the technology adoption can be continued.

The visualisation of the aforementioned recommendations in a timeline following Rogers (2003) theory is presented in *Figure 27*.

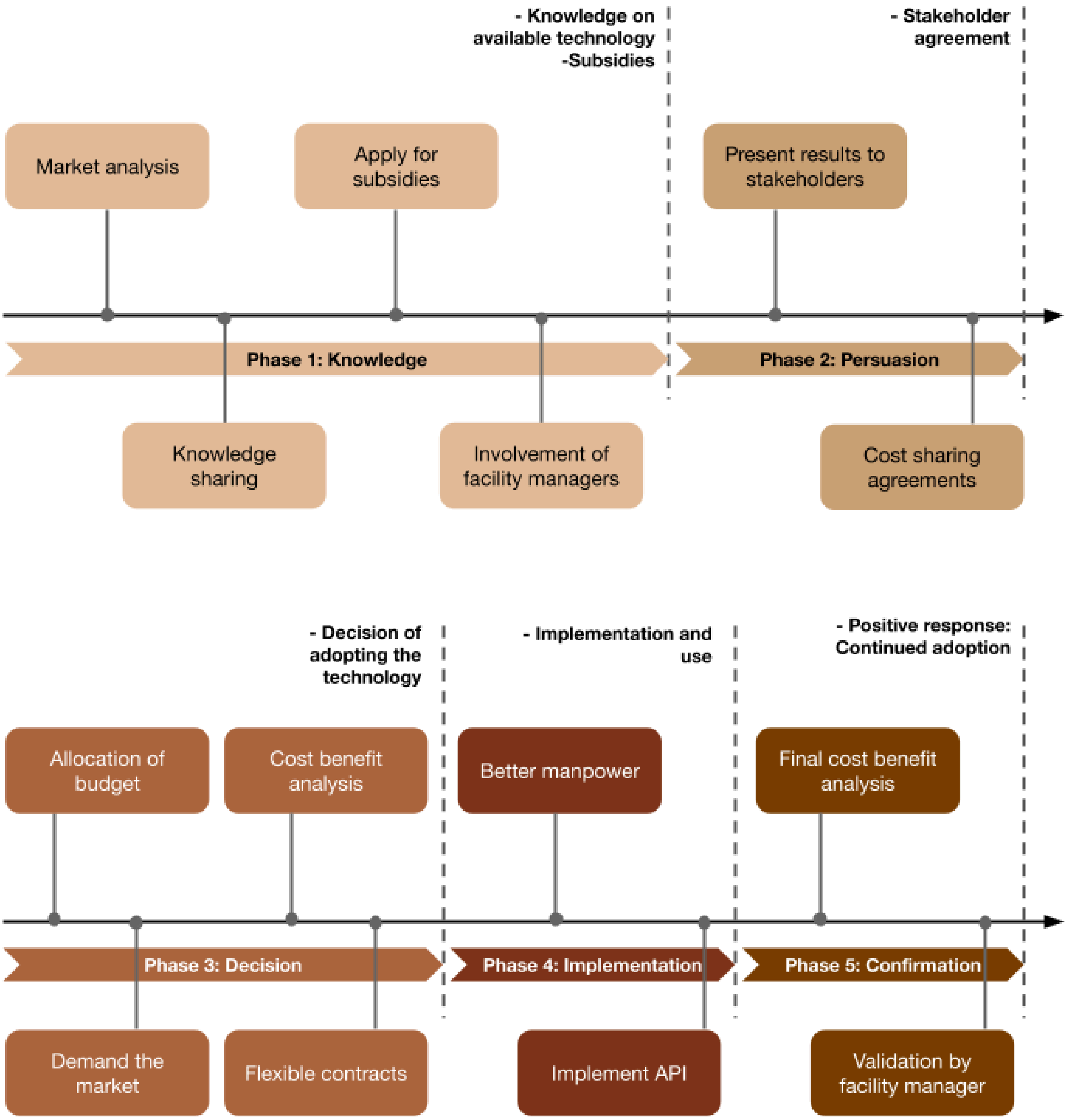

Figure 27: Recommendations presented in a timeline (author)

5.7 Validation

As the next step after analysing the data and drawing conclusions, the recommendations were validated through an expert interview. This interview was conducted with the project coordinator of Brains 4 Buildings. The findings were presented to the interviewee by a poster which included tailored recommendations that the project could use to facilitate the adoption of a new IAQ dashboard for the facility managers, however, the recommendations can be potentially generalised for the adoption of any new technology which aids the end users, particularly facility managers. The poster presentation which includes the identified barriers, recommendations, and elaboration of the steps on how to apply the recommendations can be found in *Appendix D*.

The main points of discussion from the expert validation were as follows:

- The recommendations are recognised by the expert, they are in line with what the Brains 4 Buildings project is experiencing at the current stage.
- In most cases, the B4B project knows what needs to be done but the problem is finding the right moment, hence the clearly elaborated steps to take according to the stages provides a useful direction for the project.
- The B4B project is more research focused than implementation focused, but now they are in the stage of the end results of the project and to determine who is going to implement the experimented technologies, method, softwares.
- Furthermore, they acknowledge that they need to get different stakeholders on board for the next steps.
- The expert considered the focus of the research from the perspective of the facility managers relevant as they are the end users who need to find the technologies reliable and beneficial

"It is very good that you focus on the facility manager because they are very important people, because in the end, they need to trust the technology that's being implemented and they also need to see what the benefits are and I think that is certainly something that we could work on further "

- B4B-2, Project Coordinator, Brains 4 Buildings

Overall, the expert interview was useful to validate the recommendations as it is identified that the study aligns with the current needs of the project, highlights the important role of involving facility managers and provides clear sequential recommendations. Sharing the recommendations with the project member and seeking their validation has helped in increasing the credibility, validity and impact of this research.

06 DISCUSSION

6.1 Comfort vs Energy

6.2 Overcoming barriers

6.3 Use of Innovation decision process framework

6.4 Data privacy and security

6.5 Interrelation of different perspectives

06 DISCUSSION

This section provides a critical review on some aspects of the research findings which will help to draw better conclusions for the results. In addition to the evaluation of the findings, this section also highlights the limitations of the research method and findings as well as suggests recommendations for further research.

6.1 Comfort vs Energy

The first point of discussion arises from the findings for SQ1 regarding the role of facility managers in creating a healthy indoor air quality. It is found in the literature that IAQ is a priority for facility managers, however, there is a significant emphasis on sustainability and energy efficiency. Moreover, in relation to smart technologies, tools that help the facility managers to achieve energy efficiency have been highly promoted. It could be possible that since energy efficiency can be measured in terms of cost savings, the benefits are more evident and the return on investments is clear. Additionally, due to climate change, international and national governments have implemented several sustainability measures that need to be followed in the construction and real estate industry. This allows for easier convincing or obligation for the stakeholders to invest in the new technology as it is already embedded in the mission of the universities.

"we want to green the campus so we want to save a lot (of energy), we want to be climate neutral in 2040 so that's also why they have reserved a budget for using smart buildings"

- B4B-2, Project Coordinator, Brains 4 Buildings

"the sustainability coordinator of the whole TU Delft made a whole plan and in the plan it also states to make the BMS even smarter and better energy monitoring systems so there is already in the mission vision of the TU Delft"

- B4B1, Project associate Building 28, Brains 4 Buildings

This was explicit also during the empirical research. The interviewees mentioned the importance of achieving the sustainability goals of the university and how technologies have been implemented with a focus to fulfil their goals. For example, in Case study C, the FM mentions how important sustainability is in his job:

"…sustainability…It's very important in my function. We want to comply with the Paris accord of sustainability, not in 2050, but in 2030. So that's a part of my job to look for new concepts to reduce energy leakage..and my installations are the ones that are consuming energy…"

- *FMC, Facility manager, Delft Branch, HHS*

Furthermore, most smart IAQ technologies are embedded within the building management system which has other components including energy. It has been found that the BMS is used primarily for energy efficiency with lesser importance given to air quality or comfort. However, these components are interrelated to each other. For example when an HVAC installation is maintained or replaced for energy efficiency, it often yields better results in maintaining better indoor air quality.

The evaluation done in the theoretical research on different companies that provide smart IAQ technologies have embedded energy efficiency in their SaaS platforms as well. However, some companies have found to have put more emphasis on indoor air quality than energy. Inbiot is an example of such a company whose primary mission is to provide smart solutions for IAQ monitoring and management (Inbiot, n.d.). Additionally they focus on achieving healthy building certificates such as WELL. In the case studies as well, it has been found that only the company Unica was used for the sole purpose of indoor air quality data gathering in addition to the BMS system.

On the other hand, more ventilation means higher energy use. So there is an obvious tension between better IAQ and controlling ventilation for energy efficiency. Using occupancy data, the ventilation can be optimised to spaces only where airflow is required. This is only possible from real time data collected by sensors and IoT connection to the ventilation system. It is essential to create a balance between good indoor air quality and energy efficiency according to the needs of the built environments (Dai et al., 2023).

Overall, energy efficiency is an important factor to consider in the real estate industry specially by the facility managers due to its high impact on the societal level, and therefore smart technologies have been used to achieve energy efficiency. However, it should be made sure that the comfort of occupants is not compromised in the process of reducing energy consumption. Indoor air quality should be given due importance by facility managers and focus should be drawn on using IAQ data from the smart technologies to maintain and create a healthy indoor air quality in the university buildings.

6.2 Subsidy as a solution

From the interviews conducted, several barriers have been identified from the perspective of facility managers as well as from the project members. The most important barrier in the process of adopting a new technology has been found to be the need for convincing the stakeholder who is in charge of purchasing and implementing the system. Convincing these higher level stakeholders is difficult when the proposed technology is not proven. Therefore, a cost benefit analysis is essential to calculate the return on investments and convince the stakeholders. Another solution identified is getting subsidies to fund the adoption. Not having to invest money makes it easier to convince the authorities and hence the decision taking process is shorter. However, it also has to be noted that most of the subsidies are aimed at achieving sustainability goals. Hence, if the technology also contributes to sustainability along with better IAQ, these subsidies could be applied for and utilised.

6.3 Use of Innovation decision process framework

Rogers' innovation decision process theory was used as a theoretical framework for this research. This theory provides a framework for understanding the adoption process of innovations, highlighting the roles of various factors that influence the acceptance of new technologies. The aim of this research was to explore the use of technology as well as identify barriers encountered during the adoption process. Therefore, the theory of Rogers was well suited and beneficial to structure the research findings. The attributes of innovation defined by Rogers in the persuasion stage was used to evaluate the IAQ technology of online platforms. However, it could not be used for the analysis of the multi case study because the level of IAQ technologies used in all cases were different, resulting in using the framework for comparison difficult. Instead of this framework, the cross case analysis was done using themes identified to answer the sub research questions. The framework was used to analyse the findings of the single case study where the identified barriers and recommendations were arranged in a timeline following stages of the theory.

6.4 Data privacy and security

All smart technologies and systems implemented collect data and therefore, data privacy and security issues associated should be identified and the risks should be mitigated. For the time and scope of this study, this point of concern aspect of the smart technologies was not addressed during the research. However, to guarantee responsible application of the technologies, ethical and privacy issues must be addressed. Research is also required to develop legislation and regulations that address their ethical and privacy concerns and data security. These regulations should promote transparency and fairness and protect user privacy. Studies should also assess the long-term social effect, as well as the hazards and implications of integrating AI and IoT in IAQ management (Quarks, 2023). Additionally, during the interview, the FMC of HHS revealed his wish to be a directing organisation who orders an external company to look at the building data and fix the issues raised. However, there is a question of trust and security as you are giving the control and authority over the university buildings to an external organisation. These concerns can pose barriers when it comes to the ethics of data management. Therefore, while employing technology in IAQ management has enormous prospects, future efforts must focus on continuous research and development to overcome these barriers and maximise the potential of these technologies.

6.5 Interrelation of different perspectives

The final point of discussion aims to bring back all aspects of the research together. This research explored findings mainly from the perspective of the facility manager regarding the use of smart IAQ technologies, however, other perspectives were included as well such as the technology service providers and researchers.

The theoretical research conducted by evaluation of the latest smart IAQ technologies provided information on the vast benefits of using them. The case studies mentioned in section 3.4.3 present results of how their technologies have solved the issues in educational buildings regarding indoor air quality. However, from the case studies of the empirical research, it is found that there is a gap that exists between what the service providers promise about the use and benefits of their technology and how much of it is actually being translated to the end user which is the facility manager. Therefore, these companies should involve the opinions of the end users in their design phase which will result in the technology being more user focused. These companies can become more end-user focused, particularly for facility managers, by engaging in several key strategies. First, they should conduct thorough user research to understand the specific needs and challenges of facility managers, tailoring solutions to address pain points such as ease of installation and real-time monitoring. Providing comprehensive training programs and robust customer support can ensure facility managers are well-educated and supported. Developing user-friendly interfaces, including intuitive dashboards and mobile access, will enhance usability. Offering customizable and scalable solutions allows facility managers to adapt the technology to their specific requirements. Emphasising data and analytics by providing actionable insights and real-time monitoring helps facility managers make informed decisions. Moreover, building a community for facility managers to share experiences and feedback, along with maintaining a continuous improvement loop, fosters user engagement. Lastly, highlighting the cost-benefit analysis, such as ROI and sharing successful case studies, demonstrates the tangible benefits of the technology. By focusing on these strategies, smart IAQ technology companies can significantly enhance the user experience and adoption rates among facility managers in university buildings.

The researchers in this case have been found to act as a mediator to bridge the gap between technology companies and universities (clients) by experimenting, communicating and facilitating technology adoption. Researchers can further facilitate the use of new technologies in universities by adopting a comprehensive approach that includes understanding needs, raising awareness, providing training, collaborating with stakeholders, ensuring accessibility, securing funding, evaluating impact, and promoting a culture of innovation. They can begin by conducting surveys, interviews, and focus groups to identify specific needs and challenges. Raising awareness through workshops, seminars, and pilot programs can demonstrate the technology's capabilities and benefits. Providing comprehensive training and establishing support services ensure users are comfortable and proficient. Collaboration with interdisciplinary teams and creating feedback loops help refine and improve the technology. Researchers can secure funding through grants and proposals and allocate resources effectively. Ongoing research to evaluate effectiveness and sharing results through publications helps communicate impact. Establishing innovation labs and encouraging experimentation foster a culture of continuous improvement. Therefore, by implementing these strategies, researchers can effectively facilitate the adoption and integration of new technologies in university settings, enhancing educational outcomes and operational efficiency.

07 CONCLUSION

7.1 Sub question 1

7.2 Sub question 2

7.3 Sub question 3

7.4 Sub question 4

7.5 Main research question

07 CONCLUSION

7.1 Sub question 1

[SQ1] What is the role of facility managers in creating healthy indoor air quality?

The first sub-question aimed to explore and establish the relationship between the two main domains of the conceptual framework: Facility management and Indoor air quality. Theoretical research was conducted on the topic of the role that facility managers play in the management of indoor air quality. It is found that facility managers are responsible to undertake necessary tasks for occupants' health and safety. Since indoor air quality is one of the key determinants of occupant health, facility managers play a direct role by being responsible to monitor, manage and maintain a healthy air inside the buildings. They use technologies which measure the different parameters of indoor air such as CO2, PM, temperature, relative humidity and VOC in order to compare it with set values determined from the national government or professional organisations. FMs, who are in charge of effective management of the facility utilise the available resources such as the HVAC installations to maintain an optimum air flow and temperature. They are also responsible to respond to the comfort complaints of the occupants and to ensure that issues are fixed. The role of FM ranges from recognition of the hazards, ensuring adequate level of all IAQ parameters, scheduled maintenance of HVAC systems, solving current problems and preventing future ones. Moreover, the Covid-19 pandemic put a greater emphasis on facility managers with regard to IAQ due to the heightened awareness of it amongst the general public. The facility management sector has been crucial in combating the virus by ensuring ventilation enhancements to ensure a safe and sanitary indoor environment. They have been tasked with adhering to the changes in government regulations and guidelines suggested by organisations like WHO and ASHRAE. The health and safety of occupants during and after the pandemic has been a priority task for facility managers. As a response to the sudden challenges faced due to the pandemic, FMs have used new technology to support them in their duties and responsibilities. These technologies help them in monitoring real time IAQ data and therefore allow for a more efficient IAQ management.

For the empirical research, the facility managers were asked about how important maintaining a good indoor air is to them. In contrast to the general information gathered to answer SQ1 from the theoretical research, the empirical research allowed to explore the answer specific to the context of the research which is the Dutch universities. In response, it was found that the FMs of Dutch universities prioritise indoor air quality significantly. Some FMs consider it important because they have to adhere to the changing governmental regulations whereas some consider it very important for the health and comfort of the users. In addition to the health and comfort, the FMs also understand the effect of IAQ on performance of students in the universities. The positive correlation between a healthy indoor air quality and the concentration level of students is well understood and therefore efforts have been applied to cater to their needs. Having known these requirements, the

FMs use different levels of smart IAQ technologies to measure, monitor and manage the indoor air quality in the university buildings. The use of these technologies is aimed to help them in creating a healthy indoor air to provide the students with the best study environment.

Therefore, from both theoretical and empirical research, it can be concluded that facility management plays a very important role in creating a healthy indoor air quality by understanding the importance of IAQ and taking actions to ensure an optimum standard of air by controlling the HVAC installations and prioritising the health, comfort and safety of the occupants.

7.2 Sub question 2

[SQ2] What is the current status of smart technologies available in indoor air quality management?

The current status of smart technologies was researched through desk research. The development of technology in the field of indoor air quality management was reviewed and categorised into three levels. Level 1 technology refers to the use of sensors, Level 2 is the use of sensors and IoT and Level 3 is the utilisation of sensors, IoT and SaaS. The first two levels of smart IAQ technologies have existed for a long time and numerous literature is present on these topics, however, SaaS is a relatively new service provided by the tech companies for IAQ. In the current situation, use of SaaS is growing as they are easy to understand and use. Additionally, software platforms are most useful to the target group of facility managers since they can be directly used by them without having to understand complex phenomena. Therefore, SaaS was chosen to be explored further in this research.

From the study on three software solutions provided by three different companies, it can be concluded that the current status of smart IAQ technologies available is quite advanced and caters to the needs of building/facility managers by providing easy to interpret visualisation of air quality data that can be effectively used by the managers to identify trends and implement necessary comfort enhancing measures. The SaaS platforms were evaluated using the attributes of innovation included in Rogers (2003) diffusion of innovation theory. From the evaluation it can be concluded that there is a significant scope of this technology to be adopted by facility managers due to its advantages and tailored assistance to the facility managers.

7.3 Sub question 3

[SQ3] What are the benefits of smart IAQ technologies for the facility managers of Dutch universities?

The literature research conducted on the use and benefits of smart IAQ technologies was general. Hence, this context specific sub-question is answered through a multi case study conducted through interviews with the facility managers of three Dutch universities, of

Maastricht, Delft and The Hague. From the case studies it is found that different levels of smart IAQ technologies are used in these universities.

Sensors connected by IoT to the BMS system were used to measure the CO2 levels in the room which sent alerts to the FM if the set threshold value was exceeded. This benefits the facility manager by informing them about the situation of a room and enables them to adjust the ventilation remotely even when they are not present in the room. The technology is used by the FMs to solve comfort complaints of the occupants by changing the set temperatures and air flows into the specific rooms. The FMs can check the installation status periodically, identifying system efficiency and recommending upgrades or replacements. The monitoring of historical data collected and real time data analysed by these systems provides the FMs with the overview to identify patterns and trends. The software platform presents easy to read dashboards which visualises the data and trends for the FMs without having to hire a data analyst or learn complex technical knowledge. In addition to the efficiency in their tasks of managing the building, some of these technologies facilitate the FM to gain the trust of the occupants. Access to the analysed IAQ data in mobile apps for the occupants, helps them to gain satisfaction of the quality of air their breathing. This also solves to clear the perceived doubt in discomfort which is sometimes just mental. In conclusion, the use of smart IAQ technology has benefited the facility managers of Dutch universities to maintain a healthy indoor air quality and ensure occupant comfort and satisfaction.

7.4 Sub question 4

[SQ4] What are the barriers encountered in adoption of smart IAQ technologies in Dutch universities and how can they be overcome?

Several barriers to the adoption of smart IAQ technologies are identified from the findings of the empirical research in both Part 2 and Part 3. The multi case studies identified the barriers encountered from the perspective of the facility managers whereas in the single case study, more barriers were identified which included the perspectives of other involved stakeholders as well. There is a lack of knowledge of the facility managers regarding the latest technologies available and how they can help them. This is a consequence of and also results in a more reactive role of the FM. A proactive behaviour and engagement with peers and other stakeholders is essential in gaining knowledge in the first stage of technology adoption. Technological barriers such as the reliability of the installations, need for maintenance or the perceived trust of FMs on the technologies also contribute as a barrier to their adoption. Additionally, the FMs generally do not have a high authority in the decision making process of adopting new technologies for the university, hence, the need for convincing all stakeholders has a negative outcome in the process. Technological and stakeholder barriers occur in the persuasion stage of the innovation decision process and can be possibly overcome by providing proof of benefits for the reliability, durability and return on investment. Moreover, some university buildings are listed as monumental buildings which have regulations imposed by the government regarding any changes or transformation projects that can be undertaken. These regulatory measures can also pose significant restrictions in implementation of new IAQ technologies, most likely in the decision stage of the process.

A number of barriers were also identified from the single case study from the perspective of the Brains 4 Buildings project, which also included information on potential barriers that other stakeholders may pose. From the project side, there is lack of communication and involvement of facility managers in knowledge sharing and reporting the research findings conducted by the B4B project. This has been acknowledged and they are working on developing a handbook for the FMs for steps to take for technology use and data integration. Lack of resources is another barrier as the B4B project can only do pilot projects at the moment as bigger investments are needed to scale up the pilots. On the university level, there is a lack of employees available or trained in using the technologies. There is a problem of split incentive among the different stakeholders which needs to be clearly sorted out for the allocation of budget for adopting new technology. It is also difficult to convince the managerial stakeholders for investments with proof of benefits. Therefore, a proper cost benefit analysis has been identified to be important. Furthermore, there are safety and security concerns posed by the university regarding the collection of data and giving control and access to external technology companies.

Overall, the various barriers identified can be summarised into lack of knowledge, technological, regulatory, authority of facility managers, lack of resources, communication and involvement of facility managers, stakeholer's conflicts and safety and security issues.

These barriers can be overcome with a joint effort of the stakeholders involved. Better communication with and involvement of facility managers in the early stages of technology adoption and provision of handbooks to inform them about the steps to take will allow the FMs to gain the required knowledge. Applying and using subsidies to finance investments in technology is recommended as it solves the issue of depending solely on the higher management for investments. Moreover, cost benefits analysis and proof of benefits is a significantly essential factor in overcoming the barrier of convincing the stakeholders involved. Furthermore, strengthening human resources by hiring/ training and upgrading technological resources for data safety and security is recommended.

7.5 Main research question

[MQ] How does the adoption of smart IAQ technologies help the facility managers of Dutch universities and what are the barriers to it?

The synthesis of the answers to the sub questions leads to the conclusion for the main research question of this study. This research explored how smart IAQ technologies are used and how it helps the facility managers. From the theoretical and empirical research, it can be concluded that smart IAQ technologies help the facility managers in different ways depending on the level of the technology used.

IAQ sensors connected by IoT provide continuous, real-time data on various air quality parameters, such as temperature, humidity, CO2 levels, PM and VOCs. The facility managers of the universities receive instant alerts and notifications if air quality levels deviate from the set threshold values. This helps them to take immediate action to address potential issues and air quality hazards to maintain an optimum indoor air quality. They also receive alerts regarding the condition of the HVAC installations. This allows better maintenance of HVAC installations by enabling condition-based maintenance, where servicing is done based on the actual condition of the equipment instead of time schedule, leading to more effective use of resources. It has been found from the case studies that the FMs can respond well to the complaints of the occupants regarding the comfort in their work/study place by accessing the BMS and checking the data of the comfort parameters. They can resolve these complaints by changing the set values of the room condition. IoT enables the FMs to do this remotely without having to be present on campus or at the rooms of complaint. Hence, helps the FMs in making their job easier and flexible. Moreover, the IAQ sensors are often a part of a broader IoT ecosystem connected to the building management system, where data from various sensors and devices are combined to provide comprehensive building insights to the FMs. In addition to these measures, a more proactive role can be played by the FM by using the historical data to identify IAQ trends and make long term campus strategies based on them.

The use of online dashboards along with the IoT-BMS has additional benefits to the FMs as these softwares are mostly designed with the aim of helping the facility managers in easy interpretation and understanding of complex data produced by the systems. SaaS enables visual representation of IAQ data that is already analysed, hence the FMs can use the data without the necessity of technical data analysis knowledge. Data history and smart reports can be downloaded by the FMs to use for better planning and management. Therefore, the online dashboards help the facility managers to be more proactive in their role.

It can also be concluded that additional technological services such as building insight for occupants and weekly reporting service can help the facility managers even further in their role and responsibilities. By giving access to the occupants to check the quality of the air they are in, allows the FM to be transparent and gain trust of the occupants. The weekly reports enable FMs to identify faults that could have been overlooked so that they can take effective actions and ensure occupant health, safety and comfort.

There are several barriers encountered in the process of adopting new smart IAQ technologies such as lack of knowledge, resources and manpower, conflict of stakeholders, split incentive, security issues and involvement of facility managers in the process. The facility managers are not aware of the availability and use of latest technologies which can be solved by better communication. There is a need for the involvement of FM in the early stages of innovation adoption and provision of handbooks to guide them. Convincing different stakeholders for investment is another barrier that can be possibly overcome by providing proof of benefits and calculation of return on investments. Therefore, a cost benefit analysis of new technologies such as the online dashboards is identified as a significant necessity. It has also been found that there is a gap that exists between what the service providers promise about the use and benefits of their technology and how much of it is actually being translated to the end user which is the facility manager. The researchers in this case have found to bridge this gap by adopting a comprehensive approach to new technology adoption that includes understanding needs, raising awareness, providing training, collaborating with stakeholders, ensuring accessibility, securing funding, evaluating impact, and promoting a culture of innovation.

In conclusion, the adoption of smart IAQ technologies, depending on their level, can help the facility managers of Dutch universities in maintaining and enhancing an optimum indoor air quality, ensuring occupant health and safety, and taking a proactive role by making data driven decisions. However, there are several barriers in the process of adoption that need to be overcome to make use of these technologies effectively and to their full potential.

08 LIMITATIONS & FURTHER RESEARCH

8.1 Research limitations

8.2 Further research

08 LIMITATIONS & FURTHER RESEARCH

8.1 Research limitations

There are a number of limitations to the research due to the time, resource and methodology of this research. Although there have been efforts made to mitigate the risks of these limitations, the following limitations affect the findings of the research:

Limitations in theoretical research

The aim for the theoretical research to answer the research questions was to focus on the context of Dutch universities for all the aspects, however, for some parts of the literature review such as the responsibility of facility managers in indoor air quality and use of technology in facility management was general and not specific to the context of Dutch universities. Moreover, due to the time constraint of the research the literature on the market analysis of smart IAQ technologies available was limited to only three companies. The findings could have possibly drawn better conclusions on the technologies available if more companies were included for the exploration and evaluation.

Generalisability of case studies

Case study research methods are renowned for their detailed, context-specific insights, but they often have limited generalisability. This limitation arises because case studies typically focus on a single instance or a small number of cases within a specific context, making it challenging to extrapolate findings to a broader population. The uniqueness of each case means that the particular circumstances, behaviours, and outcomes observed may not be representative of other situations. Consequently, the conclusions drawn from case studies are often context-dependent and may not apply universally (Blaike and Priest, 2019). In this research, the context and perspective is very specific to the facility managers of Dutch university, therefore, this specificity can restrict the ability to develop generalisable theories or principles that hold across different settings and populations.

One perspective focus

The purpose of this research was to explore the use of technology for indoor air quality in Dutch universities from the perspective of the facility managers. Therefore, the study only focused on one specific group of stakeholder who is affected by the intervention. Other stakeholder groups such as other members within the university, the technology service providers, and most importantly the occupants of the building were not included in the research. The inclusion of occupants could have yielded a better understanding of the actual difference that the technologies have made in their comfort level. It could have also been useful to validate the information given by the FMs regarding the response time of the occupants' complaints and action taken by FM to resolve the issue by using the data from smart technologies. Similarly, for the in depth single case study, interviews were conducted only with the associates of Brains 4 Buildings project, resulting in the identification of the barriers to using the latest technology from a single perspective. Interviewing other stakeholders in this case would have also helped in identifying more barriers from different perspectives.

8.2 Further research

Having acknowledged the limitations of this research as mentioned in the previous section, suggestions and recommendations on future research which can overcome these limitations are provided in this section.

Firstly, in order to mitigate the limitation of generalisability arised from the method of research, the context of the research could be broadened by geographic location; to the context of Europe or universities across the globe. This research focused on a specific type of real estate which is university buildings, further research can conduct studies into more types of real estate such as offices and retail.

Secondly, this study explored the research questions only from the perspective of the facility manager. However, the effectiveness of using smart IAQ technologies is highly affected by the satisfaction of the occupants of the university buildings. Further research could include this perspective by interviewing the teachers and students of universities on what positive or negative changes they have encountered after the implementation of a new smart technology. Quantitative research could also be conducted which measures the impact of the technology on the academic performance of students to evaluate the benefits and effectiveness of the IAQ technologies. Furthermore, the next research could provide focus on the development of IoT-based IAQ platforms which include occupants in the loop for the creation of an occupant-centric IAQ management approach.

Thirdly, the single in depth case study conducted for this research only identified the barriers from the interviews with members of a specific project. A multi stakeholder perspective case study can be conducted as a further step which includes other members from different departments of the university such as Asset Manager (from CRE), Building management system manager (Team Energy), Technical information manager (from B&O department of CRE). Apart from the stakeholders of the university, the technology service providing companies should also be included in the identification of the barriers. This will provide a more comprehensive result of the research findings.

Lastly, the need for a cost benefit analysis has been identified as a solution to significant barriers identified from the research. Although smart IAQ technologies, with a focus on SaaS, have been evaluated in this research, a step further could be taken by conducting an in-depth cost benefit analysis of SaaS. This further research can contribute as a beneficial tool to inform facility managers and to convince the managerial stakeholders who are responsible for making the investment decisions.

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APPENDICES

Appendix A: Interview Protocol

Introduction

Hello, thanks for taking the time to participate in this interview.

Before we begin, I would like to ask for your permission again to start the recording for the purpose of transcription and documentation. The audio recording will be destroyed after being transcribed. Additionally, I would like to request you to please sign the consent form. Your participation in this study is entirely voluntary and you can withdraw at any time.

My name is Aaditi Singh and I am conducting this research as a master student of Management in the Built Environment at TU Delft, Faculty of Architecture. My research focuses on how smart IAQ technologies help the facility managers of universities.

This interview is planned to last no longer than one hour. During this hour, I will ask questions regarding your role and responsibilities regarding indoor air quality management, how smart technologies are utilised in managing indoor air quality, the role of data produced by these technologies in your decision making and if there are any barriers to it.

Questions

General

1. Could you please give an introduction of your role as a facility manager (FM) at _____?

Indoor air quality

2. As a facility manager, how important is maintaining a good indoor air quality for you? How has the Covid-19 pandemic impacted its prioritisation?

Smart technology used in IAQ management

3. What kind of smart technologies and tools are used currently to monitor and manage the indoor air quality of this building?
4. How have these technologies been useful in your tasks?
5. Do you use the data produced by smart technologies in making long term strategies?
6. What are the barriers to adopting and using smart IAQ technologies?
7. Who are the stakeholders involved in this process of adopting a new technology?
8. What are the improvements that you want to gain in future from these smart technologies in making your tasks easier?

Appendix B: Informed Consent Form

Participant Information/Opening Statement

You are being invited to participate in a research study titled Smart technology in Facility Management. This study is being done by Aaditi Singh from the TU Delft.

Interview group 1: The purpose of this research study is to gain insights on the use of smart technologies in facility management. This interview takes approximately __ minutes to complete. I will be asking you for information regarding your role as a building manager, the smart technologies used in the university, how they help you and what are the challenges of the facility managers.

Interview group 2: The purpose of this research study is to gain insights on the use of smart technologies in facility management. This interview takes approximately __ minutes to complete. I will be asking you for information regarding the project you are working on, your role in association with the project, how the project helps the facility managers in adopting new technologies and any barriers encountered in the process.

The audio recording of this interview will be destroyed after transcription.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. For more information, you can contact me at my email a.singh-20@student.tudelft.nl.

Thank you for taking the time to participate in this research!

Explicit Consent points

PLEASE TICK THE APPROPRIATE BOXES	Yes	No
GENERAL AGREEMENT – RESEARCH GOALS, PARTICIPANT TASKS AND VOLUNTARY PARTICIPATION		
1. I have read and understood the study information dated __, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	☐	☐
2. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐	☐
3. I understand that taking part in this study involves audio recording which will be destroyed after transcription.	☐	☐
POTENTIAL RISK OF PARTICIPATING		

4. I understand that the audio material (or its editing) and other collected data will only be used for analysis and scientific presentation and publications. The audio recording will be destroyed after being transcribed.	☐	☐
5. I understand that taking part in this research means that certain personally identifiable information (PII) and personally identifiable research data with the potential risk of identity being revealed such as: i) Name and email address ii) Job/role description and name of organisation iii) Audio recordings	☐	☐
6. I understand that the following steps will be taken to protect my identity and reduce the risk of data breach: i) Data will be pseudonymised (Name will be coded) but the role and name of the organisation may be disclosed for the purpose of this research ii) Audio recordings will be destroyed after transcription	☐	☐
RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION		
7. I understand that after the research study the de-identified information I provide will be used for publishing a thesis report in the TU Delft education repository.	☐	☐
8. I agree that my responses, views or other input can be quoted anonymously in research outputs.	☐	☐

Signatures

__________________________ _________________________ ________

Name of participant **Signature** **Date**

I, as researcher, have accurately read out the information sheet to the potential participant and, to the best of my ability, ensured that the participant understands to what they are freely consenting.

________________________ __________________ ________

Researcher name **Signature** **Date**

Student contact details for further information: [Aaditi Singh, a.singh-20@student.tudelft.nl]

Appendix C: Data Management Plan

PLAN OVERVIEW

A Data Management Plan created using DMPonline

Title: Smart technology in Indoor air quality management

Creator: Aaditi Singh

Affiliation: Delft University of Technology

Template: TU Delft Data Management Plan template (2021)

Project abstract:
This Data Management Plan constitutes a plan for a MSc Graduation Project at the Faculty of Architecture and the Built Environment, involving audio-recorded interviews.The purpose of the research is to explore the use of smart technologies in indoor air quality (IAQ) management and its impact on the decision making of facility managers in IAQ management decision making. Three case studies will be conducted: TU Delft, TU Eindhoven and The Hague University of Applied Sciences. From each of the organisations, the facility manager will be interviewed. Questions that will be asked to them are regarding their role and responsibilities regarding indoor air quality management, how smart technologies are utilised in managing indoor air quality, the role of data produced by these technologies in their decision making and if there are any barriers to it. Additionally, some other participants will also be interviewed if time allows, who are experts in air quality, smart technology providers and people from the organisation who are involved in technology management.

ID: 148092
Start date: 11-09-2023
End date: 01-07-2024
Last modified: 28-04-2024

SMART TECHNOLOGY IN INDOOR AIR QUALITY MANAGEMENT

0. ADMINISTRATIVE QUESTIONS

1. Name of data management support staff consulted during the preparation of this plan.

Janine Strandberg

2. Date of consultation with support staff.

2024-04-15

I. DATA DESCRIPTION AND COLLECTION OR RE-USE OF EXISTING DATA

3. Provide a general description of the type of data you will be working with, including any re-used data:

Type of data	File format (s)	How will data be collected (for re-used data: source and terms of use)?	Purpose of processing	Storage location	Who will have access to the data
Audio recording of the interviews	.mp3	The interviews that will be taken on site will be recorded on an external device (mobile phone). The interviews that are taken online will be recorded on softwares (ms teams).	To answer the research question about how the smart technologies help the facility managers	External storage device (temporary) One drive	The project team Researcher, Tong Wang (first mentor), Herman Vande Putte (second mentor)
Transcript of the interview (pseudonymised)	.pdf	By transcribing the audio recordings of the interviews manually	To answer the research question about how the smart technologies help the facility managers	One drive	The project team
Written response of facility managers	.pdf	Online questionnaire	To answer the research question about how the smart technologies help the facility managers	One drive	The project team
Signed consent forms	.pdf	online/printed form handed in to the interviewees			The project team
Data about case studies (Pdf file with information of building such as the functions, hvac system, smart technologies in the building)	.pdf, .exl	Dataset received from Brains4Buildings project of TU Delft	To conduct case study about the building context, HVAC installations, air quality requirements etc	One drive	The project team
PIRD (job title and description)	.pdf	Questionnaire/Interview	To answer the research question about the role of facility managers in universities	One drive	The project team
PII (Name and email address)	.pdf	Questionnaire/Interview	To answer the research question about the role of facility managers in universities	One drive	The project team
Final thesis report	.pdf	Compiling the information collected in the research process	To document the research process and product	One drive	The project team

4. How much data storage will you require during the project lifetime?

- < 250 GB

II. DOCUMENTATION AND DATA QUALITY

5. What documentation will accompany data?

- Other - explain below

The research will be uploaded in the Education repository of TU Delft.

III. STORAGE AND BACKUP DURING RESEARCH PROCESS

6. Where will the data (and code, if applicable) be stored and backed-up during the project lifetime?

- OneDrive

Data will be stored in One drive of TU delft.

IV. LEGAL AND ETHICAL REQUIREMENTS, CODES OF CONDUCT

7. Does your research involve human subjects or 3rd party datasets collected from human participants?

- Yes

8A. Will you work with personal data? (information about an identified or identifiable natural person)

If you are not sure which option to select, first ask your Faculty Data Steward *for advice. You can also check with the* privacy website *. If you would like to contact the privacy team: privacy-tud@tudelft.nl, please bring your DMP.*

- Yes

8B. Will you work with any other types of confidential or classified data or code as listed below? (tick all that apply)

If you are not sure which option to select, ask your Faculty Data Steward ***for advice.***

- No, I will not work with any confidential or classified data/code

9. How will ownership of the data and intellectual property rights to the data be managed?

For projects involving commercially-sensitive research or research involving third parties, seek advice of your Faculty Contract Manager *when answering this question. If this is not the case, you can use the example below.*

The datasets underlying the published papers will be publicly released following the TU Delft Research Data Framework Policy. During the active phase of research, the project leader from TU Delft will oversee the access rights to data (and other outputs), as well as any requests for access from external parties. They will be released publicly no later than at the time of publication of corresponding research papers. The data will be openly accessible as it will be uploaded to the TU Delft Education repository in accordance with the FAIR principles.

10. Which personal data will you process? Tick all that apply

- Other types of personal data - please explain below
- Data collected in Informed Consent form (names and email addresses)
- Signed consent forms

- Email addresses and/or other addresses for digital communication
- Names and addresses

I will collect data about the description their job role and responsibilities. The audio recording of the interview participants will also be collected, however, as mentioned, the recording will be destroyed after transcription.

11. Please list the categories of data subjects

Facility/building managers, air quality researchers, technology service providers of universities and organisations based in the Netherlands

12. Will you be sharing personal data with individuals/organisations outside of the EEA (European Economic Area)?

- No

15. What is the legal ground for personal data processing?

- Informed consent

16. Please describe the informed consent procedure you will follow:
All study participants will be asked for their written consent for taking part in the study and for data processing before the start of the interview.

17. Where will you store the signed consent forms?

- Same storage solutions as explained in question 6

18. Does the processing of the personal data result in a high risk to the data subjects?

If the processing of the personal data results in a high risk to the data subjects, it is required to perform a Data Protection Impact Assessment (DPIA). In order to determine if there is a high risk for the data subjects, please check if any of the options below that are applicable to the processing of the personal data during your research (check all that apply).
If two or more of the options listed below apply, you will have to complete the DPIA. Please get in touch with the privacy team: privacy-tud@tudelft.nl to receive support with DPIA.
If you have any additional comments, please add them in the box below.

- None of the above applies

19. Did the privacy team advise you to perform a DPIA?

- No

22. What will happen with personal research data after the end of the research project?

- Other - please explain below
- Personal research data will be destroyed after the end of the research project

The data will be pseudonymised and will be shared in the education repository.

23. How long will (pseudonymised) personal data be stored for?

- Other - please state the duration and explain the rationale below

The necessary personal data will be stored for the duration of the project + 1 month for clean up

24. What is the purpose of sharing personal data?

- For research purposes, which are in-line with the original research purpose for which data have been collected

25. Will your study participants be asked for their consent for data sharing?

- Yes, in consent form - please explain below what you will do with data from participants who did not consent to data sharing

Data will be deleted.

V. DATA SHARING AND LONG-TERM PRESERVATION

27. Apart from personal data mentioned in question 22, will any other data be publicly shared?

- I do not work with any data other than personal data

29. How will you share research data (and code), including the one mentioned in question 22?

- My data will be shared in a different way - please explain below

Data as a part of the thesis report will be uploaded to TU Delft repository.

30. How much of your data will be shared in a research data repository?

- < 100 GB

31. When will the data (or code) be shared?

- At the end of the research project

32. Under what licence will be the data/code released?

- CC0

VI. DATA MANAGEMENT RESPONSIBILITIES AND RESOURCES

33. Is TU Delft the lead institution for this project?

- Yes, the only institution involved

34. If you leave TU Delft (or are unavailable), who is going to be responsible for the data resulting from this project?

First mentor, Dr Tong Wang. (T.wang-12@tudelft.nl)

35. What resources (for example financial and time) will be dedicated to data management and ensuring that data will be FAIR (Findable, Accessible, Interoperable, Re-usable)?

The thesis will be uploaded to the TU Delft Education repository in accordance to the FAIR principles.

Appendix D: Recommendations poster for B4B project

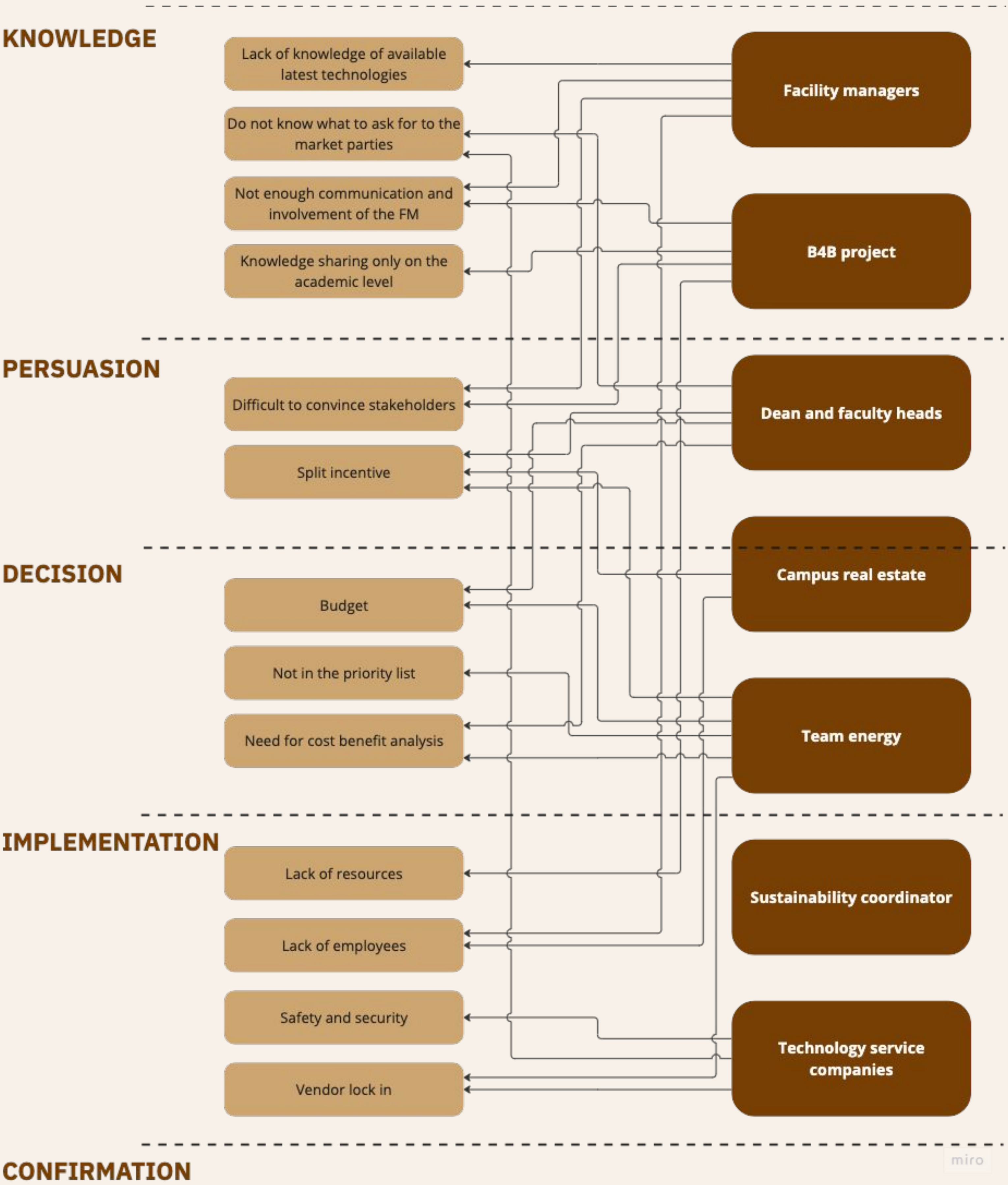
BRAINS 4 BUILDINGS

Facilitating a New Technology Adoption

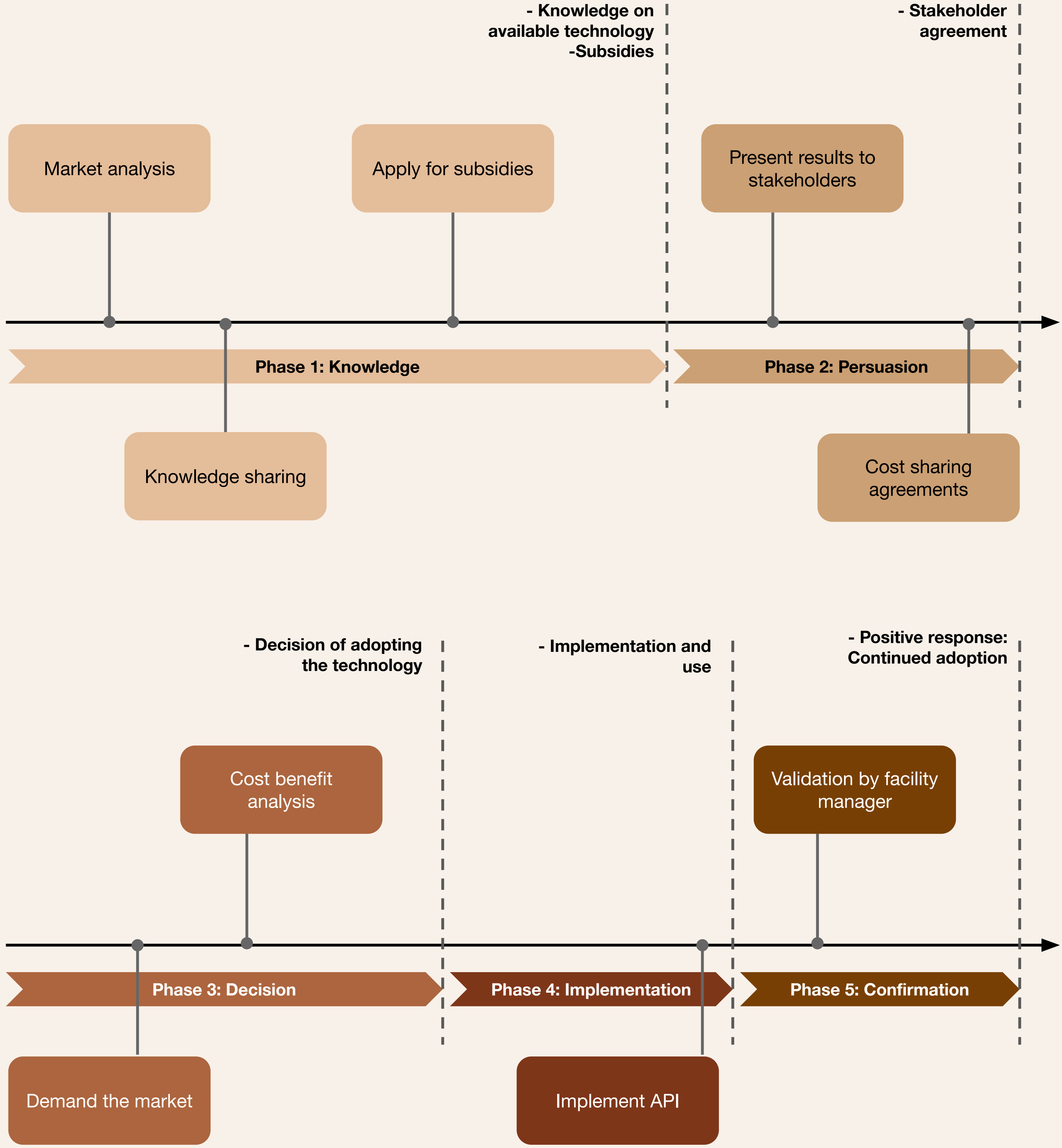
Identification of barriers and provision of recommendations to the B4B project

Case Study of Building 28, TU Delft

BARRIERS IDENTIFIED



RECOMMENDATIONS



ELABORATION OF STEPS

Phase 1: KNOWLEDGE

Do a market analysis

- To resolve the barrier of lack of knowledge of facility managers and the client (the university) not knowing what to ask for from the market parties, conducting a market analysis of the emerging technologies and their benefits should be conducted.
- Communicating these findings of the technology and benefits of use with facility managers mitigated the barrier of lack of their knowledge.
- Similarly, doing such research by the university can also benefit in knowing what to ask the market parties or technology companies that are in contract with the university.

HOW: The market analysis should be conducted by internet search on websites of technology providing companies. The project should be updated with the latest services that these companies provide to make the buildings more smarter and help the facility managers better.

Knowledge sharing

- The knowledge sharing should be extended from the academic level to a practical level which involves communicating findings with the relevant stakeholders including the facility managers which provides them information with what kinds of research are being conducted in the living labs.

HOW: Better communication and involvement of stakeholders such as facility managers through webinar invitations and regular workshops. Completing the handbook that the B4B project has been working on about data integration which includes the steps to take on smart technology adoptions.

Use subsidies

- Bigger investments are needed to scale up the pilot projects.

HOW: B4B can apply for more subsidies to aid the scaling up. Since adopting new technologies often come with the added advantage of sustainability and benefit to the environment, subsidies aimed at sustainability and energy efficiency can be targeted.

ELABORATION OF STEPS

Phase 2: PERSUASION

Provide proof of benefits

- The proof of benefits concluded from Phase 1 should be presented to the relevant stakeholders. Different benefits should be presented to different stakeholders depending on their interests.

HOW: For example, energy saving opportunities which come as an added benefit to better comfort management should be presented to Team energy. Similarly, the savings on costs allowed by better planning through historical data should be presented to the Dean and Faculty heads.

Cost sharing agreements

- To overcome the barrier of split incentive which involves different stakeholders, a cost sharing agreement should be proposed by the B4B project to the stakeholders involved.

HOW: This agreement should be based on the amount of savings the different parties gain from the new technology and should be binded legally into a contract signed by the stakeholder so that issues will not arise in the later stages due to conflicts.

Phase 3: DECISION

Help university demand the market

- The client (the university) should know what to ask the market in terms of the kind of technology, its benefits and how it works.

HOW: The information gained during the knowledge stage by market analysis and knowledge sharing has a positive influence on this. Moreover, the involvement of the facility managers in an early stage allows them to identify the exact needs of the end users and hence, the university can present their demands more clearly to the market parties.

ELABORATION OF STEPS

Cost benefit analysis

- A cost benefit analysis (CBA) should also be conducted in order to convince the relevant stakeholders to invest in the new technology. The purpose of the CBA is to evaluate the financial viability, potential benefits, and associated costs of the technology to determine if it is worth pursuing. The results of the CBA can be used to make an informed decision about whether to proceed with the technology implementation. This analysis helps stakeholders understand the return on investment (ROI) and justify the expenditure.

HOW: In the CBA, the costs involved in acquiring, implementing, and maintaining the new technology and the potential benefits such as efficiency, cost savings, and improved satisfaction should be assessed.

Phase 4: IMPLEMENTATION

Implement APIs

- Standardised APIs can promote interoperability between different systems and vendors, reducing the risk of vendor lock-in and making it easier to switch providers if necessary. By using APIs, organisations can integrate diverse services and components, allowing greater flexibility and adaptability to changing business needs.

HOW: B4B project can facilitate the process of implementing such API by connecting the client (the university) to one of their partner technological companies.

Phase 5: CONFIRMATION

Validation by end users

- Since the use of the online platform and dashboard is a technology aimed at helping facility managers in their tasks, the confirmation should also come from them.

HOW: Surveys and interviews should be conducted to ask the FMs if the use of such dashboards are actually being helpful or not. If it is confirmed by them that it is beneficial, the technology adoption can be continued.